ismar10
INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE
Madrid, 2019 May

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United Nations Educational, Scientific and Cultural Organization · International Hydrological Programme

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Managed Aquifer Recharge: Local solutions to the global water crisis

PROCEEDINGS OF THE SYMPOSIUM
ISMAR 10

GrupoTragsa

Proceedings of the International Symposium on Managed Aquifer Recharge (ISMAR 10)

Managed Aquifer Recharge: Local solutions to the global water crisis

ismar10
INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE
Madrid, 2019 May

Madrid, Spain. 2019 May 20th to 24th

Organized by:

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Proceedings of the International Symposium on Managed Aquifer Recharge (ISMAR 10)

Managed Aquifer Recharge: Local solutions to the global water crisis

Subdirección de Innovación y Desarrollo de Servicios

Author: Multiauthor
ISBN-13: 978-84-09-15736-5

Empresa de Transformación Agraria, S.A. (TRAGSA)
C/ Maldonado, 58
28006 Madrid Spain

Editor:
Enrique Fernández Escalante. Dr. in Hydrogeology, Innovation Subdirectorate, Tragsa Group.

Editorial team:
Jon San Sebastián Sauto. Dr. in Biology, Tragsatec.
Rodrigo Calero Gil. Agronomic Engineer. Innovation Subdirectorate, Tragsa Group.
Rocío Ortega Labrandero Agronomic Engineer. Innovation Subdirectorate, Tragsa Group.
José Antonio de la Orden. Dr. Minning Engineer. Instituto Geológico y Minero de España.

Madrid, 2019, November

Proceedings of the International Symposium on Managed Aquifer Recharge (ISMAR 10)

Managed Aquifer Recharge: Local solutions to the global water crisis

Madrid, Spain. **2019 May 20th to 24th**

Introduction

The ISMAR conference series was born in August 1988 in Anaheim California as the 1st International Symposium on Artificial Recharge of Ground Water. Pioneered by the American Society of Civil Engineers (ASCE), it continued in Orlando, Florida (1994) before the International Association of Hydrogeologists (IAH) partnered ASCE in Amsterdam (1998).

Following the 4th Symposium in Adelaide (2002) the name changed to International Symposium on Managed Aquifer Recharge to reflect the growing scientific basis supporting overt management of quantity and quality of recharge, and reflected the name of the IAH Commission on MAR, which was established in 2002. ASCE has also adopted this name for its relevant standards committee. Dedicated to a global reach, recent ISMAR conferences have been ISMAR 5 (Berlin, Germany, 2005), ISMAR 6 (Phoenix, USA, 2007), ISMAR 7 (Abu Dhabi, U.A.E., 2010), ISMAR 8 (Beijing, China, 2013), ISMAR 9 (México City, Mexico, 2016) and ISMAR 10, Madrid, Spain, 20-24 May 2019.
The Symposium continued as a joint venture of IAH/ASCE and is the prime international meeting in this field, adopting the Commissions aims, "to expand water resources and improve water quality in ways that are appropriate, environmentally sustainable, technically viable, economical, and socially desirable. It will do this by encouraging development and adoption of improved practices for management of aquifer recharge," IAH, January 2002.

This book collects all the presentations revised by pairs and exposed at the Symposium.

From 2019 May 20th to 24th has taken place in Madrid, La N@ve the 10th International Symposium on Managed Aquifer Recharge (ISMAR 10), promoted by Grupo Tragsa and the Spanish Geological survey (IGME) under the auspices of the International Association of Hydrogeologists (IAH), UNESCO and ASCE, among others, under the title: *“MAR to solve the global water crisis”.*

This event was supported by institutions and companies, such as the ministries of Agriculture…, Ecological Transition and Science… of the Spanish government and private companies such as Suez, Molecor, Catalana de Perforacions, Allied Waters, Regaber, Amiblu, Prefabricados Delta, Odín Water Solutions, etc.

The Symposium was attended by 320 delegates from 62 countries, and counted on 22 technical sessions, 123 oral presentations, 98 posters, 4 round tables, 3 keynote presentations, side events, six first day short courses, two workshops, three technical field trips, and a lot of knowledge recharged. Detailed info is provided at http://ismar10.net under the title: *“Affection and faith in MAR is noticeable and contagious”.*

This proceedings book of the Symposium is entitled “Managed Aquifer Recharge: Local solutions to the global water crisis” is composed by papers and extended abstracts. At least 18 remarkable papers were gathered in a Special edition of the Journal Water (MDPI) entitled “Managed Aquifer Recharge for Water Resilience”.

Poster´s authors were specifically requested by the organizers either they had a parallel written paper or not. Posters have been published in a book entitled P-ISMAR 10. http://www.dina-mar.es/pdf/P-ISMAR-10.pdf

You can hereby enjoy the publication resulting from this cooperation, which consists of 73 papers and 16 extended abstracts, what allows us to share some information that, otherwise, could have been lost.

The papers are listed in the next index, with mention to their titles and authors, ordered by sessions. Unfortunately, not all the papers could be collected as the participation had a volunteer character.

Tragsa Group organizers team would like to thank all the authors, whose contribution is sincerely appreciated. We would also like to thank IAH MAR Commission for their kind assistance.

Further information on ISMAR 10 event at:
http://recharge.iah.org
http://ismar10.net
http://dina-mar.es

ISMAR 10 Scientific Committee
(in alphabetical order)

Dr. Alice Aureli
UNESCO-IHP
France
a.aureli@unesco.org
Dr. Andrew Ross
Australian National University
Australia-France
a.ross@anu.edu.au

Dr. Arnaud Sterckx
IGRAC - International Groundwater Centre
The Netherlands-Belgium
arnaud.sterckx@un-igrac.org
MSc. Bob Bower
WGA
New Zealand
BBower@wganz.co.nz
Dr. Carlos Gutiérrez Ojeda
Instituto Mexicano de Tecnología del Agua (IMTA)
Mexico
cgutierr@tlaloc.imta.mx

PhD. Carola Rojas Vega
Autoridad Nacional del Agua (ANA)
Peru
carojas@ana.gob.pe
Dr. Catalin Stefan
University of Dresden
Germany
catalin.stefan@tu-dresden.de
Dr. Christoph Sprenger
Berlin Kompetenz Wasser
Germany
Christoph.Sprenger@kompetenz-wasser.de
Dr. David G. Pyne
ASR Systems
USA
DPyne@asrsystems.ws
Dr. Declan Page
CSIRO Land and Water
Australia
Declan.Page@csiro.au

Eng. Doug Bartlett
Clear Creek Associates – ASCE
USA
dbartlett@geo-logic.com
Dr. Emilio Custodio Gimena
Universidad Politécnica de Cataliña
Spain
Ecustodio@upc.es

Dr. José María García Asensio
Tragsa International – DINA-MAR
Ecuador-Colombia
jgarci36@tragsa.es
Dr. Juan Grima Olmedo
International Water Resources Association-IGME
Spain
j.grima@igme.es
Dr. Kim Yongcheol
KIGAM
Korea
yckim@kigam.re.kr
Dr. Koen Zuurbier
KWR
The Netherlands
Koen.Zuurbier@kwrwater.nl
Dr. Luis Martínez Cortina
Water General Directorate
Ministry for the Ecological Transition
(MITECO). Spain
LMCortina@miteco.es
D. Manuel Navarro Comalrena de Sobregrau
Ministry of Agriculture, Fisheries and Food
Spain
mnacomal@mapama.es
Dr. Noureddine Gaaloul
INRGREF-Tunis
Tunisia-France
ngaaloul2003@yahoo.fr
Dr. Othman Almashaqbeh
Royal Scientific Society
Jordan
othman.mashaqbeh@rss.jo
Dr. Paul Pavelic
IWMI
Laos
P.Pavelic@cgiar.org
Dr. Peter Dillon
Former CSIRO Land and Water
IAH-MAR Commission
Australia
pdillon500@gmail.com
Dr. Pieter J. Stuyfzand
University of Delft-KWR
The Netherlands
Pieter.Stuyfzand@kwrwater.nl
Dr. Rudy Rossetto
Schola Superior Ingenieria Santa Anna, Pisa
Italy
r.rossetto@sssup.it

Dr. Enrique Fernández Escalante
Tragsa Group- IAH-MAR Commission-DINA-MAR.
Spain
efernan6@tragsa.es
Eng. Francisco Javier Sánchez Martínez
Water General Directorate
Ministry for the Ecological Transition (MITECO)
Spain
Jsanchez@miteco.es
Dr. Ido Negev
Mekorot Inc.
Israel
nido@mekoro
Prof. Jeff Camkin
University of Western Australia
Australia-Portugal
Jeff.camkin@uwa.edu.au
Dr. Jon San Sebastián Sauto
Tragsatec (ISMAR 10 Technical Secretary)
Spain
jsss@tragsa.es
Dr. Jordan Clark
Dept. of Earth Science and Program of Environmental Studies
University of California, Santa Barbara USA
jfclark@geol.ucsb.edu

Dr. José Antonio de la Orden Gómez
Instituto Geológico y Minero de España (IGME)
Spain
ja.delaorden@igme.es
Prof. José Antonio Iglesias Martín
Canal de Isabel II
Spain
jaiglesias@canaldeisabelii.es
Dr. Shakeel Ahmed
CSIR-National Geophysical Research Institute.
Saphpani. India
shakeelifcgr@gmail.com
Dr. Sharon Megdal
Water Resources Research Center
The University of Arizona
USA
smegdal@email.arizona.edu
Dr. Suzana de Lima Montenegro
Pernambuco University. BRAMAR
Brasil
suzanam@ufpe.br
DEA Mr Simón Pulido Leboeuf
Suez
España
simon.pulido@suez.com
Dr. Teresa Leitão
LNEC
Portugal
tleitao@lnec.pt
Dr. Wang Weiping
School of Resources and Environment
University of Jinan Shandong
IAH-MAR Commission
China
wangweipingwwp@126.com
Dr. Yan Zheng
University of Science and Technology, Beiging
China-USA
yan.zheng.unicef@gmail.com

Mentions

The Committee would like to thank the following for their assistance (in alphabetical order):

- Manuel Meléndez (DGA-MITECO)
- Isabel Bombal (MAPA)
- María Fernández (MAPA)
- Samuel Moraleda (CHG-MITECO)
- Dolores Pascual (CHE, MITECO)
- Paloma López-Izquierdo Botín (Grupo TRAGSA)
- Manuel López Hernández (Grupo TRAGSA)
- Esther Sánchez Sánchez (Canal de Isabel II)
- Rocío Ortega Labrandero (Grupo TRAGSA)
- Cristina Granada Ruiz (Grupo TRAGSA)
- Ramiro Angulo Sánchez (Suez).

Themes and topics (=sessions)

1. MAR AND INTEGRATED WRM
MAR & rural. MAR for rural and irrigation water supplies
Potential of MAR in long-term/distance water diversion schemes
Establishing strategic groundwater reserves

2. MAR AS A KEY CLIMATE CHANGE…
Innovation in harvesting and storing flood water
Detention and infiltration systems
Mitigation of climate change adverse impacts by means of MAR

3. NEW REGIONAL CASE STUDIES
MAR in developing countries

4. MAR MAPPING
Advanced methodologies for the selection of aquifers/sites
MAR maps methods & new MAR maps

5. MAR AND ECONOMIC ASPECTS
Quantification of benefits and costs of MAR
Circular economy and MAR (from cradle to cradle)
Financing MAR for water and food security
Water footprint from MAR activities. Green and blue waters
Public Procurement of MAR Innovative Solutions

6. MAR to MAR-k€t
MAR to complement groundwater demand management
Industrial applications of MAR, agroindustry and mining
Geothermal injection, MAR to source heat pumps…

7. MAR AND WATER REUSE
Water reclamation technologies for MAR
Reclaimed water reuse via aquifers

8. SUSTAINABLE MAR TECHNICAL SOLUTIONS
Advances in design and construction criteria of MAR systems, BIM
MAR Technical Solutions (SMARTS). Methods and strategies
Alternative and innovative water recharge systems
Operations and maintenance of MAR

9. MAR AND MANAGEMENT OF CLOGGING

10. MAR & REGULATIONS
MAR worldwide regulations
Recharge policies, quality standards
Institutional innovation for MAR. Water banks, groundwater user groups…
Governance & Decision Support Systems (DSS)

11. MAR AND MONITORING
Water management and MAR innovative systems
IT applications
Normalization, standardization and interoperability advances

12. MAR AND MODELING
New developments and codes. Practical examples
Water quality interaction codes & hydro-economic modeling

13. MAR AND ECOSYSTEMS
Riparian restoration
Mitigating geological/geotechnical impacts using MAR, land subsidence…

14. MAR IN COASTAL AREAS…
MAR for mitigating saltwater intrusion
MAR with desalinated water

15. MAR AND ENVIRONMENT…
Risk and impacts assessment. Specific indicator systems for MAR
MAR activities impact evaluation assessment & Benchmarking

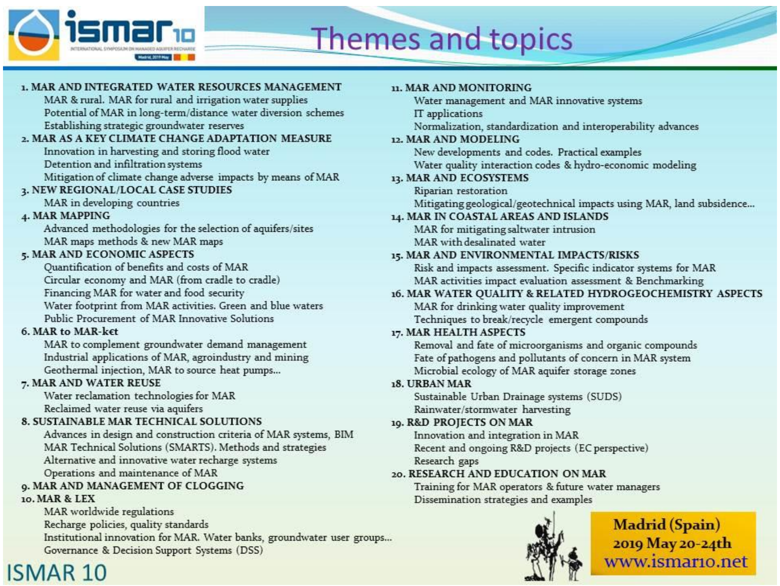
16. MAR WATER QUALITY…
MAR for drinking water quality improvement
Techniques to break/recycle emergent compounds

17. MAR HEALTH ASPECTS
Removal and fate of microorganisms and organic compounds
Fate of pathogens and pollutants of concern in MAR system
Microbial ecology of MAR aquifer storage zones

18. URBAN MAR
Sustainable Urban Drainage systems (SUDS)
Rainwater/stormwater harvesting

19. R&D PROJECTS ON MAR
Innovation and integration in MAR
Recent and ongoing R&D projects (EC perspective)
Research gaps

20. TRAINING ON MAR
Training for MAR operators & future water managers
Dissemination strategies and examples



ISMAR 10 slogan: MAR to solve the global water crisis

"MAR is part of the palette of solutions to water shortage, water security, water quality decline, falling water tables and endangered groundwater dependent ecosystems. Often it is the most economic, most benign, most resilient and most socially acceptable solution, but has not been considered out of lack of awareness, inadequate knowledge of aquifers, immature perception of risk and inadequate policies for integrated water management, including linking MAR with demand management. MAR can achieve much towards solving the myriad of local water problems that collectively have been termed "the global water crisis", if it is included among the options evaluated locally. ISMAR10 strives to make transparent the effectiveness, benefits, constraints, limitations and applicability of MAR, together with its supporting scientific advances, to a wide variety of situations that have global relevance. No groundwater manager or consultant is complete without a comprehensive knowledge of MAR, and the fastest way to get up to date with international knowledge and connections is to attend ISMAR10. This premium international symposium dedicated to MAR comes along only once in three years. Spain has been a hotbed of innovation and application in this field, with the fastest national rate of growth in MAR, so Madrid is the perfect destination for water problem solvers from around the world. You are warmly invited and will be truly welcome and vocationally recharged at ISMAR10."

Peter Dillon, Weiping Wang and Enrique Fernández Escalante (Co-chairs of IAH Commission on Managing Aquifer Recharge until ISMAR 10).

Special sessions

- **Arid zones**
- **Adaptation**

Journal Water Special issue

Most of the papers included as “extended abstract” (red color in the index) have been published in the special issue:
Managed Aquifer Recharge for Water Resilience

A special issue of *Water* (ISSN 2073-4441). This special issue belongs to the section "Water Resources Management and Governance".

Deadline for manuscript submissions: **20 November 2019**.

Share This Special Issue

Special Issue Editors

Dr. Peter Dillon E-Mail Website
Guest Editor
CSIRO Hon Fellow, NCGRT (Adj Chair), WGA Pty Ltd, Co-Chair IAH Commission on MAR
Tel. +61 8 8303 8714
Interests: hydrogeology; water quality protection; risk management; policy
Special Issues and Collections in MDPI journals

Dr. Gudrun Massmann E-Mail Website
Guest Editor
Carl con Ossietzky Universität Oldenburg, Hydrogeology & Landscape Hydrology, IBU, Fk. V, Gebäude A1, Germany
Tel. +49 441 7984837
Interests: hydrogeology; groundwater; organic trace pollutants; coastal aquifers; ecohydrology

Dr. Sharon B. Megdal E-Mail Website
Guest Editor
University of Arizona, Water Resources Research Center, Tucson, AZ, USA
Fax: +1 520 792-8518
Interests: water management and policy; groundwater; water banking and recharge; water governance and institutions; transboundary water
Special Issues and Collections in MDPI journals

Dr. Enrique Fernández Escalante E-Mail Website
Guest Editor
Tragsa R&D, WB Consulter, Co-Chair IAH MAR Commission
Tel. +34913226106
Interests: IWRM; hydrogeology; technical solutions on water management

https://www.mdpi.com/journal/water/special_issues/ISMAR10_2019

extended abstract
Full papers

INDEX Papers (oral or posters presentations) ordered by sessions

16 Extended abstract

73 Full papers

*All the papers have been reviewed by pairs by ISMAR 10´s Scientific Committee members.

Presentations* posted in YouTube (videos) list:

*Marked with (YouTube) in the Index at the end of the authors cell.

Auditory. May 21th. Tuesday

-Lindhe, Andreas- **Dynamic water balance modelling for risk assessment and decission support on MAR potential in Botswana**- https://youtu.be/YyA21goQDb0

- Anis Chekirbane- **Tunisian experience in managed aquifer recharge by hill dam water release: case of some groundwater flow systems in North of Tunisia**- https://youtu.be/q-hDccHsC48

- Bob Bower- **Integrated Water Management Utilising the tools of Managed Aquifer Recharge (MAR): Developing a Catchment-Scale Groundwater Replenishment System for the Hekeao/Hinds Plains, Canterbury, New Zealand**- https://youtu.be/KegVme5iSnI

- McGibbon, David- **Emergency response to drought - the City of Cape Town's groundwater abstraction and MAR scheme (South Africa)-** https://youtu.be/bgQRDyKmIzU

- Tuthill, David R- **Implementing Incentivized Managed Aquifer Recharge on a Basin Scale-** https://youtu.be/SAwk2Fm3JcU

- Kalbus, Edda- **Strategic Water Storage and Recovery with Desalinated Seawater in Liwa, UAE-** https://youtu.be/dU7lPaAF2PM

- Greg Woodside- **Integration of Stormwater Capture at Flood Management Reservoir with Managed Aquifer Recharge, Orange County, California**- https://youtu.be/Ih_tlVpc710

- Harrie Timmer- **Seeking Simplicity, Reliability and Sustainability in Drinking Water Purification for Future: the River Bank Filtration Based One Step Reverse Osmosis Process: from Concept to Practice**- https://youtu.be/5at4ZyUgpnc

- Karapanos, Ilias- **Artificial recharge mechanisms via a leaky river bed – a case study in the outskirts of London, UK**- https://youtu.be/JUs5ADhdyHM

- Karen Villholth- **Groundwater-based natural infrastructure: a critical piece in supporting water security and resilience**- https://youtu.be/cEhJh8Esj0k

- Lukas Rolf- **Implementing an energy-neutral Aquifer Storage and Recovery (ASR) system in a complex geological context in Lebanon**- https://youtu.be/7Q_G0T65hiw

- Towers, Luke- **The Atlantis Water Resource Management Scheme – resource management is people management**. - https://youtu.be/sEek2j7mRjU

- Cruz A. Mary-Belle- **Use of Managed Aquifer Recharge to improve Water Management in Arid and Semi-Arid Regions of Mexico**- https://youtu.be/al_sPB4e8JI

- P.K. Singh- **Managing Aquifer Recharge at Local Level in India: Developing a Framework for Village Groundwater Co-operatives**- https://youtu.be/oXEP-qWP4jk

- P. Soni- **Managed Aquifer Recharge at a Farm Level: Evaluating the Performance of Direct Well Recharge Structures**- https://youtu.be/U2EcYyMbNiQ

- Navarro Venegas, Roberto & Massa, Francisco- **The MAR system in Ica, Peru. Technical and social lessons learned from a Mega-scale MAR system and improvement possibilities-** https://youtu.be/oeLy6e8BIPc

- Steven Wallander- **Postdoctoral Research Associate at University of Arkansas, Associate Professor at University of Arkansas and Economist at USDA Economic Research Service-** https://youtu.be/jXAGYAgbFts

- Kissane, Stephen- **Managed Aquifer Recharge and Aquifer Storage and Recovery in Kabul, Afghanistan**- https://youtu.be/uFRoHemf6q4

- Grischek, Thomas- **Riverbank filtration with siphon wells – breathing new life into an old idea-** https://youtu.be/hVVepCX0Ahw

- Hartog;van Nieuwkerk- **Scaling-up river water-fed Managed Aquifer Recharge in the deeply anoxic Makauri Aquifer, Gisborne (New Zealand)**- https://youtu.be/BToV37X48ow

Auditory. May 22th. Wednesday

- Weisbrod, Alex**- Geo-electrical monitoring of soil aquifer treatment**- https://youtu.be/u_o-ZqrqWh0
-Weisbrod, Alex- **On the mechanisms affecting and controlling SAT operation**- https://youtu.be/JLgV_OuGs7I
-Mukhopadhyay, Amitabha- **Numerical modeling of pumping test data at an artificial recharge site in Kuwait**- https://youtu.be/d6RTXljpoCc
-Kacimov, Anvar- **Dipolic MAR "Bubble" Inside Confined Brine Formation or Floating "Lens" on Top of Unconfined Saline Aquifer**- https://youtu.be/R-aFNOo_Rio
- Guo Chunyan- **Using environmental isotope and major ions to characterize recharge and mixing properties in the aquifer system along Fen River in Taiyuan basin, northern China**- https://youtu.be/-F8Dwclv4Lc
- Houlbrooke, Clare- **Initial Results from Managed Aquifer Recharge Trials in the Hekeao/Hinds Plains, Canterbury, New Zealand**- https://youtu.be/LVpmjBwEyzA
- Pyne, R. David- **Conjunctive Use of Aquifer Storage Recovery Wells and Desalination to Mitigate Salt Water Intrusion and Achieve Water Supply Reliability**- https://youtu.be/c-vg-1PD7rE
- Bartlett, R. Douglas- **Comprehensive Guidelines for Managed Aquifer Recharge to Be Published by ASCE/EWRI**- https://youtu.be/5wCtEn1Hpvw
-Fernández Escalante, Enrique**- Ancient techniques of Managed Aquifer Recharge: Spanish Careos and Peruvian Amunas as an Adaptive Complex System. Breakdown, pathology and comparative analysis**- https://youtu.be/ct1J-Oxx_Zc
-Musche,Fabian-**Flood-protection of riverbank filtration wells**- https://youtu.be/TBDXwUznHfw
-De Filippis, Giovanna- **Design and operation of the MAR infiltration scheme in Suvereto (Italy)**- https://youtu.be/XYP5o8B6Zbg
-Sallwey, Jana- **MAR assessment through physical models: comparison of laboratory and field experiments**- https://youtu.be/jCKSEcePzAM
-Brindha, K- **Influence of aquifer recharge structures and surface water bodies on geogenic fluoride contamination**- https://youtu.be/NfxKwRV_ZUM
-Li Ya-song- **Study on the groundwater recharge based on South to North Water Diversion Project in Hutuo River Alluvial Plain, North China**- https://youtu.be/1x-W6tsIBYQ
-Pascual, Mª Dolores- **The Water in Spain**- https://youtu.be/l0S-ajiK-HY
-Imaz Lamadrid, Miguel A- **Managed Aquifer Recharge Plan based on a surface water- groundwater model for the Santo Domingo creek, Baja California Sur, Mexico**- https://youtu.be/VIub6bAauBQ
-Stuyfzand, Pieter J- **Environmental impact and mitigation of intake interruptions for Basin Aquifer Transfer Recovery systems**- https://youtu.be/qsAz0hdFr3U
-Rossetto, Rudy- **ECT solutions from monitoring and operation**- https://youtu.be/wm2wy_FmJ6k
-Roehl, Karl, on behalf of-Ortega, R; Fernández, E; Sapiano, M; Lobo, J P.; Guttman, Y; Schütz, C*.; Weffer-Roelh, A.; San Sebastián, J.; Kallioras, A. & Dietrich, P- **Managed Aquifer Recharge Solutions (MARSOL). Final statements VIDEO**- https://youtu.be/t9kvVRrKEMg

Auditory. May 23th. Thursday

- Benton, Andrés- **Recharge of aquifers through wells in urban areas of Mexico City**- https://youtu.be/q3g-bEfaBls
- Page, Declan- **Managed aquifer recharge as a strategic storage and urban water management tool in the Darwin rural area, Northern Territory, Australia**- https://youtu.be/ECAxAtZgI-Y

- Kruisdijk, Emiel- Push-Pull test – **Reactive transport modelling: A new approach to study water quality changes**- https://youtu.be/7gKIl4f0XTk
- Prieto Leache, Ignacio- **SUDS and resilience to climate change**- https://youtu.be/HuA_BZwlnGo
- Masse-Dufresne Janie- **Anticipating pathways and timing for cyanobacteria 12 breakthrough at a 2-lake bank filtration site via environmental tracers**- https://youtu.be/rDOsuYQE3kQ
- Drewes, Jörg- **Next generation Managed Aquifer Recharge Systems for Enhanced Trace Organic Chemical and Pathogen Removal**- https://youtu.be/-ANe62Nf9Ew
- Zuurbier, Koen- **Preventing pluvial flooding and water shortages on various scales by integrating aquifer storage and recovery in urban áreas**- https://youtu.be/2yGdVAYaAUM
- Jones-Sánchez, Mark- **Riverbank filtration in a narrow river valley of the Barranca River, Costa Rica**- https://youtu.be/Ls_08_tGBtU
- Rodríguez-Escales, Paula- **Modeling the influence of temperature in the infiltration rates and redox reactions of an infiltration pond located in the Llobregat River Basin**- https://youtu.be/6Tf1DSLQ2iw
- Dillon, Peter- **Principles for rainwater management in a multisponge city using soil, unconfined- and confined aquifers**- https://youtu.be/Oy29jv6Mts8
- Rafiq, Muhammad- **Key hydrogeochemical processes (im)mobilizing trace metals (arsenic, iron, manganese) in MAR for drinking water provision in Bangladesh**- https://youtu.be/TxJfeNOI7hQ
- S.K. Sharma- **The role of organic matter in the release of iron and manganese during bank filtration**- https://youtu.be/Y80eINBDIjs
- Kissane, Stephen- **Groundwater and Water Bourne disease in Kabul Matti, Boris; Klein, Hugh; Tookhi, Mohammad Naim**- https://youtu.be/dx2t8yxlNvE
- Price, Victoria- **Investigating a Strategic Aquifer Storage and Recovery Scheme in the Sherwood Sandstone to Improve Resilience**- https://youtu.be/9J7UlkN1HGY
- Jadeja Y. J- **Participatory Aquifer Management an Alternative Approach to Sustain Urban Water Supply – a case study of Bhuj City – Gujarat, India**- https://youtu.be/13v0CLeeBTs

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-Miguel Ángel González Nuñez- **Correlation of the infiltration velocity with the hydraulic load of operation of the treated wastewater infiltration basin**- https://youtu.be/6pSEfPh0B-M
-Miguel Ángel González Nuñez-**Manejo de la recarga de acuíferos: Un enfoque hacia Latinoamérica**- https://youtu.be/w8kEX5Si3xE
-Rania Abd-El-Baky- **Groundwater Hydraulics - Computing Groundwater Into/Out Flow for Lakes. (Study Case Lake Qarun, Egypt)**- https://youtu.be/COp4GpeXyeA

Sala 2. May 22th. Wednesday

-Troeger, Uwe- **Flash floods – possibilities of artificial recharge, example Egypt**- https://youtu.be/VKm2A5utBbg
-Alam, Mohammad Faiz-**Underground Taming of Floods for Irrigation (UTFI): Global to field scale assessments**- https://youtu.be/CixLQUWhVWU
-Kalwa, Fritz-**Biological and Physical Clogging in Infiltration Wells – The Effect of Well Diameter and Gravel Pack**- https://youtu.be/CS_T7qZ_O9s
-Keller, Jason- **Alluvial Aquifer Filtration as a Pretreatment Option for ASR**- https://youtu.be/eOxXpB0GUVg
-Zhang Hexuan-**Laboratory Research on the Laws of Fe(III) Clogging during Urban Stormwater Groundwater Recharge**-https://youtu.be/JPztqMKaYNE

-Barquero; Felix-**Laboratory experiments for the assessment of the impact of solar irradiance on clogging of MAR basins**- https://youtu.be/Cf5abprzDj4
-Shechter Tamir-**The Effect of Soil Tillage Equipment on Recharge Capacity of Infiltration Ponds**-https://youtu.be/AjxVYdUVogA

Sala 2. May 23th. Thursday

-Dahlqvist, Peter, Karin, Lindhe-**MAR on the Island of Gotland, Sweden – exploring the potential and feasibility in comparison to alternative measures**-https://youtu.be/Z8UCn_klcvE
-Hasan, Mohammad Imran-**Assessment of aquifer storage and recovery efficiency in coastal aquifers**-https://youtu.be/lAgY9qpuaus
-Kurtzman Daniel-**Monitoring and modeling MAR of desalinated seawater to a Mediterranean fresh-water aquifer, from ground-surface to wells' perforations**-https://youtu.be/sLkMCVDEyiQ
-Jylhä-Ollila, Maija-**Seasonal Variations in Water Quality and NOM Removal in Natural Bank Infiltration of Boreal Lake Water**-**https://youtu.be/vZyV6J-07fU**
-Reeve, Peter- **Emerging organic contaminants in managed aquifer recharge: investigating their removal to ensure a sustained, safe, high quality water resource**-https://youtu.be/Hu0rSDScyhI
-Pontoreau, Coralie-**Deciphering the long-term evolution of groundwater mixings at a multi-aquifer river bank filtration site**-https://youtu.be/6m6xkUW5Dag
-Burke, Victoria-**Coupling bank filtration to pond infiltration – a useful option in terms of quality improvement?**-https://youtu.be/VEBSK5VSDxI
-Modrzyński, Jakub-**Combined removal of organic micropollutants and ammonium in a column study with reactive barriers simulating MAR**-https://youtu.be/-uuI_A_9Dns
-Donn, Mike- **E. coli attenuation during infiltration of treated wastewater**-https://youtu.be/uv_wvUFwxZc
-Eisfeld, Carina- **Fate of plant pathogenic bacteria in drainage water during managed aquifer recharge for agricultural irrigation**-https://youtu.be/Q8sWiNwFh1c
-Ma, Yunjie- **Antibiotic Degradation during Riverbank Infiltration of Reclaimed Water at Beiyun River in the North China Plain**-https://youtu.be/w1nWpcQPLWo
-Zsuzsanna Nagy-Kovács- **Water quality changes during river bank filtration at Budapest, Hungary**-https://youtu.be/vakFgH4ua1Q

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Topic 1- MAR AND INTEGRATED WRM

Paper for ISMAR10 symposium. ***Topic No: 1 (002#)***

Integration of Stormwater Capture at Flood Management Reservoir with Managed Aquifer Recharge, Orange County, California

Adam Hutchinson[1] and Greg Woodside[2*]

[1] Orange County Water District, Fountain Valley, CA; ahutchinson@ocwd.com
[2] Orange County Water District, Fountain Valley, CA
* Correspondence: gwoodside@ocwd.com; 01-714-378-3275

Abstract: The United States Army Corps of Engineers (USACE) and Orange County Water District (OCWD) are implementing an innovative integrated water resources management program utilizing Prado Dam in Riverside County, California. USACE owns and operates Prado Dam for flood risk management. The program provides for temporary stormwater capture at the dam and subsequent water release for groundwater recharge. Temporary capture (short-term storage) of stormwater cannot impact the dam's primary flood risk management purpose. Water pooled at the dam submerges lands with habitat for endangered species. The program required overcoming three obstacles: (1) capturing stormwater without impacting the dam's flood risk management purpose, (2) solving endangered species habitat and nesting conflicts in the reservoir area where water is pooled, and (3) developing facilities downstream of Prado Dam to recharge stormwater. Capturing stormwater at Prado Dam without impacting flood risk management requires USACE to rapidly release stormwater captured under the program if holding the water would reduce flood management in a pending rainfall event. USACE and OCWD coordinate closely to release stormwater captured at the dam so that release rates are maximized but do not exceed OCWD's recharge capacity. USACE can temporarily store 24 Mm^3 at Prado Dam for downstream groundwater recharge. OCWD's recharge facilities are located approximately 20 km downstream of Prado Dam. OCWD constructed two inflatable rubber dams to divert Santa Ana River water released from Prado Dam. Water diverted from the river is recharged into the groundwater basin through 22 surface recharge facilities. The recharge facilities sustainably recharge 10 to 20 m^3/s of river water. OCWD's recharge capacity allows 24 Mm^3 captured at Prado Dam to be recharged in approximately 25 to 40 days. Environmental laws prioritize protection of endangered species. The Least Bell's vireo, a small songbird, is now breeding successfully in the lands upstream of Prado Dam. When the integrated water resources management program was proposed, wildlife management agencies initial reaction was negative due to the vireos near extirpation. However, OCWD and USACE developed a new program to increase vireo habitat and nesting success. In the last 30 years, the number of male nesting territories has increased from less than 20 to over 500 as a result of the program's efforts to expand habitat, control nest parasitism, and other management activities. The program has successfully achieved an average of 62 Mm^3 of stormwater recharge per year.

Keywords: MAR in conjunctive use of surface water and groundwater; integrated water resources management; groundwater recharge.

1. Introduction

OCWD is a special governmental water agency that was created by the state of California in 1933 to manage the surface water and groundwater resources in northern and central Orange County. OCWD programs include aquifer recharge, seawater intrusion control, water quality protection and improvement, water recycling, and storm water conservation [1]. OCWD covers an area of approximately 900 km² (350 mi²) in the lower portion of the Santa Ana River Watershed (Figure 1). The Mediterranean-type climate in Orange County is generally mild, with annual rainfall of approximately 350 mm (14 in), and average monthly temperatures ranging from 14 to 24 °C (58–75 °F). Most of the rainfall occurs in the months of December through March. The Orange County Groundwater Basin managed by OCWD is the primary source of water for 2.5 million people, businesses and other water users in the area.

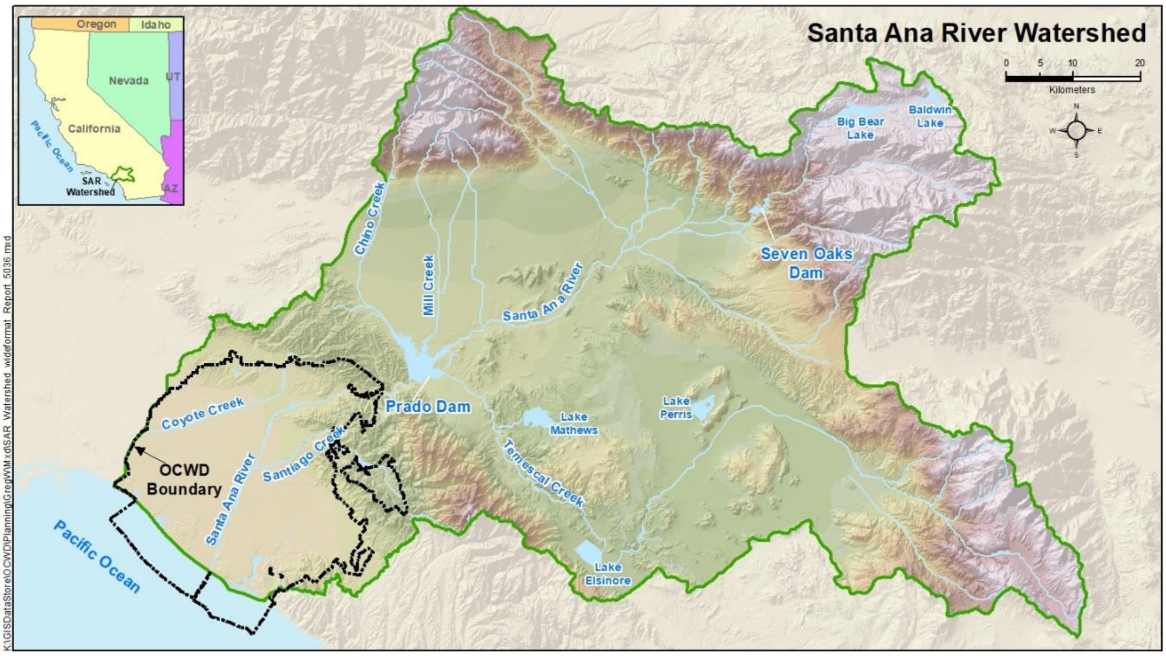

Figure 1. Santa Ana River Watershed.

A primary source of recharge water to the Orange County groundwater basin is the Santa Ana River (SAR), the longest river in coastal southern California. SAR flows are generally comprised of seasonal stormflow and treated wastewater discharged from upstream sewage treatment plants. On average, the total amount of SAR flow OCWD is able to capture and recharge in its recharge system is approximately 185 Mm^3 (150,000 acre-ft) each year. During periods of heavy rainfall, high flow SAR flow in the SAR may greatly exceed OCWD's recharge capacity and discharge to the Pacific Ocean. Due to urbanization, the Santa Ana River has large, rapid increases in flow rate due to stormwater runoff. The flow rate in the river can increase from 10 m^3/sec (350 ft^3/s) to more than 200 m^3/sec (7,200 ft^3/s) in less than 12 hours.

OCWD has worked for over 40 years with the United States Army Corps of Engineers (USACE), the owner and operator of Prado Dam on the SAR, to utilize Prado Dam in coordination with OCWD's managed aquifer recharge (MAR) facilities. Prado Dam is located near the middle of the Santa Ana River Watershed (Figure 1).

Integration of Prado Dam operations with OCWD's MAR required overcoming the following challenges:

- Capturing stormwater without impacting Prado Dam's flood risk management purpose.
- Solving endangered species habitat and nesting conflicts in the reservoir area upstream of Prado Dam where water is temporarily pooled.
- Developing facilities downstream of Prado Dam to divert stormwater from the SAR to recharge facilities.

Stormwater conserved at Prado Dam is recharged into the Orange County Groundwater Basin approximately 20 km downstream of Prado Dam. OCWD's MAR facilities for recharge include approximately 4.5 km^2 (1,100 acres) of surface recharge facilities that include desilting ponds, in-stream channels and recharge basins (Figure 2).

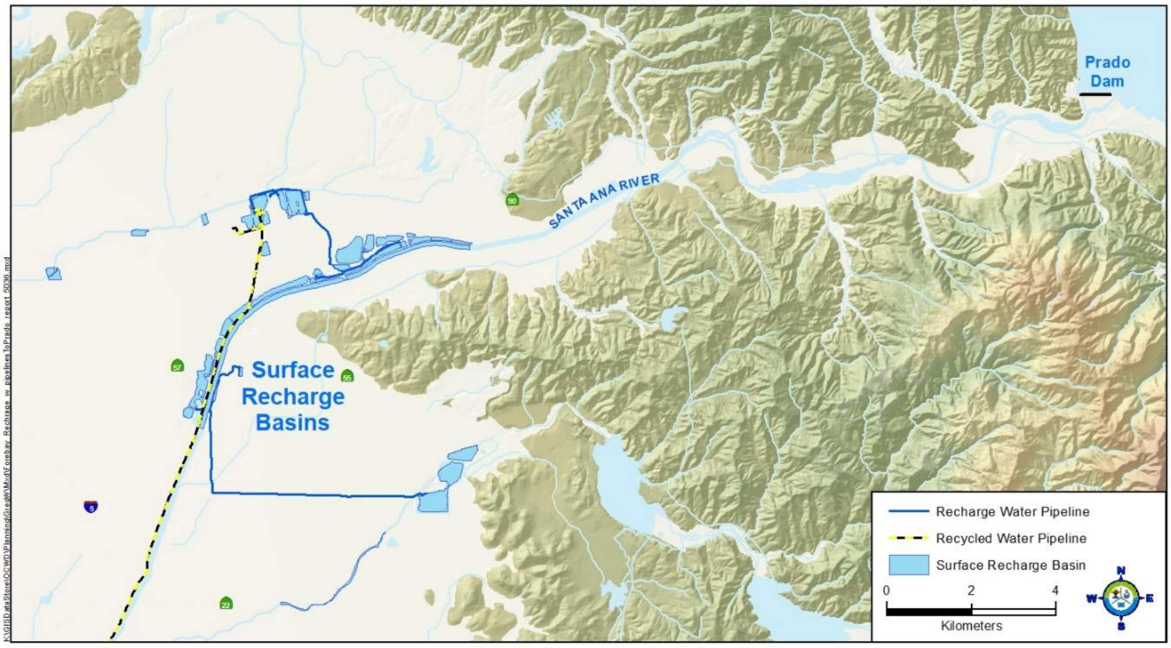

Figure 2. OCWD MAR Facilities Downstream of Prado Dam.

Stormwater infiltration through OCWD's MAR facilities reduces the amount of imported water OCWD needs to purchase. Imported water from the Colorado River Watershed or northern CA watersheds can be infiltrated at OCWD's MAR facilities but cost approximately $650 per 1,000 m^3 ($800 per acre-foot) and has a large energy footprint. Imported water originates over 300 km from OCWD and has to be pumped, creating an energy footprint of 2 GigaW-hour/Mm^3. Supplies of imported water supplies are also subject to disruption by earthquakes since the imported water aqueducts and pipelines cross major fault zones. SAR water flows from Prado Dam to most of OCWD's recharge facilities by gravity. OCWD uses pumps to dewater some facilities and pumps SAR water to the Santiago Basins. The energy footprint of OCWD's MAR system for SAR water is approximately 0.2 GigaW-hour/Mm^3, approximately 10% of the energy footprint of imported water used for MAR.

2. Materials and Methods

OCWD and USACE collaborated to prepare technical studies of environmental, hydrology and hydraulics, and related issues to implement stormwater capture at Prado Dam [2-4]. The methods included technical analyses by engineers, hydrologists, wildlife biologists, planners, environmental planners and other subject area experts. These technical analyses were required to answer fundamental questions regarding the feasibility of stormwater capture at Prado Dam, comply with USACE and OCWD policy requirements, and comply with federal and state environmental laws.

3. Results

3.1. Stormwater Capture at Prado Dam

The primary purpose of Prado Dam is flood risk management. Temporary capture of stormwater for subsequent groundwater recharge is an authorized secondary purpose. Capture of stormwater for groundwater recharge must be implemented in a manner that does not reduce the flood risk management purpose of Prado Dam.

Capturing stormwater at Prado Dam without impacting flood risk management requires USACE to rapidly release stormwater captured under the program if holding the water would reduce flood management in a pending rainfall event. USACE and OCWD coordinate closely to release stormwater captured at the dam so that release rates are maximized but do not exceed OCWD's ability to divert water from the SAR and overall recharge capacity, unless a higher rate of release is needed to maintain flood risk management. When the program was begun in the early 1990s, USACE and OCWD determined to develop a program that would start relatively small, test the initial concept, and then expand to larger storage volumes as appropriate.

The water storage volume for stormwater capture increased through time as USACE developed a longer period of record of operating the dam (Table 1). The volumes shown in Table 1 are based on the volume of water that could need to be released within one to two days before a pending rainfall event. The volumes were originally the same in the flood season (October through February) and non-flood season. The first seasonal variation was established in 1993. The higher non-flood season storage volume can be utilized within the first ten days of March and extending through September of each year. The flood season is identified as October through the end of February, with a transition period the first ten days of March. However, at all times, USACE retains complete authority and flexibility to release water as needed to maintain flood risk management.

Table 1. Summary of Temporary Stormwater Capture Volumes at Prado Dam for MAR.

Year Established	Flood Season Volume (Mm^3)	Non-Flood Season Volume (Mm^3)
1969	7	7
1990	10	10
1993	10	32
2006	17	32
2018	24	24[1]

[1] Decline in non-flood season volume due to sedimentation in reservoir

In 2019, USACE can temporarily store 24 Mm^3 at Prado Dam for downstream groundwater recharge (Figure 3). When storage to elevation 154 m above sea level (505 ft) was authorized in 2006, the storage volume at this elevation was 32 Mm^3 (26,000 acre-feet). The most recent survey indicates the storage volume at 154 m (505 ft) elevation has reduced to 24 Mm^3 (19,800 acre-feet) due to sedimentation behind the dam.

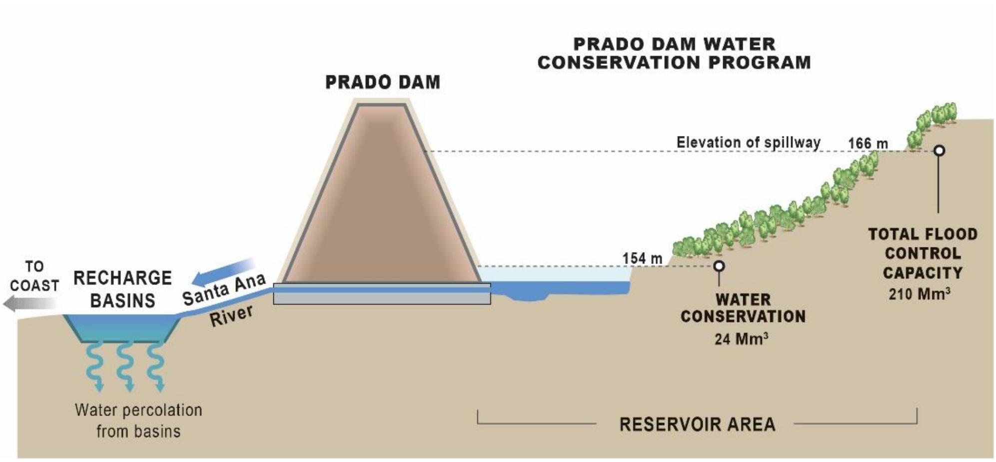

Figure 3. Schematic Cross-Section of Prado Reservoir Area and Downstream MAR Facilities.

An example of how the USACE operates the dam for both flood risk management and water conservation is shown in Figure 4. This figure is a hydrograph showing release of water prior to a storm in February 2017. Prior to the storm, up to 20 Mm³ was held for downstream groundwater recharge. Approximately 9 Mm³ was released on February 16-17, prior to the storm to minimize the extent to which the temporary water storage would exceed 24 Mm³. The rainfall and stormwater runoff forecast were generally accurate, and most of the water released was recaptured in the runoff event on February 18.

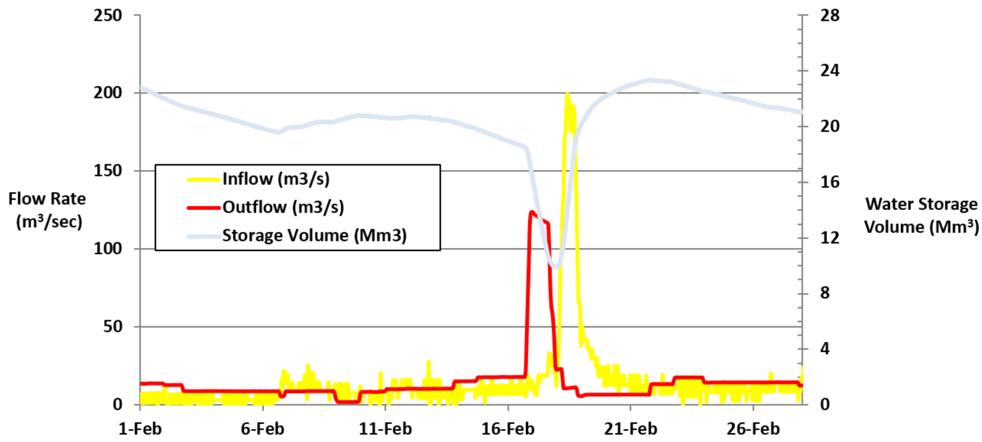

Figure 4. February 2017 Hydrograph of Stormwater Release and Capture at Prado Dam.

OCWD's downstream MAR facilites to divert and infiltrate SAR water released from Prado Dam include two inflatable dams to divert water off the river and recharge basins (Figure 2). The SAR channel also infiltrates 3 m³/s (100 ft³/s). Early in the storm season, OCWD can divert and manage about 14 m³/s (500 ft³/s) to 20 m³/s (700 ft³/s) of SAR water. In a year with average to above average rainfall, the sediment carried by SAR water clogs the recharge basins and the infiltration rates decline. By mid- to late-February, the SAR diversion rate to recharge basins declines to approximately 11 m³/s (400 ft³/s). There are no diversions downstream of OCWD's diversion points. SAR water flowing in excess of OCWD's diversion rates flows to the Pacific Ocean.

OCWD's recharge facilities provide approximately 31 Mm³ of storage space downstream of Prado Dam in Orange County. Early in the flood season, OCWD can divert SAR water from the river to storage in Orange County. In an average to above average year, the storage space in the MAR facilities in Orange County will be filled by storm water released from Prado Dam and some local inflow below the dam When system storage is full, the diversion rate of SAR water is reduced to the combined infiltration rate of the MAR facilities.

To reduce the inundation duration of riparian habitat, OCWD committed to a threshold release rate from Prado Dam during the non-flood season. Starting March 1 of each year, the minimum flow-weighted release rate from Prado Dam must be equal to or greater than 10 m^3/s (350 ft^3/s). This minimum release rate applies when the water surface elevation is greater than 152 m.

3.2. Natural Resources Program

United States and State of California environmental laws prioritize protection of endangered species. In the late 1980s and early 1990s,OCWD began exploring how to capture additional stormwater at Prado Dam. Prior to this time, the dam was operated to drain water as quickly as possible and maintain a nearly empty dam through the rainy season ending in early March. A major hurdle to temporarily capturing more stormwater at Prado Dam was the occurrence of endangered species habitat in the reservoir area behind the dam. Capturing more stormwater for downstream groundwater recharge would temporarily inundate riparian vegetation. If the inundation was too long, the riparian vegetation could be harmed. Wildlife management agencies initial reaction to increased stormwater capture at Prado Dam was negative due to the near extirpation of an endangered species, the least Bells vireo, a neotropical migratory song bird.

OCWD, USACE, and other partners developed a natural resources management program to recover the least Bells vireo. In 1983, there were approximately 10 male vireo territories in Prado Basin (Figure 5). The vireo recovery program implemented management measures to control nest parasitism by cowbirds, remove non-native, invasive weeds, and plant native riparian vegetation. As a result of the management program, in 2018 there are over 600 male vireo territories in Prado Basin (Figure 6). The vireo population in the Santa Ana Watershed is now the largest in southern California.

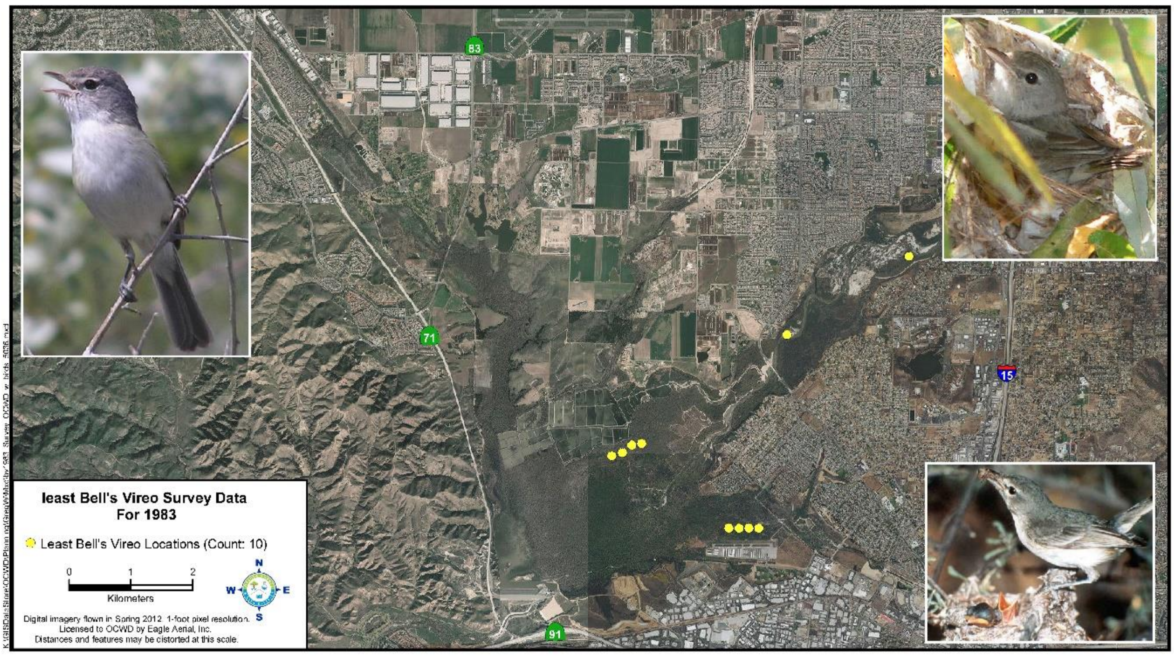

Figure 5. Least Bell's Vireo Territories in 1983.

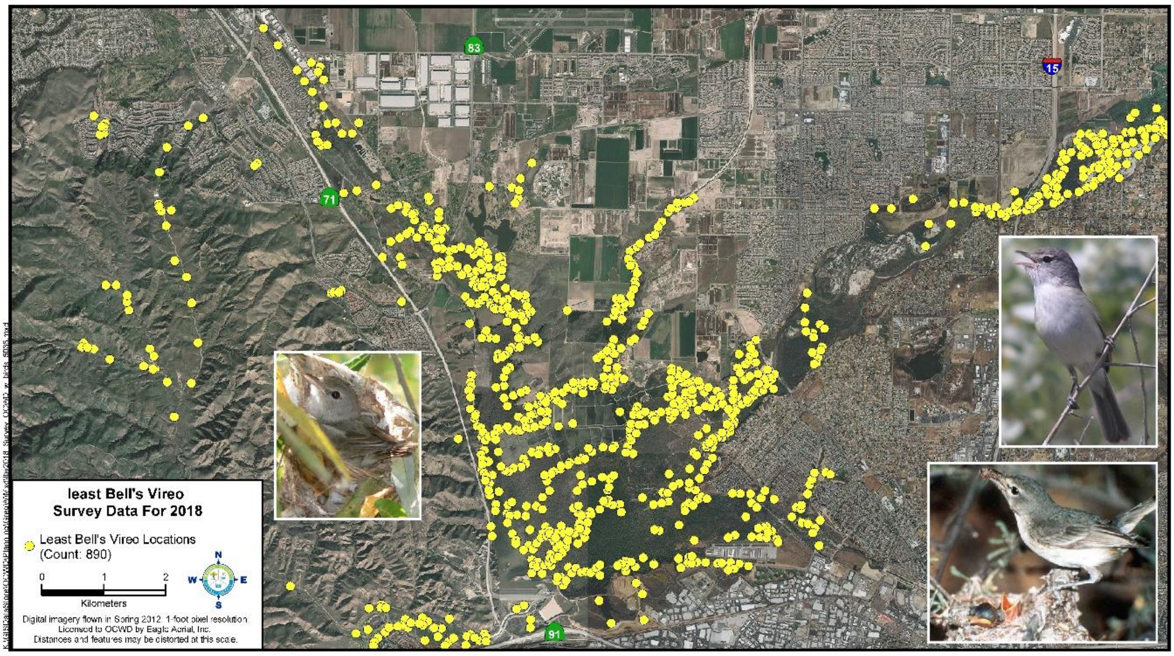

Figure 6. Least Bell's Vireo Territories in 2018.

OCWD formed partnerships to work on invasive weed control in the upper SAR watershed. OCWD also developed partnerships to cooperatively manage OCWD property in Prado Basin with the signing of a landmark agreement among OCWD, USACE, and the U. S. Department of Interior in 1995. Invasive weed control is a successful strategy to improve the environment since the non-native invasive weeds do not provide suitable habitat for endangered native birds. Removal of the invasive weeds allows native plants to grow and provide riparian habitat for native birds. Invasive weed removal also conserves water since the primary invasive weed, Arundo Donax, uses more than three times as much water as native riparian vegetation. Because of the invasive weed control and nest parasitism management beyond Prado Basin into the larger area of the SAR Watershed, in 2018 there were over 2,000 male vireo territories [5].

3.3. Expansion of MAR Facilities to Capture Stormwater

Starting in the 1930s, OCWD identified a need to increase its surface MAR capacity to recharge SAR and imported water. OCWD began purchasing land along and adjacent to the SARin 1936. Figure 7 shows the progression of land purchases through time. This area has favorable geology for surficial recharge, since the aquifer crops out at the ground surface and the aquifer permeability is high. Through purchasing land in this area, OCWD has increased its ability to recharge SAR water by a factor of five compared to the prior baseline condition.

A significant expansion of OCWD's MAR facilities began in 1985, when OCWD completed purchase of the Santiago Basins. Santiago Basins are former sand-and-gravel (aggregate) mines that now provide approxixmately 17 Mm^3 of storage space. SAR water is conveyed through a pipeline from the SAR to Santiago Basins using a pump station with a capacity of 6 m^3/s (200 ft^3/s).

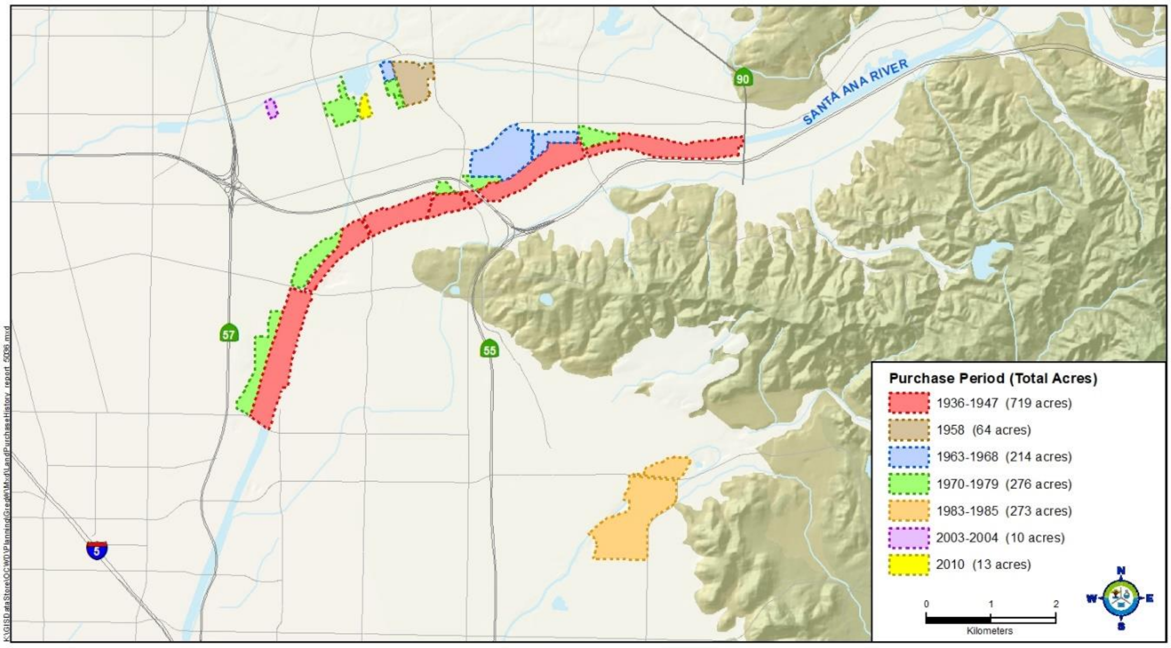

Figure 7. History of OCWD Land Purchase for MAR Facilities.

4. Discussion

Developing the stormwater capture program at Prado Dam involved multiple technical and policy disciplines. Wildlife biologists, habitat restoration managers, and environmental planners were critical to overcoming challenges posed by endangered species habitat that occurs in Prado Basin. Engineers, reservoir operations managers, water resource managers, and hydrogeologists played a vital role in analyzing potential increased stormwater capture elevations, dam release rates, and potential impacts of the program. OCWD's recharge capacity downstream of the dam also needed to expand, which involved the cooperation of the Cities of Anaheim and Orange and other stakeholders. The Orange County Flood Control District, Riverside County Flood Control and Water Conservation District, and San Bernardino County Flood Control District also supported the program. The United States Fish and Wildlife Service and California Department of Fish and Wildlife also supported the program. These and other stakeholders worked together to develop an innovative program that stores additional water on a temporary basis without having to build any new infrastructure. Stormwater capture at Prado Dam supports an on-going natural resource program in Prado Basin that has recovered the least Bells vireo, expanding the number of vireo territories by more than 50-fold.

5. Conclusions

Increasing the amount of stormwater infiltrated into the Orange County Groundwater Basin by successful integration of Prado Dam with OCWD's MAR facilities enhances local water supplies, saves energy, and saves money compared to reliance on imported water supplies. The program has successfully achieved an average of 62 Mm^3 of stormwater recharge per year.

Acknowledgments: Funding for this work was provided by OCWD. The overall stormwater management program was funded by OCWD and USACE. The vireo management program and invasive weed removal was funded by OCWD, USACE, and the Santa Ana Watershed Association. The State of California and The Nature Conservancy also contributed funds.

Author Contributions: Greg Woodside and Adam Hutchinson both contributed to this effort.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
OCWD: Orange County Water District
USACE: United States Army Corps of Engineers
Mm^3: million cubic meters
SAR: Santa Ana River.

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Paper for ISMAR10 symposium. ***Topic No: 1 (007#)***

Title IWRM approach and rainwater harvesting in drought-prone Barind Tract, Bangladesh: Practiced potential

Md. Ferozur Rahaman[1]; Chowdhury S. Jahan[2]* and Quamrul H. Mazumder[2]

[1] Institute of Environmental Science, University of Rajshahi, Bangladesh; feroz90ru@gmail.com
[2] Department of Geology and Mining, University of Rajshahi, Bangladesh; qhm27@yahoo.com
* Correspondence: sarwar_geology@yahoo.com; Tel.: +880-1712-612142

Abstract: To meet the challenge of water scarcity in agro-based Barind Tract in northwest Bangladesh, RWH schemes with IWRM approach under the BWA (2013) [1] are implemented as management practices - the first attempt of this type in the country. In the present study, the major aspects of IWRM include availability of appropriate quality water and human water need with scientific basis for collecting, concentrating, and conserving rain and runoff water from various sources. Moreover, impact assessment of implemented schemes is conducted through number of field visits and FGD using pre-tested questionnaire. Annual bimodal distribution of rainfall has high harvesting potentiality during rainy season where total harvested rainfall and runoff fulfill 71% of total water demand for household and agriculture. Before implementation of the schemes inhabitants faced severe water scarcity even for drinking purposes. To delineate potential sites for RWH and runoff conservation structures, multi-parametric data and geospatial techniques are used. Accordingly, implemented RWH schemes increase surface water availability, reduce pressure on groundwater withdrawal, augment groundwater recharge condition, provide benefits to farmers particularly women for domestic uses, psciculture, duck rearing etc. Performance of implemented schemes is socially, financially, economically and environmentally acceptable. Moreover, beneficiaries are hopeful about the inclusiveness and sustainability of schemes with very positive attitude for IWRM practice in Bangladesh.

Keywords: IWRM, RWH, MAR, Barind Tract, Bangladesh.

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1. Introduction

Bangladesh is one of the most disaster-prone countries in the world. The NWMP in the country considers drought as a major water deficiency issue in agro-based, water scarce area popularly known as 'Barind Tract'. The study area in the Tract includes Godagari and Tanore *Upazilas* of Rajshahi district, and Nachole, and Gomastapur *Upazilas* of Chapai Nawabganj district with a total of 34 *Unions* (District, *Upazila* and *Unions* are the second, third and lowest tiers of the administrative unit in Bangladesh) having population of 944704 covering an area of 1942 km^2 (Figure 1). The area enjoys sub-tropical monsoon climate with seasons like winter (Nov.-Feb.), pre-monsoon or dry summer (Mar-May) and monsoon or rainy (June-Sept.).

In the area, meager allocation of rainfall, recurring drought effect, soil moisture deficiency, surface water scarcity and constrains for groundwater development result shortage of drinking water, and demands for supplementary irrigation even at the end of rainy and severely during winter and summer seasons. The Tract is typically characterized by highly elevated (27-47 m AMSL) dome shaped undulatory land mass with highly irregular to irregular topography and high drainage density does not conserve rain water adequately and losses as runoff water, and ultimately flows into major rivers. At the same time, the poor to very poor groundwater potential zones (58%) [2], and low infiltration capacity (2-3 mm/day) top soil cover (Barind Clay of Pleistocene age) [3] to recharge groundwater has effect on potentiality [4-6]. Simultaneously, due to excessive withdrawal of groundwater and extension of irrigated agriculture, GWT has been declining at an alarming rate since beginning of last decades which undermines the water availability and put threat on sustainability [7-8]. Here agricultural and drinking water demands are needed to be balanced for the livelihood and environment.

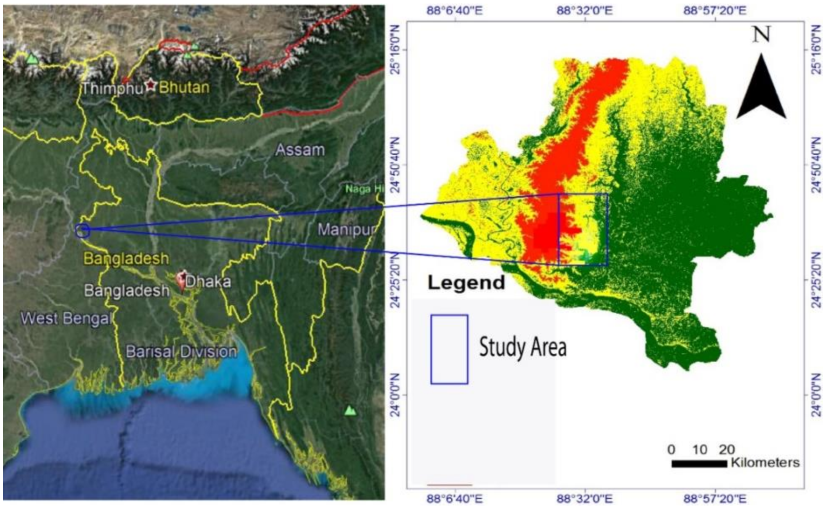

Figure 1. Study area location in Barind Tract along with topography map of north-western part of Bangladesh.

On the other hand, the area has been the focus of strong agricultural development over last 30 years with increasing agricultural productivity. The Barind Multipurpose Development Authority (BMDA) under the Ministry of Agriculture (MoA), Government of Bangladesh (GoB) plays central role for water resource management for agriculture and domestic use. Here 77% area is under agricultural practice, but surface water bodies cover only 7% which mostly dries up during summer [9]. Cropping pattern is dominated by rice (*Boro*, *Aman* and *Aus*) where rain-fed *Aman* covers maximum area followed by *Boro* (dry season variety). Other crops (wheat, oilseed, pulse, fruit and maize) have 1-9% share in cropping pattern.

Moreover, water resource management in Bangladesh remains fragmented as it is supply led, sector focused, technically driven, and top-down approach focusing high economic, social and ecological cost. In this context, enabling sufficient and safe access to drinking water for purpose, food productivity etc. is not a sub-sectoral service provision challenge for the water resources sector, but rather should be a cross-sectoral regulatory and management approach. Different government organizations in the country have taken efforts to improve IWRM for people, food, nature and industry. But unfortunately these are insufficiently coordinated among different actors who are primarily concerned with their own specific business and legal framework.

But the irrigation demand is increasing day by day, so implementation of RWH techniques with IWRM approach is a demand of time. So far no study has carried out to establish the sustainable IWRM practices in this water stressed area considering water as a finite and vulnerable resource. In present study, technical aspects of IWRM are practiced that including RWH (re-use), capture of rainwater or runoff (recycle), enhanced groundwater resource (recharge), and ultimately restoration of resource from further depletion through groundwater recharge, i.e., the 4R (recharge, re-use, recycle and restore). Moreover, the piloted model of RWH technique is an integral scientific outcome of the present research along with the impact assessment of practiced technologies in order to improve well-being of people.

2. Concepts, Materials and Methods

IWRM as logical and intuitively appealing concept seeks to manage the water resources in comprehensive and holistic way [10]. It is intended to improve well-being of people through coordinated and equitability way for promoting sustainable water resource management framework in the Tract including both physical (demand for drinking water) and socio-economic components (demand for food). Three basic 'Pillars' of IWRM are enabling environment of appropriate policies and laws; institutional roles and framework; and management instruments to apply on a daily basis [11].

There is hardly any dedicated policy related to water resource management in Bangladesh. The recently enacted BWA (2013) [1] provides framework to address holistically the institutional challenges associated with resource management, and establishes the authority and responsibility of government to regulate its abstraction and usage with the explicit purpose of ensuring sufficient allocation to all sectors, in all places, at all times. The new ordinance (in Bengali) named '*Krishi Kaje Bhugorvostho Pani Bebosthapona Ain*, 2017' (Groundwater Management Law in Agriculture, 2017) [12] and the BWR (2018) [13] under [1] are framed by GoB to implement the clauses and sub-clauses through IWRM at grass-root level.

Here major issues of IWRM are taken into consideration like availability of fresh water of appropriate quality (includes investigation on climate or rainfall pattern; availability of runoff water; geology; vegetation or cropping pattern; topography; fresh water of appropriate quality etc.); and human water need [14] (involves technology, science based decision making aspects, and basin level management activities) as noble approach for collecting, concentrating, and conserving rain and runoff water or RWH from various sources. At the simplest level, RWH techniques can be divided into two groups [15]: rooftop, and non-rooftop, i.e., settlement and agriculture land areas. On the other hand, the legal aspects and social considerations of IWRM are kept outside present study purposefully.

The present study includes in-depth field observation and survey; data collection (both primary and secondary); calculation using software etc. Here primary and secondary data for the domestic and agriculture water use are collected using structured questionnaire from five HH randomly selected from each *Union* through FDG consisting of at least 10 farmers for information like number of HHs per village; average HH size; irrigation and drinking water source and requirement; area of agricultural land and crop production; cropping pattern; required number of irrigation (crop wise); average cost of production per *bigha;* and cost of irrigation.

The long-term rainfall and GWT data for the period of 1980-2017 are collected from RGS and PHS from four *Upazilas* by the BWDB. Other basic climatic data like evaporation, temperature etc. are collected from the BMD. The rainfall data are analyzed to show average monthly, seasonal and annual; and annual in monthly basis at 5-years interval (1980, 1985, 1990, 1995, 2000, 2005, 2010 and 2015) to show its distribution pattern. The inter-annual variability of the annual cumulative rainfall shows the existence of high variability in the rainfall distributions, but low over the years. The long-term mean annual average rainfall values ranges from 1359-1399 mm which is almost half of the national average.

The SCS-CN method [16] for water balance equation can be expressed as:

$$P = Ia + F + Q; \frac{Q}{P-Ia} = \frac{F}{S}; Ia = S \,, \quad (1)$$

where, P - total precipitation (mm) (In present study P = 45 mm/day); Ia - initial abstraction (mm); F - cumulative infiltration (mm); Q - direct runoff (mm); S - potential maximum retention (mm); and λ - initial abstraction coefficient (0.2). The typical runoff coefficients values (c) using SCS-CN method for cultivated lands, settlement areas and roof areas area are 0.08-0.41, 0.3-0.75 and 0.75-0.95 respectively [17-20] are used. The composite runoff coefficient (C) for the total drainage area is expressed:

$$Composite\ C = \frac{\sum(C_{individual\ area})(A_{individual\ area})}{A_{total\ area}} \,, \quad (2)$$

Accordingly, the calculated values of λ, S, I and CN are 0.2, 169 mm, 34 mm and 60, and that of Q value is 1215 mm. Finally, the RWH quantity from rooftop through gutter system and non-rooftop area (Q) are calculated by:

$$Q = (RC \times P \times A)1000 \,, \quad (3)$$

where, RC - Runoff coefficient (RC values for the settlement area i.e., the roof top area and that of cultivated land are 0.7 and 0.6 respectively as considered for the present study); and A - Roof area or the catchment area (m^2).

The land use and land cover (LULC) in the study area as assessed from satellite data of Landsat-8 December, 2014 (30 m spatial resolution) using Erdas Imagine 9.1 software [2,21], shows 84% (1153 km^2) cultivated area, and followed by settlement area and water bodies of 14.25% (200 km^2) and 1.5% (18 km^2) respectively.

The application of artificial groundwater recharge or MAR technique - an engineered system for RWH [14] have been implemented as model practices at HH using well recharge technique in villages Mallickpur (Union: Fatehpur) and Ganoir (Union: Nachole) of Nachole *Upazila* in 2014 , and in office building in village Mondumala in Tanore *Upazila* in 2016. The RWH technique has also implemented through MAR technique using technologically modified dug well recharge in auditorium building (village: Kakonhat) and at HH level (village: Kadipur) in Godagari *Upazila* in 2016. The roof area of auditorium has area of 692 m^2 with respective harvested amount of rainwater are 765 m^3 (recharge dug well diameter: 1 m). In generally, the area has earth-made houses with roof of galvanized corrugated iron sheets, and one or two storied buildings with concrete roof. The approximate size of earth-made house is 40 m^2 in rural Bangladesh [22] and that of one or two storied buildings like *Union* /*Upazila* office buildings, auditoriums, schools, colleges etc. having average roof size of 350 m^2. Here roof water harvesting system at HH level is only option that delivers water at the doorstep where the rainwater is collected on a roof of corrugated iron and poured through a gutter into a storage system. Before injecting rainwater through recharge structure, it makes free from any sorts of silt and debris present. From roof, rainwater through pipes is poured directly in aquifer through recharge box (1.5 × 1.5 m^2 size) filled with brick cheeps of 6, 10 and 20 mm sizes. The recharge boxes have depth of 3 m in the top clay layer. The groundwater level is monitored from PHS installed in the aquifer zone. The physical (pH, EC and temperature) and chemical (Fe^{Total}, SO_4^{-2}, PO_4^-, NO_3^- and As) parameters of groundwater in recharged aquifer zone as well as its bacteriological (*Fecal Coliform*) content are analyzed for pre- and post- MAR technique application stages [23-25].

The runoff water flowing through *Kharies* (canals) are conserved by constructed cross/check dams and provides irrigation water for agriculture and also helps for psciculture and domestic use. These *Kharies* are perennial, silted and loses water holding capacity, are re-excavated for conservation of more runoff water in villages Sikpur (Badhair *Union*) and Baurigram (Kalma *Union*) of Tanore *Upazila*, and village Paharpur of Godagari *Upazila* with respective length of 610, 2500 and 2500 m covering command area of 72, 96 and 130 ha respectively for irrigation.

Impact assessment of implemented RWH schemes are performed through number of field visits, and data collection by 16 FGD comprising 155 respondents using pre-tested questionnaire. Important output components of the study are participation and pursuance of citizens, particularly the underprivileged and disadvantaged people with their interests in piloted RWH schemes; adaptation, governance issues, and initialization of IWRM process for improved water related services by the LGIs in the area.

3. Results and Discussions

3.1. Rainwater harvesting potentiality

The mean annual rainfall of Godagari, Tanore, Gomastapur and Nachole *Upazilas* are 1359, 1999, 1368 and 1399 mm respectively. Monthly distribution of rainfall of different *Upazilas* show maximum rainfall in July. The rainfall amount is more than 500 mm during rainy season (Jun-Sep). The intra-annual variability in Godagari, Tanore, Gomastapur and Nachole *Upazilas* range between 0.38-3.61, 0.44-3.56, 0.35-3.18 and 0.45 and 2.79 respectively whereas respective inter-annual variability are 0.83, 0.76, 0.62 and 0.52. This variability is high in distributions of rainfall and low over the years, i.e., time with bimodal rainfall distribution patterns in different *Upazilas.* On the other hand, calculated values of Q is 1215 mm.

In the area, the number of HH varies from 32922-72186 with daily demand of water ranges from 183-419 liter/HH. The amount of water needed for drinking and cooking purposes/day/HH are only 19 liter and 23 liter respectively while other domestic purposes (e.g., cleaning, washing, bathing, toileting, etc.) consume 224 liter/HH/day. So daily, monthly and yearly total HH water demand range from 11479-14018, 344376-420545 and 4132519-5046545 m^3 respectively, where the share stands for 7, 9 and 84% respectively. The total agriculture water demand of the major crops as obtained from farmers experience, research field experience and water footprint study vary from 264906890-589883365 m^3, 211236841-473809866 m^3, and 178745805-328814110 m^3 respectively. The *Upazila* wise i.e., Godagari, Tanore, Gomastapur and Nachole average values of water demand for agriculture are 464169120, 311464155, 218296512 and 396848227 m^3 with a total agriculture demand of 1390778014 m^3.

In the rainy seasons (June-Sept.), the *Upazila*-wise total harvested amount of rainwater from rooftop, settlement and cultivated areas are 9670869, 145329128 and 730431628 m^3 respectively with total amount of 885431625 m^3. On the other hand, the total water demand for HH and agriculture are 18909103 and 1390778014 m^3 respectively with a total amount of 1409687117 m^3. So the harvested amount of rainwater that can fulfill 71% of the total water demand with respective values of 58%, 48%, and 52% deficit for Godagari, Tanore and Nachole *Upazilas*, and rest 32% surplus for Gomastapur *Upazila*.

The relationship between rainfall trends, depth of GWT, and sub-surface lithology [2] of the study area shows that the rainfall amount is decreasing with declining trend of GWT. The thick top clay layer (Barind Clay) (thickness : <8-40 m) with low permeability, and overlies the main aquifer of thickness < 26 to 30 m has hydrological importance for harvesting rainwater. The average depth of GWT from ground surface in the area is 9 m (1980) and 21 m (2017) i.e., the area has potentiality of vertically 121.75 m vacuum space which can be filled up by RWH. So the RWH potentiality of the area is very high during rainy season and the annual as well as monthly harvested and storage amount of rainwater is enough to ensure sustainability in water supply.

In the context of high rainwater and runoff harvesting potentiality in the area, artificial process of groundwater recharge like well and dug well recharge structures using MAR technique; and water conservation structure like recharge pond and *Beels*, check/cross dam in *Kharies* are suggested as adoptive measure for sustainable use of water resource. The appropriate potential sites for implementation of harvesting and conservation structures [26] are identified as criteria in selecting suitable sites for harvesting structures [27-30] and is given in Figure 2.

3.2. Rainwater harvesting practice

3.2.1. Rooftop RWH Practice: The long-run trend of GWT shows that it almost regained its original level before 2004, and thereafter resulted permanent depletion due to inadequate natural recharge of groundwater and over-exploitation of groundwater for irrigation use. After implementation of MAR technique situation started to reverse i.e., GWT started rising in response to the augmented groundwater recharge artificially. The hydrograph of GWT pre- and post- implementation of MAR technique are shown in Figure 3. Moreover, the analyzed physical (pH, EC and temperature), chemical (Fe^{Total}, SO_4^{-2}, PO_4^-, NO_3^- and As) and bacteriological *(Fecal Coliform)* parameters of groundwater samples in the area for pre- and post- MAR technique application stages found suitable for drinking purpose, and free from arsenic toxicity and *Fecal Coliform* bacteria contamination [23-25].

3.2.2 Runoff Water Conservation: The runoff water in the study area is also conserved in re-excavated ponds which act as infiltration tank and helps peoples in domestic use, cultivation of vegetables, fisheries and duck rearing. At the same time, huge amount of runoff water is also conserved in re-excavated *Beels* in Gomastapur *Upazila* to provide irrigation in paddy and vegetables fields. Before re-excavation and construction of embankments water was available for only for three-five months during and after rainy seasons.

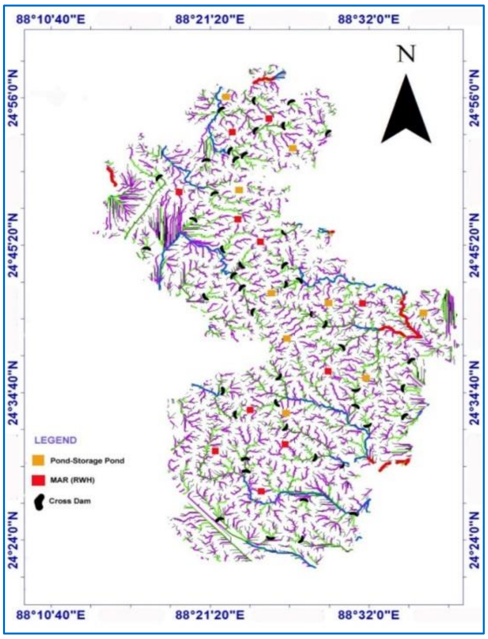

Figure 2. Resultant map of potential groundwater recharge and runoff conservation suitability structures in the study area.

3.2.3 Impact assessment of RWH Technique: The opinion of beneficiaries about the impact of implemented RWH schemes reveals that irrigation coverage substantially has increased with diversified cropping pattern in the command areas and the withdrawal of groundwater has substantially decreased. 100% inhabitants get access to drinking purpose round the year and reported that GWT has been increasing. Moreover, rain and run-off water harvesting and conservation opportunities has created new employment through increasing agricultural activities; reducing cost of crop production; bringing financial benefit with a profit of average by 60US$ (considering 1US$ = 80 BDT) per *bigha* per year along with about their inclusiveness in the planning and implementation process of the schemes. They are mostly satisfied about the transparency and accountability of the schemes works at implementation stages. Finally, the

RWH schemes as implemented in the area are socially, financially, economically and environmentally acceptable to the beneficiaries through their inclusiveness.

4. Conclusions

The area has high potentiality for RWH which fulfills 71% of the total water demand enough for domestic and irrigation uses in spite of seasonal rainfall variability. The RWH schemes have been implemented as pilot study through aquifer recharge well and technologically modified dug well using MAR technology; and re-excavated *Kharies* along with constructed cross/check dam, ponds and *Beels* to replenish groundwater resource through increasing infiltration rate, and conserve more runoff water for the use in agriculture. The implemented schemes are socially, financially, economically and environmentally acceptable to the beneficiaries, which is positive attitude unlike other water related implemented projects in Bangladesh. Finally, the appropriate IWRM strategies for sustainable resource management with good governance performance should be kept in mind for targeting Vision 2021 and 2041 of the GoB and achieving SDG goals as declared by UN General Assembly by 2030.

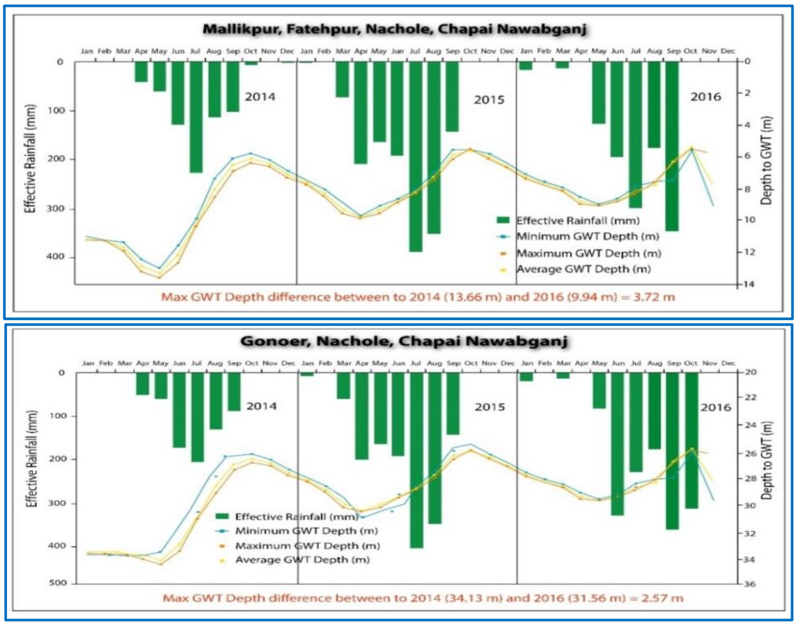

Figure 3. Hydrograph of GWT before and after implementation of MAR technique during 2014-2016 in Mallickpur and Ganoir villages of Nachole *Upazila* in the study area.

Acknowledgments: The authors would you like to acknowledge the generous financial, logistic and data support of the DASCOH Foundation, Rajshahi, Bangladesh; and NGO Forum for Public Health, Bangladesh for their support of this research.

Author Contributions: As a part of the doctoral research work, Rahaman designed the present proposal under the supervision of Jahan and Mazumder, Rahaman made field observation and survey, data collection (primary and secondary), conducted FGD in presence of Jahan and Mazumder. Rahaman designed and helped to implemented RWH model practice through MAR technology; planned for conservation of rain/runoff water through cross-dam construction; conducted chemical analysis of groundwater samples in pre- and post-MAR implementation stages etc. Rahaman conducted FGD on impact assessment of RWH practice through field visit using pre-tested questionnaires under supervision of Jahan and Mazumder.

Conflicts of Interest: We the authors of the paper solemnly declare that there has been no conflict of interest between the authors and the organizations supporting the research with data, advice

etc. from time to time. These organizations had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

1. AMSL: Above Mean Sea Level
2. BDWS: Bangladesh Drinking Water Standard
3. BMD: Bangladesh Meteorological Department
4. BWA: Bangladesh Water Act
5. BWDB: Bangladesh Water Development Board
6. BWR: Bangladesh Water Rules
7. CSE: Center for Science and Environment
8. DAE: Department of Agricultural Extension
9. DASCOH Foundation: Development Association for Self-Reliance, Communication and Health
10. ECR: Environment Conservation Rules
11. FDG: Focus Group Discussion
12. GWP: Global Water Partnership
13. GWMLA: Groundwater Management Law in Agriculture, 2017
14. GWT: Groundwater table
15. HH: Households
16. IMSD: Integrated Mission for Sustainable Development
17. IWRM: Integrated Water Resource Management
18. LGI: Local Government Institutions
19. LULC: Land use and land cover
20. MAR: Managed Aquifer Recharge
21. NWMP: National Water Management Plan
22. PHS: Permanent Hydrograph Stations
23. RGS: Rain-gauge Stations
24. RWH: Rainwater harvesting
25. SDC: Swiss Agency for International Development
26. SDG: Sustainable Development Goals
27. WHO: World Health Organization
28. 1 ha = 7.47 *bigha*;

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Paper for ISMAR10 symposium. ***Topic No: 1 (027#)***

Slippage Effects of Managed Aquifer Recharge Under Increased Drought Risk

Dat Q. Tran[1], Kent Kovacs[2] and Steven Wallander[3]

[1] Postdoctoral Research Associate, University of Arkansas at Fayetteville, Department of Agricultural Economics and Agribusiness ; datquoct@uark.edu/tranquocdat1506@gmail.com
[2] Associate Professor, University of Arkansas, Department of Agricultural Economics and Agribusiness; kkovacs@uark.edu
[3] USDA Economic Research Service ; swallander@ers.usda.gov
*Correspondence e-mail: swallander@ers.usda.gov

Abstract: Economic analyses of managed aquifer recharge (MAR) typically focuses on identifying the quantity of water to cost effectively add to natural rates of recharge. However, to the extent that MAR is successful, rising groundwater levels or at least slowing depletion are likely to influence crop choice and groundwater pumping dynamics. This study uses a landscape level model to simulate net return maximizing MAR pathways taking into account on-farm surface reservoir storage, crop choice, and the impacts of drought on groundwater use in Eastern Arkansas, USA over a 120-year period. There is evidence of a large slippage, the percentage increase in groundwater use relative to a scenario with no MAR, under a range of MAR cost scenarios. Total slippage ranges from about 32 to 75% of total MAR water. Even with slippage and relatively high costs for MAR, the total net returns to farms in this region are greater with MAR.

Keywords: Slippage (rebound) effects, agricultural managed aquifer recharge (MAR), surface reservoir storage

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1. Introduction

The Mississippi Embayment encompasses an area of about 78,000 square miles over eight states in the USA. The larger portions of embayment lie within Arkansas, Louisiana, Mississippi and Tennessee while smaller portions of the embayment are in Alabama, Kentucky, Missouri and Illinois. The Mississippi Embayment aquifer system is comprised of six aquifers and three confining units. The two primary aquifers are the upper most unit, Mississippi River Valley Alluvial aquifer (locally referred to as Alluvial aquifer), and the lower unit, middle Claiborne aquifer [1].

Although rainfall in the embayment is relatively abundant, its timing and quantity often does not coincide with the crops demand for water. About half of annual rainfall occurs outside the typical growing season for spring crops. Due to large groundwater reserves, the farmers thus rely heavily on irrigation to optimize yields and mitigate risks associated with drought [2]. Decades of pumping from the Alluvial aquifer for irrigation and from the middle Claiborne aquifer for industry and public water supply have reduced groundwater levels throughout the Mississippi embayment in Arkansas, Louisiana, Mississippi and Tennessee. During 2001-2008, the Mississippi embayment has an annual rate of groundwater depletion of 1.93 cubic mile per year, which makes it the second most depleted aquifer in the USA [3]. Approximately 36% of the Alluvial aquifer area had water-level declines more than 25 feet in 2007 compared to pre-groundwater irrigation period (1900s), and the share is predicted to increase to 60% by 2038 [1].

The projected trajectory of changing climate is likely to intensify the groundwater depletion in heavily depleted aquifers such as Alluvial aquifer [4]. More frequent and longer droughts place more demand on groundwater resources in the regions that depend heavily on groundwater for sustaining crop production such as Eastern Arkansas. Irrigation efficiency may reduce the groundwater overdraft in the region, but the adoption is slow. In 2016, only about 20% of farmers surveyed reported that they used irrigation efficiency practices, and most of this adoption occurred over the last ten years [5]. Previous studies show that irrigation efficiency adoption alone has not been effective in reducing groundwater overdraft [6]. One potential solution to conserve groundwater is the conjunctive use of surface and groundwater [7, 8]. An alternative to conjunctive use is to store excess surface water in aquifers through managed aquifer recharge (MAR) [4, 9, 10]. Excess surface water could be injected into depleted aquifers to increase sustainable groundwater yields [11].

MAR has proved technically feasible in the region [12, 13]. However, less information is available about the effects of MAR on groundwater pumping, land use and farmers' net return accounting for the impact of drought on an agricultural landscape. Most previous research focuses on identifying the suitability of MAR with geographic information systems and scoring functions, e.g. fuzzy logic scoring functions [9, 14] or hydrologic models (e.g., MODLOW) [15, 16] rather than economic feasibility. Here, we develop landscape model to examine an optimal allocation of excess water to MAR and evaluate the effects of MAR on land use and groundwater pumping rate. We also consider the impact of a hypothetical increase in drought frequency (i.e., risk) in Eastern Arkansas. Our model accounts for the essential relationships between the choices irrigators make about land use, groundwater withdrawal rates, and MAR use.

2. Materials and Methods

This study uses a dynamic optimization model of irrigation water use, land allocation, and groundwater recharge decisions over a time horizon of 120 years. The MAR method used in the model is well injection during the winter and early spring months. The economic optimization problem is constrained by a model of the aquifer hydrology, which is also a source of the model's dynamics. We run the model for a variety of MAR cost scenarios interacted with drought risk scenarios.

2.1. The optimization model of agricultural land use allocation decisions

The land use of the study area is spatially heterogeneous [17]. Here, we include six-crops, i.e., rice, irrigated soybean, corn, and cotton, non-irrigated soybean and double cropped irrigated soybean with winter wheat. These crops may use, *k*, irrigation practices, e.g. conventional (contour-levee flood for rice and furrow for other irrigated crops), conservation furrow (poly-pipe hole selection software and soil sensors), and zero-grade leveling flood for rice [18-20]. Two other land uses include fallowing the land and constructing on-farm reservoirs. If a unit of land is allocated to on-farm reservoirs, the unit of land remains as reservoir for the rest of time-horizon.

The groundwater level in time, $t+1$, $H_f(t+1)$, is the function of the well-pumping for irrigation in time t, $GW_f(t)$, natural recharge in time t, $NR_f(t)$, the size of the site/farm *f*, A_f, storativity, S_f and MAR water, $MAR_f(t)$. We only consider well injection as a MAR approach because an extensive part of the study area overlays a thick confining unit (more than ten feet), which makes recharge through basins less effective due to the expense of removing the confining units [12, 13]. The MAR water is scaled by, recovery efficiency, RE_f, because only a portion of MAR water is recoverable. MAR water can be lost to surface water bodies or other aquifers [21].

The net change in volume of groundwater due to irrigation and MAR in time, t, at site, f, is scaled by the return flow coefficient, α, which indicates the proportion of irrigation water unused by crops that would return to the aquifer. Here, we adopt the forward difference approximation method to solve Laplace's equation [22]. Therefore, the groundwater level in time, $t+1$, showed as in equation 2.

$$H_f(t+1) = H_f(t) - \frac{NR_f(t) + (1-\alpha)\left(RE_f MAR_f(t) - GW_f(t) - RW_f(t)\right)}{A_f S_f} \quad (1)$$

The irrigation water in the region comes from two sources, including groundwater as the main source and on-farm water from constructed reservoirs [2]. The irrigation water applied per unit of land crop, l, at site, f, with irrigation practice, i, in time, t, is wr_{flti}. The total amount water needed for irrigation at site, f, is, $\sum_l^m \sum_{i=1}^k wr_{fli} A_{fli}(t)$, which equals to the sum of groundwater use, $GW_{ft}(t)$, and on-farm reservoir water use, $RW_{ft}(t)$. The well injection would operate over a 6-month period (October through April), when surplus water is available, no irrigation occurs, and obtaining water rights is the most flexible [23]. The wells are dual-purpose, useful for both recharge surplus of surface water in the winter and early spring, followed by pumping groundwater during periods of irrigation. Thus, the MAR water being recharged to the aquifers in year, t, immediately becomes groundwater in the same year. As a result, the water balance constraint is written as

$$\sum_l^m \sum_{i=1}^k wr_{fli} A_{fli}(t) = GW_{ft}(t) + RW_{ft}(t). \quad (2)$$

$C^{ar}(t) = \sum_f^n \left(c_f^{ar_{fix}}(t) + c_f^{ar_{var}}(t)\right) MAR_f(t)$ is the total cost of MAR water, and this includes fixed, $c_f^{ar_{fix}}(t)$, (e.g. pipeline, and other infrastructure and equipment) and variable cost, $c_f^{ar_{var}}(t)$ [1], components (e.g. energy costs to transport the water to recharge wells). $C^{gw}(t) = \sum_f^n \left(c_f^{gw} H_f(t) + c_f^{cw}\right) GW_f(t)$ is the total cost of groundwater pumping, and this depends on the cost to lift one unit of water by one unit of depth, $c_f^{gw}(t)$, multiplied by the depth, $H_f(t)$, plus the capital costs per unit of water extracted for the well, $c_f^{cw}(t)$, which accounts for new well drilling in response to aquifer decline. $C^{rw}(t) = \sum_f^n \left(c_f^{rw} RW_f(t) + c_f^{cw} \sum_i^k A_{fri}(t)\right)$ is the total cost of pumping from an on-farm reservoir, and this includes the cost of irrigating with a unit of water from a reservoir, c_f^{rw}, multiplied by the volume of reservoir water, $RW_f(t)$, and the construction cost of a unit of reservoir land, c_f^{cw} multiplied by size of the reservoir, $\sum_i^k A_{fri}(t)$.

Maximum injection rate depends on specific hydro-geologic conditions at the site, e.g. transmissivity, T_f. Here, we estimate the maximum injection rate based on hydraulic properties of the aquifer [23, 24] and results from actual recharge tests in the region [12]. [24, 25] simplified the Theis equation for large values of time, *t*, and/or small values or well radius, *r*, to be equation 4.

$$h_{fw} - h_{f0} = \frac{2.3 MAR_f(t)}{4\pi T_f} \log \frac{2.25 T_f t}{r^2 S_f} \quad (3)$$

Where h_{fw} is the hydraulic head undergoing injection and h_{f0} is the initial hydraulic head prior to injection. T_f is the transmissivity. Solving for MAR on the right hand side of Eq. 4, when $\frac{DTW_f}{h_{fw} - h_{f0}}$ is set equal to one, indicate the maximum annual injection rates by site.

[1] We assume that farmer uses bank infiltration to extract surface water through extraction wells and transport/convey that water to recharge wells. The concept is to induce flow through the streambed into the aquifer and capture that water, rather than groundwater from storage, and use a pipeline to transfer water to where recharge is needed, and inject it into the aquifer using a recharge well. For the study, the groundwater transfer system will extract water from near the main Rivers (e.g., White and Arkansas Rivers) and inject that water into sites/cells that can maximize the total net return.

Each year, t, a producer, f, decides to allocate, $A_{fli}(t)$, acres to land use, l, and irrigation practice, i. Therefore, a farm, f, can have more than one crop and irrigation practice in each time, t. The irrigators seek to maximize total net return through optimal use of land, groundwater, MAR and other related inputs in the planning time horizon, T. The costs include production costs of crop, l, with irrigation practice, i, c_{li}, cost of MAR water, $C^{ar}(t)$, cost of on-farm reservoir water, $C^{rw}(t)$, and cost of groundwater pumping, $C^{gw}(t)$. The revenue is the price of crop, l, p_l, multiplied by the yield of crop, l, planted at site, f, with irrigation practice, i, y_{fli}. Given the time horizon, T (120 years), the model maximizes the total net return over all, n, farm sites, which have variation in land use, hydrologic conditions (e.g., depth to water level, saturated thickness, and hydraulic conductivity), groundwater pumping rate and the costs of surface water conveyance for MAR. The real discount factor in each year, t, is, δ_t. The objective function is showed in equation 4.

$$\max_{\substack{A_{fli}(t),RW_f(t)\\ ,GW_f(t),AR_f(t)}} \sum_t^T \delta_t \left(\sum_f^n \sum_l^m \sum_i^k \left(\left(p_l y_{fli} - c_{li} \right) A_{fli}(t) - C^{ar}(t) - C^{gw}(t) - C^{rw}(t) \right) \right) \tag{4}$$

Subject to non-negativity and land availability constraints as well as a groundwater level, a water balance, and maximum water injection rate constraints shown as in equation 1 to 3.

2.2. Optimal MAR, groundwater pumping and land use, and sensitivity analysis

MAR using injection wells has not occurred in Eastern Arkansas. Herein, we assume a range from \$10-\$100/acre-foot, equal for all sites, for the capital costs (e.g., infrastructure, equipment and interest). The MAR variable cost is the water conveyance costs that depend on required volume for MAR and the distance from an excess surface water source such as river to recharge site.[2] Because recovery efficiency has a strong effect of a MAR system performance [21], we simulate the model with six recovery efficiencies between 50% and 100% with 10% intervals.

2.3. Data

The study location is in Eastern Arkansas, United States (Figure 1). The study area covers three eight-digit hydrologic unit code (HUC) watersheds and overlaps with eleven Arkansas counties (Figure 1). The study area overlays critical groundwater areas (CGA), defined by the Arkansas Natural Resources Commission (ANRC) as aquifers with significant groundwater depletion and degradation [8].

[2] Agricultural lands in the study area currently do not have access to off-farm stored water might have water rights from planned and/or under-construction United States of Army Corps of Engineers (USACE) reservoirs. Thus, in this case, water would need to be transported from one of rivers that is downstream from one of the reservoirs. The capital costs of planned off-farm delivery projects in Arkansas are available, but highly speculative whereas MAR cost largely depend on piping cost from main rivers/streams to recharge sites (personal communications with Dr. James Rigby, a research hydrologist at USDA). In this study, we vary the costs per acre foot of MAR and off-farm water based on the costs of irrigation projects in Arkansas and the costs provided by Agricultural Research Service personnel and Eley-Barkley Engineering and Architecture, Cleveland, MS.

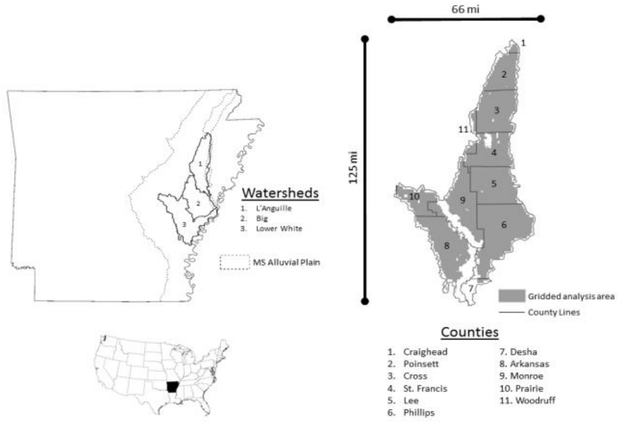

Figure 1. Three eight-digit hydrologic unit code (HUC) watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. County lines overlay the study area. Public land and urban areas are excluded. The location of the study area within the State of Arkansas is shown.

We create a grid of 2000 cells and overlay the grid on the study area to extract spatial heterogeneous information on geo-hydrologic conditions and crop yields for the model. The 2017 Cropland Data Layer (CDL) serves as initial land use input for the model [25]. The irrigated vs. non-irrigated soybean acreage comes from the harvested acreage for 2016-2017 [34]. The estimate of yield for each of the crops is based on the average county crop yield for the past five-years [26]. The construction, and operation and maintenance costs for irrigation technologies, on-farm reservoirs, MAR, wells and production costs for the crops are constant over time in real terms. A 2% real discount rate equals a 30-year Treasury Bond yield over the last decade of 5% [27] less an inflation expectation of 3%. The irrigation costs include costs of labor, fuel, lube and oil, and poly pipe for border irrigation plus the levee gates for the flood irrigation of rice, purchase and maintenance costs of the wells, pumps, gearheads, and units cost (e.g., energy cost) to lift a volume of a unit of irrigation water [28, 29]. The annual on-farm capacity and cost of an unit of on-farm reservoir come from The Modified Arkansas Off-Stream Reservoir Analysis (MARORA) tool [30, 31].

The depth to the water table, initial saturated thickness, b_f , and hydraulic conductivity , K_f , of the Alluvial aquifer varies across the landscape [8]. The natural recharge, nr_f , and storativity, S_f , values come from U.S. Geologic Survey [32]. Palmer Drought Severity Indices (PDSI) values come from National Oceanic Atmospheric Administration [33]. The distances from rivers to recharge site come from comparing recharge well locations, which is assumed to be at the center of each site, to the river network distribution in the National Hydrography Dataset (NHD) [34]. We set the return flow coefficient equal to 29% given the current level of irrigation efficiency in the Delta [5].

The current proportion of producers that use more efficient irrigation practices is less than 20%, and this proportion increases by about 1% per year [14]. Furrow irrigation is the conventional irrigation practice for corn, soybean and cotton, and contour-levee flood is the conventional irrigation practice for rice. Alternative irrigation practices (e.g., center pivot, surge irrigation, precision leveling, and poly-pipe with computerized hole selection) to conventional irrigation reduce water use and potentially raise yields. Adjustment coefficients to the costs of production and water use by crop relative to conventional for alternative irrigation practices depend on various agronomic sources [5, 18-20].

Based on the geo-hydrologic conditions across the sites, we estimate maximum injection rate between 155 to 6,782 acre-feet per year. Also, a U.S. Geological Survey (USGS) pilot study of

MAR through well injection shows that water could be injected at rates varying between 37 and 860 gallon/minute (60-1400 acre-feet per year) in Eastern Arkansas [12]. Combining these two independent approaches to calculating the injection rate, the maximum injection annually across recharge sites is between 155 to700 acre-feet over non-irrigation periods even though hydro-geologic conditions in many sites can withstand much higher injection rate.

Drought has a moderate effect on crop yields in the study area, but a significant effect on groundwater withdrawal because the area has intensive groundwater use for irrigation [35]. To investigate the long-term impacts of drought on the feasibility of MAR and land use, we create a synthetic 120-year drought record by repeating the historical PDSI values [33] for four successive 30-year periods for the baseline scenario. The reduction in dryland crop yields come from yield data for the last 30 years [17] whereas the increase in groundwater pumping comes from how field crop producers responded to the 2012 drought in Arkansas [35]. We also include a drought scenario that the frequency of drought during the 120-year time horizon is the frequency of drought during the most recent major drought period of 2010-2014 in the region. Historical PDSI values indicate that thirteen out of the last thirty-years are drought because their PDSI values are negative [13]. During the drought period of 2010-2014, three out of five-years are drought.

3. Results

3.1. Optimal MAR, groundwater pumping and land use

Since the model solves for groundwater use, crop choice, and MAR dynamically, under each scenario the model solution is a set of dynamic paths. In terms of the quantity of water recharged (figure 2), the results show that when the cost of MAR is $20/acre-foot, well below the average pumping cost ($40/acre-foot), there is significant MAR early in the time horizon. This reduces the pumping costs and reverses aquifer decline progressively over the time horizon, which leads to a declining trend in the quantity of water recharged through MAR. In contrast, when the cost of MAR is higher than initial groundwater pumping costs, MAR begins at a low level of recharge and gradually rises as the persistent groundwater declines increase the returns to MAR. Under scenarios with greater drought risk (more frequent drought), the dynamic pathways look broadly similar. Greater drought risk only has a slight effect on the MAR use when its cost is $40/acre-foot or above. At this cost, the results show that farmers increase net returns with adaptive crop management by growing less irrigation intensive crops than by banking groundwater through MAR for irrigation (Table 1).

Table 1 shows land use impacts with different levels of drought risks and cost of MAR. MAR leads to expansion of all irrigated crops and the expansion is bigger, in the absolute terms, under greater drought risk scenario. When the cost of MAR is $20, $40 and $60/acre-foot, the total annual expansion of irrigated crops is 74,000, 32,400 and 10,300 acres, respectively under greater drought risk scenario, in comparison to 70,200, 30,000 and 8,400 acres, respectively under baseline scenario. However, greater drought risk causes shifts out of rice, the most irrigation intensive crop, and non-irrigated crops and fallow.

Table 2 shows how MAR effects water conditions and total net returns by MAR cost and drought scenario. MAR increases total farm net returns and aquifer stock, but the increases are also associated with increased groundwater use. Under baseline and no MAR scenario, total net return and aquifer stock are $6.098 billion and 54.1 millions of acre-feet, respectively. When the cost of MAR is $20, $40 and $60/acre-foot, the total net returns under MAR scenarios increase by $108, $16 and $3 million, respectively. Likewise, the aquifer stock rises by 18.65 million acre-feet with MAR cost of $20/acre-foot, remains at about 54.11 million of acre-feet with MAR cost of $40 and $60/acre-foot. Groundwater use also increases, with additional 120,000, 30,000 and 10,000 acre-foot per year groundwater pumping for MAR cost of $20, $40 and $60/acre-foot, respectively. Under scenarios with greater drought risk, the changes in farm net returns and aquifer stock look broadly similar, but slightly bigger.

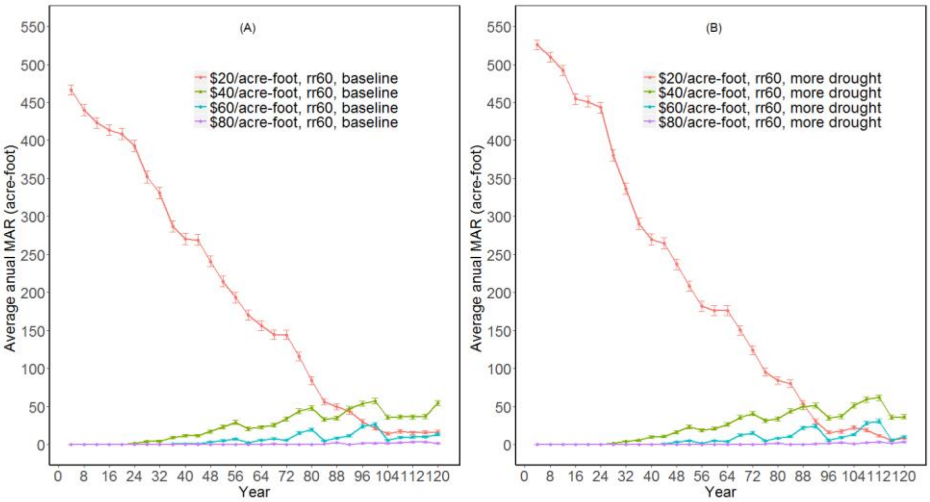

Figure 2. Simulated annual optimal amount of water and its standard error for MAR over 2000 sites for the 120-year period for four-cost of MAR scenarios and 60% recovery efficiency. A) Baseline drought frequency is 43%, 52 drought years out of 120 years. B) The increased drought frequency is 60%, 72 drought years out of 120-years.

Table 1. Initial and 2136 major crop allocations with 60% recovery efficiency rate for MAR[a].

		Baseline				More frequent drought			
			Cost of MAR ($/acre-foot)				Cost of MAR ($/acre-foot)		
Crop	Initial, 2017	No MAR	20	40	60	No MAR	20	40	60
Rice	1.762	1.236	+0.479	+0.051	+0.004	0.948	+0.50.0	+0.036	+0.003
Corn	1.103	2.273	+0.062	+0.162	+0.063	2.396	+0.083	+0.173	+0.074
Soybeans & cotton	6.454	5.847	+0.161	+0.087	+0.017	6.218	+0.157	+0.115	+0.026
Non-irrigated crops & fallow	1.525	1.494	-0.708	-0.305	-0.091	1.282	-0.740	-0.322	-0.103
On-farm reservoir	N/A	2.333	-2.333	-2.333	-2.333	4.858	-4.858	-4.858	-4.858
Total change in irrigated crops	N/A	N/A	+0.702	+0.300	+0.084	N/A	+0.740	+0.324	+0.103
Total irrigated crops	9.319	9.356	10.058	9.656	9.440	9.562	10.302	9.883	9.665

[a]Average annual crop allocations acres are in hundred thousands of acres. Average annual on-farm reservoir allocation is in ten of acres. Total irrigated crops are the summation of irrigated rice, corn, soybeans and cotton. For MAR scenarios, average annual crop and on-farm reservoir allocations acres are presented relative to No MAR scenarios; positive values indicate increases whereas negative numbers indicate decreases. No MAR represents a scenario that MAR is unavailable. Number of simulated years are 120, from 2017 to 2,136.

Table 2. Initial and 2136 water conditions and farm profits with 60% recovery efficiency rate for MAR[a].

		Baseline				More frequent drought			
			Cost of MAR ($/acre-foot)				Cost of MAR ($/acre-foot)		
Water conditions and total net returns	Initial 2017	No MAR	20	40	60	No MAR	20	40	60
120-year PV farm net return	N/A	6.098	+0.108	+0.016	+0.003	5.812	+0.115	+0.017	+0.004
MAR water use	N/A	N/A	+0.387	+0.049	+0.013	N/A	+0.408	+0.050	+0.015
Groundwater use	N/A	0.896	+0.120	+0.029	+0.006	0.921	+0.131	+0.035	+0.011
Aquifer stock	9.277	5.410	+1.865	+0.067	+0.026	4.912	+1.973	+0.084	+0.037

[a]Average annual groundwater and MAR uses, and aquifer stock are in millions and ten millions of acre-feet, respectively. Farm net return is in billion dollar. For MAR scenarios, water conditions and total net returns are presented relative to No MAR scenarios; positive values indicate increases whereas negative numbers indicate decreases. Total net returns of entire time horizon is in millions of 2017 dollars. Aquifer stock is the groundwater stock in the end of simulated year, 2136, for all scenarios. No MAR represents a scenario that MAR is unavailable. Number of simulated years are 120, from 2017 to 2,136.

4. Discussion

4.1. Effects of MAR on land use, net returns, groundwater withdrawl and aquifer stock

Table 3. Selected annual percentage of slippage[a] of selected MAR costs with 60% recovery efficiency rate for MAR and drought scenarios.

Cost of MAR ($/acre-foot)	Percentage slippage (%)	
	Baseline	More frequent drought
$20	31.010%	31.732%
$40	68.112%	68.997%
$60	71.658%	74.559%

[a] The percentage slippage (or rebound) effect refers to the percent of the increase in groundwater use divided by the MAR water.

MAR increases total net returns, but a large injection of water to the aquifer only occurs when MAR cost is considerably less than initial groundwater withdrawal costs, which is approximately $40/acre-foot for most sites (Table 2). The findings show that MAR is unlikely to eliminate groundwater depletion, even at an optimistically low cost of MAR, e.g., $20/acre-foot, because MAR leads to an increases in irrigated crops acreage and thus groundwater pumping (Table 1). When the cost of MAR is equal to or higher than $40/acre-foot, the effectiveness of MAR use to increase groundwater stock is moderate because less MAR water is recharged and about 70% of recharged water is pumped back up for irrigation (Table 3). As groundwater pumping is cheaper due to a higher level of groundwater because of MAR use, the farmers increase irrigation water applied because the acres of irrigation intensive crops increase (Table 1). The expansion of irrigation intensive crops undermines considerably the effectiveness of MAR to reduce groundwater depletion. Additional measures such as pumping cap or fee therefore might be necessary to extend the aquifer lifespan because only about 44% groundwater pumping for irrigation in the region is sustainable [4]. The use of MAR always increases farm net returns, although modestly, through shifts to more profitable irrigation intensive crops.

The percentage slippage (or rebound) effect shown in Table 3 refers to the percent of the increase in groundwater use divided by the MAR water. For example, from Table 1, the annual percentage slippage at a cost of MAR of $20/acre-foot and drought scenario is (0.12/0.387)*100 = 31.010%. Drought generally has a smaller effect on the percentage of slippage than the cost of MAR. When the cost of MAR is $20/acre-foot, the percentage of slippage is 31.010% with baseline and 31.732% with more frequent drought scenario. The percentage of slippage is almost double when the cost of MAR is $40/acre-foot and at the highest level at the MAR cost of $60/acre-foot. The change of percentage slippage indicates that when the cost of MAR is greater than the initial groundwater pumping costs, such as at MAR cost of $60/acre-foot, producers begin to use MAR when groundwater levels fall to a certain level, and the recharged water through MAR is mostly then pumped back up to stabilize net returns.

4.2. Effects of drought on land use, net returns, groundwater withdrawl and aquifer stock

Greater drought risk decreases rice acreage, but increases total irrigated and non-irrigated acreage. The change in crop acreage and irrigation requirements under greater drought risk scenario places more demand on MAR water compared with baseline scenario, and aquifer stock falls more because the greater MAR water is not enough to offset the increase in groundwater withdrawals. For example, from table 2, when the cost of MAR is $20/acre-foot under baseline scenario, greater drought risk causes annual MAR to increase by 0.408 – 0.387 = 0.021 million acre-feet, but the annual increase in groundwater withdrawals is higher at (0.921 + 0.131) - (0.896 + 0.12) = 0.036 million acre-feet. Thus, groundwater conservation policies, e.g., subsidy to MAR and pumping cap or fee, might be needed to limit groundwater withdrawals during drought years. We find that MAR increases farm net return with greater drought risk by an amount similar to that under baseline scenario.

We evaluate the effects of potential drought risk in the future by creating a synthesis of drought frequency based on the historical PDSI index. A more sophisticated and accurate approach to obtain a drought frequency, e.g. numerical modelling, could be useful for future research. To the extent that future long-term trends, such as climate change, which might enhance the incentives for farmers to invest in efficient technologies and apply irrigation deficit when precipitation is more scarce [36, 37], the role of irrigation capital, farm net return and policies affecting them may be even more important. Modeling these effects through time-varying policy instruments is a potentially fruitful topic for further research [38].

Acknowledgments: This work supported by the USDA Economic Research Service through a cooperative agreement 58-6000-7-0090. Any opinion, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of USDA.

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Paper for ISMAR10 symposium. **Topic No: 16 (048#)**

Tracking the fate of Waipaoa river water infiltrated in the deeply anoxic Makauri Aquifer, Gisborne, New Zealand

Niels Hartog [1], Eric van Nieuwkerk [2] , Roger Cudmore [2] and Graeme Card [3,*]

[1] KWR Watercycle Research Institute; The Netherlands Niels.Hartog@kwrwater.nl
[2] Golder Associates (NZ) Limited; New Zealand, evannieuwkerk@golder.com
[3] Gisborne District Council ; New Zealand
* Correspondence: Niels.Hartog@kwrwater.nl; Tel.: +31-653-43-6286

Abstract: The Gisborne MAR project aims to reverse long-term decline of water levels, increase yield and improve water quality of the Makauri alluvial gravel aquifer used for high-value crop irrigation. Therefore, a trial injection of oxic Waipaoa river water into the anoxic highly-mineralised Makauri aquifer through Aquifer Storage Transfer and Recovery (ASTR) was performed. The use of bromide and chloride concentrations allows a detailed tracking of the infiltrated river water volume and appears to provide a relatively straightforward means to track which of the horticultural abstraction wells are (partly) abstracting infiltrated river water. The interactions of the oxic river water with the deeply anoxic Makauri Aquifer water do thus far seem to result in positive water quality changes with removal of nitrate, decrease in arsenic concentrations and no apparent impacts by trace element mobilization. Due to freshening of the aquifer with river water, however, temporary increase of sodium concentrations relatively to the infiltrated river water should be expected initially. Further investigation should also address the fate of organic contaminants potentially present in the river water such as pesticides, and the extent to which operational abstraction well can be affected by clogging risks in the zone of mixing and displacement of native groundwater with river water. Overall, the results of the trial so far suggest that a full ASTR scheme could have both an overall stabilizing effect on the Makauri aquifer, with groundwater levels enhancing aquifer yield, as well as net beneficial effects on water quality.

Keywords: managed aquifer recharge; aquifer storage; river water infiltration, sea water intrusion, freshening, nitrate removal, tracer, mixing.

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1. Introduction

World-wide availability of high quality fresh water is under pressure due to a combination of pressures on local groundwater resources, such as climate change, increasing water demands and sea water intrusion [1].

Declining groundwater levels over the past decades identified in the Poverty Bay area, Gisborne, New Zealand, [2, 3] and potential sea water intrusion risks, are currently considered as an important environmental and water supply reliability issue. Uncertainty about long-term water availability may affect future regional development as irrigation for growing horticultural use depends for a substantial proportion on groundwater abstractions.

The use of managed aquifer recharge (MAR) is under consideration to improve water security in the area. The aim is to replenish the methane-bearing Makauri aquifer with winter-runoff water from the Waipaoa River to ensure sustained yields from the aquifers beneath the Poverty Bay Flats.

To assess the technical and environmental feasibility for an aquifer storage, transfer and recovery (ASTR) type MAR system involving the infiltration of Waipaoa River water, an injection trial was performed and monitored. Objective of the study was to assess whether the long-term groundwater level decline and degradation of the water quality of the Makauri aquifer can be reversed.

2. Materials and Methods

2.1. Hydrogeology

Beneath the Poverty Bay Flat up to four aquifers can be distinguished (Figure 3). Apart from the unconfined top aquifer (Te Hapara), the deeper aquifers (Waipaoa, Makauri and Matokitoki) are all confined alluvial gravel aquifers, which are separated from each other by organic-rich marine silts and clays and some sands. The deeper aquifers are mainly recharged by the Waipaoa River in the upper catchment to the north, and through rainfall recharge near the hills that confine the Poverty Bay flat to the west and east. Infiltrating recharge water will pass organic-rich layers before entering the deeper confined aquifers and this leaves a distinct anoxic signature of the confined aquifer water quality across a large part of the Poverty Bay Flat, although oxygenated groundwaters are also encountered [4]. All aquifer water will eventually discharge in coastal streams and in the Pacific Ocean, which forms the southern boundary of the Poverty Bay Flat.

The injection trial described in this study was performed in the Makauri Gravel Aquifer, which is the most extensive of the five main aquifers and is the target aquifer for the planned aquifer storage transfer and recovery (ASTR) MAR scheme. This aquifer is an important source of water for irrigation purposes on the Poverty Bay Flats. Groundwater levels in this aquifer have shown declines at least in part related to increased groundwater abstraction [2, 3].

The Makauri Aquifer covers an area of at least 6,000 ha beneath the Poverty Bay Flats, from Caesar Road in the north to the Gisborne city outskirts in the south. This aquifer constitutes a series of limestone gravel layers covering most of the Poverty Bay Flats area. The gravel layers are considered to have been deposited as delta deposits when the river was down cutting into gravel terrace deposits upstream of Te Karaka [5]. The Makauri Aquifer is shallower beneath the northern edge of the flats (-45 m RL at Ormond) dipping down to -60 m RL in the middle of the basin. Lithological logs from bores near the coast indicate that only a thin gravel layer is locally present in this area at approximately 66 m below ground level [3]. Preliminary geological modelling by Golder indicates that the Makauri aquifer has a thickness between 1 and 15 m but is mostly less than 3 m thick.

2.2. Geological and Hydrogeological Model

As part of the ongoing investigations a three-dimensional numerical geological model of the Poverty Bay Flat area was developed in MAPTEK Vulcan based on bore logs from water supply wells installed throughout the Poverty Bay Flat area. This was used to development of a three-dimensional numerical groundwater and solute transport model in Groundwater Vistas version 6 (Modflow and MT3D) of the same area. Initial steady-state and transient calibration of the groundwater model were undertaken using long-term groundwater level monitoring data from 94 wells screened across all four aquifers. However, it is acknowledged that a lack of accurate historic groundwater abstraction data limits the ability for transient calibration. Data from the injection trial monitoring programme will be used to further optimize the groundwater model.

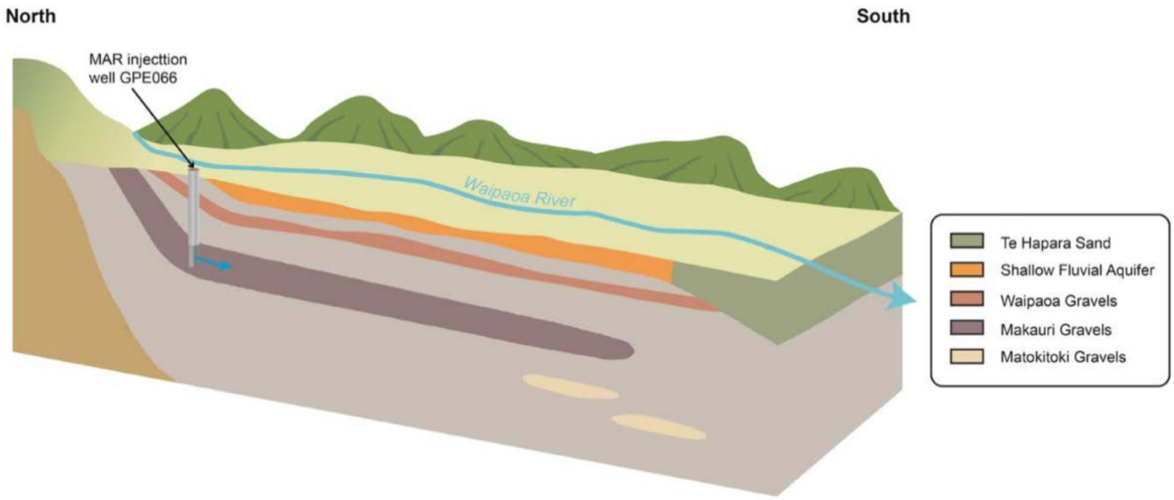

Figure 3. Conceptual cross-section of Poverty Bay flats aquifers. Confining layers of silts and clays are marked gray.

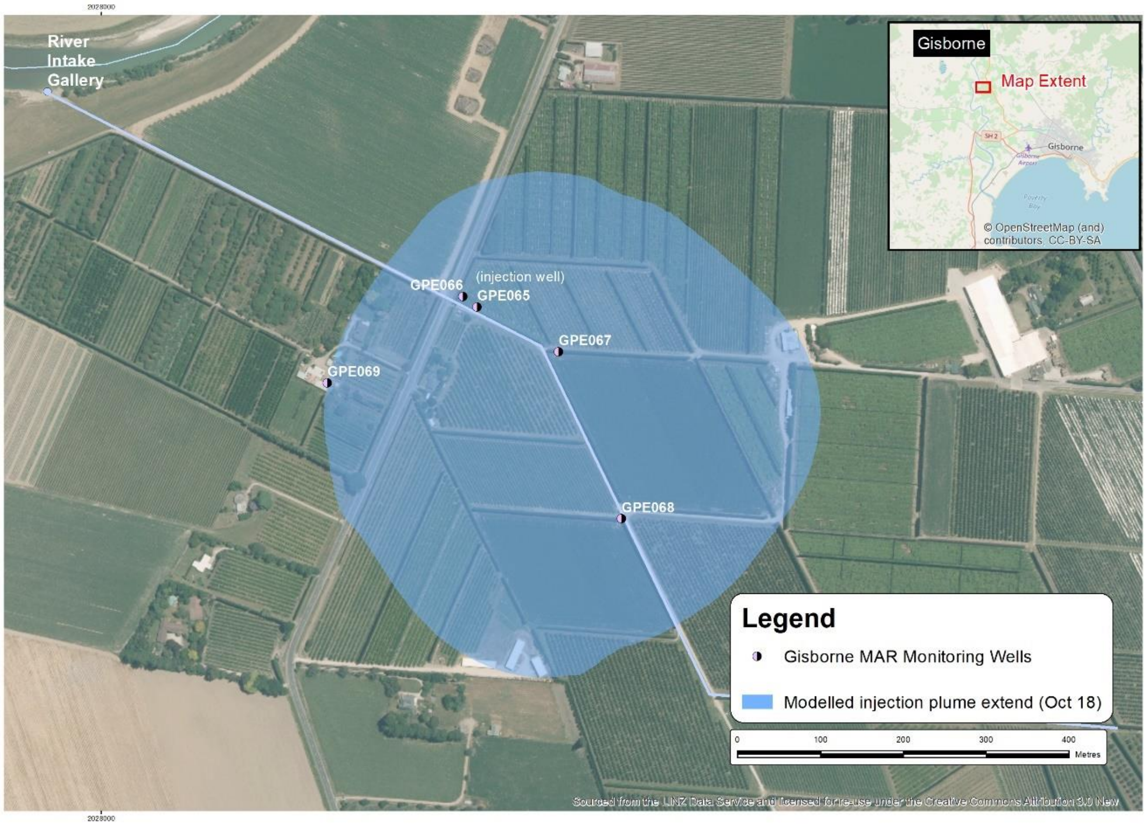

Figure 4. Overview map of Gisborne MAR injection well and river take infiltration gallery at Bushmere Road, Gisborne.

2.3. Injection Trial

The installation of a Makauri Aquifer injection well (Figure 5a), headworks and filter system was completed in May 2017 and injection trial undertaken between June – September 2017. Waipaoa River water was sourced via an existing infiltration gallery at Kaiaponi Farms (Figure

5b) and after filtering injected into the Makauri Aquifer at the MAR site. During the injection trial a total of 73,180 m^3 of river water was injected in 59 days at an approximate injection rate of 15 L/s. After winter 2017 the injection trial was completed, and injection was stopped. New monitoring wells GPE067, GPE068 and GPE069 (Figure 4) were installed and monitoring has been ongoing ever since to track the injected river water. The development of groundwater quality was determined by field testing and laboratory analysis of groundwater samples.

(**a**)

(**b**)

Figure 5. **(a)** Gisborne MAR injection well (GPE066) at Bushmere Road, Gisborne; **(b)** Kaiaponi infiltration gallery and river intake.

3. Results and Discussion

3.1. Aquifer level response to injection trial and seasonal changes

The injection trial showed that artificially recharging the Makauri Aquifer through infiltration wells is technically viable. An increase in groundwater levels during injection was clearly visible, with mounding effects up to 2 meters (Figure 6) observed at 20 m distance (GPE065, Figure 4) from the infiltration well during the winter 2017 injection trial.

Irrigation season has commenced late-October 2017 and groundwater levels in all aquifers are declining as a result of summer groundwater abstractions. In winter 2018 groundwater levels recovered as irrigation abstraction ceases and rainfall recharge outweighs evapotranspiration. The irrigation season commence in October – November most years (i.e. Southern Hemisphere spring), but significant rainfall in mid-November 2018 has reduced pumping requirements followed by some increase in aquifer levels. From mid-December 2018 groundwater levels have fallen again, caused by groundwater abstractions for irrigation in response to drier weather.

3.2. Water quality changes upon river water injection and migration through the aquifer

During field testing in January 2019, one and half year after the Waipaoa River water volume was injected, the groundwater quality in the near infiltration monitoring well GPE065 (20m distance downgradient, Figure 4) showed the lowest electrical conductivity, akin to the injected river water. In contrast, the electrical conductivity of GPE069 (200 m distance upgradient Figure 4) reflected the salinity of native groundwater in the Makauri Aquifer as was also observed prior to infiltration at the injection site (Table 2). Although calculations indicate that the fringe of the injected volume may have reached GPE069 (Figure 4), it has now been displaced by southwardly inflowing native groundwater. Although the infiltrated river water contained atmospherically saturated oxygen (O_2) concentrations (~10 mg/L), observed oxygen concentrations are low in all monitoring wells (i.e., <1 mg/L) reflecting the oxygen consumption by reactive species in the aquifer sediment or in the native groundwater.

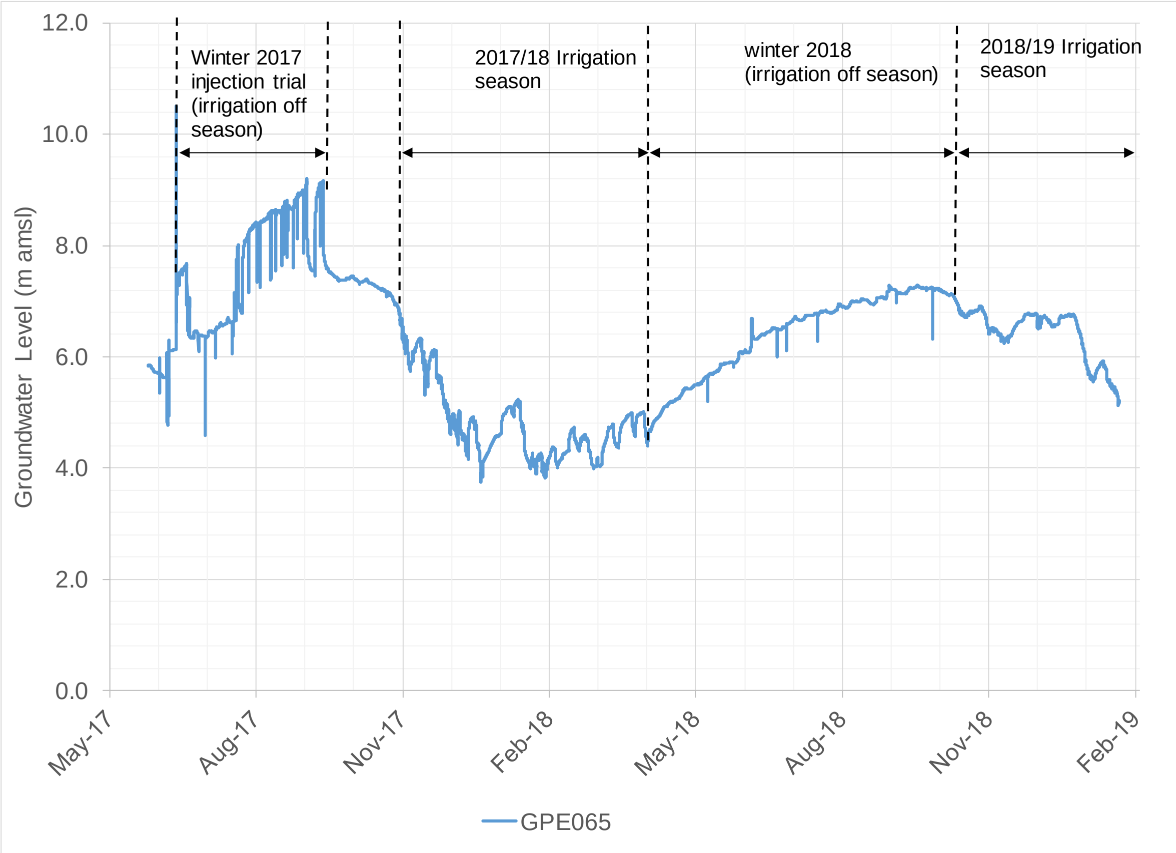

Figure 6. Recorded Makauri aquifer water levels in monitoring well GPE065 at 20 m distance from the injection well GPE066 (Figure 4).

3.2.1. Infiltrated river water mixing with native groundwater

To assess the nature and degree of mixing between the infiltrated river water and native groundwater, the concentrations of the conservative species chloride and bromide were used (Figure 7). In keeping with the relative differences in electrical conductivity (Table 2), lowest chloride and bromide concentrations were found in the observation well nearest to where infiltration had occurred (GPE065) and the highest concentrations in GPE069. The very strong positive correlation between chloride and bromide, across the monitoring rounds of both October 2018 and January 2019, indicates that binary mixing between an endmember with a Waipaoa River water composition and an endmember with native groundwater composition can be assumed.

The chloride/bromide mass ratio of the correlation of about 200 (Figure 7) is similar to that found for groundwater elsewhere in New Zealand [6] and distinctively lower than typical for current seawater composition (~290). The latter suggests that the observed salinity in the native groundwater has not been affected by modern sea water intrusion and that chloride/bromide ratio's elsewhere in the Makauri aquifer can be used to confirm if and where sea water intrusion occurs [7].

Where the chloride concentration at GPE065 is similar to that of the Waipaoa river (Figure 8), the fraction of river water at GPE067 and GPE068 appears to be above 60%. These monitoring wells therefore seem within the hydraulic boundary of the infiltrated river water volume where dispersive mixing would be expected to result in a 50% mixing fraction. Interestingly, although GPE068 is further from the infiltration well than GPE067, its bromide and chloride concentrations indicate a higher fraction of infiltrated river water. Although the numerically calculated extent of the injected volume in December 2018 (Figure 4) takes into account a southward regional flow, the recorded chloride and bromide concentrations indicate that the injected volume has spread less eastward than calculated. GPE069 does not seem to show the signature of infiltrated river, and the westward spreading of the injected volume was likely less than calculated. This indicates an overall more southward oriented, elongated spreading of the injection volume, likely due to a higher effective regional groundwater flow velocity. Since the chloride and bromide concentrations at GPE067 increased and at GPE068 decreased between the monitoring rounds in October 2018 and January 2019, the tail end and the front end of the injected river water volume seem to have shifted (Figure 7).

Table 2. Field testing results Gisborne MAR monitoring wells.

Monitoring well	Sample date	Temperature	Dissolved Oxygen (mg/L)	Conductivity (µS/cm)
GPE065 (prior to injection)	17-05-17			1,347
GPE066 (prior to injection)	08-05-17			1,302
INJECTION at GPE066				
GPE065	08-01-19	15.9	0.14	572
GPE067	08-01-19	15.7	0.19	969
GPE068	08-01-19	17.3	0.31	943
GPE069	08-01-19	18.9	0.28	1485

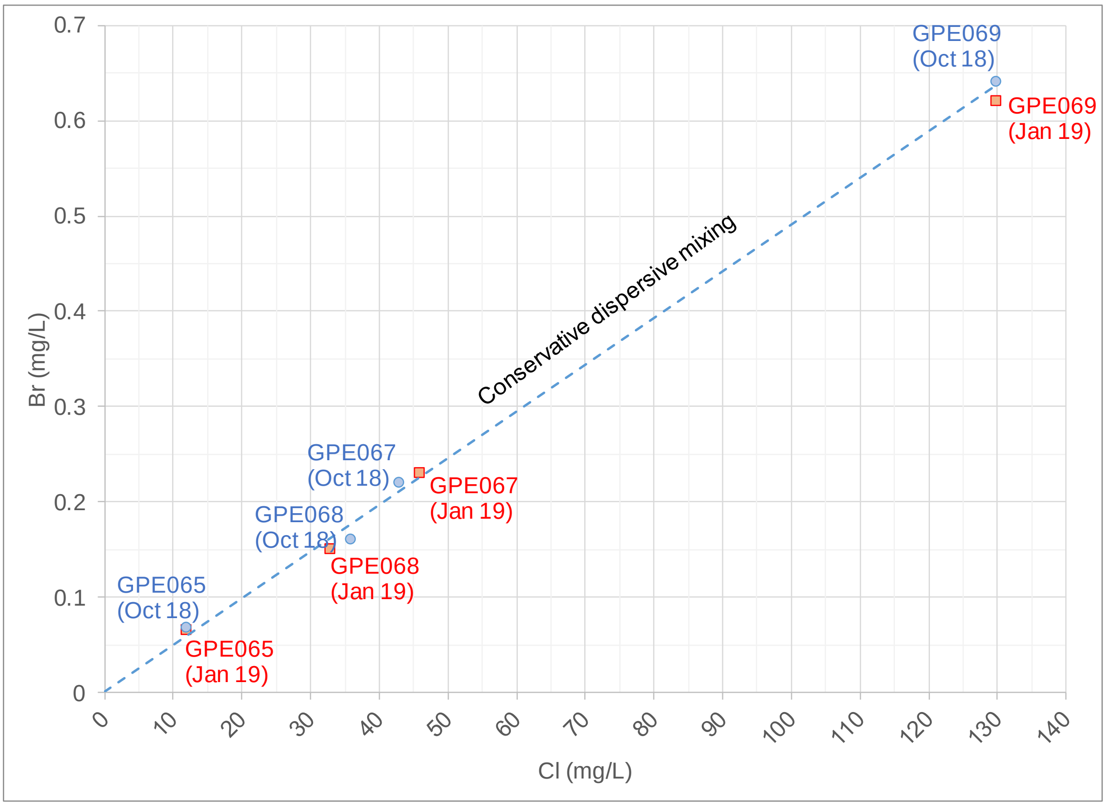

Figure 7. Observed bromide versus chloride concentrations in the groundwater monitoring wells at the site of the Gisborne MAR infiltration site (Figure 4).

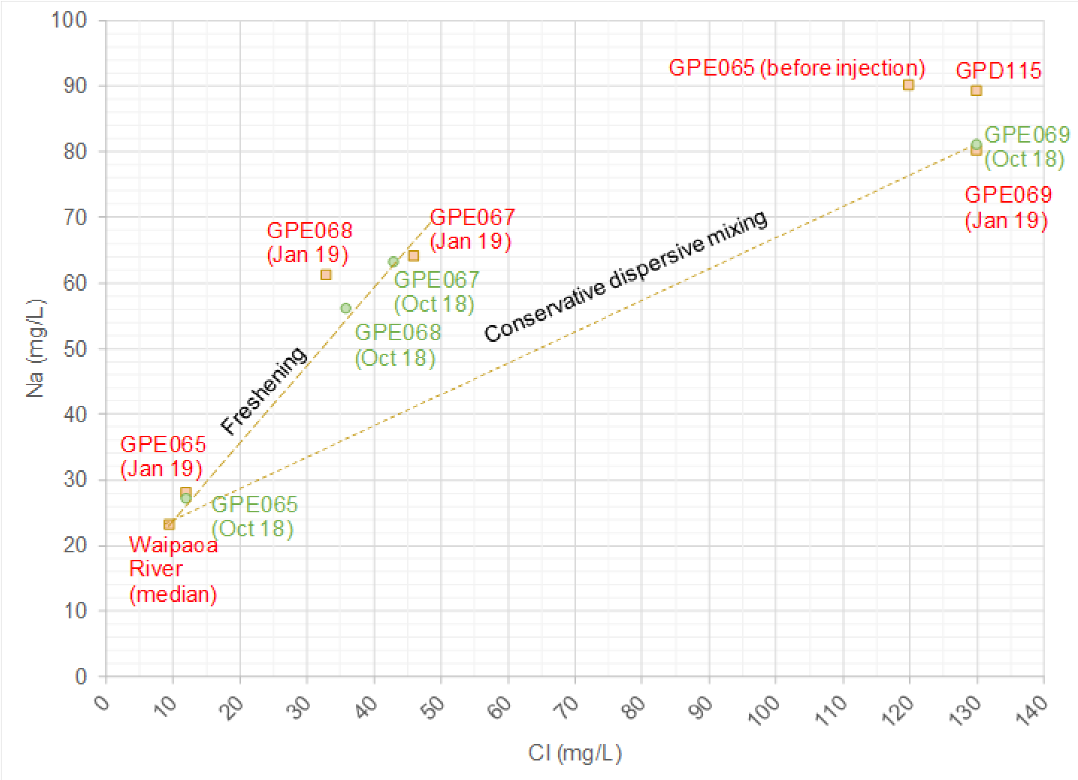

Figure 8. Observed Sodium versus chloride concentrations in the groundwater monitoring wells at the site of the Gisborne MAR infiltration site (Figure 4).

3.2.2. Aquifer Freshening

As a result of the infiltration of fresh river water, sodium (Na) concentrations increase relative to what would be expected from conservative mixing with native groundwater (Figure 8). This is indicative for the occurrence of aquifer freshening, where calcium, the dominant cation in the river water, displaces sodium from the cation exchange sites in the sediment. Although sodium concentrations in the groundwater will drop to low concentrations of the river water with continued freshening, temporarily relatively elevated sodium concentrations should be expected initially and this may have implications for the horticultural use.

3.2.3. Redox-related water quality changes

In addition to the described removal of dissolved oxygen from the infiltrated river water (Table 2), nitrate appears to be also removed rapidly from the infiltrated river water (Figure 9). Nitrate concentrations are well below median values for Waipaoa River water, and are well below the expected concentrations when taking into account mixing with the nitrate free native groundwater. In the January 2019 monitoring round, all nitrate concentrations had further reduced down to non-detect. The rapid removal of nitrate indicates the occurrence of denitrification. Since sulfate concentrations are not concurrently elevated (Figure 10) with the disappearance of nitrate, pyrite oxidation does not seem to contribute to the removal of either oxygen or nitrate from the river water in the Makauri Aquifer. Based on the concentration difference between the sulfate concentration in the Waipaoa River from July 2017 and the concentrations measured in groundwater in GPE065 in October 2018 and January 2019, there seems to be some sulfate reduction, although the concentration in the other wells seem to decrease concurrently with their native groundwater fraction indicating mainly the effect of dispersive mixing. Also, the concentrations of other redox-sensitive species (not shown), like arsenic, seem predominantly affected by conservative mixing by dispersion between the infiltrated river water (As, 2 µg/L) and the native groundwater (As, 10 µg/L).

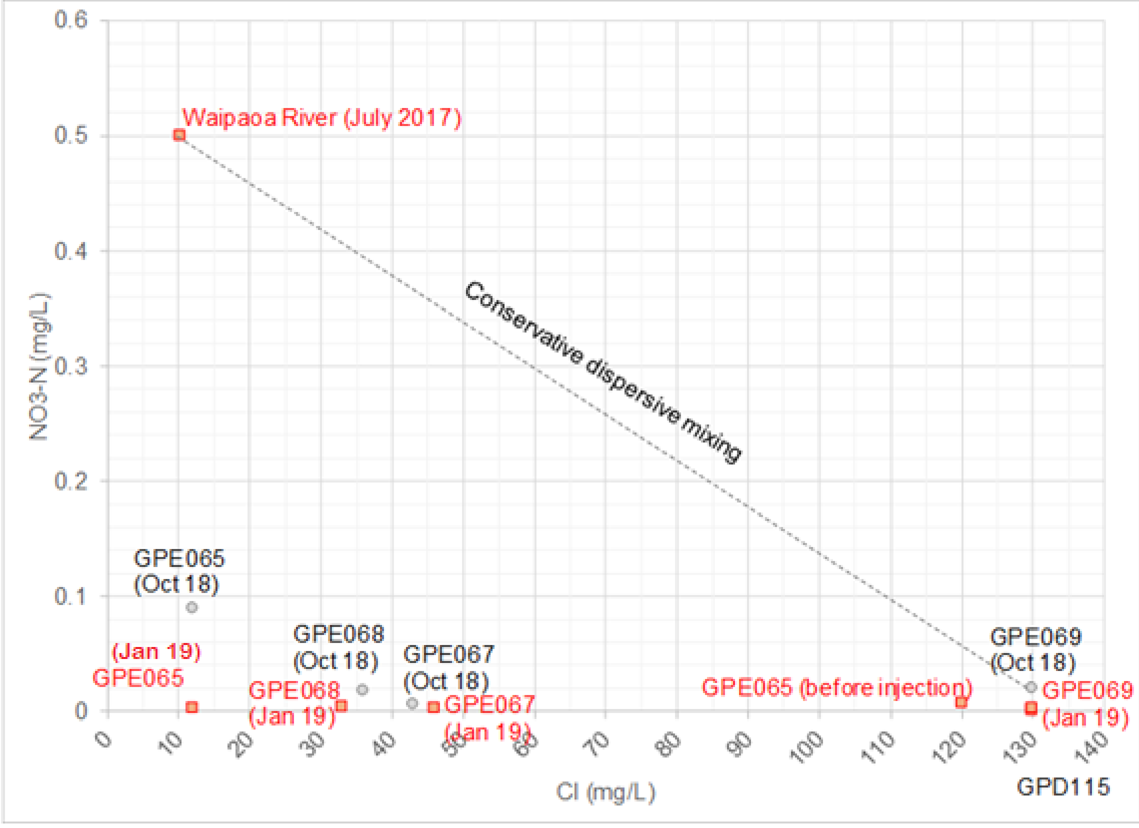

Figure 9. Observed nitrate-nitrogen versus chloride concentrations in the groundwater monitoring wells at the site of the Gisborne MAR infiltration site (Figure 4).

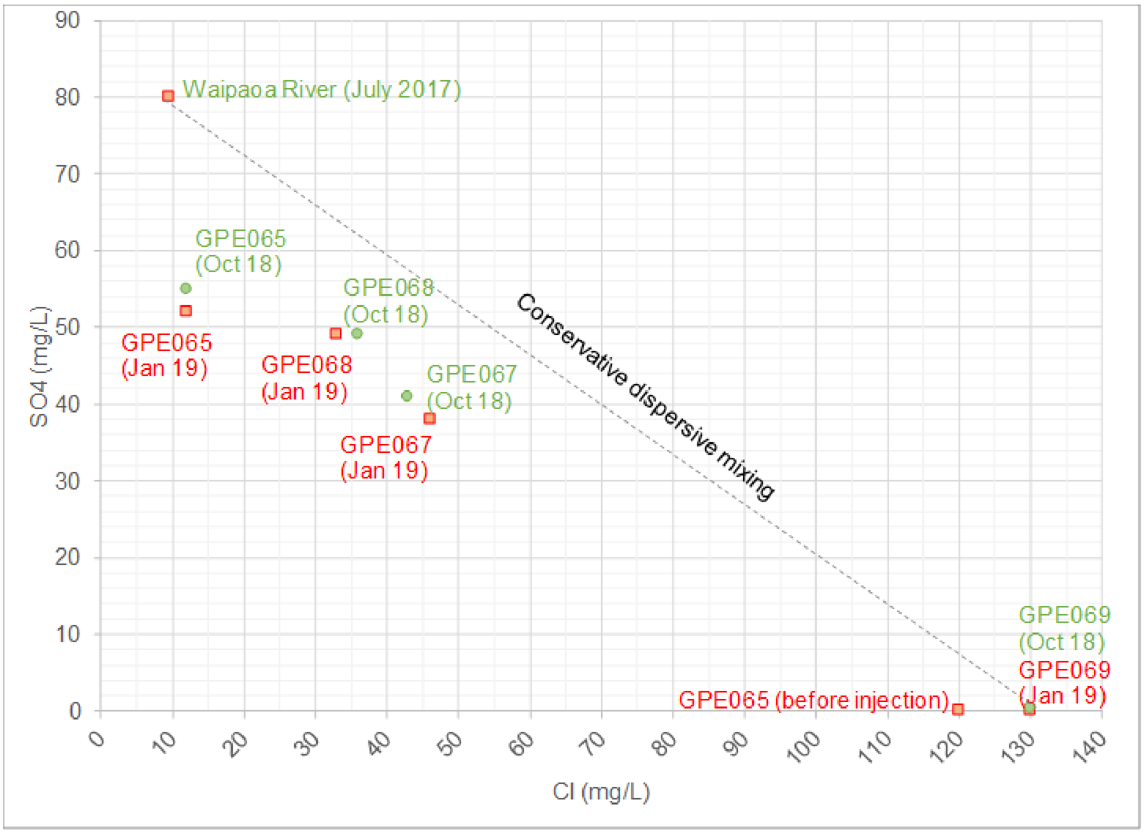

Figure 10. Observed sulphate versus chloride concentrations in the groundwater monitoring wells at the site of the Gisborne MAR infiltration site (Figure 4).

4. Conclusions

The results of the infiltration trial so far suggest that a full ASTR scheme could have both an overall stabilizing effect on Makauri Aquifer groundwater levels enhancing aquifer yield, as well as net beneficial effects on water quality. The use of bromide and chloride concentrations allows a detailed tracking of the infiltrated river water volume and appears to provide a relatively straightforward means to track which of the horticultural abstraction wells are (partly) abstracting infiltrated river water. The interactions of the oxic river water with the deeply anoxic Makauri Aquifer water do thus far seem to result in positive water quality changes with removal of nitrate, decrease in arsenic concentrations and no apparent impacts by trace element mobilization. Due to freshening of the aquifer with river water, however, temporary increase of sodium concentrations relatively to the infiltrated river water should be expected initially. Further investigation should also address the fate of organic contaminants potentially present in the river water such as pesticides, and the extent to which operational abstraction well can be affected by clogging risks in the zone of mixing and displacement of native groundwater with river water.

Acknowledgments: This research was funded by the Gisborne District Council.

Author Contributions: N.H. and E.v.N.: writing and interpretation of results, R.C. and G.C. provided writing and research support. Authors contributed to this paper in the given order.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharge
ASTR: Aquifer Storage, Transfer and Recovery.

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Paper for ISMAR10 symposium. **Topic No: 1 (057#)**

Strategic Water Storage and Recovery with Desalinated Seawater in Liwa, UAE

Edda Kalbus[1]*, Georg Koziorowski[2], Mohamed Husain Alhosani[3] and Abdulla Mohamed Al Kamali[4]

[1] Transco - Abu Dhabi Transmission and Despatch Company; edda.kalbus@transco.ae
[2] Transco - Abu Dhabi Transmission and Despatch Company; georg.koziorowski@transco.ae
[3] Transco - Abu Dhabi Transmission and Despatch Company; MH.Alhosani@transco.ae
[4] Transco - Abu Dhabi Transmission and Despatch Company; abdulla.alkamali@transco.ae
*****Correspondence: edda.kalbus@transco.ae; Tel.: +971-2-416-4038

Abstract: The secure supply of municipalities with potable water is a major concern for governments worldwide and particularly in arid regions. The Emirate of Abu Dhabi, United Arab Emirates, has only limited natural freshwater resources and therefore relies on desalinated seawater for domestic water supply. The storage capacity within Abu Dhabi's water distribution network used to be in the order of a few days, and taking into account a certain vulnerability of desalination plants to environmental or technical hazards, the security of water supply was considered low. Therefore, a Strategic Water Storage and Recovery (SWSR) facility was constructed to store desalinated seawater in a dune sand aquifer. The facility can provide potable water recovered from the aquifer for a population of one million over a period of 90 days, which has significantly increased the security of water supply in Abu Dhabi. Despite comparatively high costs of desalinated seawater relative to groundwater or surface water, such projects are deemed feasible and highly needed to secure the well-being of the population in the absence of natural freshwater resources. This paper discusses the rationale, history and key considerations of the project.

Keywords: MAR; desalinated seawater; strategic storage; dune sand aquifer.

1. Introduction

Providing a safe, secure supply of drinking water is a major concern for governments worldwide. In arid regions, this task is particularly challenging due to the prevailing freshwater scarcity. Therefore, many countries in arid regions increasingly rely on desalinated seawater for their potable water supply. In the Emirate of Abu Dhabi, United Arab Emirates (UAE), the source of domestic water supply is entirely desalinated seawater as natural freshwater resources are limited.

The major portion of desalinated seawater in the UAE is produced in a combined power and water production process. Five power plants supply water to the Emirate of Abu Dhabi (population in 2016: 2.9 million [1]) with a total current desalination capacity of about 4 Mm^3/d [2]. Just like every other production process, the production of potable water is vulnerable to interruptions. Threats to the production process include contamination of the seawater source such as red tides [3–5], oil spills [6,7], raw sewage discharge and other land-based sources [8]; technical failures; or intentional disturbance.

While water storage tanks typically exist at every desalination plant and pumping station in the transmission networks, the total storage capacity within the distribution system is low. Estimates from across the region place the system storage in the order of 12 hours to 3 days [9]. Any disturbance of the production process may therefore have direct impacts on the security of potable water supply. Therefore, the establishment of strategic storage capacity to overcome long-term supply interruptions is deemed necessary as integral part of the Emirate's water management strategy [10].

As the climate in Abu Dhabi is hot and arid, and the Emirate is largely covered by sand dunes, large surface storage reservoirs are out of question. Ground storage tanks for the large volumes required for strategic storage are also considered unfeasible [11]. Managed Aquifer Recharge (MAR) is likely to be the only feasible solution for the creation of large-scale strategic storage capacity [12].

MAR, defined as "the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit" [13] has become an increasingly important water management strategy in many parts of the world [14]. While a range of water sources are commonly used for MAR including river and lake water or treated sewage effluent, desalinated seawater is not (yet) a widely used source. However, the benefits of combining power and water production with MAR and the potential of this approach to increase water security in the region have been highlighted by various authors [9,15].

This paper describes the implementation of a MAR scheme for strategic storage using desalinated seawater in Liwa, Abu Dhabi Emirate. It provides the rationale for developing the project, briefly describes the project history, and explains how the MAR scheme is integrated into the water supply strategy of the Emirate.

2. Water management in Abu Dhabi

2.1. Water resources

The only natural water resource in the Emirate of Abu Dhabi is groundwater. However, most of the groundwater is saline or brackish, with only 3% being fresh [16]. Groundwater is mainly used for agricultural purposes and accounts for 61% of the total water supply, while potable water for domestic, municipal, commercial and industrial use is entirely supplied from desalinated seawater, accounting for 34% of the total water supply (Figure 1a). Recycled water is used for landscaping and contributes 5% of the total water supply.

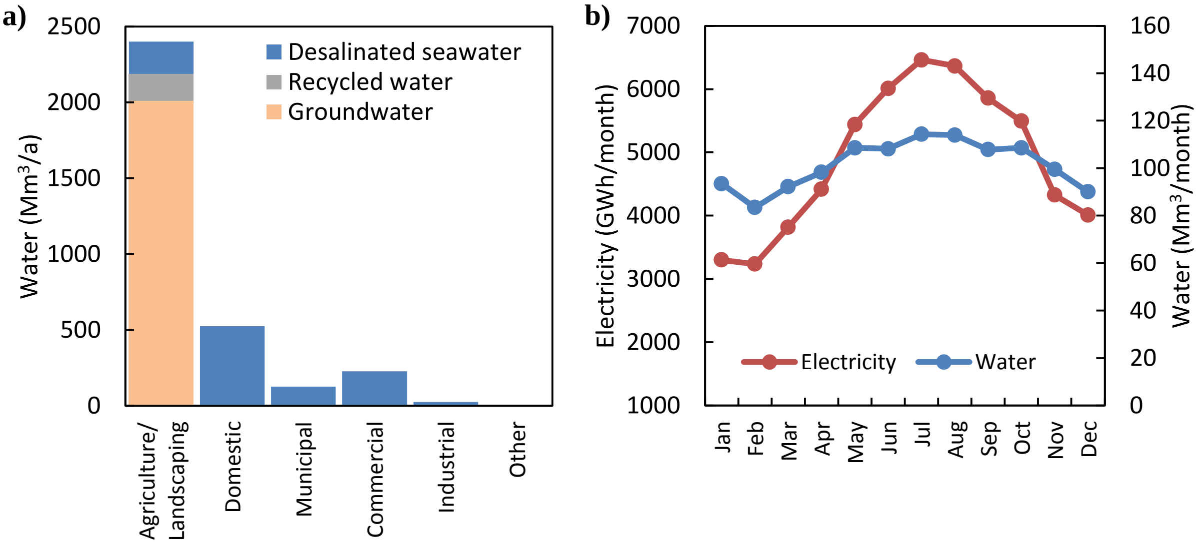

Figure 1. a) Water demand by sector, 2017 [1,17]; b) Monthly water and electricity demand, 2017 [2].

Desalinated seawater is provided by five plants with a total desalination capacity of 4.36 Mm^3/d (Figure 2). Potable water is mainly produced in a power/water co-generation process, which is largely driven by seasonal variations in electricity demand. As shown in Figure 1b, electricity demand increases by 100% in summer compared to winter due to the cooling requirements in the hot climate of Abu Dhabi. In contrast, water demand increases only by 40% in summer.

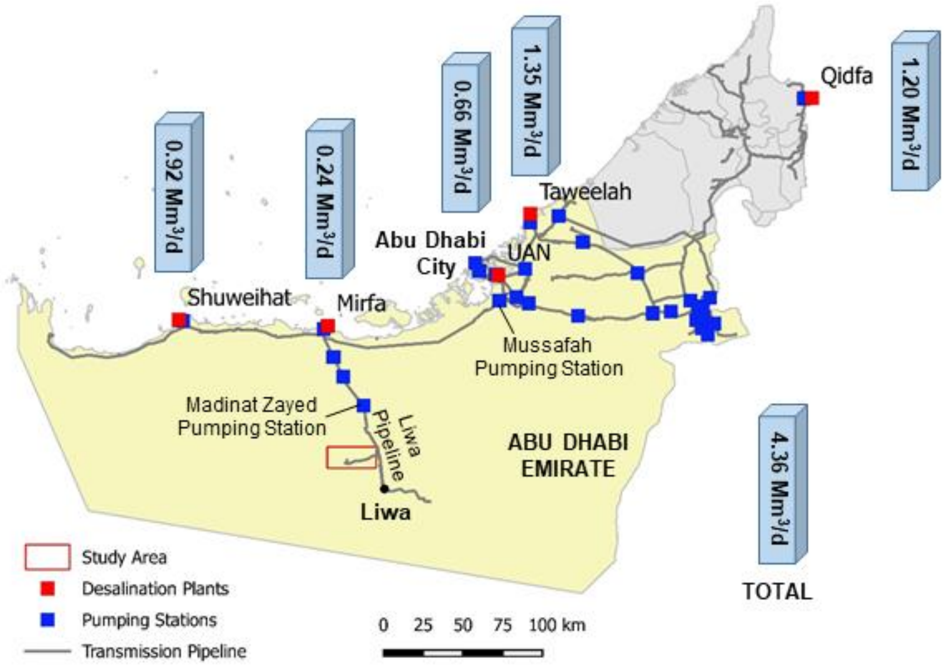

Figure 2. Overview of the study area and desalination capacities 2018 (after [2]).

2.2. Water transmission, distribution and storage

The Emirate of Abu Dhabi is equipped with water transmission networks covering all urban areas as illustrated in Figure 2. Each desalination plant has water storage tanks supporting the transmission network with a storage capacity equivalent to 24 hours of water supply at the rated design output of the plant. Water is pumped through the network spending between a few hours to one week to reach the end-users. Depending on the location and height of the supplied area, water transmission may require one to four consecutive pumping operations to reach the end-users. Therefore, in addition to the storage reserves at the water desalination plants, terminal pumping stations that supply the distribution system are also equipped with storage capacity equivalent to 24 hours' supply at the average daily demand of the distribution system. The end-users receive the water through individual storage tanks on their property, which provide water for a few days.

Most of the transmission network, including storage tanks, is monitored in real time by the Water Control Centre of the Emirate of Abu Dhabi, which is responsible for maintaining the storage capacity available and meeting the demand in the most economical way. In case of shortage and emergency, the Water Control Centre is also responsible for operating the supply in emergency mode, which includes water recovery from strategic storage facilities.

2.3. Implications for water security

As discussed in the previous section, the storage capacity within the water transmission and distribution network is low. Even considering the end-user storage tanks, the stored volume of potable water likely suffices for few days only. In the event of an interruption of the desalination process, a threat to the supply of Abu Dhabi's population with potable water would be immediate. While a simultaneous failure of all plants is unlikely to happen, water security would be affected even if only one plant failed. Therefore, the creation of strategic storage capacity to overcome supply interruptions was deemed necessary.

3. The Strategic Water Storage and Recovery Project in Liwa

3.1. Project history

Due to the differences in demand between water and electricity, desalinated seawater (DSW) was occasionally available in excess of demand for limited time periods. Solutions were sought to make use of the excess water which otherwise would be returned to the sea. As extensive hydrogeological investigations undertaken across the UAE from the 1990s onwards revealed immense natural storage capacities in the vast dune sand aquifers in the western part of the country [18,19], the idea was born to store the excess water in the aquifers and create a strategic storage reservoir. In 2001, a feasibility study was initiated to investigate the possibility of storing large quantities of DSW underground for later utilization [20]. A study area of approx. 400 km^2 in the Al Dhafra Region of the Abu Dhabi Emirate was selected based on the following characteristics:

- The geological setting offers a vast natural storage capacity
- The vadose zone is sufficiently thick to provide storage capacity and protection from surface contamination
- The saturated aquifer is sufficiently thick to allow pumping operations
- The aquifer has a large lateral extent
- A large freshwater lens exists in the area
- There are no urban, agricultural or industrial activities in the remote area that could cause contamination or interfere with the pumping operation
- There are no other competing well fields in the area
- Water transmission mains and electrical power supply are accessible
- The relatively high elevation of the area provides opportunity for gravity supply of the stored water to Abu Dhabi City.

The feasibility study concluded that water quantities of up to 2.5 Mm^3/km^2 could be reasonably stored and recovered in the study area [20]. A pilot project was proposed to determine the efficiency of the recharge process in terms of quality and quantity, verify the total effective storage capacity, and optimize the layout and cost estimation for the final project.

The pilot project was constructed in 2003 and was the first large-scale field test worldwide using DSW on a semi-industrial scale. It included one infiltration basin recharge/ recovery scheme and one well gallery recharge/recovery scheme to compare and determine the optimal recharge approach [21].

The infiltration scheme consisted of one infiltration basin of 2,160 m^2 and four recovery wells. Infiltration and recovery capacity were 250 m^3/h. The well gallery scheme consisted of five dual-purpose injection/production wells with a total injection capacity of 250 m^3/h and a total recovery capacity of 500 m^3/h. The monitoring network comprised 50 new monitoring wells and incorporated 43 existing monitoring wells. Furthermore, a connection point to supply DSW from the nearby transmission main and two storage tanks with a volume of 2,500 m^3 each for intermediate storage of the supplied water before infiltration/injection were constructed.

Recharge/recovery operations were performed from October 2003 to October 2004 and monitoring continued until January 2005. The infiltration scheme was recharged with a total volume of 1.47 Mm^3 over a period of 250 days and after 48 days of rest, a volume of 0.37 Mm^3 was recovered over a period of 70 days. The operation of the well gallery scheme comprised four recharge/recovery cycles separated by break periods of 1-20 days. A total volume of 0.69 Mm^3 was injected and almost the same volume (0.68 Mm^3) was recovered.

Major findings from the pilot project included the following [21]:

- The manageable storage capacity of the subsurface is enormous. Based on the storage properties of vadose zone and saturated aquifer, the aquifer size and geometry, and the effective porosity, the dune sand aquifer offers capacity for large-scale recharge projects of almost any size compatible with the aquifer dimensions.
- Evaporation losses are negligible. The vadose zone with an average thickness of 40 m provides sufficient buffer to prevent evaporation losses.
- The hydrogeological impact on the regional aquifer system is negligible. While groundwater levels increased by a maximum of 14.25 m at the recharge facilities, the average regional groundwater level increase was around 0.22 m. The total area affected by the cone of impression after 250 days of infiltration was around 10.7 km^2.
- The lateral migration of the artificially created freshwater reservoir is small. Observations and numerical simulations indicate a lateral movement of less than 10 m per year. Considering the size of the created water body (spatial extension of 0.17 km^2), this migration rate can be considered negligible even for storage periods beyond 10 years.
- The physical recovery efficiency was 85%-90% when the water was recovered immediately after recharge. Recovery efficiency based on water quality criteria was estimated between 75% and 100%, depending on the desired maximum salinity level.
- The water quality of the recovered water adhered to the water quality regulations for drinking water [22].
- The infiltration basin approach was found superior to the well gallery approach for the given site conditions, as it is easier to operate and maintain and less prone to clogging.

The pilot project confirmed excellent prospects for the construction of a large-scale project. It demonstrated that the selected area and the selected methods are capable of delivering the desired outcomes. Following a design and planning phase, the construction of the final project, termed "Strategic Water Storage and Recovery" (SWSR) project, started in 2009. Details of the final project are given in the following sections.

3.2. Project scaling

The initial idea of storing occasionally available excess DSW in local aquifer systems soon developed into the much broader approach of creating an underground strategic water reserve to supply the population with potable water in case of emergency. The aim was to significantly extend the emergency supply period from few days to up to three months.

According to tested infiltration rates, and availability of DSW, the design recharge rate for the SWSR plant was set to 31,823 m^3/d (7 MIGD). Continuous recharge at that rate over 27 months resulted in a total DSW storage of 26.15 Mm^3 (5,753 MIG).

The design recovery rate of the SWSR plant was set to 181,844 m^3/d (40 MIGD). Hence, a population of one million could be supplied with about 182 litres per person and day. During an emergency supply period of three months, 62.6% of the total stored DSW would be recovered. Although longer recovery periods are possible (on the expense of increasing salinity), the remaining 37.4% underground DSW storage is considered a buffer between the inner DSW plume and native groundwater of higher salinity.

The final figures of recharge and recovery rates, total volumes and periods were given by the government of the Emirate of Abu Dhabi and determined the overall design of the facilities. In particular, the recharge/recovery-ratio of 1:5.7 had a significant impact on the well field design. For instance, the implementation of only one scheme instead of three (refer to section 3.4 below) would result in wells falling dry after certain recovery periods.

Test operation of the completed SWSR facility revealed that due to the favourable natural site conditions, the SWSR facility could be extended by adding other scheme modules to any size compatible with the aquifer dimensions.

3.3. Site description

The final location for the SWSR facility was selected at a site where the hydraulic gradient is very low, hence minimizing the lateral drifts of the infiltrated water. Furthermore, the site is characterised by moderate aquifer transmissivity, maximum saturated thickness and low groundwater salinity.

The unconfined dune sand aquifer utilized for the SWSR operation consists of Aeolian, loose, fine to medium sand with occasional intercalations of fine-grained, slightly cemented interdunal deposits. Cementation and consolidation generally increase with depth. This layer has a thickness of approx. 80 m. The regional water table is encountered within this layer at a depth of approx. 40 m below ground level (BGL). The dune sand is underlain by a layer of calcarenaceous sandstone with intercalations of siltstone, mudstone, marl, and thin sand lenses. Layer thickness is approximately 80-90 m. This unit acts as an aquitard. Below the aquitard lies a layer of mudstone and evaporites that is considered an aquiclude.

The project site is located above a local groundwater mound that forms part of a major groundwater divide. North of the divide, the shallow groundwater flows towards the Arabian Gulf, while south of the divide, the groundwater flows towards extensive sabkha areas in the south that function as discharge area due to high evaporation rates. The groundwater flows away from the project site with a velocity ranging from 1 to 10 m/a at a hydraulic gradient of 0.5‰ under natural conditions. The groundwater mound is recharged naturally through infiltration from occasional local precipitation in the greater Liwa area forming an isolated lens of native fresh to slightly brackish groundwater. Due to the low natural groundwater salinity, quality losses following the mixing with DSW were minimal compared to areas with brackish or saline native groundwater.

3.4. SWSR Schemes

The SWSR facility consists of three schemes (A, B and C) arranged at the corners of an equilateral triangle. The radial distance between the schemes is 2.1 km. Each scheme comprises one circular infiltration basin of 50 m base diameter and 105 recovery wells arranged in nine rings around the centre of the basin. Each of the inner five rings has 15 recovery wells, while the number of wells in the outer rings varies between ten and five (Figure 3). The location of the outer ring wells corresponds to the predicted direction of plume movement. Each scheme takes an equal share of the infiltration and recovery process. The design infiltration capacity of each scheme is 10,608 m^3/d (2.33 MIGD), and the design recovery rate is 60,615 m^3/d (13.33 MIGD).

All the recovery wells are constructed down to an elevation of 55-60 m above sea level (ASL), which corresponds to a total drilled depth of 85 m BGL on average, covering the entire thickness of the sand aquifer. The applied reverse circulation drilling method, the installation of high-performance well screens (from approx. 93 to 65 m ASL) and a comprehensive well development programme provided maximum possible well efficiency. Having an average well capacity of about 150 m^3/h, the performance of these recovery wells is significantly higher than the performance of conventional wells drilled in the region. The assigned pumping rates of the recovery wells range from 45 m^3/h each in the inner ring to 35 m^3/h in the intermediate rings and 25 m^3/h in the outer rings. In recovery mode, 84 out of 105 wells are active at any given time, while the remaining wells are on standby.

Each recovery well is equipped with a pressure probe to monitor the water level. Additionally, one-third of the recovery wells has a multi-parameter probe installed, measuring water level, water temperature and electrical conductivity. Each scheme has 30 clustered monitoring wells (10 monitoring sites with three wells screened at different depths). 27 solitary monitoring wells are distributed between and around the schemes, and 62 monitoring wells that already existed in the area (including the Pilot Project wells) were integrated into the monitoring network (Figure 3). All monitoring wells are equipped with multi-parameter probes measuring water level, water temperature and electrical conductivity. Data loggers collect the monitoring data and transmit them through telemetry.

The recovered water is supplied to the water transmission network after chlorination, but without further treatment. Therefore, it is required to have drinking water quality. To monitor water quality, water samples were taken frequently before and during recharge from the monitoring wells and selected recovery wells. Since completion of recharge, water samples from the combined scheme production are taken at regular intervals to ensure compliance with Abu Dhabi's water quality regulations [23].

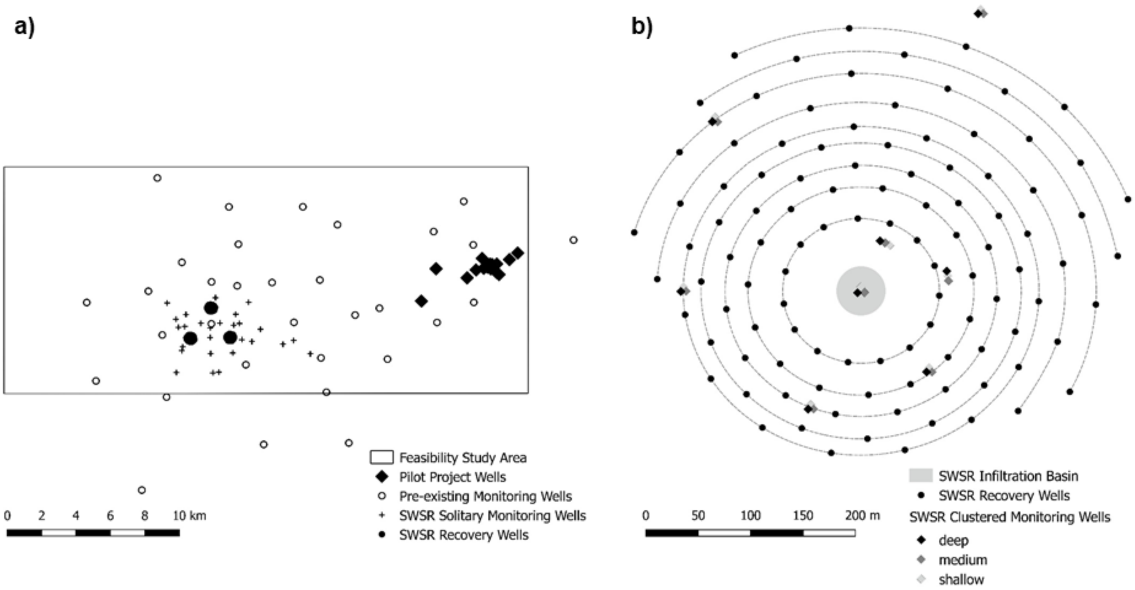

Figure 3. a) Overview of the wells in the project area; b) SWSR scheme features (scheme A as example).

3.5. Integration of the SWSR facility into the water transmission network

One criterion for the selection of the SWSR facility location was that it is reasonably close to the water transmission network to utilize the regular transmission pipeline in recharge and recovery operations. The selected location is 25 km away from the water transmission pipeline supplying the Liwa area (Figure 2). Two DN 900 pipelines were laid to connect the SWSR facility with the Liwa pipeline, forming a loop configuration along the three SWSR schemes to allow water circulation and avoid water stagnation. After completion of recharge, when no recovery operation is required (standby mode), water is pumped bi-weekly from the SWSR facility to the transmission network for a short duration to prevent water stagnation and equipment failures.

When a recovery operation is required, the Liwa pipeline is operated in reverse direction to supply water from the SWSR facility towards the Abu Dhabi City pipeline. Three pumping stations at the SWSR schemes supply water during recovery to Madinat Zayed Pumping Station and from there, the water flows further to Mussafah Pumping Station in the vicinity of Abu Dhabi City. Madinat Zayed Pumping Station is the centralized pumping station for the recharge and recovery operation and it houses the master control of the entire SWSR facility and related pipeline. The centralized and master control concept of the SWSR facility and related pipeline, together with a high automation in pumping, allows the start of a recovery operation within four hours only. In addition to the centralized control in Madinat Zayed Pumping Station, the entire SWSR facility and related pipeline is under real time monitoring by the Water Control Centre of the Emirate of Abu Dhabi.

3.6. Effect of the SWSR facility on water security

The establishment of the SWSR facility has significantly increased the security of water supply of the Emirate of Abu Dhabi. Compared to a previous storage capacity of only a few days, potable water can now be supplied for a population of one million for a duration of up to 90 days. The design supply rate is 180 L/d per person, which is much more than required for drinking and hygiene purposes alone. In fact, the system is designed in a way that a disruption in the water production would not cause major inconvenience or considerably restrict the lifestyle of the population for three months. In a scenario where major damage to the desalination plants would result in a longer outage, emergency-level supply rates could be maintained for a much longer period. For instance, a medium-term emergency supply rate of 70 L/d per person recommended by WHO [24] could be supplied for one million people for 228 days, and a survival supply rate of 20 L/d could be provided for 800 days. These numbers show that the SWSR facility is able to secure the water supply for the population of Abu Dhabi even in severe emergencies.

4. Future work

4.1. Power-independent transmission of the water from the SWSR facility to Abu Dhabi City

As the recovery operation from the SWSR facility is designed for the case of emergency, plans are underway to operate the facility independently from electricity supply through the power grid by providing the facility with its own back-up power plant. In addition, all intermediate pumping stations are planned to be by-passed to pump the water directly from the SWSR facility to Abu Dhabi City's distribution network, utilizing the available head of 130 m resulting from the elevation difference between the SWSR location and Abu Dhabi City. Having single pumping from the SWSR facility through 250 km of pipeline with direct connections with end-users requires further studies to establish proper operation procedures that allow supplying water as per the emergency plan and prevent risks of high or low pressure on the pipeline.

4.2. Dynamic use of the SWSR facility

The SWSR facility was planned as a strategic storage, i.e. the water was planned to be in storage for extended periods and only used in case of emergency. However, the combined power/water production process is affected by inherent inefficiencies due to the differences in seasonal demand as shown in Figure 1b and discussed by [9,12,15]. It could therefore be attractive to optimise production and storage scheduling by recharging the aquifer when DSW production is cheap and convenient; and recovering water from the aquifer when DSW production is expensive and less convenient. Further investigations of the recharge and recovery capacity of the SWSR system are required to ensure that dynamic use options would not compromise the operational readiness of the system in case of emergency.

4.3. Establishment of groundwater protection zones

The SWSR facility makes use of an unconfined aquifer with a vadose zone thickness of around 40 m. Unconfined aquifers are generally sensitive to contamination from above-ground activities as they are directly exposed to the surface. Land uses such as agriculture or industry may release contaminants to the surface, which may then percolate through the vadose zone and eventually reach the water table. In order to reduce the risk of groundwater contamination, many countries establish groundwater protection zones around their groundwater sources and restrict land use activities. In the planning phase of the SWSR project, the project area has been proposed to be classified into three groundwater protection zones with varying degrees of restrictions [25].

Zone I was proposed to include the facilities of each individual SWSR scheme (infiltration basin, recovery and monitoring wells, scheme pumping station and tank). This zone was established by fencing off the scheme facilities, allowing access only for operation/maintenance activities. In addition, Zones II and III (Inner and Outer Protection Zone) were proposed at different distances from the SWSR facility with varying degrees of land use restrictions. However, these zones have not been established, and land use restrictions are not yet in place. Due to the remoteness of the location, there is no immediate threat to the groundwater source, but future developments may occur in the area and therefore the establishment of the protection zones requires further consideration.

5. Summary

The storage capacity within Abu Dhabi's water transmission and distribution network used to suffice for supplying potable water for only a few days. Taking into account the vulnerability of desalination plants to environmental or technical hazards, the security of water supply was considered low. Therefore, a feasibility study for a Strategic Water Storage and Recovery (SWSR) facility to increase storage capacity and enhance resilience of the water supply was initiated in 2001, followed by a pilot project (2003-2004) and the planning and implementation of the final project (2005-2018).

The SWSR facility is located near Liwa in the Western Region of the Emirate of Abu Dhabi. Desalinated seawater is used to recharge a dune sand aquifer containing fresh to brackish native groundwater. The facility consists of three individual schemes, each constructed with one infiltration basin for recharge and 105 wells for recovery. During recovery, the pumped water is returned to the water supply system without any treatment other than chlorination. A network of monitoring wells continuously monitors water levels, water temperature and electrical conductivity across the three schemes and the wider area. Water quality is monitored through a sampling programme to ensure adherence to Abu Dhabi's drinking water quality regulations.

The design recharge capacity of the SWSR facility is 11.6 Mm^3 per year and the total recharged volume is 26.15 Mm^3. About 16 Mm^3 can be recovered over a period of 90 days without compromising the desired water quality. This is sufficient water to supply a population of 1 million with 180 litres per person per day over this period.

The SWSR project has significantly increased the security of water supply in the Emirate of Abu Dhabi. Despite comparatively high costs of desalinated seawater relative to groundwater or surface water, such projects are deemed feasible and highly needed to secure the well-being of the population in the absence of natural freshwater resources.

Future work includes developing power-grid-independent transmission of the water from the SWSR facility to the end-users, assessing options for the dynamic use of the SWSR for power and water production optimisation, and establishing groundwater protection zones around the SWSR facility.

Author Contributions: E.K. wrote the paper; G.K. was the Technical Advisor to the project and contributed information on the history and technical details; M.H.A. provided information on the future work; A.M.A. contributed information on the transmission network.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
ASL: above sea level
BGL: below ground level
DSW: Desalinated Seawater
MAR: Managed Aquifer Recharge
MIG: Million imperial gallon
MIGD: Million imperial gallon per day
SWSR: Strategic Water Storage and Recovery
UAE: United Arab Emirates.

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Extended abstract for ISMAR10 symposium. ***Topic No: 1 (115#)***

Dynamic water balance modelling for risk assessment and decision support on MAR potential in Botswana

Andreas Lindhe[1,*], Lars Rosén[2], Per-Olof Johansson[3] and Tommy Norberg[4]

[1] Chalmers university of Technology, Gothenburg, Sweden; andreas.lindhe@chalmers.se
[2] Chalmers university of Technology, Gothenburg, Sweden; lars.rosen@chalmers.se
[3] Artesia Groundwater Consulting, Täby, Sweden; per-olof.johansson@artesia.se
[4] Chalmers university of Technology, Gothenburg, Sweden; sten.tommy.norberg@gmail.com
* Correspondence: andreas.lindhe@chalmers.se; Tel.: +46-31-772-20-60

Abstract: When assessing the feasibility of using Managed Aquifer Recharge (MAR) and the potential benefits it may provide, it is not enough to identify suitable sites and estimate the groundwater yield. The potential improvement in water supply safety must be assessed considering the dynamic behaviour of both supply and demand. Hence, there is a need of methods for performing this type of analysis. Due to climate conditions in Botswana, the country experiences water stress and MAR is considered as one of several measures. To evaluate the possibility for increased water supply safety, a probabilistic and dynamic water supply safety model was developed and used to model scenarios with and without MAR. The results show the need of measures and quantifies the possible contribution of MAR to improve water supply safety in Botswana.

Keywords: water supply safety model; risk assessment; decision support; dynamic; probabilistic; managed aquifer recharge.

EXTENDED ABSTRACT

1. Introduction

Water scarcity and drought are major challenges on all continents and climate change, increased water demand and other factors will enhance the problem. Mitigation measures are thus needed and Managed Aquifer Recharge (MAR) [1,2] have in several international studies been pointed out as an important measure to mitigate water drought and scarcity situations [e.g. 3,4]. Botswana is an example where the natural conditions in combination with an increasing water demand cause water stress and MAR is considered as one option to improve the situation [5 (vol. 4),6].

The main drinking water supply system in Botswana is dependent on a nearly 400 km long pipeline, the North-South Carrier (NCS) system, transferring raw water from eight surface water dams to several treatment plants and connected demand centres. Due to large losses of water to evaporation from the dams, groundwater aquifers are used to add to the supply of the demand centres during drought periods. The natural recharge to these aquifers is, however, limited and the long-term sustainable capacity could be improved by MAR using surface water from the dams. This may also reduce the evaporation losses.

In addition to selecting suitable sites and designing MAR facilities [e.g. 7,8], the potential improvement in water supply safety must be assessed considering the dynamic behaviour of both supply and demand. Suitable methods and models are, however, limited. The water supply in Botswana has previously been modelled but not including any MAR scenarios [5] (vol. 11 & 13). A Water Supply Safety Model (WSSM) which facilitates the evaluation of MAR potential is presented here. The WSSM is applied on the NSC system in Botswana to provide decision support on future implementation of MAR in the NSC system. The model has general applicability and its use is not limited to the NSC system.

2. Methods

The WSSM is a dynamic water balance model considering uncertainties by means of Monte Carlo simulations. Time series of source water availability are statistically generated based on historical data and used in combination with the dynamic storages in dams and aquifers. A detailed water balance calculation is performed for each dam and wellfield and the capacity of treatment plants, pumping stations etc. is considered. A set of operational rules are defined to reflect when different water sources are used, when water is injected or abstracted from MAR wellfields, etc. The possible supply is compared with the demand to estimate the magnitude and probability of water supply shortages.

The model of the NCS system included 6 surface water dams, 8 wellfields, 7 water works and 18 demand centres. Several scenarios were modelled but we here focus on: (A) the original system as when the was performed in 2013; (B) adding the Dikgatlhong Dam (*implemented after the study*); and (C) large-scale MAR including the wellfields mentioned above. A time step of 1 month was used and a period of 23 years (2013 to 2035) was simulated. The period matches the forecast in the National Water Master Plan Review [5 (vol. 7)]. The input data to the model were based on [5,9-13].

4. Results

For scenario A, the results show that water shortage will be a severe problem causing a deficit of 20–60% in around 70% of the months for most demand centres. The connection of the additional dam (Scenario B), reduced the expected total water shortage (summed over the 23 years) by approximately 90%. There will, however, still will be a significant risk for water shortage during the late part of the simulation period for Scenario B. Including the MAR wellfields, Scenario C, further improves the water supply safety. For example, the probability of having a 10% (8 Mm3) water shortage in the Great Gaborone (capital city and surrounding areas) year 2035 is reduced from 40% (Scenario B) to 10%. The model results show that the effects of implementing MAR is limited due to insufficient capacity of different system components. If these limitations are eliminated, the probability of an annual water deficit of e.g. 2 Mm^3 (2.5% of the demand) will be reduce from 32 to 10%.

5. Discussion and Conclusions

The case study results show that implementing MAR in the NCS system in Botswana may substantially improve the water supply safety, although not eliminate the risk of future water shortage. The WSSM makes it possible to thoroughly analyse the water supply safety in the original system as well as simulating the effect of MAR scenarios and other measures. Limiting factors may be identified to further improve the performed of analysed measures. A key advantage of the WSSM is the ability to not only model the possible enhanced groundwater recharge over time but to compare the possible supply and demand for all system components.

Acknowledgments: The research presented in this paper has been performed with support from the Swedish International Development Cooperation Agency (Sida) and the Botswana Department of Water Affairs (DWA). We would like to thank the DWA and the Water Utility Corporation (WUC) in Botswana for a valuable and fruitful collaboration.

Author Contributions: The study was initiated by all authors. L. Rosén was the project leader and P.-O. Johansson analyzed and estimated input data related to aquifers and water demand. A. Lindhe created the water supply safety model with support from the other authors. T. Norberg analyzed and modelled time series of inflows to surface water dams. A. Lindhe performed the calculations and was the main author of the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharge
WSSM: Water Supply Safety Model

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Paper for ISMAR10 symposium. **Topic No: 1 (129#)**

Artificial recharge mechanisms via a leaky river bed. A case study in the outskirts of London, UK

Ilias Karapanos[1]* and Robert Sage[2]

[1] Asset Specialist; ilias.karapanos@affinitywater.co.uk
[2] Water Resources Specialist; wetrockwr@gmail.com
* Correspondence: ilias.karapanos@affinitywater.co.uk; Tel.: +44(0)1707679203

Abstract: Managed Aquifer Recharge (MAR) schemes have been explored in the Southeast of the UK for water resources management, but depending on the local geology and the local water availability, it is not always possible to follow the conventional methods for MAR. Through a case study in the chalk aquifer providing baseflow to a main river as well as supporting groundwater abstractions for public supply, the flow regime was investigated under average and low groundwater level conditions. The purpose of this case study was to quantify flow losses through the river bed to either the underlying alluvial gravel or chalk aquifers. The results indicate that under certain groundwater level conditions it is possible to recharge the chalk aquifer storage which would in turn support the groundwater abstractions under drought conditions and also boost low river flows. This mechanism could be further investigated, with the aim to capture winter flows, store and release the water in times of drought via the river system in upstream locations. This would negate the need for expensive treatment of surface-derived stored water, but instead using the existing groundwater abstractions supported via the river bed infiltration mechanism, this water could be supplied with minimal treatment.

Keywords: artificial recharge; leaky river bed; drought resilience; leakage assessment; water resources management

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1. Introduction

The Chalk (a biogenic limestone) is the most important aquifer in the Southeast of the UK as it supports flows in the ecologically important chalk streams as well as significant groundwater abstractions for public water supply purposes [1, 2]. The Water Framework Directive (EU directive) objectives, requires all rivers to be in good ecological status or support good ecological potential by 2027 [3, 4]. As such, understanding the surface – groundwater interactions is of paramount importance in order to quantify the groundwater abstraction impacts on river flows and the ecology, and implement an appropriate water resources management strategy.

Managed Aquifer Recharge (MAR) schemes have been widely explored in many parts of the world and especially in arid and semi-arid environments for water resources management [5-9]. However, in the Southeast of the UK, it is not always possible to follow the conventional methods for MAR, depending on the local geology and the local water availability. An alternative approach is presented in this study near London, in an unconfined chalk aquifer setting, supporting a number of groundwater abstractions, as well as providing baseflow to a river which is also supported by an effluent discharge. The leaky nature of the river bed in this particular stretch of the river, has been the focus of this study using standard river flow measurement methods in order to quantify the losses from the river system to the chalk aquifer under different background groundwater level and climatic conditions. This would help specify the conditions under which losses through the river system do occur, so that MAR can be used more effectively. Once the system is optimized, it could be developed further for capturing and storing winter river flows in existing raw water reservoirs and releasing in upstream locations at times of drought.

2. Site Description, Geological setting and Methods

2.1. Site Description

The study area is located in the outskirts of London, UK in a semi-urban part of the catchment covering an area of approximately 47Km^2 (Figure 1). To the north of the study area, the main river is flowing in a westerly direction and is joined by a minor tributary (Tributary A) approximately 1Km downstream. Both of these are predominantly fed by runoff from a clay catchment, which is dependent on rainfall, making it quite flashy and containing very little base flow. The main river continues to flow westerly, where it is joined by another tributary (Tributary B) and then turns southwards. River flow in Tributary B is measured by a gauging station (GS1) located 1.1km upstream of the confluence with the main river and drains a medium size chalk catchment. A Sewage Treatment Works (STW) discharges treated effluent to the main river 1Km downstream of the confluence of these two rivers, whilst the main river gauging station (GS2) is at 3.5Km downstream of the STW discharge point (Figure 1).

2.2. Geological and hydrogeological Setting

The main geological unit underlying the study area is the chalk which is a biogenic limestone, mainly consisting of coccoliths deposited during the Late Cretaceous [10]. The modern division of the chalk aquifer into sub-units has been derived using a comprehensive lithostratigraphical investigation [11, 12] and the revised stratigraphic classifications of the Chalk Group are summarised in [13-15]. The chalk forms a principle aquifer. It is locally overlain by the Lambeth Group to the south and east of the main river, or fluvio-glacial Superficial deposits [16 - 18].

The main chalk sequence outcropping in the study area comprises the Lewes Chalk Formation. The newer units (Seaford and Newhaven Chalk undifferentiated) are present at the bottom of the catchment and outside of the study area. The Chalk generally dips towards the southeast at an angle between 0-1 degrees [19]. The proto-Thames river terrace deposits (mainly gravels) and the Glacial Till (boulder clay) cover are also present in the valley. Thin Quaternary alluvium (gravel, sand and silt) occurs adjacent to the current river alignment.

To the northeast of the STW discharge, the presence of low permeability sediments overlying the chalk (boulder clay) gives rise to semi-confining or confining characteristics within the chalk, hence minimizing any surface water – chalk groundwater interaction in this section. The river terrace deposits are present throughout the area, and in the northeastern part of the study area based on borehole logs [20], form a secondary aquifer above the boulder clay, which is in hydraulic contact with the river. In the southern part of the study area below the STW, the boulder clay pinches out and the gravels directly overly the chalk and being in hydraulic continuity, give the chalk unconfined characteristics.

2.3. Methods

As part of the field investigations, a monitoring network consisting of spot flow measurements in selected locations (SF1 – SF7) and groundwater level loggers in chalk observation boreholes (OBH1 – OBH3), was established within the study area, which forms part of a larger river catchment (Figure 1). River flow data were also monitored by the Environment Agency in gauges GS1 and GS2 to assist with the development of the conceptual understanding of the catchment. Effluent discharge data from the STW were measured by the local sewerage company and abstraction data from chalk boreholes (BHA – BHD) was derived from Affinity Water's telemetry system. The geological data and borehole logs used to derive the study area's conceptual model, were sourced from published borehole logs [20].

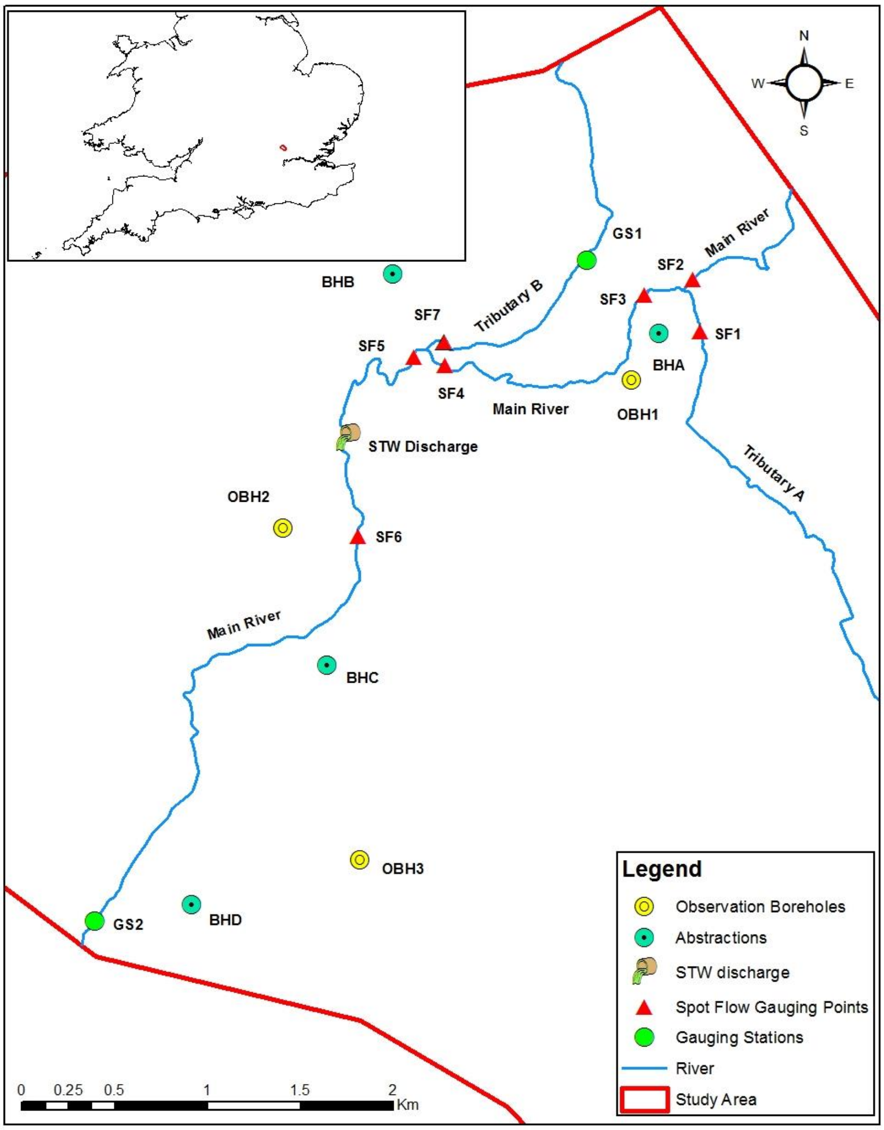

Figure 1. Location map of the study area showing the main river, tributaries A and B, the spot flow gauging points, the gauging stations, the abstraction and observation boreholes and the STW discharge.

3. Results

The data presented in this study was collected by Affinity Water as part of a number of different studies and investigations within the catchment. The aim of these studies was to understand the river flow patterns relative to the STW discharges, the geological characteristics and the public water supply abstractions (BHA – BHD) that are present in the area. In order to achieve this, two river bed leakage assessments were undertaken under different background chalk groundwater level conditions. The April 2016 assessment was carried out under high background groundwater level conditions, while the November 2017 was under regionally low groundwater levels as derived by the hydrograph of OBH3, shown in Figure 2.

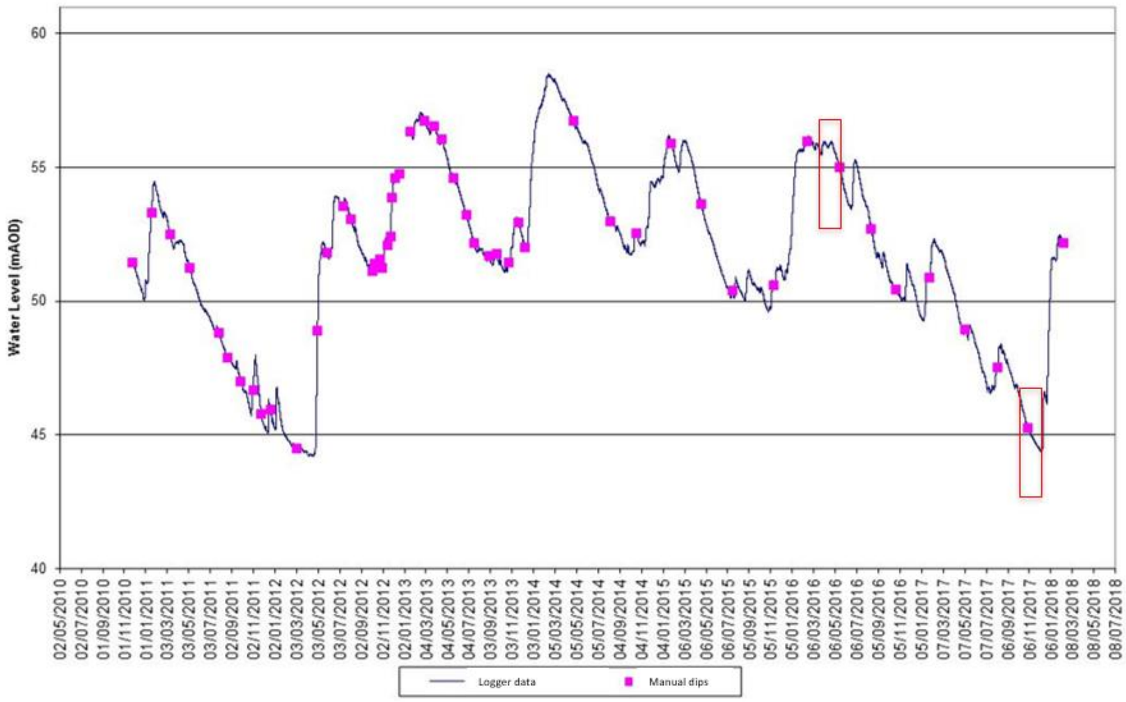

Figure 2. Groundwater level data (in metres above sea level – mAOD) from OBH3 for the duration of the two river bed leakage assessment periods (indicated in red rectangles).

3.1. River Bed Leakage Assessment in April 2016

During the assessment undertaken under high groundwater level conditions (April 2016), there was an outage at the STW, so no artificial discharge was taking place. Spot flow measurements were taken at six locations (SF1-6) throughout a two-week period. Figure 3 shows the accretion profile in kilometres upstream of GS2, whilst river flow measurements are in Megalitres per day (million litres per day). Rainfall events occurring near the start of the monitoring period impact on the results from the 12, 15 and 18 April and were responsible for the elevated flow at all measurement points as shown in Figure 3. The overall flow pattern however was maintained throughout the two-week period, even when flows receded due to lack of rainfall in the second week of the monitoring period.

River flow was maintained with little losses or accretion between SF1 and SF4, whilst the significant inflow originating between SF4 and SF5, was due to Tributary B joining the main river and providing an average increase of 39Ml/d in baseflow terms (excluding the 12 April to eliminate runoff effects). Between spot flow points SF5 and SF6, the main river gained on average 3.94Ml/d, whilst losses occurred almost consistently between SF6 and GS2 as shown in Figure 3 (excluding the 15th April runoff event). The losses in this section of the river were calculated to be an average of 10.22Ml/d. As mentioned in section 2.2, the chalk aquifer displays unconfined characteristics in the southern part of the study area due to the absence of boulder clay and low permeability units (e.g. marls) in the chalk sequence. This results in the river bed acting as a leaky media, recharging the underlying chalk aquifer even during high background groundwater levels (see Figure 2). This leakage may be exacerbated by the presence of chalk groundwater abstractions in the study area, artificially lowering the groundwater table and causing a head differential between the river and chalk groundwater in the vicinity of the abstraction sites.

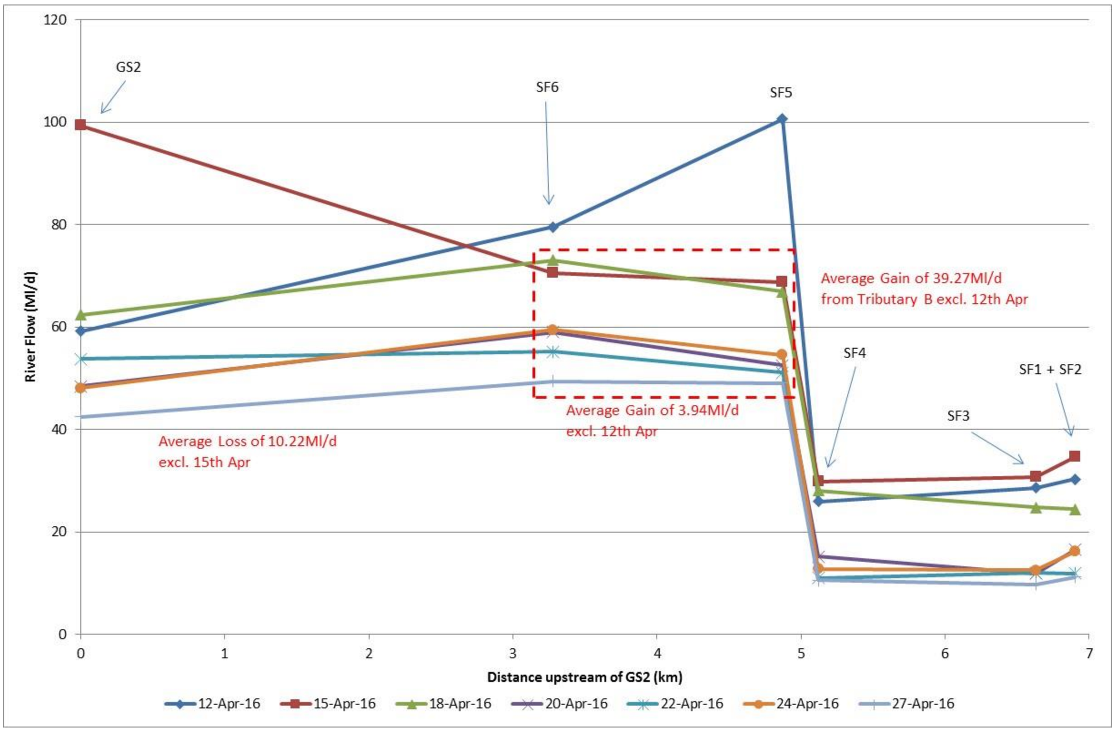

Figure 3. Spot flow measurements without STW or other discharges.

3.2. River Bed Leakage Assessment in November 2017

A second river bed leakage assessment was undertaken under low background groundwater level conditions (November and December 2017) in order to assess any changes in the flow regime. Throughout this four-week period, there was ongoing discharge from the STW and also raw groundwater was continuously discharged from BHA at a rate of 5Ml/d between 20th and 30th November just upstream of SF3. The purpose of this discharge was to assess any losses from the river to the alluvial gravel aquifer between SF3 and SF6.

In order to establish that no leakage from the river to the chalk aquifer would take place in the section SF3 and SF4, a monitoring borehole (OBH1) into the chalk was utilised and equipped with a logger, taking measurements on an hourly basis. Figure 4 shows the groundwater level data from OBH1 (in the left Y-axis) plotted against abstraction data from BHA chalk abstraction borehole (in the right Y-axis). The two vertical lines (green and red) indicate the beginning and the end of the groundwater discharge to the river upstream of SF3. As shown by the black dashed line, the same slightly declining pattern seems to be maintained before and during the discharge period, indicating that no recirculation is taking place near the abstraction site through river bed losses to the chalk aquifer.

Spot flow measurements were taken throughout the four-week period in the same six locations (SF1-6) as in the previous assessment, along with an additional measurement point on the Tributary B just upstream of the confluence with the main river (SF7). During this testing period there was no measurable flow in SF2 but Tributary A was flowing as measured in SF1. Figure 5 shows the river accretion profile for all flow measurements undertaken before (14th & 16th November), during (20th & 28th November) and after the raw groundwater discharge (1st, 5th & 8th December). The data indicates losses to the shallow gravel aquifer overlying the chalk and no accretion in the main River between SF3 and SF4. The average loss is in the order of 0.77Ml/d with the groundwater discharge off and 2.19Ml/d when it was on.

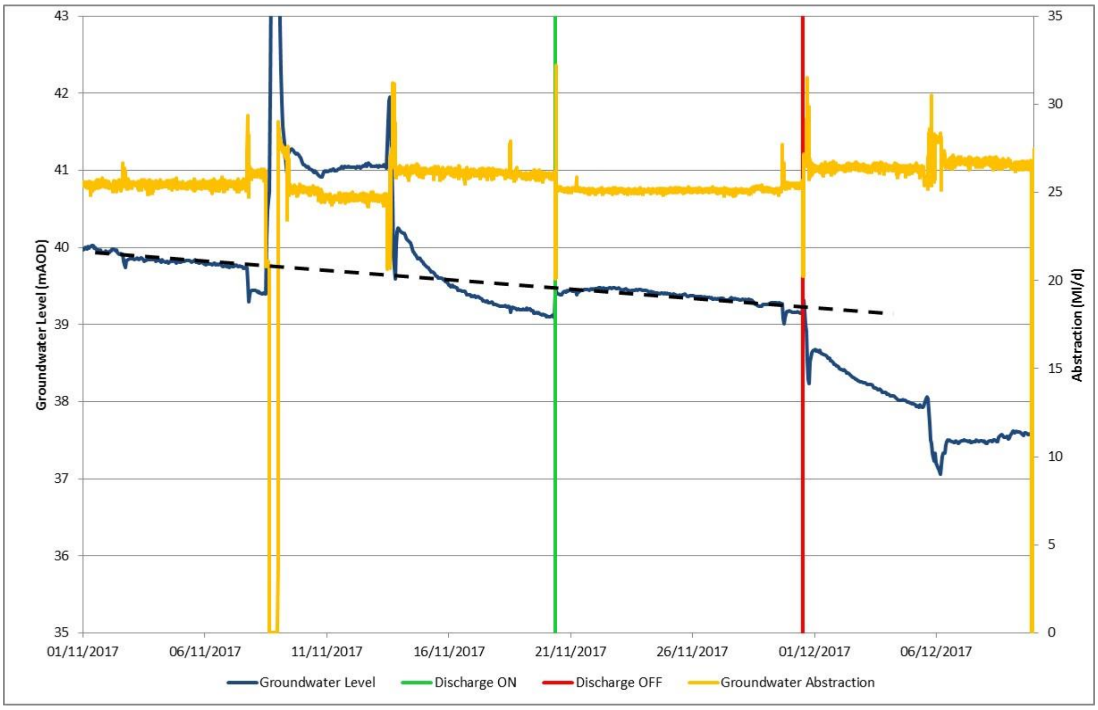

Figure 4. Groundwater level with raw groundwater discharge ON and OFF plotted against groundwater abstraction (right Y-axis). The black dashed line indicates no recirculation taking place.

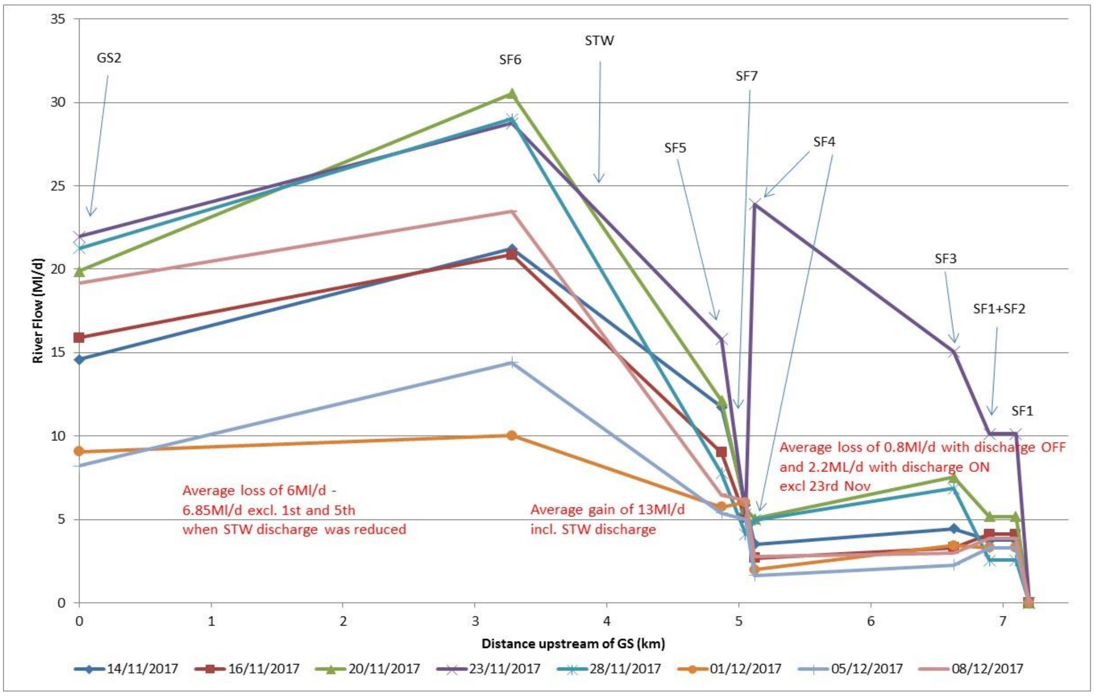

Figure 5. Spot flow measurements with STW discharge ON and raw groundwater discharges ON and OFF.

When comparing the river flow in SF5 with the sum of the flow at SF4 and that from Tributary B (SF7), this is showing average gains of 1.68Ml/d up to the 20th November, whilst losses occurred from the 28th November onwards at 1.81Ml/d on average. It is likely that under higher background groundwater levels similar to those seen prior to the 20th November, there is a small gain in flows but this turns to losses when groundwater levels decline further. The losses from the 28th November onwards occurred despite the 5Ml/d discharge between the 20th to the 30th November and suggest that the water leaked to the gravel aquifer between SF3 and SF5. Between SF5 and SF6, the STW discharge results in flow increases under all occasions, with an average increase of 13Ml/d. As seen in section 3.1, there is natural accretion in this reach (around 4Ml/d) under above average background groundwater level conditions, so this increase constitutes of chalk baseflow as well as STW discharge (in the order of 15-20Ml/d). Further downstream between SF6 and GS2, it appears that the average losses are now lower than those seen in April 2016, despite the fact that the overall chalk baseflow has reduced in line with the receding groundwater levels as shown in Figure 2. This suggests that the STW discharge is more significant at times of low background groundwater levels in maintaining the river flows as well as recharging the chalk aquifer via its unconfined section between SF6 and GS2.

3.3. Flow regime in the period 2010-2017

Timeseries data from the flow gauging stations GS1 and GS2 have been derived for the period 2010 – 2017 and plotted against STW discharge data and the background chalk groundwater levels (in the right Y-axis) in the study area as shown in Figure 6. As shown in sections 3.1 and 3.2, the majority of the flow in the norther part of the study area originates from Tributary B. As such, when the background chalk groundwater levels are at or above average, the GS2 flow will be equal to or greater than GS1 flow, even when there is no discharge from the STW (2011 and 2012-13 periods in Figure 6). Under such background groundwater level conditions, when the STW discharge is on, the river flow would increase further as seen in GS2 and the deviation between GS1 and GS2 would be greater indicating minimal losses and hence minimal recharge to the chalk aquifer, since the groundwater storage is full.

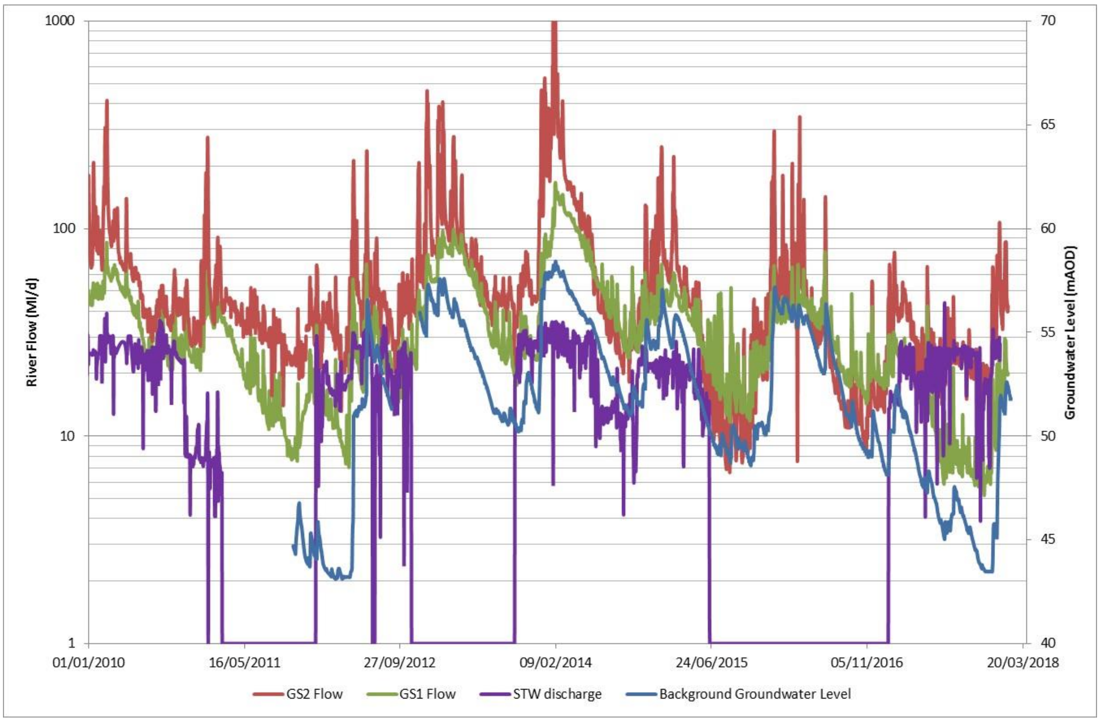

Figure 6. River flow data plotted against effluent discharge and groundwater level data.

When background groundwater levels decrease further though, as seen in Figure 7, and reach their lowest as in December 2017, the STW contribution becomes critical for maintaining river flows and also recharging the chalk aquifer between SF6 and GS2. The flow losses in 2017 reached a maximum of 10Ml/d in this section which is calculated based on flow recorded at GS1, since all the flow seen in GS2 was originating from the STW as the two lines indicate very similar absolute flows.

As can be seen in Figure 7, without sewerage discharge, flows at GS1 can be greater than GS2, whilst with the discharge they are always above, even in low groundwater level periods.

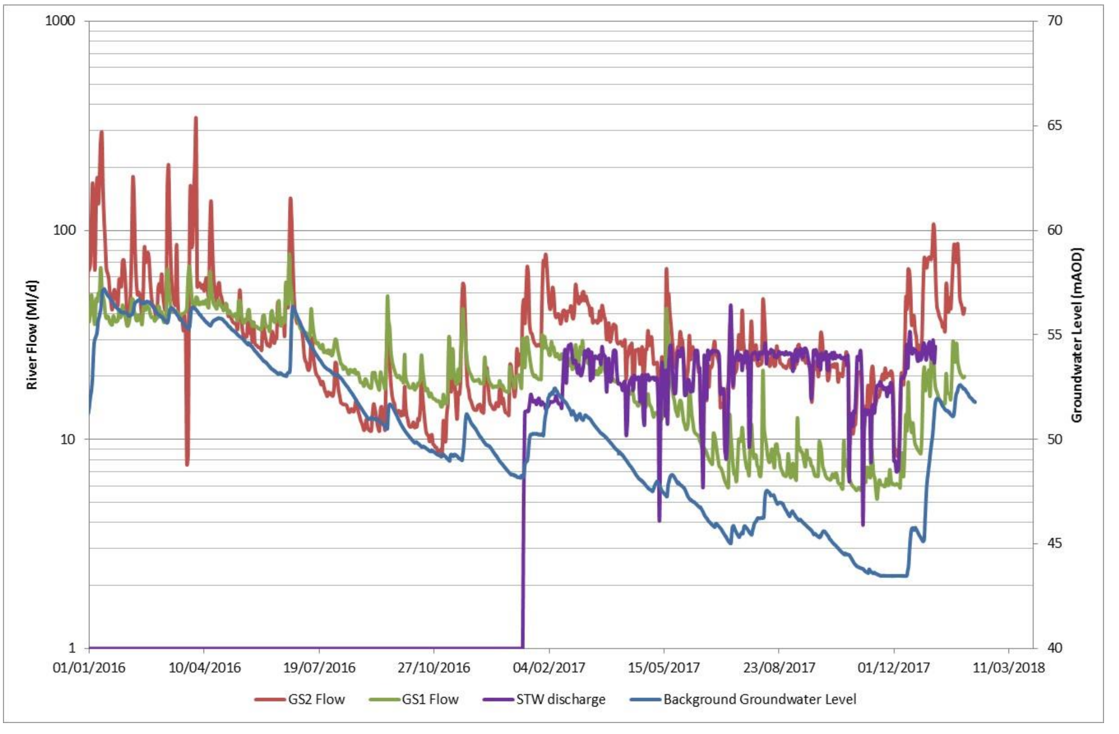

Figure 7. River flow data plotted against STW discharge and groundwater level data during low background groundwater level conditions.

4. Discussion

Managed Aquifer Recharge (MAR) schemes have been explored in the Southeast of the UK for water resources management, but depending on the local geology and the local water availability, it is not always possible to follow the conventional methods for MAR. An alternative approach is presented in this study, in an unconfined chalk aquifer setting, supporting a number of groundwater abstractions, as well as providing baseflow to a river which is also supported by an effluent discharge.

In this case study, the groundwater abstractions were found to be supported by river flows during drought conditions, which were in turn supported by effluent discharge directly into the river, upstream of the abstractions. The leaky nature of the river bed in this particular stretch of the river, has also been studied for other potential uses such as capturing and storage of winter river flows into an existing raw water reservoir and then releasing the water at the top of Tributary A to flow into the main river and recharge the chalk aquifer at times of drought. During such instances, the river flows and the ecology would also benefit from this unconventional form of MAR. Using the leaky nature of the river bed to support the output of the groundwater sources in such instances, could also negate the need for additional treatment prior to use for public water supply. This can be classified as a type of MAR which albeit unconventional, has been proven to work under various climatic conditions as seen in section 3. It can also prove a very cost-effective scheme due to the lack of treatment needed for the surface-derived water. As such, there are wider water resources management options that can benefit from such MAR applications that can be more cost effective than conventional methods and should be explored further.

Acknowledgments: The authors would like to thank Affinity Water Limited for giving permission to publish the data collected during environmental investigations. Special thanks also to the local sewerage company for providing the STW data and to the Environment Agency for providing the GS data.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
STW: Sewage Treatment Works
MAR: Managed Aquifer Recharge
GS: Gauging Station
SF: Spot Flow measurement point
Ml/d: Megalitres per day (million litres per day)
mAOD: Metres Above Ordnance Datum (above average sea level)

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Paper for ISMAR10 symposium. ***Topic No: 1 (160#)***

Implementing Incentivized Managed Aquifer Recharge on a Basin Scale

David R. Tuthill, Jr.[1] and Ronald D. Carlson[2]*

[1] Recharge Development Corporation, PO Box 8, 144 S. Main St., Aberdeen, ID 83210-0008, USA. dave@idahowaterengineering.com
[2] Recharge Development Corporation, PO Box 8, 144 S. Main St., Aberdeen, ID 83210-0008, USA. theARUsolution@outlook.com
* Correspondence: dave@idahowaterengineering.com; Tel.: +01-208-870-0345.

Abstract: Managed Aquifer Recharge (MAR) may be defined as processes designed to move water from land surface to aquifer storage. MAR has been conducted in various locations throughout the world since ancient times. But virtually all of these efforts have been undertaken by or through a governmental entity (state or municipal), or by a private entity at a local scale involving one or just a few wells. Recharge Development Corporation (RDC) incentivizes entities to be involved in MAR through a patent-pending approach which includes eight elements that are assembled to create a unique Incentivized Managed Aquifer Recharge (IMAR) process. The paper discusses owned Aquifer Recharge Units (ARUs), municipal applications, groundwater district applications, tribal opportunities, and costs. The existing implementation in the Eastern Snake Plain Aquifer in Idaho is described. Criteria for other eligible basins are listed. The result is a case for application of these concepts in other basins throughout the western United States and internationally.

Keywords: Managed Aquifer Recharge (MAR), Recharge Development Corporation (RDC), Incentivized Managed Aquifer Recharge (IMAR), Aquifer Recharge Unit (ARU).

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1. Introduction

Water users are challenged by less reliable water supplies as demands increase for water in arid and semi-arid locations. Climate change is resulting in lower annual precipitation or earlier runoff caused by the earlier melt-out of snowpack storage. High costs for constructing surface water storage and the associated environmental challenges incentivize inclusion of managed aquifer recharge (MAR) as a tool to enhance management options.

MAR has been a topic of significant discussion in The Water Report [1-6], a trade journal in the Western United States. No fewer than 34 issues have contained articles that incorporate this concept. These articles provide a broad survey of concepts and successful implementations of MAR. However, before the Research Development Corporation (RDC) concept, none of the articles has set out an incentivized mechanism for encouraging recharge to enhance usable water supplies in a basin. The recognition that such a mechanism is needed resulted in the creation of RDC, and three years ago led RDC to file a patent application for incentivizing local individuals and entities to become invested in basin water management.

RDC's contribution to water management is to incentivize MAR by making recoverable MAR fungible and usable at the discretion of the Aquifer Recharge Unit (ARU) owner. An ARU is defined as one acre-foot (1,233 cubic meters) of water storage space in an aquifer. Incentives are intended to motivate all sectors which have built the water infrastructure in a nation to implement true conjunctive management in a hydrologically eligible basin. As clarified below this process not only results in incentivized aquifer storage but also enables the delivery of water for domestic, commercial, industrial, municipal and agricultural uses.

This paper provides an overview of a unique Incentivized Managed Aquifer Recharge (IMAR) process. From its genesis, a group of Idaho water users, lawyers, engineers and technical experts developed the operational concepts and legal approach for a defensible and robust IMAR program. The paper discusses ARUs, and the municipal applications, groundwater district applications, tribal opportunities, and costs. The existing implementation in the Eastern Snake Plain Aquifer in Idaho is described. Criteria for other eligible basins are identified. The result is a case for application of these concepts as the vehicle for not only incentivizing MAR, but also for implementing conjunctive water management in other basins throughout the western United States and internationally.

2. Conceptual Design

Eight fundamental concepts comprise the RDC Conceptual Design, as follows. The example aquifer in this paper is the Upper Snake River Basin Aquifer shown in Figure 1 below.

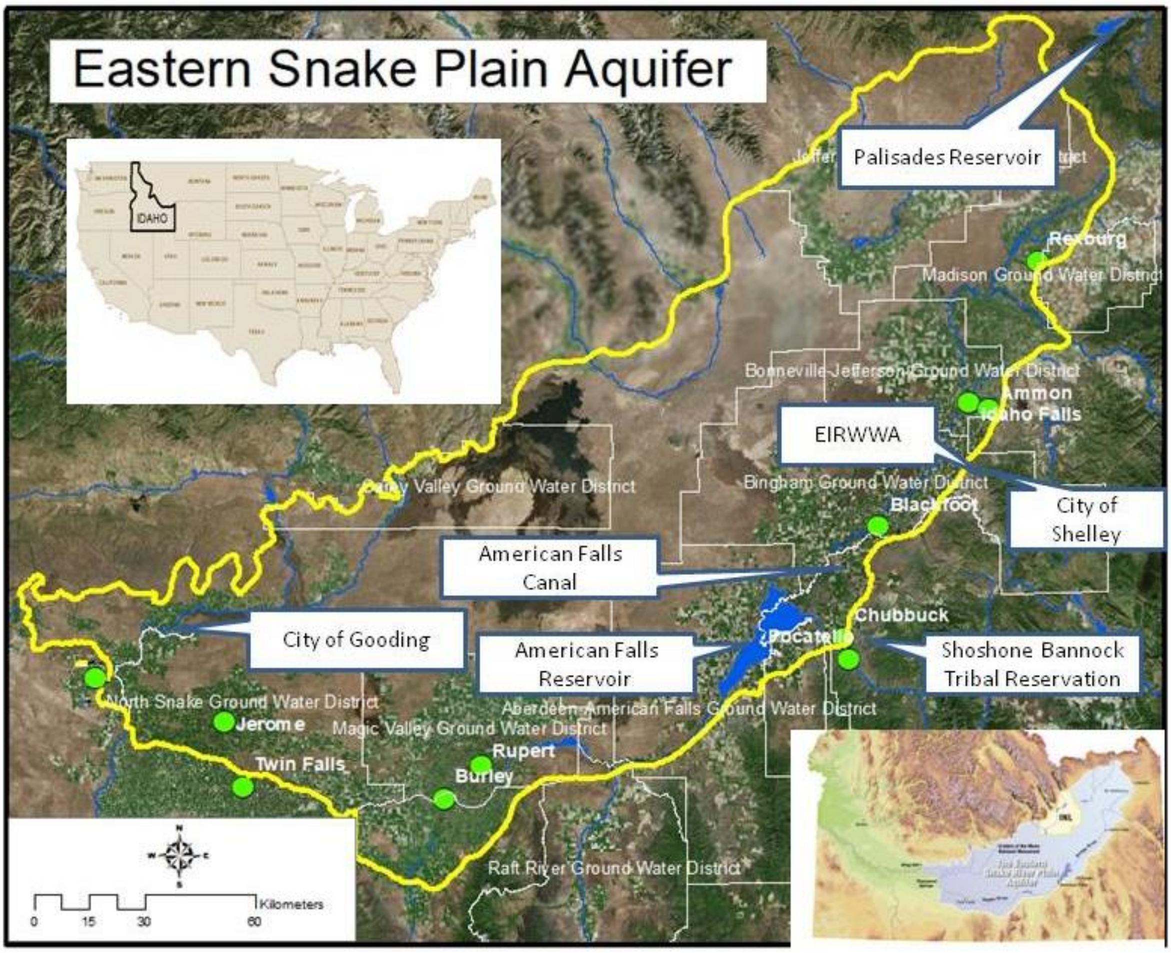

Figure 1. Eastern Snake Plain Aquifer.

Concept 1. Incentivize private ownership of Aquifer Recharge Units (ARUs). The first concept of the RDC approach is that a water user can acquire title to virtual space in the aquifer via an ARU. Many water users are already familiar with contracting for space with the U.S. Bureau of Reclamation in a federally constructed reservoir. The reservoir space holders paid for the development of storage space which they acquire through contract. Space ownership guarantees a “bucket” to put water in but not the water to fill it. Some upper Snake reservoirs, like Jackson (upstream from the area of the Eastern Snake Plain Aquifer) and American Falls Reservoirs (see Figure 1) in the western United States have the earliest priority storage water rights, and space in these reservoirs is filled virtually every year. Reservoirs like Palisades Reservoir that fills under later priority water rights may not fill every year. Because storage space-holders rights must be balanced against flood control obligations, these reservoirs can be expected to have less than a 100 percent allocation 40 percent of the time. Similarly, an ARU holder in the Eastern Snake Plain Aquifer in southeastern Idaho holds a certificate representing their ownership interest in ARUs. As stated above, one ARU is equivalent to one acre-foot (1,233 cubic meters) of space. On the eastern Snake River Plain, an ARU can be filled annually by authorized MAR. Under current procedures, the ground water (Class G) ARU holder is offered water to fill the space at a cost based on the associated annual MAR costs. The owner can decide whether or not to fill his ARUs. Costs are discussed below. The Eastern Snake Plain Aquifer in known to have a storage capacity in excess of 500 million acre-feet (62 million hectare meters). Through defining an ARU as virtual containment in the aquifer, RDC has made available the equivalent of damming a natural lake to gain ownership of the storage space created.

Concept 2. Allocate MAR to owned ARUs. In Snake River Water District 1 (the surface water users within the Eastern Snake River Aquifer) the rule is, “account for the things that can be measured.” MAR volumes are an extension of the surface water delivery system, which is by necessity an after-the-fact accounting process. The RDC protocols may accommodate real time ARU storage distribution. However, MAR accounting will continue to be subject to the after-the-fact processes used in Water District 1. Once allocated, ARU storage is deliverable to designated pumps and has on-line visibility of ARU use status by ARU holders and management organizations such as groundwater districts. The data are fed into a central location via telemetry. The technique for data handling is to conduct computations and account tracking with QuickBooks, and to serve the information to users and delivery organizations like groundwater districts via the web using cloud technology. In this way the account managers use software familiar to them while the power of the Internet is used for data serving.

Concept 3. Track containment of MAR volumes in ARUs. A MAR event is measured, credited to a receiving class of ARUs, sorted pursuant to owner desires, allocated to Class G ARUs for delivery, and distributed by the operating non-profit corporation. Recharge protocols may vary, but the intent is for an acre-foot (1,233 cubic meters) of recharge to fill one ARU. ARU holders retain the water allocated to their ARUs until the credited storage is sold or delivered by the non-profit.

Water can be carried over in ARUs to supply future needs. Water users often raise issues related to aquifer retention time. Since the RDC goal is improved water management in a basin, the rules governing surface water reservoirs must be applied to ARU carryover. Like the annual accrual in surface reservoirs, the incentivization of MAR anticipates annual MAR and an annual allocation opportunity for each ARU. Each year the allocation to an ARU will be: carryover + new accrual = the current allocation. RDC has offered to impose the same average evaporative loss that is imposed on surface storage in order to maintain uniformity between surface and ARU storage. Modeling of groundwater supplies may be required in basins where ARUs are employed. Modeling is fundamentally a sophisticated process for doing a mass balance analysis for an aquifer.

Concept 4. Use water in ARU storage as a supplemental supply. ARU storage can be used to enable pumping when the normal supplies are no longer available, just as happens with surface water systems supplemented by surface reservoir storage. One can consider a well, represented as a faucet, with two sources of supply. One is “natural storage,” or the groundwater subject to appropriation. If this source becomes unavailable due to a moratorium on certain water rights or administrative curtailment of an existing water right, the water stored in an ARU can be pumped from the well and beneficially used. This emulates a diversion from a surface water system which has a water right from the stream, is curtailed due to a priority cut, and then continues to divert water placed in the stream from a reservoir. The practice takes place on many streams in Idaho and throughout the West each summer. Water in ARUs provides access to supplemental storage that, for the first time, allows groundwater users to have a supplemental storage supply to call upon when water is not otherwise available for their use.

Concept 5. Form a privately owned water delivery company. The RDC approach is similar to surface water development companies that later turned over developed infrastructure to a local non-profit organization called a canal company. This same turnover needs to occur when MAR and the groundwater distribution infrastructure are in place. Local management made up of ARU owners is necessary to establish long-term management of the ARUs and MAR within a basin. This concept is modeled after a technique used by American Falls Canal and Power Company (AFCPC). This company, whose predecessors got their starts constructing the first U.S. intercontinental railroad across Utah, traveled to eastern Idaho to construct water works and then hand the constructed works over to non-profit canal companies. An example is a large canal system constructed upstream from American Falls Reservoir. The works were conveyed by AFCPC to Aberdeen Springfield Canal Company (ASCC), a non-profit canal company that has managed the project for more than a hundred years. While AFCPC is long gone, the shareholders of ASCC have been enjoying the fruits of the construction efforts, and been incentivized to manage and maintain the assets they acquired from AFCPC. In a similar way, RDC is establishing the structure of ARUs in the Eastern Snake Plain Aquifer (ESPA). A local non-profit organization called Eastern Snake Plain Aquifer Recharge, Inc. (ESPAR) has been created to manage this system. Day to day management for ESPAR is provided by an Executive Director, although all authority is vested in the elected Board of Directors. RDC is in the process of handing over patent-pending tasks and responsibilities to ESPAR. This turnover of RDC concepts and assets commences with the understanding that most of ESPAR's new recharge sites are being developed jointly with RDC under the leadership of ESPAR's Executive Director. During the transition period operation and maintenance charges have been billed by ESPAR. Present planning calls for a complete handoff to ESPAR within five years. This technique enables RDC to assure consistent applications of RDC patent-pending concepts as RDC moves its efforts to other basins.

Concept 6. Associate ARUs on a one-to-one basis with the shares of stock in the local non-profit corporation. ARUs mirror shares of stock in an existing local non-profit which holds storage contracts with the U.S. Bureau of Reclamation. Most canal companies in the western United States are corporations comprised of water users who hold shares of stock in the company. Each share of stock is associated with an equivalent flow rate of water. In a similar manner, each ARU acquired in a basin represents one share in the local non-profit corporation formed for that basin. As an example, water users in the ESPA hold a share of stock in ESPAR for each of their ARUs. ESPAR is structurally similar to a surface water canal company, with one vote per share or ARU held.

Concept 7. Stockholders develop specific MAR allocation protocols for each non-profit managing corporation. ARU owners have argued for the establishment of a priority fills system for ARUs. Because storage that is deliverable is acquired through a cash transaction, priority represents the "first right of refusal" for storage residing unallocated in other classes of ARUs as a result of IMAR activities. The right of refusal is based upon that ARU acquisition date. For all Class G ARUs as further defined below, the fill of the ARUs is first offered to the senior ARU priority date. Each year the local non-profit negotiates with owners of classes of ARU that directly receive MAR. A price for the water credited to these classes of ARUs is negotiated and blended and that negotiated cost establishes the water costs associated with an allocation for the year. The holders of the most senior ARUs are offered an opportunity to fill their ARUs at this price per acre-foot. When the most senior Class G ARU declines the offer to fill his ARUs, the water is offered to the holder(s) of the next priority of ARUs, and so on until all of the credited MAR water has been allocated. Those who purchased the earliest ARUs have the lowest risk of not getting an allocation and it is therefore anticipated the most senior ARUs will in the future have the highest value. This process again is similar to priority in surface reservoirs. The first reservoir built always has the first access to store available stream flow.

Because of the free-market concepts designed into ARUs and non-profit management, it is anticipated that ARUs will appreciate to have a secondary market value that is on par with surface reservoir space. While there are significant strings attached should one decide to sell storage gained through a federal space-holder contract, these infrequent transactions provide useful insight into the appreciating value of surface storage space. As a backdrop, an acre-foot (1,233 cubic meters) of new reservoir storage typically has an associated cost in excess of $2,500 US. One example in Idaho can be seen in a non-profit that was organized around many of the concepts ESPAR has adopted. This non-profit acquired space 50 years ago at the price of $7.75 US per acre-foot. A corporation was created in the 1950s, to accommodate individuals who wanted to own storage in Palisades Reservoir. Today a share of stock in this non-profit can cost more than $1,000 US a share/acre-foot. The sale of ARUs is used to construct infrastructure including IMAR sites. Ninety percent of the monies received from ARU sales go into a trust account to be used only for project development.

Concept 8. Treat the local aquifer as an additional reservoir. The seven concepts identified above have all been implemented in the ESPA, and are ready to be implemented in other basins in the western United States and internationally. A key element in basin water management on Snake River would be to store water in ARUs, through MAR, under the various surface reservoir storage rights. This could be implemented right now on a limited basis to prove the concepts involved. The U.S. Bureau of Reclamation is considering the ramifications of ARU storage under surface storage rights. It is undeniable that adding ARU storage could go a long way in solving many of the seemingly intractable problems Reclamation is encountering.

3. Legal Framework

The legal framework varies from state-to-state and country-to-country. In Idaho, RDC commissioned a study of legal requirements for MAR, reported in two issues of The Water Report [2,3]. The concepts in these documents remain in place. In addition, in a letter to RDC dated June 22, 2018, Mr. Gary Spackman, Director of the Idaho Department of Water Resources provided supplemental guidance. The letter first discussed recharge conducted under a mitigation plan, for which RDC has employed ARUs to provide mitigation for its clients. The letter goes on to discuss conditions for credit for recharge not conducted under a mitigation plan:

To the extent the Aquifer Recharge Units, as you label and describe them, may be offered as mitigation for a transfer application or new permit, the Department would expect to follow the procedures already developed by the Department. In other words, time, place, and quantity of recharge are critical and inform a decision by the Department regarding the extent to which recharge, at a specific time and place, can offset a diversion at a specific location at a specific time. Of course, transfer applications and/or new permit applications may be contested, and the arguments raised by the protestants must be addressed by the Director.

This provided helpful guidance from Idaho as the necessary initial review for use of water from ARUs. This guidance is consistent with the understanding of RDC. Another paper regarding legal considerations is being presented at this Symposium by Mr. Kent Foster.

4. Implementation in the Eastern Snake Plain Aquifer

Filling of ARUs in the Eastern Snake Plain Aquifer commenced in 2016, with one recharge location, operated by the Shoshone Bannock Tribes in the amount of 1,600 acre-feet. During 2017 the number of recharge sites increased to 6, resulting in the recharge of about 19,000 acre-feet, enabling the filling of all existing ARUs. During 2018 the number of recharge sites was doubled, with anticipation of several more being added before the end of the year. We anticipate recharging at a minimum of 20 sites by the end of 2019 and making additional ARUs available to those wanting to own aquifer storage. Currently additional ARU sales contracts are being reviewed by potential buyers. See Figure 2 below for the locations of the recharge sites.

4.1 Municipal Applications

During 2018, RDC extended the principles of IMAR to municipalities and is finding significant opportunity for municipal water providers to save costs and accommodate city growth using RDC principles. On February 21, 2018, RDC and the Eastern Idaho Water Rights Coalition jointly hosted a symposium in Idaho Falls, ID, to explore water supply alternatives with a target audience including those interested in municipal, subdivision, commercial and industrial uses. The symposium was well attended by representatives from more than a dozen communities in Eastern Idaho and other interested parties. Slides for ten of the presentations at the symposium are available on the RDC website at: www. rechargedevelopment.com/symposium/.

Three techniques were presented for obtaining additional water supplies: (1) purchase a water right associated with irrigated ground and move it to a new use, (2) install a dual system whereby in-house use is provided from groundwater and lawn watering is provided from the surface water system, and (3) use ARUs to supply additional diversions from groundwater. A presentation entitled “Water Supply Evaluation Spreadsheet” describes a spreadsheet tool for comparing the costs and benefits of the three options provided, and any other options identified, on a case by case basis. The presentations have led to more specific discussions with various water purveyors, and thus far the ARU option is proving highly cost effective. One of the pending ARU purchasers is a municipal water provider. City officials have gone on record saying, “RDC has developed the only solution for acquiring future water supplies.”

4.2 Groundwater District Applications

Idaho has established groundwater districts in locations where groundwater is now regulated or is anticipated to be regulated. These districts are located throughout eastern Idaho. As defined by the enabling statutes in Chapter 52, Title 42, Idaho Code, these districts have the power to develop mitigation solutions on behalf of their members.

In December, 2017, the Board of the American Falls Aberdeen Ground Water District presented to their general membership meeting a proposal to acquire 2,500 Class-G ARUs, if supported by the general membership. After significant discussion and debate the proposal passed unanimously pending a due diligence effort by the Board. The Board hired a water attorney to conduct a legal review of ARUs, resulting in a significant investigation of the ARU process. This review identified no reason to alter the plan for purchase. On March 14, 2018, the agreement to purchase 2,500 ARUs was signed and water has already been made available to fill the ARUs. RDC is now in discussion with other groundwater districts regarding purchase of ARUs. This technique is nicely aligned with the purposes for which the districts were formed, either on a district-wide basis or for individual water users within a district.

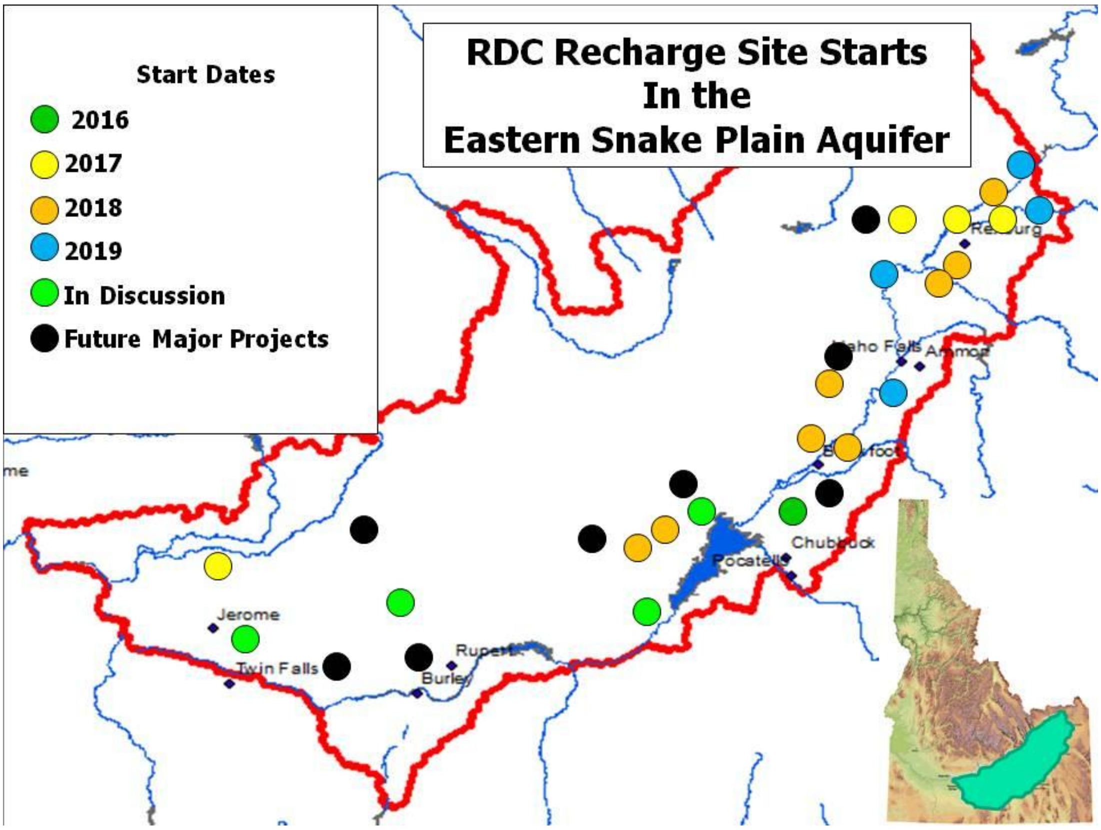

Figure 2. RDC Recharge Site Starts in the Eastern Snake Plain Aquifer.

4.3 Tribal Factor in MAR

American Indian Reservations cover significant lands in the western Unites States. Much of this land is located in headwater areas, where opportunities exist for MAR. As an example in Idaho, RDC and the Shoshone Bannock Tribes signed a two year pilot agreement in 2016 whereby credits for MAR conducted by the Tribes would be marketed by RDC, with a sharing of revenues. This agreement resulted in recharge of 1,600 acre-feet in 2016 and 1,431 acre-feet in 2017. The pilot agreement has recently been extended with a new four year agreement between the parties. The Tribes have expressed an interest in expanding their recharge capabilities, encouraged by RDC.

RDC will work to encourage participation by tribes in other basins where IMAR is being implemented.

5. Data Acquisition Techniques

Real-time data acquisition enables improved water management by providing water managers with opportunities to make decisions on water use based on water supplies. For example, watering of alfalfa for a marginally profitable fourth cutting might be influenced by water availability. Historically the costs of real-time data acquisition have been high, requiring the installation of meters and on-site inspection of read-outs. Presently in the ESPA, water users are required to install meters on irrigation wells so real-time management can be made available via the transmittal and management of the data output.

Teton Technology has developed a data sending device that can transmit digital data produced by most types of flow meters, to a radio receiver located up to 35 miles (56 km) away. RDC and two groundwater districts funded the development of a cloud-based system that was developed under a contract with Teton Technology. This system was implemented in 2018 and is being tested and expanded this year to accommodate wider application in the future.

In 2017, RDC teamed with the American Falls Aberdeen Ground Water District and the Bingham Ground Water District to develop the web based portion of tracking diversions from wells and filling of ARUs. Teton Technology developed a software package that is presently in the testing phase. This software enables individuals to see their own water pumping status, and water used from their ARUs. It also enables visibility at the groundwater district level and the basin level. The software calculates assessment algorithms that include priority dates, tiered systems and recharge credits; pairing with moisture sensing technology and other agri-sensors to enhance management capabilities; and provide greater insight to farm managers and district managers.

6. Costs

The protocols for pricing ARUs were adapted from Reclamation's pricing surface storage space for potential storage space holders. Because of the requisite processes involved in filling ARUs, a single designation of aquifer storage space can be problematic. Reclamation space is priced based upon the costs associated with creating space to retain water for space-holders. ARU pricing is analogous. The cost of an ARU depends on the Class designation. Surface water is moved through MAR to Class S ARUs (S connotes Surface water). This is analogous to the collection of surface storage in reservoirs before it is allocated to the various space holders. Idaho reservoirs may store water under several water rights and each water right is associated with a "Class" of space-holder. Class S ARUs are sold to entities that already have surface water supplies and MAR capability. When Class S ARUs are sold for $25/ARU it reflects the credit given for existing capacity and infrastructure. Class G ARUs are designated as a storage vehicle for groundwater users (Class "G" connotes Groundwater). Class S ARUs are made available to surface water delivery organizations like canal companies and irrigation districts and frequently include municipal providers. Class S ARUs are designed specifically for moving surface storage to aquifer storage. Because of the accounting processes employed by Water District 1 in eastern Idaho, the volume of storage diverted frequently is not known until the final accounting is completed. Similarly, surface storage that was intended to be moved to ARUs may not have actually been required because unappropriated stream flow is later deemed to have been available. A Class G ARU can be purchased by any water right holder within the basin, but until conjunctive management of groundwater and surface water is more fully established Class G ARUs will be most valuable to those with rights to pump groundwater.

Costs of making ARU storage available in a basin are largely based on the specific nature of that basin. The costs associated with gaining storage rights in the ESPA provide a known example. The initial cost is the cost of building the requisite infrastructure. In the case of IMAR it includes construction of one or more recharge sites. Once constructed there is the repayment period. The monies associated with federal reclamation projects had to be paid back over 40 years. The RDC repayment period is generally 10 to 20 years. Reservoir space must be maintained and that involves the annual payment of O & M (operation and maintenance). ARU owners pay for the operating costs of the non-profit through an annual assessment. The ARU repayment cost is in addition to the annual O & M. One consideration in the ESPA is many of the initial costs were borne by initial ARU holders for development purposes in exchange for ARUs. Other basins will benefit from the information gained in the ESPA.

Operation and Maintenance costs are shared costs. As the number of ARU owners increase there will be better economy of scale and the per ARU cost is expected to decrease. Costs to acquire Class S and Class G ARUs range from $25 US to $250 US each. The cost of a Class S ARU is ten percent of the cost of a Class G ARU. This is because owners of Class S ARUs are responsible for moving surface water into Class S ARUs. Class G ARUs are comparable to the development of new surface storage space. All but 10% of the monies paid to acquire Class G ARUs are used to expand MAR capacity. Ninety percent of the money paid to acquire Class G ARUs is deposited in a trust fund, like an endowment. The Class G ARU represents usable groundwater storage and is appropriate for any individual, municipality or groundwater district that wishes to use the water from the ARUs it owns.

7. Qualifying Basin

To be a candidate for implementation of RDC concepts, a basin needs the following attributes:

1. Diversions from groundwater are regulated or are soon to be regulated.
2. The aquifer has space to accept recharge.
3. A source of water for MAR is relatively nearby and in reasonable quantity and quality for at least part of most years.
4. The state or nation has a regulatory framework that accommodates the RDC concepts identified above. Our analysis suggests that most of the western United States qualify for this fourth requirement. International acceptability is currently being explored.

8. Potential for Implementation in other Basins

Starting in the summer of 2018, RDC has been actively seeking opportunities for implementation in other basins. Initial outreach has resulted in feedback for potential implementation in additional basins in Idaho, and in Oregon, Washington, Nevada and New Mexico. RDC anticipates the addition of other basins internationally, with RDC providing start-up assistance which will lead to long-term operations by local non-profit water delivery corporations.

9. Conclusion

The principals of RDC have spent many years developing the concepts and techniques described in this paper, to provide for conjunctive water management through the implementation of Incentivized Managed Aquifer Recharge. Although the patent is still pending for the concepts discussed here, the system is now operational in the Eastern Snake Plain Aquifer in Idaho. Initial steps have been implemented for starting the process in many other basins. These processes incentivize basin water management as the vector for conjunctive water management and for making water available for additional beneficial uses. The principals of RDC look forward to assisting others with implementation of these concepts.

Author Contributions: The authors wish to acknowledge the significant contributions of the full Board of

Recharge Development Corporation, who assisted in developing, refining, and implementing the concepts in this paper, including: Hal N. Anderson, Ernest M. Carlsen, Stanley M. Clark, Marc S. Elliott, Keith R Esplin, Kent W. Foster, Christopher A. Pratt, and Phillip J. Rassier.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharge
IMAR: Incentivized Managed Aquifer Recharge
ARU: Aquifer Recharge Unit
ESPA: Eastern Snake Plain Aquifer
ESPAR: Eastern Snake Plain Aquifer Recharge, Inc.

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Paper for ISMAR10 symposium. **Topic No: 1 (201#)**

Artificial recharge systems applied in the Low Llobregat aquifers (Barcelona, Spain)

Vinyet Solà[1*], Jordi Massana[1], Enric Queralt[1], Jordi Martín-Alonso[2], Meritxell Minoves[2] and Manuel Argamasilla[3]

[1] Comunitat d'Usuaris d'Aigües Delta del Llobregat (CUADLL) ; vsola@cuadll.org
[2] Aigües de Barcelona ; jma@aiguesdebarcelona.cat
[3] CETAqua ; manuel.argamasilla@cetaqua.com
*Correspondence: vsola@cuadll.org ; Tel.: +34-933793216

Abstract: The Llobregat aquifers, close to Barcelona, is a key element for the urban (2 Million population) and industrial water supply of Barcelona Metropolitan Area. The water demand of the area is historically very high relative to the small and highly variable water resources under the Mediterranean climate conditions. Since 1955, the joint use of surface- and groundwater has improved the guaranty of availability. Water transfer to Barcelona from the river Ter, waste water reclamation plant and seawater desalination conform the water system. In addition, the relation between the different water sources has been favored by means of artificial recharge, which is also relevant to prevent groundwater quality degradation.

Some recharge's technologies are operating in these aquifers, such as the scarification of a stretch of the river bed, a storage and recovery (ASR) well system, a recharge pond and a hydraulic barrier.

In all cases, an additional goal is to achieve the environmental objectives derived from the European Water Framework Directive because the groundwater body is in bad state. A protocol defines how and when these techniques of recharge are applied. Normally the decision depends on water availability and the threshold values of quality of the water source and on the piezometric level.

Keywords: Recharge pond, ASR, scarification, hydraulic barrier, water quality, reclaimed water, aquifer management.

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1. Introduction

Catalonia is a Mediterranean region with a complex water cycle, not only for its large population but also for its different water sources. In the case of groundwater Low Llobregat bodies need to improve their chemical status and to increment its quantity. This can be done with surface water from the river or with reclaimed water. Since the 1950's, Barcelona Metropolitan Area has been operating with managed aquifer recharge by scarification or river bed filtration. The injection well recharge started in 1969, the hydraulic barrier operated since 2007 and Sant Vicenç dels Horts ponds have been operating since 2009.

1.1. Geologic location of Low Valley and Delta aquifer

In the Low Valley there is a unique alluvial aquifer that separates into two aquifers when it arrives at the delta plain: a) a superficial aquifer that is the current Deltaic plain and b) a deep aquifer that is located below an impermeable silty wedge associated to the last marine transgression. Upstream the silty wedge disappears and both aquifers are connected [1]. The Low Valley aquifer is free and in consequence, we can opt for recharge by infiltration. The deep aquifer is confined; therefore, the recharge will be by injection in this case. The Low Valley aquifer and the Deep aquifer together form the Main aquifer [2]

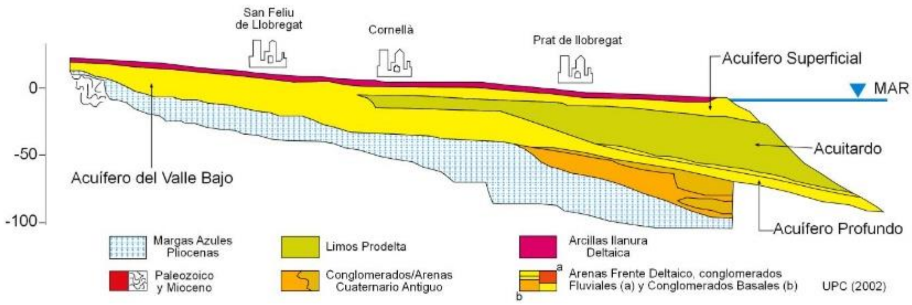
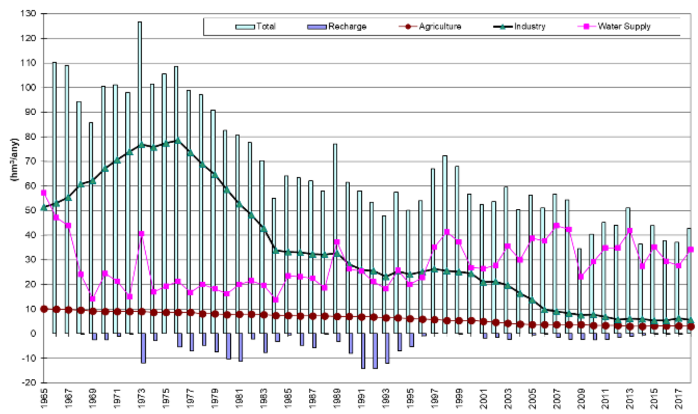


Figure 1. Geological structure of Low Valley and delta aquifer.

1.2. Groundwater uses

Groundwater is mainly used for water supply as it is a densely populated zone. However, it may also be important for industrial uses (steel, chemical, paper and alimentary industries). The agriculture is a minority activity because of the amount of pressure on the ground. [3-4].

Main aquifer was declared overexploited, due to a mismatch of the aquifer mass balance. Besides, the progressive soil impermeabilization caused by highways and urbanization soil, and harbor construction, required the need to apply artificial recharge technologies, both to increase the resource and improve quality groundwater. Previous studies quantify the loss of recharge for soil waterproofing in 10 Mm^3/y [5], in the last two decades. Moreover, intense extractions cause an important marine intrusion. At the end, groundwater body is in bad state and according to WFD has to achieve the good state.



Mass Balance (2007-2016) in Mm^3/year	
Recharge	46.1
MAR	1.5
SW Intrusion	3.4
Extractions	-52.6
Storage	-1.5

(a) (b)

Figure 2. (a) Historical evolution of extractions in Main aquifer and induced recharge volumes, (b) average values of mass balance in period 2007-2016 calculated by numerical model.

2. Managed aquifer recharge in the Llobregat aquifer

The managed aquifer recharge (MAR) is the purposeful recharge of an aquifer under controlled conditions to store the water for later extraction or to achieve environmental benefits. Type of aquifer and availability of recharge water are essential condition to apply a certain type of recharge methodology.

In the case of Llobregat aquifer are implemented Riverbed filtration, ASR, Ponds and hydraulic barrier like recharge technologies. The first two methodologies were made by Barcelona's water supply company, with the aim of increasing groundwater reservoir. St. Vicenç Pond is a soil impermeabilization compensatory measure, and in this way, another pond is projected to build. However, seawater intrusion barrier is a corrective measure of aquifer salinization, both prevent the progress of marine intrusion and to decrease aquifer salinity. In addition, this barrier helps to improve mass balance [6-7].

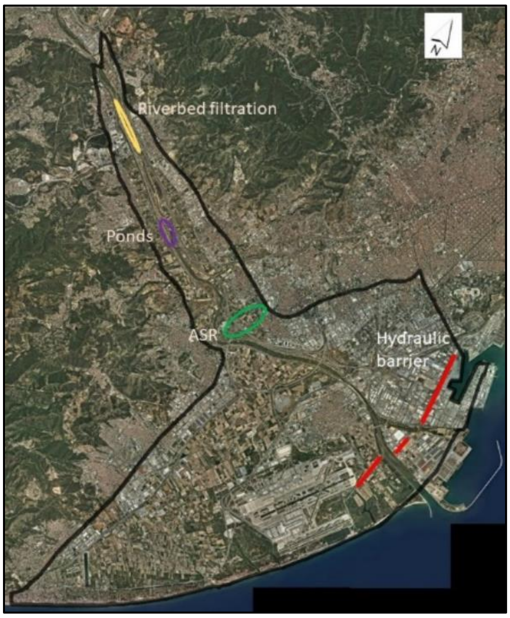


Figure 3. Location of the different systems of MAR in the Low Llobregat aquifers.

2.1. Riverbed filtration

In the Low Valley the free alluvial aquifer is below and disconnected from the river. A tractor enters into the river and scraps its bed. The sediment silts and clay flow downstream and the river water infiltrates better. This type of recharge is an induced recharge because the tractor favors a natural recharge [8].
To carry out this recharge methodology depends on the quality of river's water and flowing flow.

Table 1. Parameters which condition riverbed filtration.

Parameter	Average daily values
Turbidity	<= 100 NTU
Ammonium	<= 1 mg/L
Chloride	<= 350 mg/L
Conductivity	<= 1700 µS/cm
Flow	8-35 m^3/s

(a) (b)

Figure 4. (a) Tractor working. (b) River soil bed. It's distinguished a first layer with algae activity, below a brown clay layer (oxic level), below a gray clay layer (anoxic level) and finally below gravels and sands with a high permeability connected with the aquifer by shower effect.

2.2. Aquifer Storage and Recovery

Sant Joan Despí DWTP uses river water and groundwater jointly for Metropolitan Barcelona Area water supply prioritizing river water if quantity and quality are acceptable. The surplus of river water treated is injected to aquifer through 12 wells, which can do the two functions, to extract and to inject. This action increases the capacity of reservoir in case of surplus in the river and it provides water from the aquifer when the quality and the quantity of the river are not appropriate. The capacity of injection is 75000 m^3/d [9].

In 2015, the Life European project DESSIN allowed to inject 0.3 Mm^3. This project consists on injecting water that only has passed through a basic treatment with decantation, flocculation and sand filtration. Injection is in a pilot well and the project studies the effect into the aquifer [10].
Wells cannot operate with reclaimed water because there are wells for drinking water and Spanish legislation prohibits the direct usage of reclaimed water for water supply.

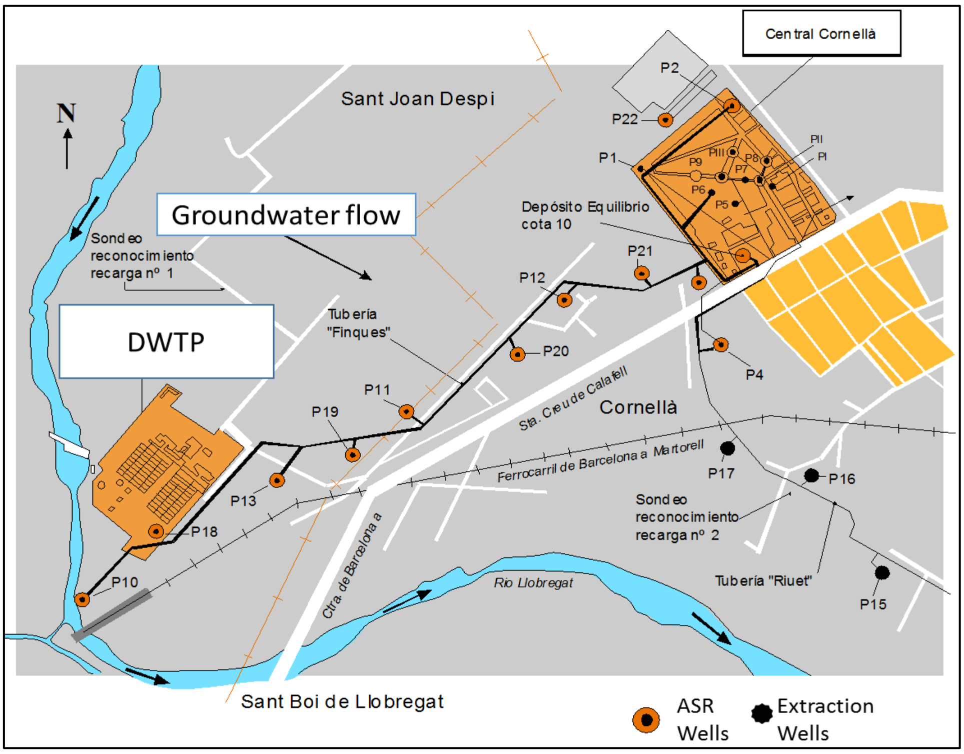


Figure 5. DWTP with two sources: water river or groundwater. 12 dual wells extract water from aquifer or inject water from DWTP. Other 10 wells only extract water from aquifer to DWTP.

2.3. St. Vicenç Ponds

Sant Vicenç dels Horts ponds: active facilities with 5000 m² of infiltration surface, with an infiltrate rate in 1 Mm³/y. The mainly source supply is river water, even though the alternative source can be also reclaimed water (only in case of drought). River water is stored in decantation pond with residence time of 1.5 days, and for gravity, water infiltrates pond. In the same way that scarification, ponds operativity is conditioned by water river quality and flowing flow.

(a)

(b)

Figure 6. (a) Aerial view of Sant Vicenç dels Horts Ponds and (b) river water catchment.

2.4. Seawater hydraulic barrier

Hydraulic barrier injection wells with reclaimed water. There are 14 injection wells close to the coast that can infiltrate up to 15000 m3/d. The reclaimed water is treated with an advanced treatment: ultraviolet and ultrafiltration system for all water and partially (50%) with a reverse osmosis system [11]. The hydraulic barrier has a protocol of operability and the injection rate largely depends on the level of the aquifer (if the level decreases the injection increases). The piezometric levels will decrease significantly if the exploitation increases and it only happens when the surface reservoirs diminish their stored volume and water supply needs more water. In consequence, the activity of the barrier it depends indirectly on droughts or periods of scarcity of water resources.

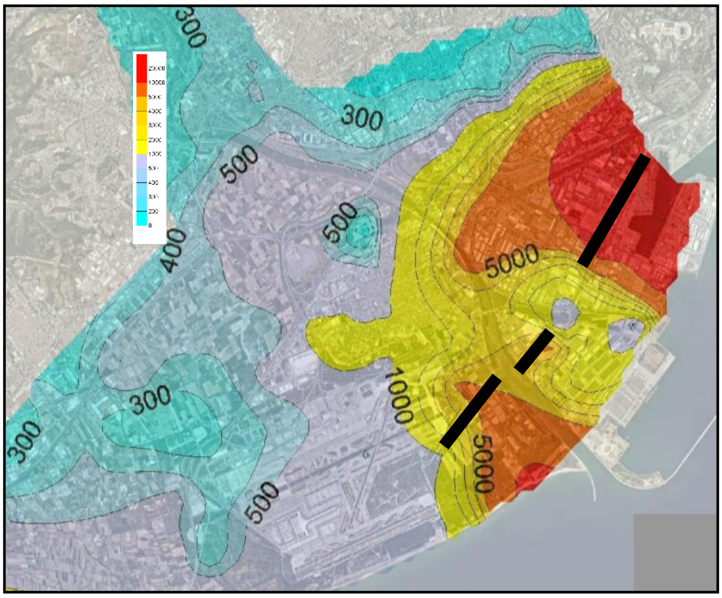


Figure 7. Hydraulic barrier situation in preferential zones of marine intrusion.

Table 2 shows a summary of recharge technologies explained, where is detailed availability of water for a good operability, maximum volume infiltration capacity, recharge cost and benefits to aquifer.

Table 2. Main characteristics of different MAR methodologies.

Characteristics	Scarification	St Vicenç Pond	ASR	Hydraulic Barrier
Availability of Water	15%	>90%	30%	>90%
Chemical impact	low	low	low	high
Volume annual objective	2	1	3 (0-14)	5.5
Quantity impact	medium	medium	Medium- high	high
Cost (€/m^3)	0.03-0.13	0.10-0.17	0.15-0.25	0.28

3. Results

In the last ten years, recharge technologies are implanted without prolonged operativity. For that, it was not possible to infiltrate maximum volumes capacity.

Table 3. Recharged volumes in 2008-2017 period

Year	Hyd. barrier	St V. Pond	Scarification	ASR	Total (Mm^3/y)
2008	0.41	0	0.31	0.72	**1.44**
2009	0.62	0.42	1	0.61	**2.65**
2010	1.68	0.12	1	0	**2.79**
2011	1.13	0.93	1.31	0	**3.37**
2012	0	1.10	0.19	0	**1.29**
2013	0	0.74	1.22	0	**1.96**
2014	0	0.42	0	0	**0.42**
2015	0	0.07	0	0.39	0.46
2016	0	0	0	0.04	**0.04**
2017	0	0	0	0	**0**

3.1. Riverbed filtration

A study realized on 2012 quantify the action of the tractor and induced filtration was about 1 Mm^3/year. Oldest studies supposed more filtration, but difficult to observe piezometric level variation in recharge period, makes it complicated to get an exact infiltrate volume. In consequence, the section of Pallejà has tended to be clogged.

Nowadays, a study was carried out to change the location on this riverbed filtration.

3.2. Aquifer Storage and Recovery

Historically this recharge action has been the most important because the volume recharged. The average recharge for the maximum operating period (1970-1995) was 5.5 Mm^3/year, reaching a maximum of 14 Mm^3 in one year. The operation was carried out with water surplus exceeding of Sant Joan Despí DWTP. Thus, the maximum recharge occurred in hydrologically good years, which means that they did not attenuate the deficit but favoured the recovery of the aquifer. During that period, no studies were carried out to evaluate the impact of this recharge. Subsequent to the year 1995 the recharge was decreasing due to the change in operation of the plant. For that, in Table 4 recharged volumes on ASR methodology are 0 in the last's years.

Currently, and thanks to the results of the DESSIN project, the intention of the supply company is to re-realize it with river water with a primary treatment. The operability and volumes to recharge are under study. Furthermore, CUADLL is modelling the possibility to inject and extract from different wells and convert ASR to ASTR.

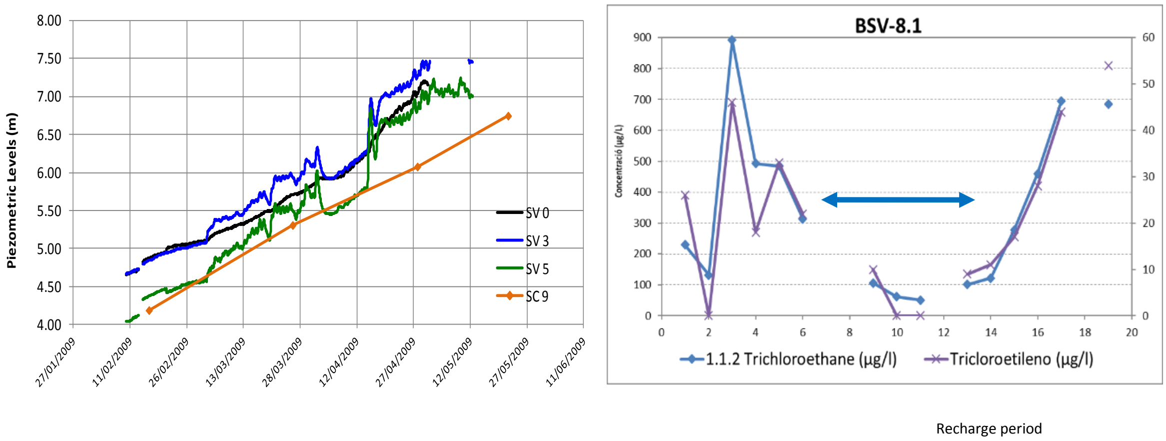
3.3. St. Vicenç Ponds

Sant Vicenç Ponds' operativity has been recharged testing during the first years of operation. Based on the knowledge acquired, now it is in adequate phase for a better operativity.

On testing period, infiltrate water volume was up to 1.1 Mm³/y for two consecutive years, decreasing gradually until most superficial layer collation.

Recharge aquifer causes local impact because of low recharged volumes in comparation of aquifer flow system. This fact is visualized in piezometric levels' evolution. Piezometers 3 and 5 are located before and after infiltration pond. Piezometer BSV0 is located 150 m upstream infiltration pond, and SC15 piezometer is located to 2.5 km downstream. Evolution piezometers' level shows that BSV0 and SC15 levels aren't influenced by recharging. Instead, the other two piezometers levels are increased when recharge is occurring. When recharge stops (April 2009), piezometric levels return to pre-recharging values.

In this case, quality water was improved for dilution effect. VOCs compounds are presents in groundwater for incontrolled dumping of industrials solvents. In recharge moments, 1,1,2-TCA, TCE and others compounds were so lower than recharge was 0.



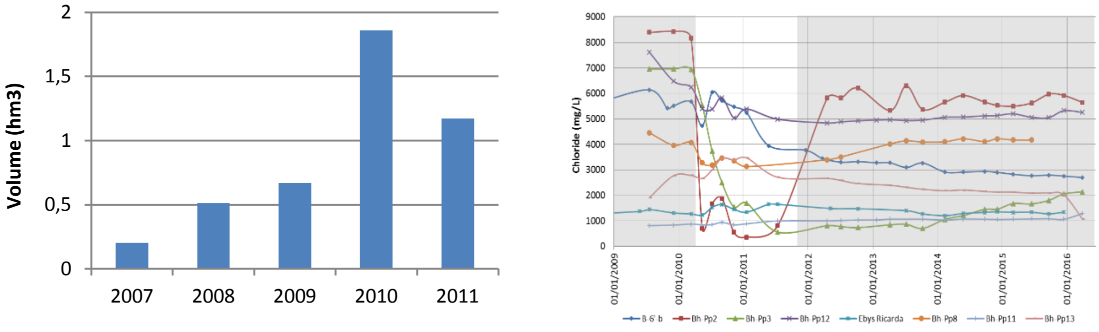
(a) (b)

Figure 8. a) Piezometric levels evolution in control piezometers near ponds, b) VOCs' compounds evolution in BSV-8.1 piezometer in the infiltration pond.

3.4. Seawater hydraulic barrier

This recharge methodology was implanted in two phases. First phase was in 2007, with treated water injection by gravity through 3 wells. In 2010 was implanted second phase, which water treated infitration through 14 injection wells. This hydraulic barrier was never in full injection volumes capacity (maximum of 15,000 m³/d). In June 2011 water injection was stopped due to the economic and social situations.

Infiltrated water volume had local quality impact, principally decreasing chloride concentrations.



(a) (b)

Figure 9. (a) Total volume annual recharged and (b) chloride evolution in control piezometers near injection wells. Injection period (white zone), chloride concentrations decrease significantly. When injection stops, chloride values increase, but without reaching the values before recharging.

4. Discussion

During the last decade, four recharge systems have been implemented in the aquifer. The operative recharge done does not respond to the potential of these recharge systems. Several are the reasons, among which are the periods of tests and adjustments of the systems, but also, and to a large extent, the lack of economic resources.

In the last ten years, the maximum recharge carried out was 3.4 Mm^3 in 2011. This value is less than the average of the recharge carried out by ASR between the years 1970 and 1995.

The mismatch of the balance still causes some increase in saline intrusion, although this imbalance has decreased significantly in the last decade, and piezometric levels have stabilized at levels close to 0 msnm near the coast. Despite it would still need to increase 3 or 4 Mm^3/year.

In addition, the use of the existing numerical model to predict the impact of the MAR operation, results in that between 3 and 4 Mm^3/year most of the aquifer would be above the 0 msnm level [7], a question that would stop the increase in saline intrusion.

These 4 Mm^3/year are available to existing infrastructures nowadays. The implementation of these is necessary for the proper functioning and recovery of the aquifer.

Another rellevant aspect is the dependence of water river conditions to put into operation recharge methodologies, such scarification, ASR and ponds. In the first two cases, theirself technical design can't be otherwise. But in St. Vicenç Ponds, there is possibility to replace river water by reclaimed water. This change would assure a continious recharge and increase total volum recharged, because decantation pond would become infiltrate pond.

5. Conclusions

Recharge systems implanted in Low Llobregat aquifers are so good to improve groundwater body state.

The four technologies are not operated at the same time. Short period of operation and infiltrated volumes less than total capacity, cause local impact. Regional improvement is not observed. The challenge, in the future is to grow the recharge to improve the aquifer state and to increase the reservoir of Ter- Llobregat system.

Total infiltration's potential is 11.5 Mm^3/year, a 20% respect annual extraction (the last ten years has been average value of 52 Mm^3/year).

Aquifer salinity improvement is local, but a continuous hydraulic barrier operation is necessary to stop the progress of marine intrusion, and improve quality water aquifer regionally.

Reclaimed water is key to achieving continuous recharge, and improve water mass status.

Institutions Contributions: ACA maintains Sant Vicenç dels Horts ponds and pays reclaimed water uses, AMB delegates the exploitation of water supply and reclaimed water to AGBCN, AGBCN exploits hydraulic barrier, ASR Cornellà and CUADLL exploits Sant Vicenç dels Horts Ponds and models the aquifer.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
ACA: Water Catalan Agency
WDF: Water Framework Directive
CUADLL: Llobregat Delta Water users Association
DWTP: Drinking Water Treatment Plant
WWTP: Waste Water Treatment Plant

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Paper for ISMAR10 symposium. **Topic No: 1 (219#)**

Book: MAR - A focus towards Latin America

Carlos Gutiérrez Ojeda[1*], Oscar A. Escolero Fuentes[2] and Edgar Y. Mendoza Cázares[1]

[1]Instituto Mexicano de Tecnología del Agua; cgutierr@tlaloc.imta.mx; edgar_mendoza@tlaloc.imta.mx
[2]Instituto de Geología, Universidad Nacional Autónoma de México; escolero@gelogia.unam.mx
*Correspondence: cgutierr@tlaloc.imta.mx; Tel.: +52-777-329-3627
** Presented at ISMAR 10 by Miguel Ángel González Núñez.

Abstract: Managed aquifer recharge (MAR) consists of a set of actions and technologies aimed to storage of water in the subsoil for later use, or to remedy the aquifer condition; for example, to reduce or prevent land subsidence or seawater intrusion. The book "MAR – a focus towards Latin America" ("Manejo de la recarga de acuíferos: un enfoque hacia Latinoamérica" in Spanish) offers a series of experiences on MAR techniques implemented in Mexico and the world. The 25 Mexican and International collaborations include site characterization, basic concepts, materials, costs, benefits, complexity of the technification, management policies, as well as good practices recommendations in the planning, design, construction, monitoring and evaluation phases. The book was conceptualized as a mean to disseminate knowledge on MAR technologies into professionals and technical personnel who need to apply and implement MAR technologies for a better management of the scarce water resources. The book has a digital format which facilitates its distribution, access and free distribution on the web.

Keywords: MAR, aquifer, recharge, book, Latin America.

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1. Introduction

In Mexico, as in the rest of Latin America, water scarcity is a big problem. The general trend is to satisfy the demand regardless of the pressure exerted on basins or aquifers. This practice has generated an intensive exploitation of the water resources. The productive sectors with greater economic resources are the dominant ones and generally achieve to satisfy all their water demands. A scheme of intensive exploitation does not favor the respectful coexistence of users nor promote the search of agreements for the sustainable management of water resources.

Water management with self-regulation ensures that the demand does not exceed water availability in basins or aquifers and promotes integral solutions that allow sustainable growth. Satisfying the required demand by the users requires the implementation of short, medium and long term strategies.

The international community has witnessed that Management of Aquifer Recharge (MAR) is a useful tool for water users and decision makers to implement concrete actions towards the sustainable management of surface and groundwater resources.

MAR can be used to replenish overexploited aquifers, to control saltwater intrusion or land subsidence, and to reduce climate change vulnerability. By itself it is not the solution for overexploited aquifers since it could only promote more groundwater abstraction. However, it can play a very important role within the set of control measures to restore the groundwater balance. Likewise, MAR can play a central role in rainwater harvesting to infiltrate the stormwater into aquifers through infiltration basins, canals or wells, for subsequent reuse for human consumption or irrigation.

MAR can be defined as the process by which water is introduced in a controlled manner into the aquifers for its subsequent recovery-use or benefit of the environment. MAR can provide effective storage of treated wastewater or stormwater by reducing losses through evaporation and transport with consequent energy savings. MAR can be used in urban and rural areas for various purposes (Figure 1).

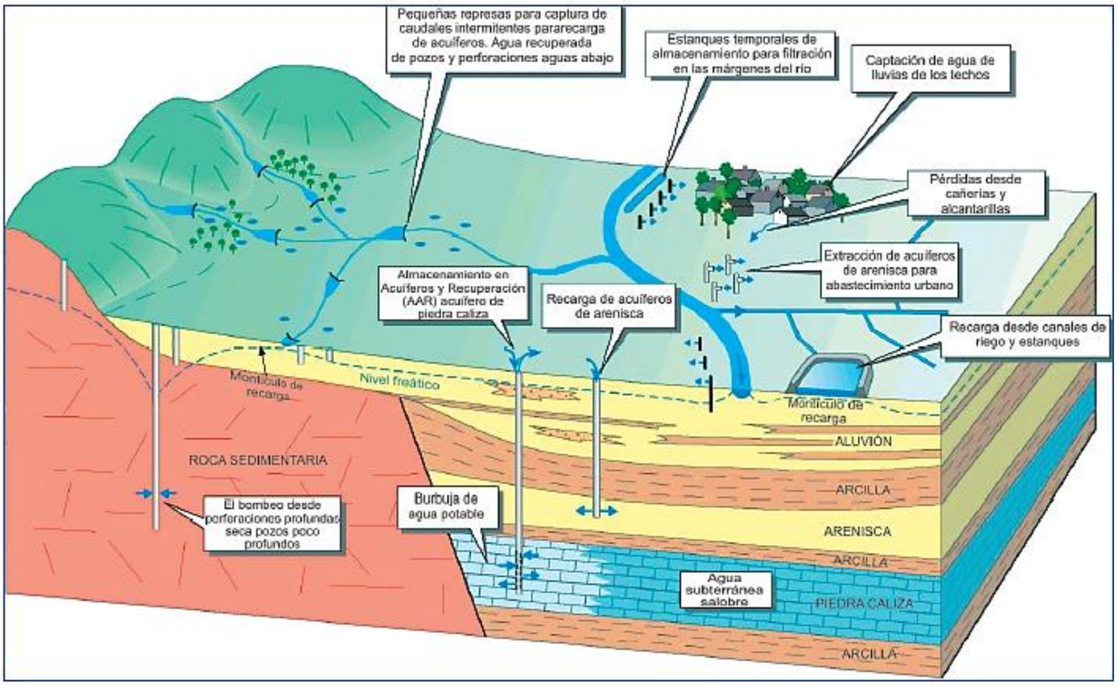

Figure 1. Illustration of main MAR techniques (Modified from [1]).

2. MAR Techniques

MAR techniques have been applied for millennia in arid and semiarid regions of the world in a great variety of arrangements and complexities: from simple infiltration basins to the injection of treated wastewater into coastal aquifers through deep wells. The applied technologies must be appropriate to meet the established objectives: store water for future use, water treatment, saline intrusion or land subsidence management, etc. MAR projects require different levels of technology and have been implemented with diverse hydrogeological and engineering knowledge. Here, we focus on intentional recharge projects which can be grouped [1] in the following categories (Table 1).

Table 1. Classification of MAR techniques[1] (descriptions in Spanish).

DESCRIPTION	TECHNOLOGY	SUBTYPE	
Infiltrate water (Infiltrar agua)	Induced bank infiltration (Infiltración inducida)		
	Wells, shaft and borehole (Pozos, excavaciones y perforaciones)	Deep well injection (Pozo de recarga profunda)	ASR
			ASTR
		Shallow well/shaft/pit infiltration (Pozos de recarga someros, excavaciones,	

		perforaciones)
	Spreading methods (Distribución)	Flooding (Inundación controlada)
		Ditch, furrow, drains (Canales, surcos y drenes)
		Irrigation (Riego)
		Infiltration ponds and basins (Estanques y balsas de infiltración)
Intercept water (Interceptar agua)	Runoff harvesting (Captación de agua de lluvia)	Barriers and bunds (Barreras que sobresalen de la superficie de la tierra)
		Trenches (Zanjas de infiltración y tinas ciegas)
	In-channel modifications (Modificación del cauce de arroyos y ríos)	Recharge dams (Presas para la recarga de acuíferos)
		Sub-surface dams (Presas sub-superficiales)
		Sand dams (Presas de almacenamiento de arena)
		Channel spreading (Técnicas de ampliación de los cauces)

[1] Modified from [1].

3. Book content

The digital book [2] is made up of contributions from professionals who have implemented MAR projects which were grouped into four sections (Table 2): Basic Concepts, Cases from Mexico, International Cases and Good Practices. The contributions include a great variety of examples with different conceptualizations, executions, costs, water quality, hydrogeology, MAR techniques, etc. They range from runoff infiltrations through channels to wells that infiltrate treated wastewater in permeable strata of aquifers for later use (Table 2).

Table 2. Index of the book "MAR: A focus on Latin America" (in Spanish).

No	DESCRIPTION	AUTHORS
	Preface	Mario López
	Foreword	Felipe Arreguín
	Presentation	Oscar Escolero, Carlos Gutiérrez y Edgar Mendoza
	BASIC CONCEPTS	
1	Research topics and technological development in groundwater (Líneas de investigación y desarrollo tecnológico en materia de aguas subterráneas)	Felipe Arreguín, Mario López, Oscar Escolero, Carlos Gutiérrez
2	Managed aquifer recharge (Manejo de la recarga de acuíferos)	José Pablo Bonilla, Catalin Stefan
3	MAR techniques classification (Clasificación de tecnologías MAR)	Edgar Mendoza
	MEXICO CASES	
4	Evaluation of recharge structures built by local communities in Ocotlán Valley, Oaxaca, Mexico	E. A. Ojeda-Olivares, S. I. Belmonte-Jiménez, M.A. Ladrón

	(Evaluación de obras de recarga hídrica construidas por comunidades autóctonas en la subcuenca del valle de Ocotlán, Oaxaca, México)	de Guevara-Torres
5	MAR projects at the Region Lagunera aquifer, México (Proyectos de recarga MAR en el acuífero principal Región Lagunera, México)	Carlos Gutiérrez, Gerardo Ortiz Flores
6	Stormwater infiltration at San Luis Potosí aquifer, Mexico: salk collector (Infiltración de agua de tormenta al acuífero de San Luis Potosí, México: colector salk)	J.V. Briseño-Ruiz, O. Escolero, E.Y. Mendoza, C. Gutiérrez
7	MAR project in Ojos del Chuvíscar aquifer, Chihuahua, Mexico (Proyecto de manejo de recarga de acuíferos en los Ojos del Chuvíscar, Chihuahua, México)	H. Silva-Hidalgo, M. A. González-Núñez, A. Pinales Munguía, A. Villalobos Aragón
8	Recharge using rainwater at Magdalena River basin, Mexico City (Recarga utilizando agua de lluvia, en la cuenca del río Magdalena Ciudad de México)	Edgar Y. Mendoza-Cázares, José M. Ramirez-León, Zaira Y. Puerto-Piedra
9	The extinct Texcoco lake and artificial infiltration (El extinto Lago de Texcoco y la infiltración artificial)	G. E. Figueroa Vega
10	Artificial recharge of aquifers: a case of study in El Caracol, Ecatepec de Morelos, State of Mexico (Recarga artificial de acuíferos: un caso de estudio en la zona de “El Caracol”, ubicado en el municipio de Ecatepec de Morelos, en el Estado México)	S. González, M.A. Juárez
11	Subsurface dam Aire no.1 Charape de los Pelones, Querétaro, México (Presa subterránea Aire no.1 Charape de los Pelones, Querétaro, México)	M. J. Álvarez
12	Artificial recharge of the aquifer in Cerro de la Estrella, Iztapalapa, Mexico City (Recarga artificial del acuífero en el Cerro de la Estrella, Iztapalapa, Ciudad de México)	F. A. Ávila, L. A. Correa , S. O. Peralta, M. Melchor
13	Artificial recharge in San Luis Colorado River Valley aquifer through infiltration ponds (Recarga artificial en el acuífero Valle de San Luis Río Colorado a través de lagunas de infiltración)	M. H. Hernández-Aguilar
14	Study to evaluate the feasibility of recharging the shallow aquifer of Valle de las Palmas, B.C. (Estudio para evaluar la factibilidad de recargar el acuífero libre somero de Valle de las Palmas, B.C.)	R. Morales-Escalante
	INTERNATIONAL CASES	
15	MAR application in Geneva, Switzerland: 35 years of success due to a proper technique and governance (La aplicación de MAR en Ginebra, Suiza: todo un éxito desde hace 35 años debido a una técnica y una gobernanza adecuadas)	Gabriel de los Cobos
16	The careo channels of Sierra Nevada, south of Spain, an ancestral recharge system at high mountain aquifers (Las acequias de careo de Sierra	S. Martos-Rosillo, A. González-Ramón, C. Marín-Lechado, J.A. Cabrera, C. Guardiola-Albert, J.

	Nevada (sur de España), un sistema de recarga ancestral en acuíferos de alta montaña)	Jodar, E. Navarrete, A. Ruiz-Constán, F. Moral, A. Pedrera, R. Navas, M, López y J.J. Durán
17	Implementation of more than 500 infiltration ponds for irrigation sustainability at the Ica aquifer, Peru (Implementación de más de 500 pozas de recarga artificial para la sostenibilidad del regadío en el acuífero de Ica, Perú)	R. Navarro Venegas, E. Fernández-Escalante
18	Windhoek, Namibia: from conceptualization to operation and expansion of a MAR scheme in a quartzitic aquifer (Windhoek, Namibia: de la conceptualización a la operación y expansión de un esquema MAR en un acuífero cuarcítico)	Ricky (EC) Murray, Ben van der Merwe, Immo Peters, Don Louw
19	Floods and droughts control through groundwater storage: from conceptualization to a pilot implementation at the Ganges river basin (Control de inundaciones y sequias mediante almacenamiento subterráneo: del concepto a la implementación piloto en la cuenca del río Ganges)	Paul Pavelic, Brindha Karthikeyan, Giriraj Amarnath, Nishadi Eriyagama, Lal Muthuwatta, Vladimir Smakhtin, Prasun K. Gangopadhyay, Ravinder P. S. Malik, Atmaram Mishra, Bharat R. Sharma, Munir A. Hanjra, Ratna V. Reddy, Vinay Kumar Mishra, Chhedi Lal Verma and Laxmi Kant
20	Managed aquifer recharge at Orange County, California, United States (Manejo de recarga de acuíferos en el Condado de Orange, California, Estados Unidos)	A. Hutchinson, J.V. Briseño-Ruiz, Carlos Gutiérrez Ojeda
21	Use of urban stormwater, water from aquifers or reservoirs for drinking and non-potable water supply: main results of the MARSUO research project (El uso de aguas de tormenta urbanas y de acuíferos o embalses para abastecimiento de agua potable y no potable: principales resultados del proyecto de investigación MARSUO)	P. Dillon, D. Page, G. Dandy, R. Leonard, G. Tjandraatmadja, J. Vanderzalm, K. Rouse, K. Barry, D. Gonzales, B. Myers
22	MAR in Los Arenales aquifer, Castilla y León, Spain. Technological solutions applied to rural development (La recarga gestionada en el acuífero Los Arenales, Castilla y León, España. Soluciones tecnológicas aplicadas al desarrollo rural)	E. Fernández-Escalante, J. San Sebastián Sauto
	GOOD PRACTICES	
23	Technological solutions for greater MAR efficiency (Soluciones tecnológicas para una mayor eficiencia en dispositivos MAR)	E. Fernández-Escalante, J. San Sebastián Sauto
24	Water banks: MAR as a tool to achieve water policy objectives (Bancos de agua: el manejo de recarga de acuíferos como herramienta para alcanzar los objetivos de la política hídrica)	Sharon B. Megdal , Peter Dillon & Kenneth Seasholes
25	The role of MAR in the integrated solution of groundwater challenges (El papel de la gestión de recarga de acuíferos en la solución integrada a los desafíos del agua subterránea)	P. Dillon

The Basic Concepts section covers the review of MAR techniques and a global inventory, and from this, some research topics on the subject are delineated.

The Mexico Cases section compiles the Mexican experiences, presenting from simple cases to the most complex in their execution. Likewise, we included at the beginning the contributions that use distribution methods (surface recharge) and then those that apply infiltration wells to recharge rainwater or treated wastewater.

The International Cases are grouped according to the criteria of the preceding section. It is important to highlight that some contributions were translated and/or adapted from documents previously published, so we were careful to maintain the original idea of the authors, and to include references and the respective copyrights. In the Spanish language contributions, we kept the technicisms which are specific of each region and at the end of the book we included a glossary with the purpose to explain the meaning of such technicisms in Latin America.

As a closing, the section called Good Practices can be used by interested parties in the Planning, Design, Construction, Monitoring and Evaluation phases of MAR projects. The section should be taken as an orientation on how to move forward according to the hydrogeological and hydrological conditions prevailing on each site.

It is important to mention that more specialists in the field were invited to participate in the book in order to share their experiences and knowledge. The editors have in mind that there are other successful MAR projects with significant knowledge which were not included in the book by diverse reasons beyond our control. However, we appreciate their intention to participate in the book.

4. Conclusions

The book "Management of aquifer recharge: a focus on Latin America" was conceptualized as a mean to disseminate MAR knowledge among professionals and technical personnel who require to apply and implement MAR technologies for a better management of water resources. Although it seems that in this field of knowledge there is available information, the fact that the greatest number of experiences are written in the English language limits its dissemination into professionals and technicians of Latin America.

The book has a digital format, in order to have a greater distribution and permanent availability in the following web pages of the Mexican Institute of Water Technology (IMTA) and Institute of Geology of the National Autonomous University of Mexico (UNAM), which allows easy access and free distribution:

https://www.gob.mx/imta

http://www.geologia.unam.mx/

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Paper for ISMAR10 symposium. ***Topic No: 1 (245#)***

Monitoring of the managed aquifer recharge (MAR) system by treated wastewater reuse (Akrotiri Limassol, Cyprus)

Achilleos Maria[1, 2*], Tzoraki Ourania[2], Antunes Isabel and Horta Ribeiro, Margarida[3]

[1] Water Development Department, Ministry of Agriculture, Rural Development and Environment, 100 - 110 Kennenty Avenue, 1047 Pallouriotissa, Nicosia, Cyprus
[2] Marine Sciences Department, School of Environment, Univ. of the Aegean, 811, Mytilene, Greece
[3] ICT/University of Minho, Campus de Gualtar, 4710 - 057 Braga, Portugal
* Correspondence: axilleosmaria@gmail.com; Tel.: +357 96570569

Abstract: Managed Aquifer Recharge (MAR) is becoming an attractive water management option, with more than 230 sites operating in Europe. A main advantage of MAR technology is its flexibility and applicability to different scales and purposes. The quality of the produced water for irrigation processes is strongly dependent on the aquifers hydrogeochemical characteristics and on the MAR design and operation [1]. Two MAR systems in two different sites are currently in operation in Cyprus. The first one is in Paphos area and enriches the Ezousa aquifer with tertiary treatment water since February 2004, while the other is in Limassol area and enriches the Akrotiri aquifer with tertiary treatment water since February 2016. Specifically, the second one recharges the Kouris Delta region of the Akrotiri aquifer, with tertiary treated water from the Sewerage Board of Limassol Amathus in order to improve quantitative and qualitative parameters of the aquifer water. In this project, two sets/systems of 17 total enrichment ponds are used to store the recycled water that are in the Kouris basin. Currently, Akrotiri Aquifer tertiary treated water is recharged during the winter, through 4 of the 10 upstream enrichment ponds along the riverbed, while the other 7 enrichment ponds are located downstream. The quantities of recycled water discharged in the Akrotiri aquifer were 847,340 m^3 in 2016 and 1566,520 m^3 in 2017. However, during the irrigation period, groundwater is pumped for irrigation purposes from boreholes located nearby. Monitoring results of water levels data's, from 2014 to February 2018, show than the enrichment inhibited the saltwater intrusion but there is still a quantitative degradation in the area, since three of five monitoring boreholes in Kouris Delta region are -1.39 m, -0.55 m, and -0.3 m below sea level. Also, enrichment decreased the contaminant contents (e.g., Chlorides and other substances) of groundwater at some points in the aquifer. Nitrate content slightly increased in some specific boreholes, mainly due to the synergistic impact of the intensive farming in the region. Specifically, the mean values of nitrate in the boreholes with hydrological numbers 1983/153, 1985/076 and 1997/047 was 11 mg/L, 5 mg/L and 7 mg/L in 2016 and 21 mg/L, 8 mg/L and 11mg/L in 2017, respectively. A slight improvement on the quality and quantity of groundwater is observed but, in the future, is expected to obtain even better results.

Keywords: over-pumping, sea intrusion, quantitative and qualitative degradation, recharge.

1. Introduction

The enrichment of groundwater with recycled water is considered a sustainable way to avoid groundwater scarcity and saline water intrusion. The geochemical processes involved during the enrichment flow path can also improve the quality of the recycled water. Different studies have been published relatively to the use of water from an infiltration lake to the aquifer which can affect its chemical composition. Some studies in California, indicated a general decrease in nitrates concentration with the intrusion of the water about a meter below the surface of the soil [2]. Other studies suggested that the quality of the water, improved with the enrichment, had a general decrease of the average chemical composition, e.g. 30% of phosphorus (P), 60% of fluorine (F), 62% of iron (Fe) and 51% of Total Organic Carbon, relatively to the initial concentration, with an intrusion rate of about 17 L/min and a residence time about 4 days in the unsaturated zone and about 2 days in the aquifer [3]. The results of SAT (Soil Aquifer Treatment) activity, after enrichment from lakes with secondary effluent in the Dan region (Israel), indicate an effective removal of various organic and other substances. It also refers to SAT's ability to effectively remove a wide range of heavy metals and toxic elements by chemical precipitation and adsorption [4]. SAT´s procedure during enrichment with recycled water showed that a large amount of organic and other substances was effectively removed. The recovered groundwater (after the SAT) covers adequately the conditions of public and agricultural constraints to unlimited irrigation [5].

The transfer and fate of more than 50 volatile organic compounds have been proved that they remain in the water for more than 50 years and can be dispersed to more than 10 km downstream [6]. In 1974 was observed that clogging by suspended solids deposited on the surface of the soil was the main cause of penetration reduction [6]. The concentration of suspended solids should be kept below 10 mg/L for maximum intrusion [7]. Otherwise, with an adequate purification of the bottom of the enrichment ponds, the intrusion ability can be almost completely restored [8].

Cyprus is one of the "water poor" countries of Europe with limited water resources and frequent occurrence of droughts. The climate models predict rise in temperature and increase in the intensity and frequency of extreme drought events. The Republic of Cyprus, during the late sixties started the implementation of a Water Master Plan to satisfy, in a sustainable way, the different users of water and safeguard human and other life. The implemented measures allow increasing water availability and decreasing water demand. One of the measures is the reuse of treated effluent from the urban waste-water treatment plants in irrigation and aquifers recharge. Aquifers are used as storage reservoirs mainly in the winter, which water is extracted and used during the irrigation period, such as Akrotiri Aquifer and Ezousa Aquifer in Limassol and Paphos area, respectively, enriched with tertiary treated water.

In order to use recycled water, produced by the existing Wastewater Treatment Plant of the Council of Sewerage Board of Limassol - Amathus (SALA) in the Moni area, various alternative solutions have been examined particularly in the winter period, where the needs for irrigation are redundant. The best solution was the storage of water in the Akrotiri aquifer and specifically in the area of Kouris Delta. This particular scenario predominated, as an effort to improve the over pumping and the resulting severe deficiency of the water balance, which is driving the salinization of extended regions of the Akrotiri aquifer due to seawater intrusion (Figure 1). The main objective of the current study is the quantitative and qualitative monitoring of the enrichment ponds and the aquifer.

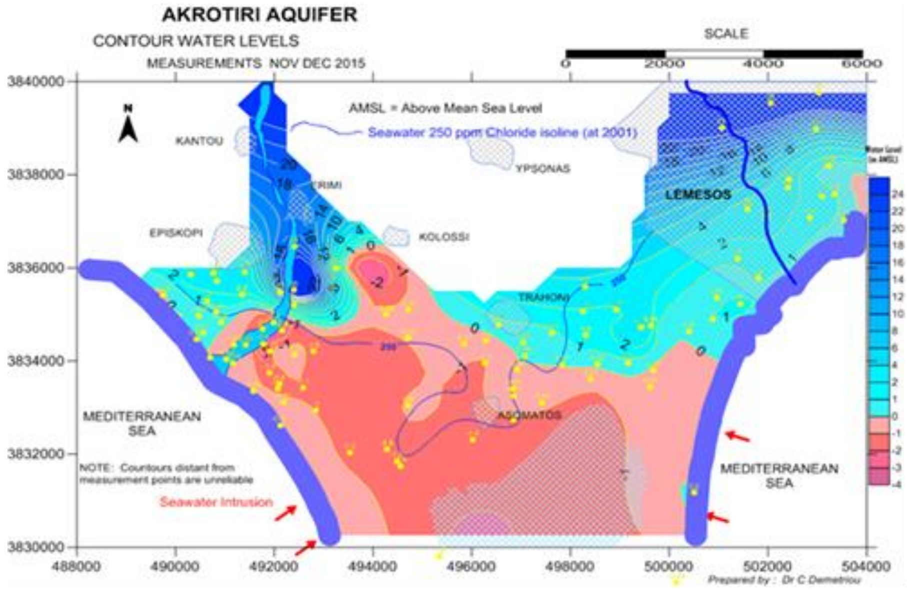

Figure 1. The Akrotiri aquifer. The red area represents the parts of the aquifer where the water level is below the mean sea level and the blue area represents the parts above sea level. The blue line defines the area affected by the intrusion of seawater.

2. Materials and Methods

The Akrotiri aquifer is the third largest continuous and most important porous aquifer of Cyprus and is in the southern most part of Cyprus. The southern boundary of the aquifer runs along the edge of a large salt lake (Akrotiri Lake).

The Akrotiri aquifer has an approximate surface area of 45 km^2 and consists of deltaic sediments, deposited in two big fan deltas, coming from the Garyllis River, in the east, and the Kouris River, in the west. The Kouris River is the largest river in Cyprus and drains a catchment area of 300 km^2, extending far up into the Troodos mountains. The Akrotiri aquifer is an unconfined aquifer composed of gravels, sands and boulders of high permeability, with intercalated thin lenses of silt and clay. Its thickness ranges from a few meters in the north to over 115 m in the south. The Kouris Delta area consists of coarse-bed deposits, sand and gravel with a high permeability coefficient. The area of the Delta and especially the river bed of Kouris has been chosen because it offers several favorable conditions. The lithology of the aquifer in the Kouris Delta area allows satisfactory infiltration and flow rates in the aquifer. Large quantities of groundwater can be stored as well.

In this project, two sets/systems of enrichment ponds are used to store the recycled water that is in the Kouris basin. More specifically, 17 enrichment ponds (or lakes) have been constructed in the Kouris River, comprising a total area of 56,000 m^2. The 7 downstream ponds (lakes) have a total area of approximately 21,000 m^2 and are located at about 1km from the sea, aiming not only to enrich the aquifer but also to prevent the intrusion of the sea. Another 10 ponds (lakes) have been built upstream, south of the M1 road, and have an area of approximately 35,000 m^2. In the region of the 10 upstream ponds (lakes) of enrichment, the unsaturated zone depth is big enough (20 m) so that it would allow in a satisfactory degree the development of the natural, chemical and mainly biological activities that will improve the quality of the recycled water (Figure 2).

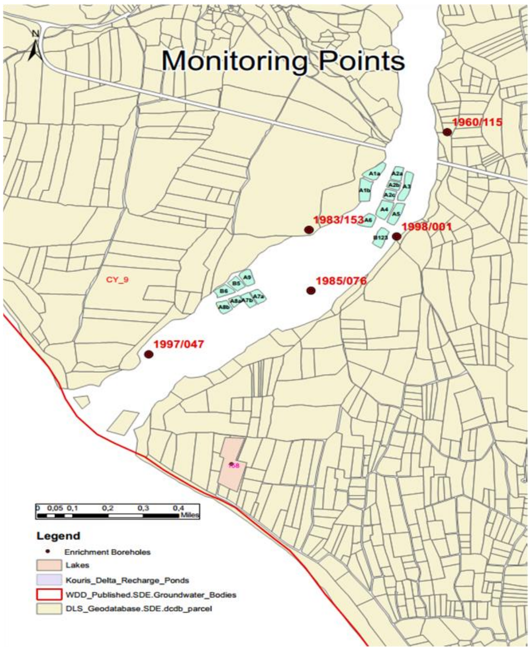

Figure 2. Monitoring Points of the studied area.

For the effective monitoring of the studied aquifer, a network of monitoring stations, included groundwater from the aquifer and recycled water from the enrichment ponds, have been defined for the assessment of water quality and quantity status before, during and after the enrichment. The quantitative characterization includes water level measurements in order to monitor the inflows and outflows to and from the aquifer over time, in an enrichment pond, in a borehole upstream of the first ten enrichment ponds, where enrichment is currently taking place and in other four boreholes located downstream of the first ten enrichment ponds. It is recommended that level-loggers are going to be installed to continuously record water level at all points in five monitoring boreholes and one enrichment pond.

The Kouris Delta enrichment started in February of 2016 with tertiary treated water from the Sewerage Board of Limassol Amathus. The quantities of discharged recycled water in the aquifer were about 847,340 m^3 in 2016 and 1,566,520 m^3 in 2017. In the context of this project, besides the quantitative status, the quality status of the aquifer is monitored, four times per year, from October to April, taking a water sample from six different monitoring points. Samples are taken from one enrichment pond and five boreholes. As regarding as the monitoring period, samples are taken before the enrichment start, two in the time between and once after the enrichment. One from the five boreholes (1960/115) is located upstream of the first ten enrichment ponds, and the remaining downstream (Figure 2).

3. Results

The aquifer water level fluctuates between winter and summer period because of enriched with recycled water and storm water. In the winter period, the water level increases due to enrichment and, in the summer period, the water level decreases due to the use of the water for irrigation. Before started the enrichment system, it was observed a decreasing trend in the water level of the aquifer, reaching below sea level.

The current situation of these boreholes, according to the latest water level measurements of July and September 2017, shows that has been an improvement after the enrichment, but there is still a quantitative degradation in the area, since three of five boreholes were -1.39 m, -0.55 m and -0.3

m below the sea level. The borehole with hydrological number 1997/047 remained approximately at the same level (Figure 3).

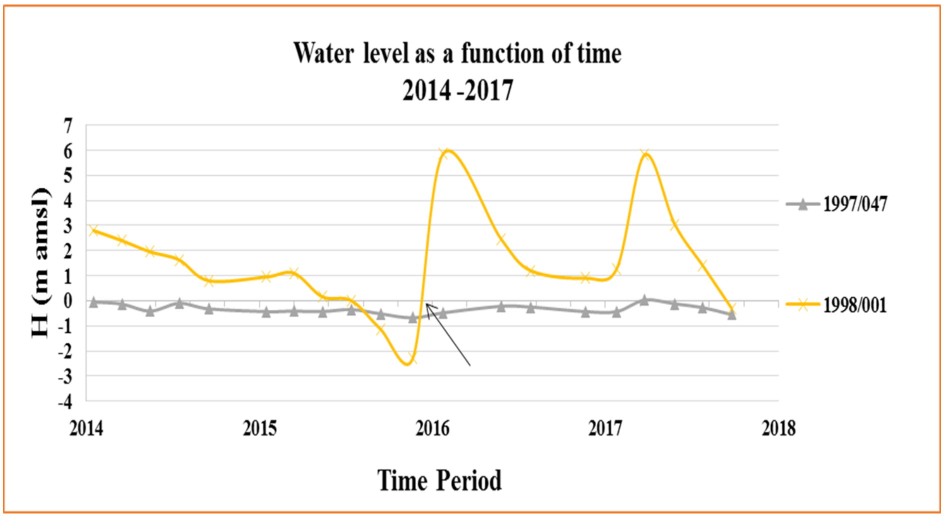

Figure 3. Water levels data's from 2014 to February 2018, as a function of time for the 2 of the 5 monitoring stations (boreholes). The narrow shows the starter of enrichment.

Moreover, as shown from the results so far, the Akrotiri aquifer has not been chemically burdened by the enrichment since almost average values of the measured parameters for the period of February 2016 to December 2017, in the monitoring boreholes, were below the Highest Acceptable Values established for the CY9 aquifer (Table 1). The exception is for chloride, sulphate and electrical conductivity with average values of 263,2 mg/L, and 4060,3 mg/L, 1351,0 mg/L and 18502 μS/cm, respectively. Also nitrate contents increased in some specific boreholes.

4. Discussion

From all the boreholes, the borehole with hydrological number 1998/001 has the biggest distance from the sea and the smallest distance from the first 10 enrichment ponds, which enrichment occur from February 2016 until actually. For this reason, the water level in this borehole had the biggest fluctuate compared with the other ones. Instead the borehole with hydrological number 1997/047 has the biggest distance from the sea and the smallest distance from the first ten enrichment ponds where enrichment take place from February 2016 until today (Figure 2).

The Akrotiri aquifer has not been chemically burdened by the enrichment since almost average parameter measured values between February 2016 to December 2017, in the monitoring boreholes, were below the Highest Acceptable Values established for the CY9 aquifer (Table 1).

The exceedances for chlorine, sulphates and electrical conductivity have been observed for some of the boreholes due to the quantitative degradation and intrusion of seawater. Specifically, chlorine exceedances from the boreholes with hydrological number 1998/001 and 1997/047 were measured to be above the 250 mg/L Highest Acceptable Value established for CY9 aquifer due to the quantitative degradation and intrusion of seawater. The largest quantitative degradation of all boreholes was observed for the borehole with hydrological number 1997/047, in which in addition to chlorides, there was an excess in the Higher Acceptable Values established for sulphates and electrical conductivity. This borehole has the smallest distance from the sea and the specific values are justified because of greater sea intrusion. Also, nitrate contents increased in some specific boreholes, mainly due to the impact of the intensive farming in the region and not for the enrichment.

Table 1. Highest Acceptable Values established for the CY9 aquifer and Average Measured Values in the monitoring points between February 2016 and December 2017.

Chemical Parameters		Total Pesticides	Conductivity (EC)	Ammonium (NH_4)	Chlorine (Cl)	Sulfate (SO_4)	Trichloroethylene (C_2HCl_3)	Tetrachloroethylene (C_2Cl_4)	-
Highest Acceptable Values (GWD limit CY 9)		0,5 μg/l	2500 μS/cm	0,5 mg/l	250 mg/l	250 mg/l	5 μg/l	2 μg/l	-
Average measured values	RCP-1	0,0	1461	0,0	280,0	125,0	0,0	0,0	-
	1983/153	0,0	910	0,0	105,5	72,7	0,0	0,0	-
	1985/076	0,0	872	0,0	95,5	58,9	0,0	0,0	-
	1998/001	0,0	1620	0,0	263,2	120,0	0,0	0,0	-
	1997/047	0,0	18501	0,0	4060,3	1351,0	0,0	0,0	-
	1960/115	0,0	1072	0,2	145,0	86,9	0,0	0,0	-
Chemical Parameters		**Arsenic (As)**	**Cadmium (Cd)**	**Μόλυβδος (Pb)**	**Mercury (Hg)**	**Nitrates (NO3-)**	**Nickel (Ni)**	**Copper (Cu)**	**Chromium (Cr)**
Highest Acceptable Values (GWD limit CY 9)		10 μg/l	5 μg/l	10 μg/l	1 μg/l	50 μg/l	20 μg/l	2000 μg/l	50 μg/l
Average measured values	RCP-1	0,0	0,0	0,1	0,0	13,2	3,2	0,2	0,0
	1983/153	0,0	0,0	0,5	0,0	24,1	1,4	0,4	0,0
	1985/076	0,3	0,0	0,5	0,0	10,2	1,1	0,0	0,3
	1998/001	0,0	0,0	0,5	0,0	39,6	7,0	10,5	0,0
	1997/047	3,9	0,0	0,5	0,0	14,9	5,4	1,7	3,9
	1960/115	0,0	0,0	0,9	0,0	2,0	3,0	0,0	0,0

5. Conclusions

The MAR system is operating in a fragile area, suffering by nitrification and salinization. It is observed still a severe sea intrusion and increase in the salinity of the coastal aquifer and nitrates increased values in some cases due to intensive farming in the region. The short period of time in which enrichment has been taking place (February 2016 - today) and the insufficient data make it impossible to draw any conclusions with certainty at that moment. Continuous monitoring, and the recording of specific parameters over the next few years, will help to draw important and more accurate conclusions. The monitoring is suggested to be improved by the installation and operation of sensors, because the monitoring of the way that the enrichment is done is decisive for the result and the charge of the aquifer.

Acknowledgments: Data collected through the project “Monitoring of the Akrotiri Aquifer which its enrichment by Treated Wastewater from the Sewerage Board of Limassol – Amathus”, which was started from February 2016. The Data was collected for the period February 2016 until December 2017. The authors want to thank Water Development Department of Cyprus for the data.

Author Contributions: MA makes the sampling in the field; MA collected the data; MA analyzed the data; MA wrote the paper; OT checked and corrected the paper; IMA checked and corrected the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharged
SALA: Sewerage Board of Limassol Amathus
SAT: Soil Aquifer Treatment
CY-9 Aquifer: Akrotiri Aquifer

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Topic 2. MAR AS A KEY CLIMATE CHANGE…

Paper for ISMAR10 symposium. ***Topic No: 2 (001#)***

Crucial Role of Managed Aquifer Recharge as an Adaptation Strategy for Groundwater Sustainability in the Face of Climate Change in India

Jain, Ratan[1]

[1] Formerly Chairman, Central Ground Water Board, Govt. of India, New Delhi, India; e-mail: *ratan.jain@gmail.com. Tel.:+91-986 810 3960

Abstract: As per key findings of climate change projections for India, the increase in the frequency of extreme precipitation, will also mean that much of the monsoon rain would be lost as direct run-off resulting in reduced groundwater recharge and increased ground water withdrawal, which might further exasperate the present scenario of imbalanced development. The adaptation strategies proposed for mitigating the increasing stress on ground water resources due to climate change for enhancing recharge of groundwater aquifers, mandating water harvesting and artificial recharge in urban areas, ground water governance, incentivising to promote recharging of ground water, intelligent power rationing for irrigation ,optimizing water use efficiency, conjunctive management etc. have been examined at great length in terms of the technical feasibility as well as social relevance of implementation in the light of extensive experience gained in the country. Sustainable development of ground water resources and various mitigation programs required in the event of possible Environment & Forests, Power, Rural Development, Agriculture, Science & Technology and the institutions working under them; State Governments & their organizations; Associations of Industry, Non-Government Organizations, District Administrations and Panchayati Raj Institutions climate change in the country can be accomplished only with the help and active cooperation of all stakeholders such as the Ministries of Government of India for Water Resources, and the individuals users. To be successful in this mission we also have to create conditions for complete synergy in the activities of all the stakeholders. The role and space for various stakeholders namely Farmers, NGOs, local communities, Canal system managers and Groundwater Recharge SPV, in groundwater recharge strategy as a major response to climate change is outlined.

Keywords: managed aquifer recharge, energy-irrigation nexus, intelligent power rationing, synergy, conjunctive management.

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1. Introduction

India's National Action on Climate Change (NAPCC), unveiled by the Prime Minister's Office in 2008, highlights the increasing stress on water resources due to climate change, and points to the need to increase efficiency of water use, explore options to augment water supply in critical areas, and ensure more efficient management of water resources"[1]. It calls for measures to enhance recharge of the sources and recharge zones of deeper groundwater aquifers, mandating water harvesting and artificial recharge in relevant urban areas, incentives to promote recharging of ground water, optimize water use by increasing water use efficiency by 20%, regulation of power tariffs for irrigation and to augment storage capacities of surface water storage structures, including through the renovation of existing tanks. Intergovernmental Panel on Climate Change [2] in its recent released report has reconfirmed that the global atmospheric concentration of carbon dioxide (CO2) and greenhouse gases (GHGs) have increased markedly as a result of human activities since 1750. The global increase in CO2 concentration is primarily due to fossil fuel use and land use change. These increases in GHGs have resulted in warming of the climate system by 0.74ºC between 1906 and 2005. The rate of warming has been much higher in recent decades. This has, in turn, resulted in increased average temperature of the global ocean, sea level rise, decline in glaciers and snow cover. There is also a global trend for increased frequency of droughts, as well as heavy precipitation events over most land areas and extreme events.

2. Climate Change

Annual mean surface temperature rise by the end of century, ranging from 3 to 5ºC under A2 scenario and 2.5 to 4ºC under B2 scenario of IPCC, with warming more pronounced in the northern parts of India, has been indicated from simulations by Indian Institute of Tropical Meteorology (IITM), Pune. Indian summer monsoon (ISM) is a manifestation of complex interactions between land, ocean and atmosphere. The simulation of ISM's mean pattern as well as variability on inter-annual and intra-seasonal scales has been a challenging ongoing problem. Some simulations by IITM, Pune, have indicated that summer monsoon intensity may increase beginning from 2040 and by 10% by 2100 under A2 scenario of IPCC.

Climate projections for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) made using the newly developed representative concentration pathways (RCPs) under the Coupled Model Inter-comparison Project 5 (CMIP5) by Rajiv Kumar Chaturvedi et al [3] of Indian Institute of Science, Bangalore ,provides multi-model and multi-scenario temperature and precipitation projections for India for the period 1860–2099 based on the new climate data. They found that that CMIP5 ensemble mean climate is closer to observed climate than any individual model. The key findings of this study are: (i) under the business-as usual (between RCP6.0 and RCP8.5) scenario, mean warming in India is likely to be in the range 1.7–2ºC by 2030s and 3.3–4.8ºC by 2080's relative to pre-industrial times; (ii) all-India precipitation under the business-as-usual scenario is projected to increase from 4% to 5% by 2030s and from 6% to 14% towards the end of the century (2080's) compared to the 1961–1990 baseline; (iii) while precipitation projections are generally less reliable than temperature projections, model agreement in precipitation projections increases from RCP 2.6 to RCP 8.5, and from short- to long-term projections, indicating that long term precipitation projections are generally more robust than their short-term counterparts and (iv) there is a consistent positive trend in frequency of extreme precipitation days (e.g. > 40 mm/day) for decades 2060s and beyond.

CMIP5 model-based time series of temperature and precipitation anomalies (historical and projections) from 1861 to 2099 relative to the 1961–1990 baseline for the RCP scenarios are given in Fig.1. Shaded area represents the range of changes projected by the 18 models for each year.The model ensemble averages for each RCP are shown with thick lines. The observed temperature and precipitation trend from CRU are shown by the green line and the solid black line 'historical' refers to model ensemble values for historical simulations. Projected change in the frequency of extreme rainfall days for future decades relative to the 1861–1870 baseline is given in Fig 2.

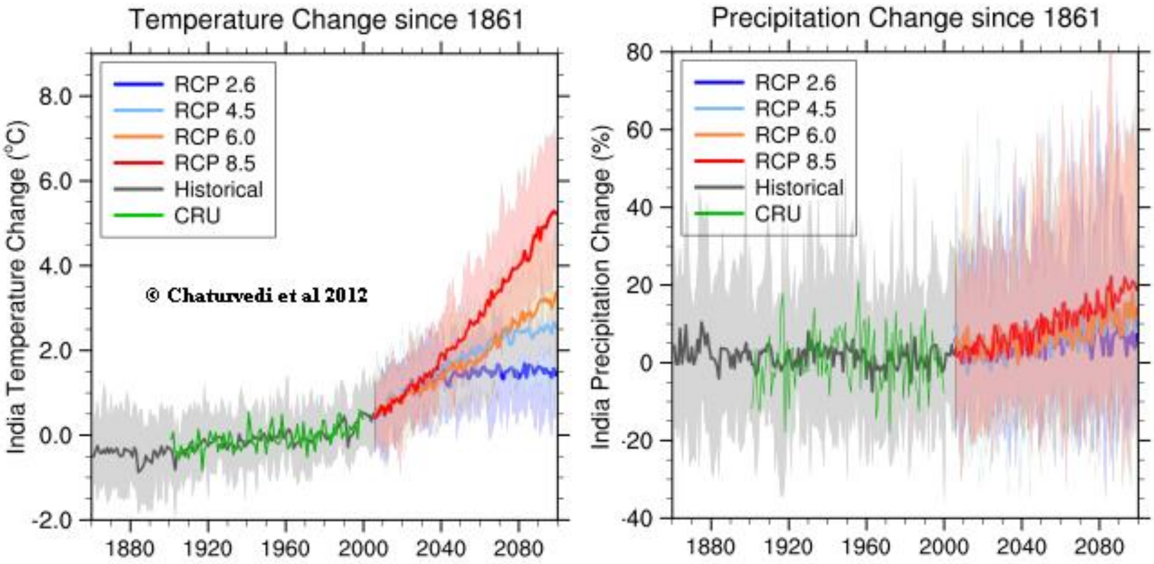

Figure 1. CMIP5 model-based time series of temperature and precipitation anomalies (historical and projections) from 1861 to 2099 relative to the 1961–1990 baseline for the RCP scenarios. (After, Rajiv Kumar Chaturvedi et al, 2012)

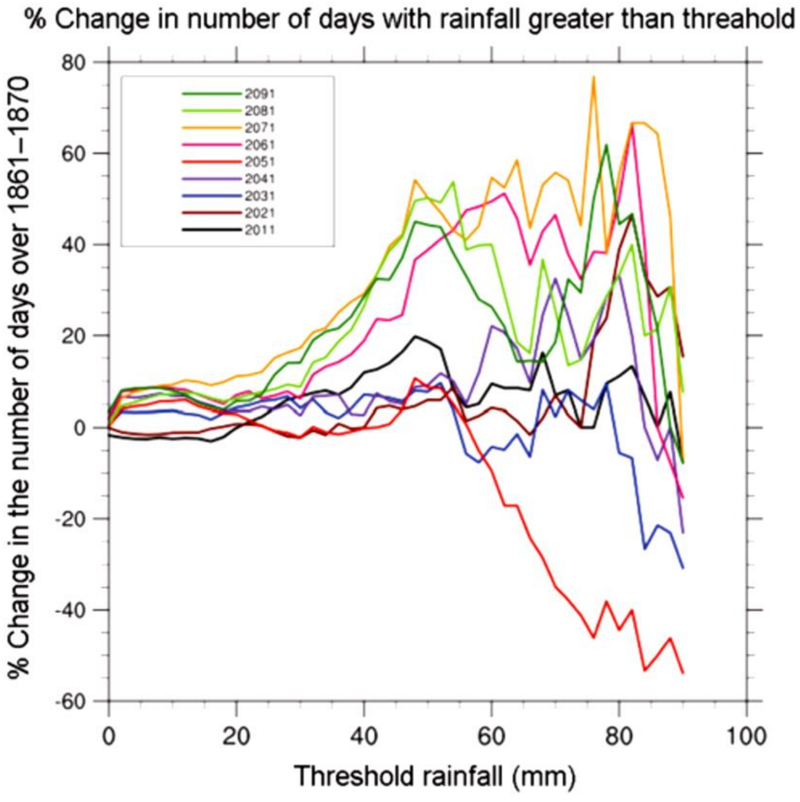

Figure 2. Projected change in the frequency of extreme rainfall days for future decades relative to the 1861–1870 baseline (After, Rajiv Kumar Chaturvedi *et al*, 2012)

3. Ground Water Scenario

Ground water is one of the most precious natural resource and has played a significant role in maintenance of India's economy, environment and standard of living. Besides being the primary source of water supply for domestic and many industrial uses, it is the single largest and most productive source of irrigation water. India is a vast country having diversified geological, climatological and topographic set-up, giving rise to divergent groundwater situation in different parts of the country. The prevalent rock formations, ranging in age from Achaean to Recent, which control occurrence and movement of groundwater, are widely varied in composition and structure. Broadly two groups of water bearing rock formations have been identified i.e. (i) Porous rock formations which can be further classified into unconsolidated and semi-consolidated formations having primary porosity; and (ii) Fissured rock formations which mostly have secondary or derived porosity. Similarly, there are significant variations of landforms from the rugged mountainous terrains of the Himalayas, Eastern and Western Ghats to the flat alluvial plains of the river valleys and coastal tracts, and the aeolian deserts of Rajasthan. The rainfall patterns too show similar region-wise variations. The topography and rainfall virtually control run-off and groundwater recharge. The entire country has been broadly divided into five distinct ground water regions considering the characteristic physiographic features as well as occurrence and distribution of ground water. The Hydrogeological map of India is depicted in Figure 3 showing ground water potential of the broad groups of water bearing formations.

3.1 Mountainous Terrain and Hilly areas: This region is occupied by varied rock types including granite, slate, sandstone and limestone. The yield potential of aquifers ranges from 1 to 40 liters per second (lps). However, because of high conductivity and hydraulic gradient, it offers very little scope; for ground water storage. The valley fills in mountains function as underflow conduits and act as the major source of recharge. Springs are main source of water supply.

3.2 Indo-Gangetic-Brahmaputra Alluvial Plains: Indo-Gangetic- Brahmaputra alluvial plains, occupy the States of Punjab, Haryana, Uttar Pradesh, Bihar, Assam and West Bengal. The plain is underlain by thick pile of sediments. Thickness of the sediments increases from north to south. At places, the thickness of the alluvium exceeds 1000m. The thick alluvial fill constitutes the most productive ground water reservoir in the country. In the present scenario the ground water development in this region is at low level except the western parts in the States of Haryana and Punjab. The deeper aquifers in these areas offer good scope for further exploitation of ground water. In Indo-Gangetic-Brahmaputra plain, the deep wells yield in the range of 25-50 lps.

3.3 Peninsular shield Area: The area is located south of Indo-Gangetic plain and consists mostly of consolidated sedimentary rocks, Deccan basalts and crystalline rocks in the states of Karnataka, Maharashtra, and Tamil Nadu. Occurrence and movement of ground water in these rock formations are restricted to weathered material and interconnected fractures at deeper levels. These have limited ground water potential. Ground water occurs within depth 50m, occasionally down to 150m, and rarely beyond 200m depth. Ground water development is largely through dug well and bore wells. The yield of borewells tapping deep fractured zones in hard rocks varies from 2-15 lps.

3.4 Coastal Area: Coastal areas have a thick cover of alluvial deposits and form potential multi-aquifer systems covering states of Gujarat, Kerala, Tamil Nadu, Andhra Pradesh and Orissa. However, inherent quality problems and the risk of seawater ingress impose severe constrains in the development of these aquifers. In addition, the ground water development in these areas is highly vulnerable to up-coning of saline water. The yield of tubewells varies from 20-25 lps.

3.5 Central Alluvial Areas: This region has been grouped separately owing to its peculiarity in terms of presence of three discrete fault basins, the Narmada, the Purna and Tapti, all of which contain extensive valley-fill deposits. The alluvial deposit ranges in thickness from about 50 to 150m. Ground water occurrence in the area is restricted to deep aquifer systems tapping fossil water. For example, in parts of Purna valley the ground water is extensively saline and unfit for various purposes. The yield potential of tubewells varies from 1-10 lps.

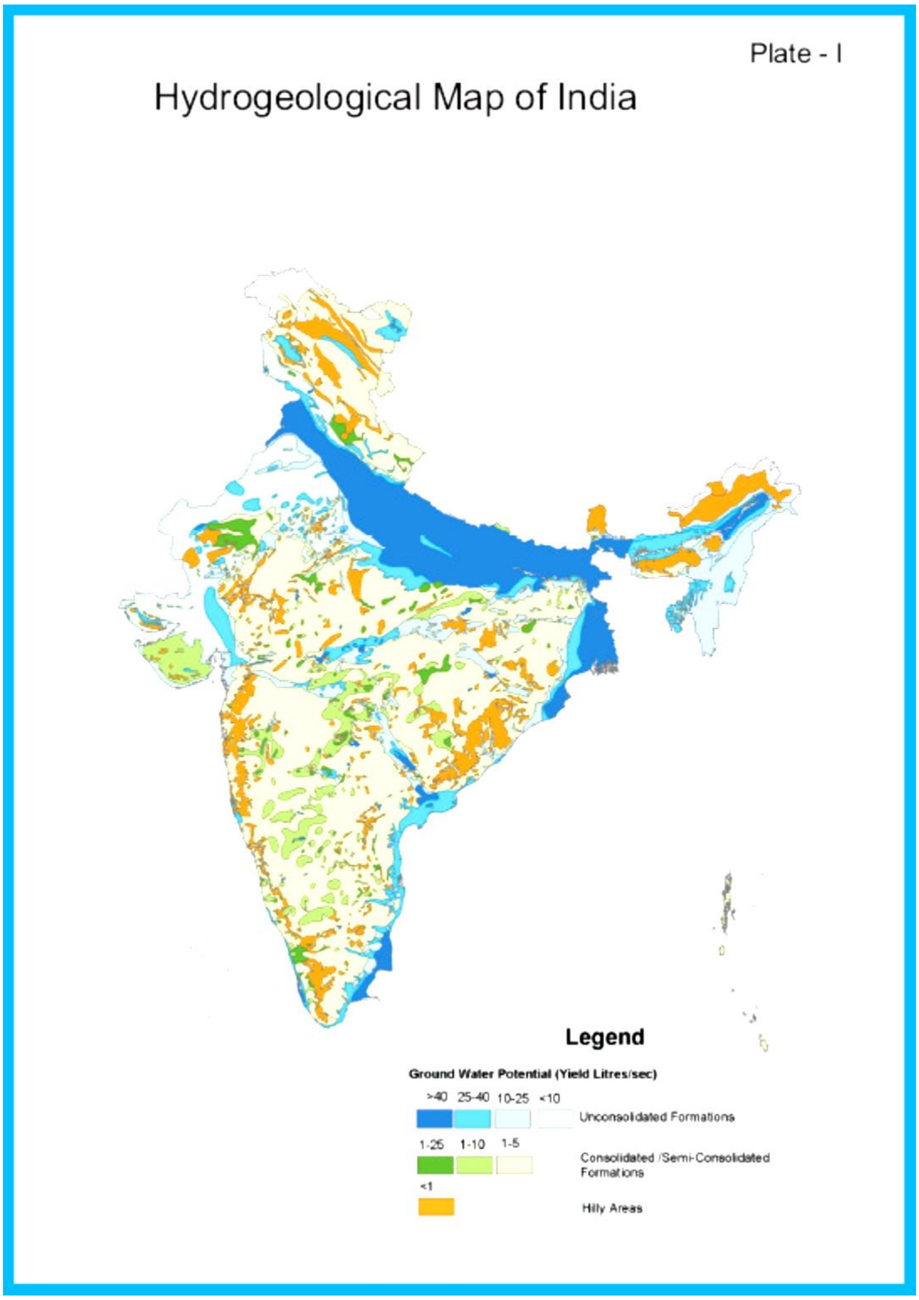

Figure 3. Hydrogeological Map of India.

4. Ground Water Availability

Rainfall is the major source of ground water recharge, which is supplemented by other sources such as recharge from canals, irrigated fields and surface water bodies. The rainfall is unevenly distributed. The average rainfall in country is around 117cm. It is below 75 cm in the northwestern part covering parts of the states of Rajasthan, Gujarat, Haryana and the southern part, covering the states of Karnataka and Tamil Nadu. The amount of ground water withdrawal and situation of low rainfall are the factors which decides the overall stress on ground water and accordingly the assessment units are being categorized as over-exploited & critical blocks.

Large development of ground water resources in the country takes place from the unconfined / shallow aquifers, which hold replenishable ground water resource. Central Ground Water Board has assessed the replenishable ground water resource in the country in association with the concerned State Government authorities [4]. The annual replenishable ground water resources have been assessed as 447 billion cubic meters(bcm). Keeping an allocation for natural discharge, the net annual ground water availability is 411 bcm. The annual ground water draft (as on 31st March 2013) is 253 bcm. The Stage of ground water development works out to be about 62%. The development of ground water in different areas of the country has not been uniform. Highly intensive development of ground water in certain areas in the country has resulted in over – exploitation leading to decline in ground water levels and sea water intrusion in coastal areas. Out of 6584 assessment units (Blocks/Mandals / Talukas) in the country, 1034 units in various States have been categorized as 'Over-exploited' i.e. the annual ground water extraction exceeds the net annual ground water availability and significant decline in long term ground water level trend has been observed either in pre-monsoon or post- monsoon or both. In addition, 253 units are 'Critical' i.e. the stage of ground water development is above 90 % and within 100% of net annual ground water availability and significant decline is observed in the long term water level trend in both pre-monsoon and post-monsoon periods. There are 681 semi-critical units, where the stage of ground water development is between 70% and 100% and significant decline in long term water level trend has been recorded in either Pre-monsoon or Post-monsoon. 4520 assessment units are Safe where there is no decline in long term ground water level trend. Apart from this, there are 96 blocks completely underlain by saline ground water.

In addition to annually replenishable ground water, extensive ground water resources occur in the confined aquifers in the Ganga-Brahmaputra alluvial plains and coastal – deltaic areas. These aquifers have their recharge zones in the upper reaches of the basins. The resources in these deep-seated aquifers are termed as 'In-storage ground water resources'. In alluvial areas, these resources are normally renewable over long periods of time, except in case of sedimentary rock aquifers in Rajasthan, which comprise essentially non-renewable fossil water.

5. Proposed adaptation strategies

In view of the clear evidences of hydrological cycle, it is pertinent to reassess the availability of water resources. It is critical for formulating relevant national change in global surface temperature, rainfall pattern, evapotranspiration and extreme events and its possible impact on the and regional long-term development strategies in a holistic way. The various mitigation measures within the constraints imposed by the possible climate change and hydrologic regimes and future research needs are discussed in following paragraphs.

5.1 Rainwater harvesting and Artificial Recharge: Extreme climate events such as aridity, drought, flood, cyclone and stormy rainfall are expected to leave an impact on human society. They are also expected to generate widespread response to adapt and mitigate the sufferings associated with these extremes. Societal and cultural responses to prolonged drought include population dislocation, cultural separation, habitation abandonment, and societal collapse. A typical response to local aridity is the human migration to safer and productive areas. However, climate and culture can interact in numerous ways. Historical societal adaptations to climate fluctuations may provide insights on potential responses of modern societies to future climate change that has a bearing on water resources, food production and management of natural systems. Decentralized rainwater harvesting from roof catchments in cities has the potential to supplement centralised water supply strategies to create an overall more resilient urban water supply. This result highlights the importance of implementing a diverse range of water sources and conservation for urban water management. The efficiency of translation of rainfall runoff into recharge is highly dependent on strategy and location.

The immediate priority for augmentation of ground water are the areas already overexploited resulting into severe decline in ground water level, coastal areas affected by sea water ingress due to haphazard and unscientific development of ground water and the areas infested with pollution due to various reasons. While prioritizing the areas, the possible impact of climate change needs to be dovetailed. As a long term measure an attempt has been made to provide a conceptual framework for utilization of surplus monsoon runoff for artificial recharge of ground water and consequently a "National perspective plan for recharge to ground water by utilizing surplus monsoon runoff" has been prepared by CGWB [5]. The report provides availability of non-committed surplus monsoon runoff in 20 river basins of the country vis-a vis the subsurface available space under different hydrogeological situations for saturating the vadose zone to 3 m below ground level. It was estimated that it is possible to store 21.4 Mham in the ground water reservoir through out the country out of which 16.05 Mham can be utilized.

As per the Master Plan for artificial recharge to ground water prepared by CGWB in 2013 [6], out of the geographical area of 32,87,263 sq. km of the country, an area of about 9,41,541 sq.km. has been identified in various parts of country which need artificial recharge to ground water. This includes the hilly terrain of Himalayas also where the structures are basically proposed to increase the fresh water recharge and improve the sustainability of springs. It is estimated that annually about 85,565 MCM of surplus surface run-off can be harnessed to augment the ground water. In rural areas, suitable civil structures like percolation tanks, check dams, nala bunds, gully plugs, gabion structures etc. and sub-surface techniques of recharge shaft, well recharge etc. have been recommended. Provision to conserve ground water flow through ground water dams has also been made. It is envisaged to construct of about 11 million artificial recharge structures in urban and rural areas at an estimated cost of about US $ 15835 Million. This comprises of mainly around 8.8 million structures utilizing rain water directly from rooftop and more than 2.3 million artificial recharge structures utilizing surplus run-off and recharging ground water in various aquifers across the country. The break-up includes around 0.29 million check dams, 0.155 million gabion structures, 0.626 million gully plugs,0.409 million nala bunds/cement plugs. 84925 percolation tanks, 8281 sub-surface dykes, 0.591million recharge shaft, 0.108 million contour bunds, 16235 injection wells and 23172 other structures which includes point recharge structures, recharge tube wells, stop dams, recharge trenches, anicuts, flooding structures, induced recharge structures, weir structures etc. In hilly terrain of Himalayas emphasis has been given for spring development and 2950 springs are proposed for augmentation and development

Assuming the importance of artificial recharge and rain water harvesting, the Model Bill on Ground water prepared and circulated by Ministry of Water Resources has been amended in 2006 to accommodate the this important aspect and all the state Governments have been asked to formulate their own rule and law for better governance of ground water adopting suitable augmentation measures where ever required or else impose regulatory measures to ensure sustainability of this vital resource.

An increase in precipitation in the basins of Mahanadi, Brahmani, Ganga, Godavari and Cauvery is projected under climate change scenario. Unless remedial measures are implemented to control the runoff, frequency of floods in these areas are unavoidable. During and after the floods, ground water plays a significant role as alternative source of drinking water. The construction of "Sanctuary wells " in such areas at suitable locations or near the shelters houses may provide a solution for solving the drinking water crisis during the flood times. Preferably the Sanctuary wells may be constructed tapping the deeper aquifers which are less vulnerable to contamination because of inundation.

5.2 Conjunctive Management: Conjunctive management will play crucial role as a mitigatory measure since climate change will lead to extreme situation of water level rise in some areas and water level decline in other areas. In such event Conjunctive management needs to be adopted so as:

- To evolve a suitable plan for controlling the problem of rising water levels by adopting the technique of conjunctive use of surface and ground water, and proper drainage.
- To prepare sector/ block-wise plans for development of ground water resource in conjunction with surface water based on mathematical model results.
- To test the sustainability of the present irrigation pattern with respect to conjunctive use of water resources and suggest improvement for future.

- To evaluate the economic aspect of groundwater development plan with respect to Cost benefits ratio, internal rate of return and payback period etc.

In areas of India with massive evaporation losses from reservoirs and canals but high rates of infiltration and percolation, the big hope for surface irrigation systems—small and large—may be to reinvent them to enhance and stabilize groundwater aquifers that offer water supply close to points of use, permitting frequent and flexible just-in-time irrigation of diverse crops. Already, many canal irrigation systems create value not through flow irrigation but by supporting well irrigation. In the Mahi Right Bank system in Gujarat, with a command area of about 250,000 ha, it is the more than 30,000 private tube wells—each complete with heavy-duty motors and buried pipe networks to service 30 to 50 ha—that really irrigate crops; the canals merely recharge the aquifers. An elaborate study by Central Groundwater Board (1995) lauded the Mahi irrigation system as a "model conjunctive use project" in which 65 percent of water was delivered by canals and 35 percent was contributed by groundwater wells. However, what conjunctive use was occurring was more by default than by design as the enterprising farming community of the area have taken the initiative and realized fully the advantages of adopting the conjunctive use techniques for reaping optimal benefits.

Further, there is an urgent need to adopt participatory Irrigation management ensuring participation of stakeholders since inception of the conjunctive use projects. Due to variations in rainfall and runoff in different basins of the country, it is expected that imbalances in availability of surface and ground water may aggravate the conditions of water logging at one end and scarcity at other end. The major irrigation command areas are more vulnerable to such extreme events and hence there is an urgent need to implement conjunctive use practices in field conditions so as to control rising water level scenario, water logging and even water shortages in tail end areas.

5.3 Intelligent management of energy-irrigation nexus: As of now, managing the energy-irrigation nexus with sensitivity and intelligence is the region's principal tool for groundwater demand management. The current challenge is twofold. First, diesel-based groundwater economies of the Indo-Gangetic basin are in the throes of an energy squeeze; some studies by Shah [7] show that, further rise in diesel prices, will undermine the potential benefits of conjunctive use of ground and surface waters in water abundant areas of Ganga basin. Electrification of the groundwater economy of these regions combined with a sensible scheme of farm power rationing may be the most feasible way of stemming distress outmigration of the agrarian poor. In the electricity-dependent groundwater economy of western and peninsular India, the challenge is to transform the current degenerate electricity-groundwater nexus into a rational one. Tariff reform has proved a political challenge in many of these states; but other 'hybrid' solutions need to be invented. Gujarat's experience under the Jyotigram scheme illustrates a 'hybrid' approach based on intelligent rationing of power supply (Shah and Verma [8]; Shah et al [9]). But other states in the region too are moving in the direction of demand management by rationing power. Punjab has effectively used stringent power rationing in summer to encourage farmers to delay rice transplantation by a month and in the process significantly reduced groundwater depletion. Andhra Pradesh gives farmers free power but has now imposed a seven-hour ration. It is surmised that power rationing can be a simple and effective instrument for groundwater demand management.

5.4 Institutional and Regulatory Measures: One of the most important mitigation measure is strengthening of institutional as well as regulatory framework of the country in relation to ground water. In spite of the fact that water is a state subject and it need to be regulated at the state level, there are several states in which there is no independent department or set up to look after the ground water governance. Hence, there is an urgent need of institutional strengthening at appropriate level and adoption of regulatory measures in strict sense. The implementing agencies for regulatory measure may be decided by the Central and State government. The implementation may be through the State Ground Water Department/PHED or local development board or authority. The implementation should be entrusted to one single department in the state and not to a number of departments with a view to better implementation, monitoring of the progress etc. If the programme has to be implemented in more than one department in the state due to unavoidable and certain special consideration, one of the departments should be designated as Nodal Department for coordinating the all the activities related mitigatory measure related climate change and ground water and sending consolidated progress to the Central Government. The Panchayati Raj Institution should also be involved in the implementation of the schemes, particularly in selecting the location of stand post spot sources, operation and maintenance. Planning Commission [10] in its report of the Expert Group on " Ground Water Management and Ownership " has discussed the requirement of certain institutional changes and suggested that the mandate of Central Ground Water Board to be shifted to a facilitator rather than a regulator to assist better implementation of management options. For effective implementation of ground water management plan a three tier institutional arrangements involving Central, State and Districts level agencies needs to be formulated.

5.5 Increasing Ground Water Use Efficiency: Water use efficiency programs, which include both water conservation and water recycling, reduce demands on existing water supplies and delay or eliminate the need for new water supplies for an expanding population. These effects are cumulative and increasing. Water conservation savings have increased each year due to expansion of and greater participation in these water conservation programs. Water recycling, or the use of treated wastewater for non-potable applications, is used in a variety of ways, including for irrigation and industrial processes. This in turn will provide environmental benefits as well as significant aesthetic and human health benefits. A reduction in water-related energy demand due to water conservation and water recycling reduces the air pollutants and allows to respond to the water supply challenges posed by global climate change. Water conservation and water recycling programs clearly save energy and reduce air pollutant emissions.

Broadening the limits of the quality of water used in agriculture can help manage the available water better in areas where scarcity of water is due to salinity of the available ground water resources. Cultivation of salt tolerant crops in arid/semi-arid lands, dual water supply system in urban settlements - fresh treated water for drinking water supply and brackish ground water for other domestic uses are some such examples. Recycling of water after proper treatment for secondary and tertiary uses is another alternative that could be popularized to meet requirements of water in face of the scarcity of resource in the cities. It has been estimated that parts of Haryana, Punjab, Delhi Rajasthan, Gujarat, Uttar Pradesh, Karnataka and Tamil Nadu have inland saline ground water of the order of about 1164 BCM. Yields of many crops, vegetables and fruit plants e.g. barley, dates and pomegranate, when irrigated with saline or brackish water are not significantly affected. Saline/ brackish water can be successfully used to irrigate such plants and fresh or good quality water can be saved for use by other sensitive crops or for other uses. Brackish water can also be utilized for pisciculture / aquaculture. Therefore, additional resource of 1164 BCM of saline/brackish ground water resource would be available for use. Studies are required to be undertaken on use and disposal of brackish / saline ground water.

Studies have shown that that substantial quantity of water could be saved by the introduction of micro irrigation techniques in agriculture. Micro irrigation sprinklers and drip systems can be adopted for meeting the water requirement of crops on any irrigable soils except in very windy and hot climates. These water conservation techniques would provide uniform wetting and efficient water use.

Changes in cropping pattern aimed at higher return of investment may lead to increased exploitation of ground water, as the experiences in Punjab and Haryana have shown. Suitable scientific innovations may be necessary to solve this issue. Less water intensive crops having higher market value, scientific on-farm management, sharing of water and rotational operation of tube wells to minimize well interference and similar alternatives can provide viable solutions for balancing agro-economics with environmental equilibrium.

In order to increase the ground water use efficiency suitable incentives for community management of new wells, for construction of recharge structures, for energy saving devices like installation of capacitors and frictionless foot valves and for adoption of micro irrigation can be offered to the users in water stressed areas (Over- exploited and Critical blocks) instead of putting ban for further exploitation of ground water.

5.6 Adopting the Concept of Virtual Water: Virtual water is defined as water embedded in commodities. It is said that the largest exported commodity in the world is 'Water', which is in terms of virtual water contained in the food grains. As a thumb of rule, a grain crop transpires about 1 cubic meter of water in order to produce 1 kilogram of grain. Thus, exporting or importing 1 kilogram of grain is approximately equivalent to exporting 1 cubic meter of water. The best example of virtual water in Indian context can be thought in terms of producing fodder in the water surplus areas of Indo Gangetic plains and transported to the water stressed areas of Gujarat, Rajasthan, Punjab etc. this way water used for fodder production in these states can be reduced and water saved can be fruitfully utilized for other priority sectors. Thus, the concept of Virtual Water can help in combating the impact of climate change on ground water by planning the suitable cropping pattern depending upon the availability of ground water.

5.7 Coastal Aquifer Management: Recent studies on the likely impact of sea level rise to the tune of one meter along Indian coast provide an idea about the land which could be inundated and the population that would be affected provided no protective measures are taken. The ingress of salinity in the coastal aquifers with respect to sea level rise and ground water abstraction is most likely in the event of climate change. Most vulnerable areas along the Indian coastline are the Kutch region of Gujarat, Mumbai and South Kerala. Deltas of rivers Ganges (West Bengal), Cauvery (Tamil Nadu), Krishna and Godawari (Andhra Pradesh) and Mahanadi (Orissa). The future studies should be focused on developing efficient monitoring mechanism, Filling the data gap through ground water exploration, hydrochemical and modeling studies.

5.8 Capacity Building and Training Needs: As per an estimate within the country about 10,000 professionals, 20,000 sub-professionals and nearly 1, 00,000 skilled personnel are employed in the work of ground water investigation, development and management. Many of the sub professionals like drillers etc. have no formal training in ground water which is very essential for getting optimum benefits for its sustainable development. In view of the increasing importance of ground water and anticipated climate change there is a need to create exclusive infrastructure to cater the need of training requirements of ground professional in the country. The country had so far not been able to create the requisite training facilities. The professionals being assigned to the work usually possessed a Master's Degree in Geology / Geophysics / Chemistry or Bachelor's Degree in Engineering. Though the Universities and Technical institutes are well equipped to carry out academic teaching programmes in the mother disciplines like geology, Geophysics they have limited facilities for training the field professional on specialized aspects of ground water assessment, management application of advanced tools like modeling, GIS etc.

In the context of water resources, training in the form of capacity building is indispensable for (a) strengthening the enabling institutional environment which takes the organizations in the right directions; (b) optimizing the available water resources which is becoming more and more critical with the passage of time; (c) establishing responsibility and accountability at all appropriate levels of hierarchy to usher in the needed efficiency; (d) understanding and appreciating value of water as a social and economic good; (e) developing and encouraging reliable information on policies, programmes, and projects, and systems of sharing this information to bring in transparency; and (f) keep finding innovative solutions to problems, technical or otherwise, facing the sector to manage the resource sustainably.

6. Synergy amongst stake holders

Sustainable development of ground water resources and various mitigation programs required in the event of possible climate change in the country can be accomplished only with the help and active cooperation of all stakeholders such as the Ministries of Government of India for Water Resources, Environment & Forests, Rural Development, Agriculture, Science & Technology and the institutions working under them; State Governments & their organizations; Associations of Industry, Non-Government Organizations, District Administrations and Panchayati Raj Institutions and the individuals users. To be successful in this mission we also have to create conditions for complete synergy in the activities of all the stakeholders. In this regard Ministry of Water Resources has taken a step forward by constituting the "Advisory Council on Artificial Recharge to Ground Water "involving members from all walks of life. However, the stakeholders in grass root levels need to be sensitized to the social relevance of technical decision on mitigation.

Although the groundwater agencies at central and state level are the custodians of our groundwater resource, in reality, multiple agencies in public and private sectors are involved as major players in India's groundwater economy. As climate change transforms groundwater into a more critical and yet threatened resource, there is dire need for coordinating mechanisms to bring these agencies under an umbrella framework to synergize their roles and actions. Even as governments evolve groundwater regulations and their enforcement mechanisms, more practical strategies for groundwater governance need to be evolved.

In hard-rock regions of the country, together with intelligent management of the energy-irrigation nexus, mass-based decentralized groundwater recharge offers a major short-run supply-side opportunity. Public agencies are likely to attract maximum farmer participation in any programs that augment on-demand water availability around farming areas. Experience also shows that engaging in groundwater recharge is often the first step for communities to evolve norms for local, community-based demand management.

In alluvial aquifer areas, conjunctive management of rain, surface water, and groundwater is the big hitherto under-exploited opportunity for supply-side management. Massive investments being planned for rehabilitating, modernizing, and extending gravity-flow irrigation from large and small reservoirs need a major rethink in India. In view of the threat of Climate Change, indeed, we need to rethink our storage technology itself. Over the past 40 years, India's landmass has been turned into a huge underground reservoir, more productive, efficient, and valuable to farmers than surface reservoirs. For millennia, it could capture and store little rainwater because in its predevelopment phase it had little unused storage. The pump irrigation revolution has created 250 km^3 of new, more efficient storage in the subcontinent. Like surface reservoirs, aquifer storage is good in some places and not so good in others. To the farmer, this reservoir is more valuable than surface reservoirs because he has direct access to it and can obtain water on demand. Therefore, he is far more likely to collaborate in managing this reservoir if it responds to his recharge pull. Indeed, he would engage in participatory management of a canal if it served his recharge pull. This is best illustrated by the emergence of strong canal water user associations of grape growers in the Vaghad system in Nasik district of Maharashtra. Vineyards under drip irrigation in this region need to be watered some 80 to 100 times a year, but canals are useless: they release water for a maximum of just 7 times. Yet grape growers have formed some of the finest water user associations in the region for proactive canal management here mostly because they value canals as the prime source of recharging the groundwater that sustains their high-value orchards.

By far the most critical response to climate change in India's water sector demands exploring synergies from a variety of players for a nation-wide groundwater recharge program. India's water policy has so far tended to focus on what governments and government agencies can do. Now, it needs to target networks of players, each with distinct capabilities and limitations. If groundwater recharge is to be a major response to hydro-climatic change, the country needs to evolve and work with an integrated groundwater recharge strategy with role and space for various players to contribute as outlined in the table 1.

Table 1. Outline of an Integrated Groundwater Recharge Strategy for India.

<table>
<tr><td>Key actors</td><td>Arid alluvial aquifer areas</td><td>Hard rock aquifer areas</td><td>Roles that need to be played by CGWB, Recharge SPV, other public agencies</td></tr>
<tr><td rowspan="3">Farmers</td><td rowspan="3">Dug wells, farm ponds, roof-water harvesting; other private recharge structures</td><td rowspan="3">Dug wells, farm ponds, roof-water harvesting; other private recharge structures</td><td>Vigorous Information, Education and Communication campaign to promote recharge to dynamic waters through dug wells & farm ponds</td></tr>
<tr><td>Technical support in constructing recharge pits, silt-load reduction, periodic desiltation of wells</td></tr>
<tr><td>Financial incentives and support to recharging farmers</td></tr>
<tr><td rowspan="3">NGOs, local communities</td><td colspan="2" rowspan="3">Percolation ponds, check dams, sub-surface dykes; stop dams and delayed-action dams on streams</td><td>Technical and financial support to local communities, NGOs for construction and maintenance</td></tr>
<tr><td>Supportive policy environment and incentive structures</td></tr>
<tr><td>Support for building local institutions for groundwater recharge</td></tr>
<tr><td rowspan="4">Canal system managers</td><td colspan="2" rowspan="4">Conjunctive management of surface and groundwater</td><td>Operate surface systems for extensive recharge</td></tr>
<tr><td>Where appropriate, retrofit irrigation systems for piped conveyance and pressurized irrigation</td></tr>
<tr><td>Where appropriate, retrofit irrigation systems for use of surplus floodwaters to maximize recharge</td></tr>
<tr><td>Where appropriate link canals through buried pipelines to dug wells/recharge tubewells for year-round recharge</td></tr>
<tr><td rowspan="3">Groundwater recharge SPV</td><td colspan="2" rowspan="3">Recharge canals to capture flood flows for recharge (e.g., Ghed canal in Saurashtra) or transport surplus flood waters for recharge in groundwater-stressed areas (e.g., Sujalam Sufalam in North Gujarat). Large recharge structures in recharge zones of confined aquifers</td><td>Create a Special Purpose Vehicle to execute, operate and maintain large-scale recharge structures</td></tr>
<tr><td>Build and operate large-scale recharge structures in upstream areas of confined aquifers. e.g. at the base of Aravalli's in North Gujarat</td></tr>
<tr><td>Build and operate large earthen recharge canals along the coasts</td></tr>
</table>

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Paper for ISMAR10 symposium. ***Topic No: 2 (042#)***

MAR of Geneva: when climate change implies to reassess management perspectives

Gabriel de los Cobos

GESDEC- OCEV/DT – Geneva, Switzerland; gabriel.deloscobos@etat.ge.ch
*Correspondence: Gabriel.deloscobos@etat.ge.ch; Tel.: +41-22-546-7070

Abstract: For nearly 40 years, the artificial recharge system in Geneva has provided more than 300 million m^3 of drinking water in the main regional Geneva aquifer, a transboundary aquifer located and shared between Switzerland and France. This system retrieves water from the Arve River, the main natural source of water supply and injects it into the Geneva aquifer. The climatic hazards of recent years have created a change in paradigm regarding the management of artificial groundwater recharge in Geneva. Indeed, on May 2nd 2015, Geneva underwent a 100-year recurrence flooding event of the Arve River that deeply changed the geological conditions of the river bed and banks. This results nowadays in an extremely high water table level, leading to conflictual situation regarding important construction sites. In addition to this already critical situation, a pollution situation by micro pollutants has been discovered in several wells of this aquifer. It is now very difficult to reduce its water table level by pumping since the natural recharge is totally dependent on the meteorological conditions, as the artificial recharge has of course been stopped for several months. The management of the entire aquifer and future solutions to regain a controlled and sustainable management of its artificial recharge are described in this paper.

Keywords: MAR; Arve River floods; Geneva; Aquifer pollution; Climate change.

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1. Introduction

In 2020 it will be 40 years since the MAR (Managing Artificial Recharge) system of the transboundary aquifer of Geneva was initiated. In fact, following overexploitation of the water table during the 1960s and 1970s, it was decided to remedy to the water shortage in the Geneva (or Genevese) aquifer by inaugurating in 1980 an artificial recharge system to store and manage the drinking water seasonally. This system draws water from the Arve River, the main natural source of water supply, to inject it, after a light treatment, into the Genevese aquifer. This artificial system therefore ensures a complementary but relatively important contribution to the total recharging cycle of this aquifer. Since 2003, experiencing the first major drought warning in Western Europe, it has been noted that high temperatures at high elevations in the catchment area are altering the water quality of the river by significantly increasing its turbidity in summer periods, a situation preventing any artificial recharge. The meteorological hazards of recent years have then created a paradigm shift in the management of artificial groundwater recharge.

Indeed, between May 2nd and 4th 2015, Geneva was faced a 100-year recurrence flood event of the Arve River that profoundly changed the geological conditions of the river bed and banks. Since then, a significant increase in the contribution of the river to the natural recharge of the water table can be measured. This phenomenon has further gained in complexity since, for reasons of pollution recently discovered in the aquifer, a majority of the wells are currently shut in and the level of the aquifer, even in the absence of artificial recharge, is particularly high. This situation is conflictual with construction sites and potentially dangerous for the protection of the resource. This worrying situation implies a complete overhaul of the recharge management conditions that used to be applied for more than 30 years without apparent concern.

This article recalls, first of all, the causes and the circumstances of the placement of an artificial recharge of the aquifer by addressing the historical context of the resource. The technical aspects are presented before analyzing the seasonal and climatic conditions which influence the regime of the Arve River, the main stakeholder in the natural recharge of the underground resource. Finally, questions are addressed regarding the impacts of the 2015 floods and potential limits linked to the quantitative and qualitative conditions of the river and its watershed on the artificial recharge system of the Genevese groundwater resource. Management of the entire aquifer and future prospects for regaining controlled management of artificial recharge are also described.

2. The artificial recharge of the Genevese aquifer

The Genevese transboundary artificial recharge system (between Switzerland and France) has been the subject of numerous publications on the technical aspects of aquifer recharge management (MAR) [1-3] and has been covered in previous ISMAR conferences (2002, 2007, 2010, 2013 and 2016). The following succinct description aims at providing the necessary elements for a fuller understanding of all the details and issues related to the system.

2.1. Location of the Genevese Aquifer and Geology

Geneva's drinking water is provided from Lake Geneva (roughly 80% of total supply) and from a dozen wells pumping in the Genevese groundwater (for the remaining 20%). As a transboundary aquifer, the Genevese aquifer is used for supplying drinking water from 10 wells on the Swiss side and 4 wells on the French side. The Genevese aquifer extends over 19 km, between the lake and the Rhône River on the western side of the Canton of Geneva (Figure 1). Its width varies between 1 and 3.5 km. The aquifer partly lies on the French border. Waterlogged gravel may reach up to 50 m. Depending on topographic conditions; the average water level is between 15 and 80 m deep.

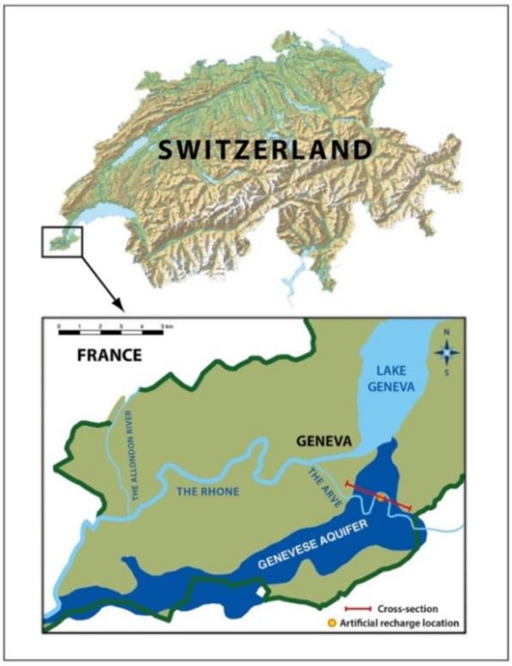

Figure 1. Location of the Genevese aquifer.

The aquifer is made of silty-sandy gravel of glacial and fluvioglacial origin (Wurm), lying directly on the eroded tertiary molasse formations, which is considered to be the impermeable substratum. This aquifer formation is overlain by a clayey Wurmian moraine which reduces meteoric water infiltration, but which has the advantage of providing natural protection. This explains the very good quality of the groundwater and the reason why no post-treatment of the water pumped is needed [4]. The Darcy permeability of the aquifer is approx. 1-2.10^{-3} m/s, but can reach 5.10^{-7} to 3.10^{-2} m/s.

2.2. *Historical Background*

Between 1940 and 1960, the groundwater extraction from of the Genevese aquifer was very close to the average sustained yield (7.5 M m^3/year). The groundwater level slowly decreased without serious effects. Between 1960 and 1980, the aquifer became overexploited with withdrawal rates of up to 14 million m^3/year in 1971, almost twice its sustainable yield. This over pumping lowered the groundwater level by more than 7 m in 20 years, consuming about a third of the total groundwater storage (Figure 2).

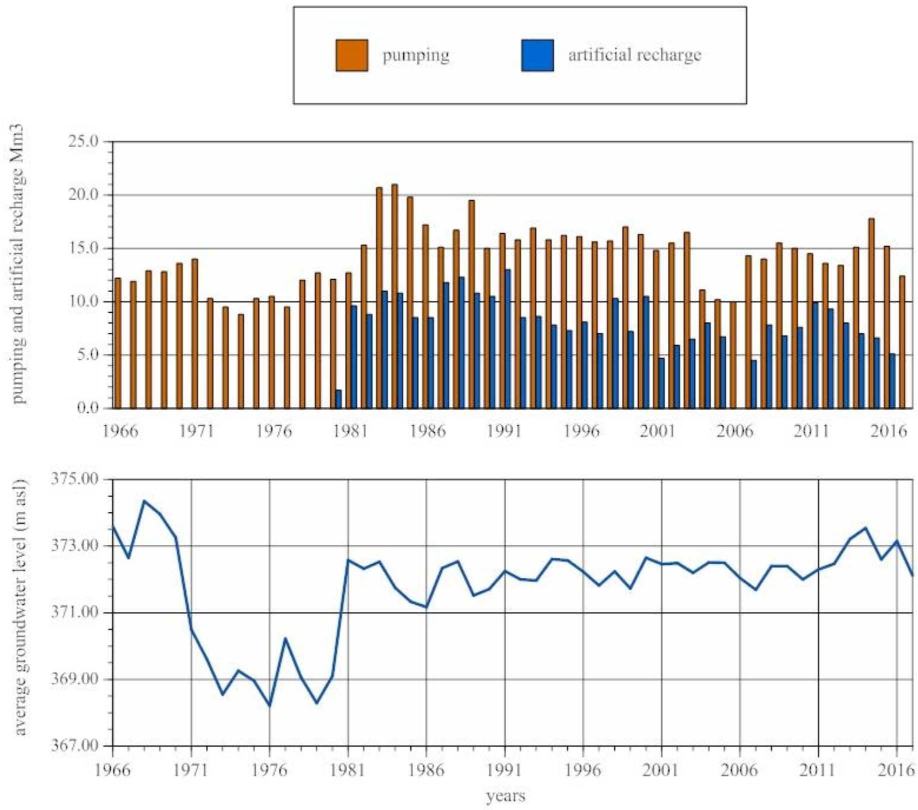

Figure 2. MAR and recovery: impact of pumping and artificial recharge on the groundwater level.

Consequently, urgent hydraulic management became necessary in order to restore the natural volume of the groundwater through artificial recharge [5].

2.3. *Technical description of the recharge system*

The artificial recharge system at Vessy (Figure 1) includes the following features (Figure. 3):

1. A water intake structure in the Arve River, 300 m upstream of the plant,
2. Transport by pipeline of the raw water to the treatment plant,
3. The water treatment plant with sedimentation, filtration and chlorination units. The total capacity is 630 l/s,
4. Piping of the treated water toward the infiltration area,

5. The underground infiltration area includes perforated pipes (reverse drainage) for a total length of 5,000 m. These pipes (200 mm in diameter) are placed 2 m deep into the glacial gravel, 7 m above the groundwater level of the aquifer in the unsaturated zone. The infiltration area covers a total surface of about 3 ha.

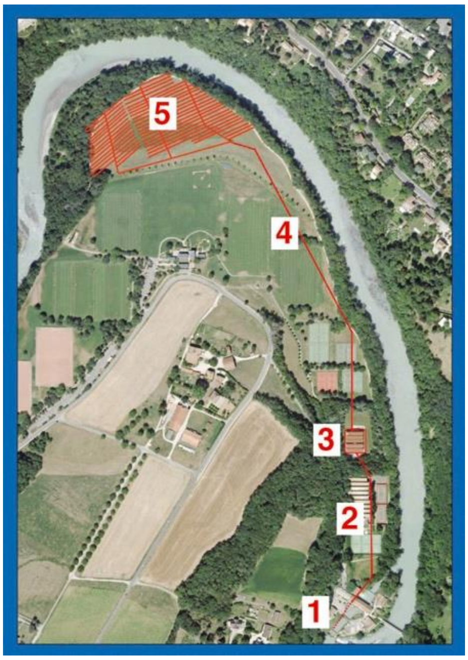

Figure 3. Description of the artificial recharge area.

The total theoretical capacity of the plant, taking into consideration that 14% of the water produced is used to wash the filters, is 17 Mm^3/year, that is equivalent to 540 l/sec. Accounting for the high turbidity of the Arve river, which implies to stop the operations during certain periods (65 days/year on average), as well as the automatic shut downs of the plant in the case of pollution, the real capacity is 11 Mm^3/year (350 l/sec).

During 38 years of service, the artificial recharge system has supplied more than 300 million m^3 of filtered water into the Genevese aquifer. This contribution has permitted to pump a total volume of almost 500 million m^3, while increasing the average level of the aquifer since the beginning of the 1970s, in order to replenish the reserves of the aquifer. Since then, this improved situation allows efficient management of the wells spread out over the entire aquifer on both French and Swiss sides. Overall, this artificial recharge system has permitted an exemplary management of a united cross-border aquifer.

3. Arve river and watershed

3.1. Characteristics

The Arve is a torrential river with a catchment basin of 2060 km^2 located at an average elevation of 1400 m, including about 120 km^2 of glaciers, which represents over 6% of its total surface (Figure. 4). The dissolved materials and bed load are of siliceous and carbonate origins, resulting from the erosion of crystalline and limestone (pre-Alpine) massifs respectively. The flow rate of the river in Geneva is 80 m^3/s on average but can decrease below 20 m^3/s in winter and exceed 600 m^3/s or even 800 m^3/s during flooding (peak value of 905 m^3/s on 2nd May 2015). These latter values are caused by storms or snow melt and can occur very suddenly, independently from the season [6].

Material in suspension in the Arve water is composed of extremely fine particles: 92% is less than 30 microns, and a simple decantation process is not sufficient to eliminate them. The final recharge structure must therefore include flocculation and a filtration steps prior to artificial recharge. The geology of the catchment basin is one of the major factors creating the turbidity of the Arve River.

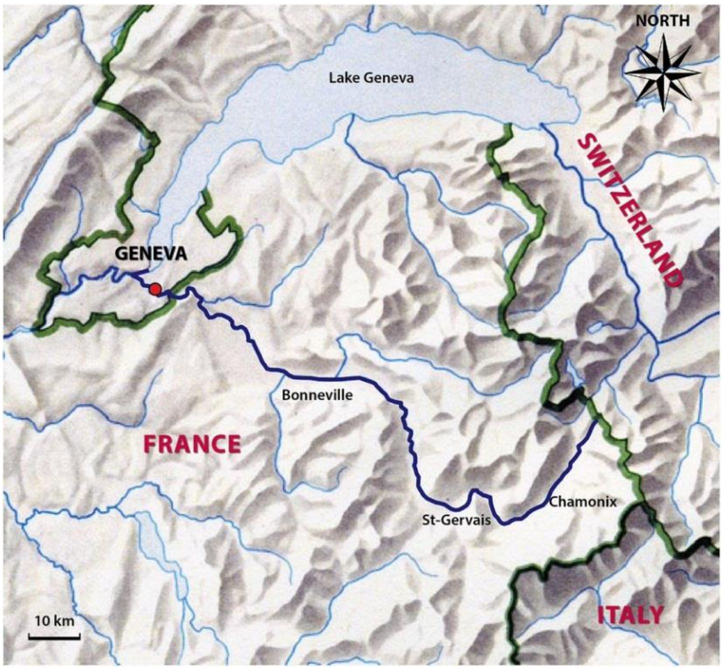

Figure 4. Drainage basin of the Arve River (red point is the artificial recharge location).

3.2. Artificial recharge versus natural recharge

Until 1980, the year in which the artificial recharge station started operating, the Genevese aquifer was naturally recharged by the Arve River only, and this only in a sporadic and seasonal way. The total pumping carried out in the 1960's and 70's has led to an overuse of the water-table with annual peaks of 14 million m^3 of pumped water, with natural annual recharge estimated at about 7.5 million m^3. This amount only occurred in periods of high water, and especially notably during the snow melt period (April to June). This can be explained by the geological configuration of the run-off zone of the Arve River. The river water flows through its own alluvium, which overlays the glacial alluvium of the Genevese water-table, 4 to 7 m below that of the river. The extremely silty character of the river water leads to a coating of silt on the river bed and banks, inhibiting a normal river- water-table relationship, except in periods of high water when the currents scour the river bed and favour the natural recharge of the water-table. This has been demonstrated by measurements carried out in periods during which the artificial recharge station has been shut down [8].

3.3. Extreme events

During the heat wave of 2003 in Western Europe, the efficiency of the artificial recharge was reduced because of the high level of turbidity of the Arve River during the summer months whereas the demand for consumption was the highest. This turbidity was not correlated to any flooding event, but rather due to the fact that the strong heat at high altitude (higher than 3500 m altitude) caused a melting of glaciers and permafrost, feeding the waters of the river with high load of mineral material. In the absence of floods, no natural recharge could take over. This episode was repeated in July 2016 (hottest month in the history of Swiss meteorology) [7].

In contrast, the summer of 2007 underwent heavy rainfall between May and August (more than 50% of the annual average). Despite the resulting significant floods (10 events of more than 300 m3/s of flow of the Arve compared to an average flow in the order of 180 m^3/s), the influence of the natural flood appeared not so important (less than 0.7 million m^3). These rainy events also caused the artificial recharge plant to be shut down from mid-June to mid-August 2007. Both of these contrasting extreme episodes reveal the important impact of river flows and turbidity on the recharge system of the Genevese aquifer [8].

4. The flood of the Arve River in 2015

4.1. Conditions

An exceptional river flood occurred in early May 2015 (Figure 5). The Arve River, cumulatively feeded by torrential rains and snowmelt in the Mont-Blanc massif, has reached unprecedented flow rates. After a month of April showing a mean river flow around 70 m^3/s, high rainfalls in the region from April 25th resulted in a first small peak of the Arve river flow to 270 m^3/s in April 28th., Three days later, in May 1st, the increase in flow became spectacular and reached an historical peak at 907 m^3/s on May 2nd. This record (exceeding the 100-year flood) was followed by a second smaller peak on May 4th, slightly below 800 m^3/s. If these events did not cause casualties, they were responsible for a lot of damage in basement cellars of buildings and in underground car parks. Bridges and wharves have been closed to traffic and, in some places, to the population.

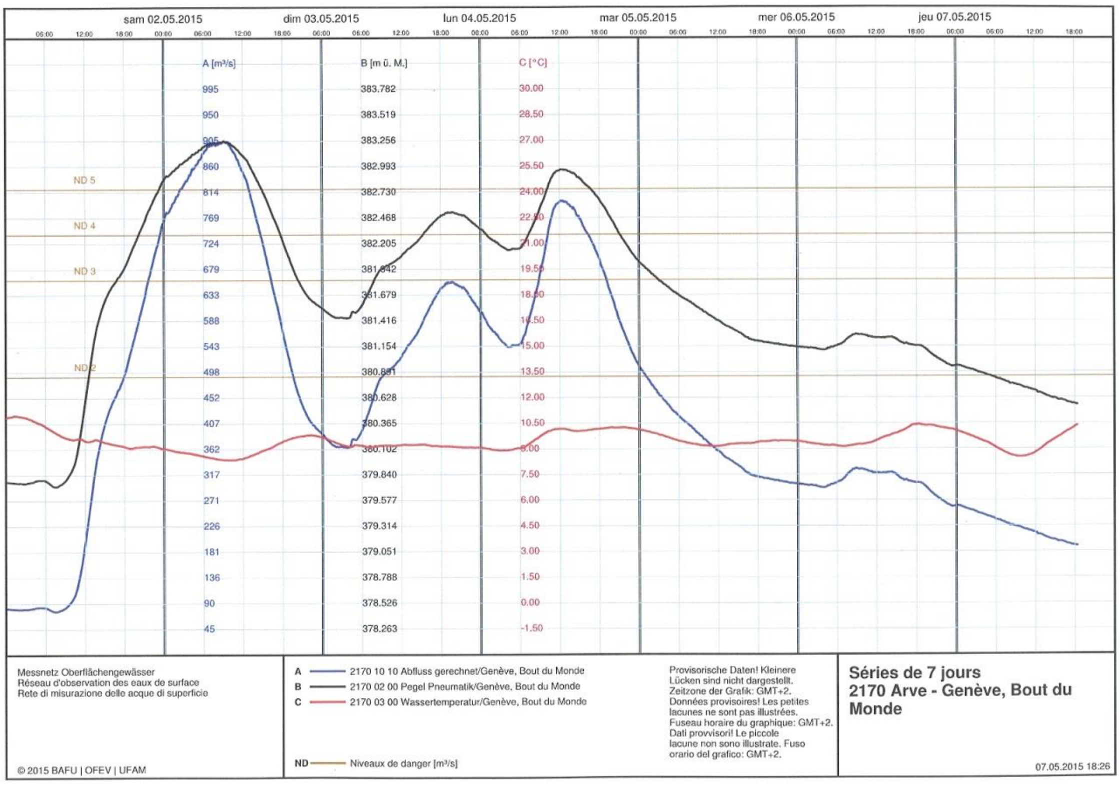

Figure 5. Flood-record in the Arve River between May 1st and May 7th 2015. The flow (blue line) reached a first peak at 907 m^3/s on May 2nd, followed by a second peak on May 4th with less than 800 m^3/s.

The impacts on the public infrastructure were the following:

- A wastewater treatment plant was flooded;

- A Regional Express Network (REN) railway construction project suffered major damages in a tunnel on the edge of the river (base of a construction site carried away) as well as on a part of the underground route (Figure 6);
- A pumping station in the Genevese aquifer on the French side has been partly immersed (80 cm)
- The artificial recharge area of the Genevese aquifer suffered an overflow of the river (Figure 7).

Figure 6: View of the flood impacting the REN railway project.

Figure 7: View of the flood impacting the artificial recharge area.

4.2. Impacts

The consequences of the flood were as follows:

- The recharge plant was stopped as soon as the water of the Arve rose due to the turbidity of the river water. The overflows of the Arve in the recharge zone did not cause any problem to the water quality since the Arve is in any case involved in the natural supply of the aquifer. There is between 5 and 8 meters of sand and gravel between the topographic surface and the average level of the water table in the infiltration area, which provides natural filtration.

- A wastewater treatment plant had its basements flooded, but it was able to start re-operating at 50% relatively quickly. However, the discharge of wastewater into the river has involved the closure of the recharge station immediately downstream of the wastewater plant, as a precautionary measure.
- The SIG (Industrial services of Geneva) wells for drinking water supply, the closest to the Arve (in Carouge city), were checked for water quality to ensure that no direct discharge of Arve water into the well was occuring.
- The French wells in Annemasse-Agglomeration were flooded and required water quality monitoring and pumping-emptying before returning to service.
- The rise of water from the aquifer in the Arve area, near the railway construction worksite was about 1.45m (Figure 8). Investigations were launched to verify the consequences of these inflows of water on the quality of the underground resource.

Over the following weeks, the artificial recharge was not restarted. In fact, the Genevese aquifer having experienced an excellent artificial recharge during the winter and spring of 2015 (more than 5 million m^3 infiltrated), the water table levels observed were already very high over the whole aquifer before this flood event. It was therefore decided to monitor these levels throughout the summer before considering restarting the recharge plant for the Fall season. The climatic and weather conditions of the summer did not change this situation.

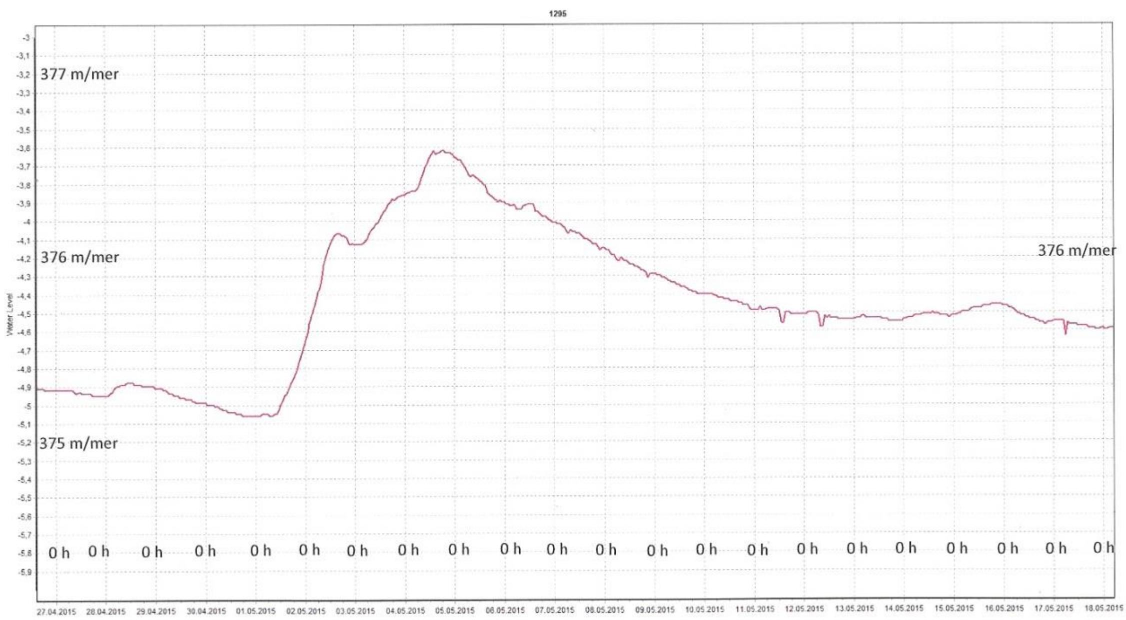

Figure 8. Impact of the flood in the Arve River on the water table level of the Genevese aquifer between April 27th and May 18th.

4.3. The new river-groundwater relationship

While the summer of 2015 was not particularly warm and therefore did not impose a large abstraction in the wells of the aquifer, the question of restarting the recharge plant in the fall season arose since the levels of the aquifer had only slightly diminished. This situation also impacted the railway worksite with major delays, not only because of the consequences of the flood of May 2015, but also because of the high level of groundwater that prevented the completion of the foundations of of a bridge across the Arve River. It should be noted that the flow rates of the pumping wells are not sufficient to substantially reduce the level of the water table. In fact, a fine follow-up on the monitoring wells shows that whenever the Arve basin undergoes significant rainfall, either over the medium term or during occasional storms, the natural recharge of the aquifer by waters of the Arve River are magnified in a surprising way (Figure 9).

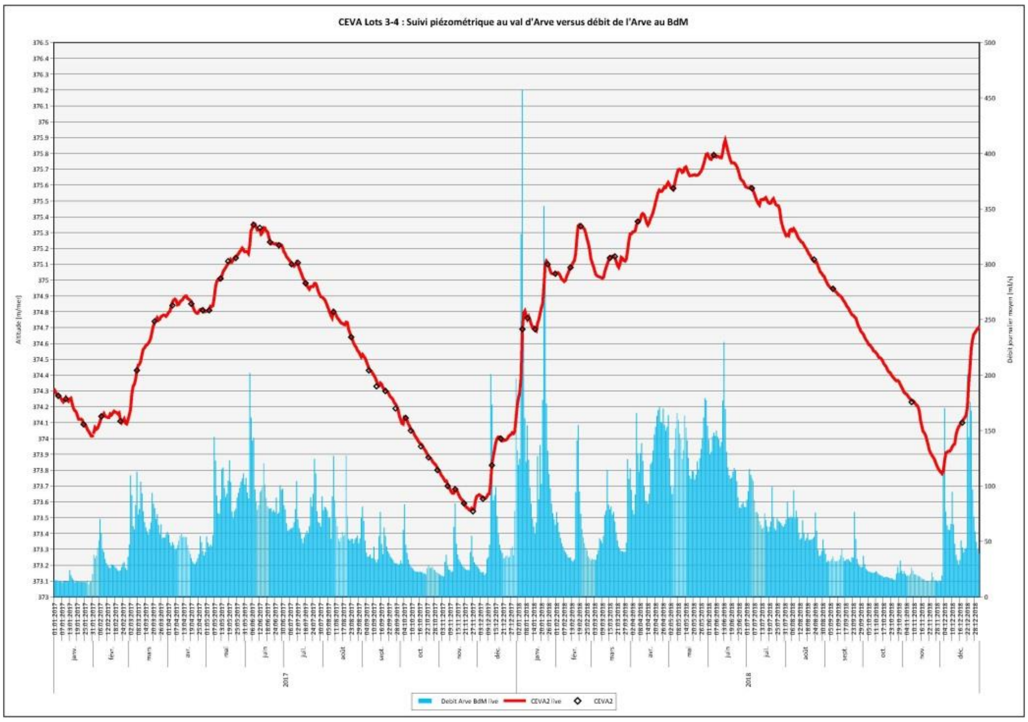

Figure 9. Impact of the natural recharge on the water table level during 2017 and 2018.

We now understand that natural recharge plays a more important role since the events of May 2015. The 100-year flood has literally cleaned the banks and the bottom of the riverbed clayed deposits thus allowing a much more efficient river-groundwater relationship. The counterpart is that in regard to the seasonal management of the recharge of the aquifer, it is no longer possible to have control, since the natural recharge, therefore randomly dependent on precipitations, has supplanted the controlled artificial recharge system.

The result nowadays is that the extremely high water table level, is in conflict with important construction projects and likely to cause risks for the protection of the resource. In addition to this already critical situation, a pollution situation discovered in several wells of the aquifer at the beginning of 2017 implied a shut-down of the majority of them. It is now even more difficult to reduce the level of the water table by pumping, whereas the natural recharge still remain totally dependent on the weather as the artificial recharge has stopped for many months.

4.4. Pollution with perchlorates and cessation of pumping in the aquifer

As mentioned above, adding bad luck on such critical situation, a perchlorate pollution was discovered early 2017 in a totally fortuitous way in the groundwater of the Genevese aquifer, affecting a majority of wells. Following investigations have shown that the pollution does not come from an accidental infiltration over the aquifer, but originates from an ancient weapons factory located upstream in the catchment area of the Arve River. It is obviously the reflection of a very old pollution that has migrated naturally in the aquifer through time, not questioning the principle of artificial recharge. It was decided in April 2017 limiting to 4 µg/L the maximum accepted perchlorate concentration for each pumping well, and at the same time, not to use artificial recharge until a perchlorate concentration of the river below 2 µg/L is effective.

The quantitative problem of the groundwater remains, because if the floods of the Arve River still favor a very good natural infiltration, the reduced pumping of the aquifer does not favor a natural purification of the quality of the groundwater of the Genevese aquifer. A new paradigm is therefore needed regarding the management of the aquifer, influencing future prospects to regain a controlled management of artificial recharge.

4.5. Discussion and prospect envisaged

While for over 38 years the recharge system has worked without any particular problem in a clear scheme of seasonal management using the waters of the Arve River, today, we undergo the consequences of a cascade of adverse events (100-year flood, contamination by micro-pollutant) and face of a new water management situation. In terms of strategic resource in combination with the fact that its use for drinking water is currently limited, we must now contend with the use of the Geneva Lake to supply almost 95% of drinking water needs, leaving the Genevese aquifer almost completely unused. This situation implies a redoubled monitoring of the variations in the levels of the water table, which are now influenced by the floods of the river and no longer by the artificial recharge. Furthermore, such a minimal withdrawal of the water from the aquifer does not participate in the flow of water from the aquifer and consequently to its qualitative cleansing. This is definitely an important paradigm shift for transboundary groundwater management in the region. Indeed, whereas previous concern regarding this resource and its management was about risks of low groundwater levels, the current issues are, on the contrary, related to high water table levels that represent an important risk for certain basements and major underground construction works in the area, as well as for the project of the Geneva REN (Regional Express Network).

The model developed in the framework of the monitoring plan of the aquifer shows that the qualitative remediation depends on the pumping possibilities of the existing wells and their combinations over time in order to envisage a decrease of the pollutants concentrations in a lapse time of several years, to a decade. If such a pumping solution would play a key role in sanitation of the aquifer, the MAR would much less. However, it must be considered as an important player since it can be used to create a high point of the water table in its whole and therefore promote a more pronounced gravity flow, thus improving the rate of sanitation.

Work on the establishment of water treatment units on high-throughput perchlorate is under development. The idea consists in promoting the implementation of wells equipped with this treatment solution in order to inject drinking water without perchlorate in the water network but also to improve, by a marked drawdown at wells, the underground flow between the infiltration area of the river and the pumping areas. The ultimate goal is to recover favorable quantitative and, of course, qualitative conditions for the waters of the Genevese aquifer. We are also counting on the slow and steady natural clogging of the banks of the river to reduce the natural recharge component of the water table, thus allowing the MAR to operate again and regain its role on seasonal control and management of the resource.

5. Conclusions

In 1980, the Geneva aquifer recharge system was set up to respond seasonally and efficiently to the over-exploitation of the aquifer over the previous 15 to 20 years. The evolution of climate change over the last years as completely changed the rules and upside a water management successfully established for some 40 years of operation. In addition, uncontrollable circumstances of pollution further disturbed the already compromised situation. This makes realize that nothing is ever gained and that any MAR manager must stay aware that disturbances can occur at any time. In view of today's assessment, the message to be conveyed is that when an MAR system is developed with a river as a source of recharge, it should be kept in mind that watershed activities may be key factors for the recharge, the vulnerability of the system and the quality of the infiltrated resource. It also highlights that variations in climatic conditions can totally disturb the equilibrium between a natural recharge and an artificial recharge can be totally and considerably modify a long-established pattern in the management of groundwater.

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Extended abstract for ISMAR10 symposium. ***Topic No: 2 (130#)***

Potential for Managed Aquifer Recharge to Mitigate Climate-Change Effects on Fish and Wildlife in the Snake River Basin, USA

Rob Van Kirk[1*], Bryce Contor[1], Christina Morrisett[2] and Sarah Null[2]

[1]Henry's Fork Foundation, P.O. Box 550, Ashton, ID 83420 USA. brycec@henrysfork.org
[2]Department of Watershed Sciences, Utah State University, 5210 Old Main Hill, NR 210, Logan, UT 84322 USA; christina.morrisett@aggiemail.usu.edu; sarah.null@usu.edu
*Correspondence: rob@henrysfork.org. Tel.: +01-208-652-3567

EXTENDED ABSTRACT

In the western USA, many important aquatic ecosystems and recreational fisheries occur in river basins with large withdrawals of water for irrigated agriculture, resulting in conflicts between management for irrigation and environmental streamflow needs. Climate change exacerbates these conflicts, as precipitation regimes shift from snowfall to rainfall and evaporative demand increases, leading to flashier streamflow in winter and spring and reduced baseflow through summer and fall. Climate warming and reduced baseflow work in tandem to warm stream temperature and are expected to reduce habitat for cold-water ecosystems. Managed aquifer recharge (MAR) is a promising strategy to mitigate effects of climate change on cold-water ecosystems because it can simultaneously increase streamflow and moderate temperatures. However the use of MAR as a climate mitigation tool for aquatic ecosystems requires further investigation to quantify the availability of water to be used for MAR and quantify the quantity and quality of MAR return flow.

The 93,000-km^2 upper Snake River basin in Idaho and Wyoming, USA is an ideal setting for assessing the potential of MAR to benefit cold-water ecosystems. The basin's water resources support an agricultural economy worth US$10 billion but also many ecologically important stream systems and recreational trout fisheries, which contribute US$100 million to local communities. The Eastern Snake Plain Aquifer (ESPA) is a highly transmissive regional aquifer hosted in sediments interbedded within fractured Quaternary basalts. Water levels in and discharge from the ESPA have been declining for 60 years due to a combination of decreased recharge incidental to surface water irrigation and increased groundwater pumping. As part of a comprehensive plan to increase storage in the ESPA, Idaho has implemented publicly funded MAR, with an annual objective of 330 Mm^3. In addition, private irrigation entities are using MAR to meet requirements of a recent legal settlement between surface water and groundwater users. Concurrently, research describing benefits to aquatic systems from incidental and managed recharge in irrigated landscapes has motivated conservation organizations to consider MAR as a tool for maintaining and enhancing cold-water ecosystems in a changing climate.

In this study, we used water temperature data, a regional aquifer model, and analysis of water administration procedures to assess potential benefits to cold-water fisheries from MAR and potential impediments to implementation. We conducted this assessment on the lower reach of Henry's Fork Snake River, which is a popular trout fishing destination, provides irrigation water for 1,000 km^2 of agricultural land and has historically received a large amount of groundwater return flow from recharge incidental to irrigation.

In 2010, we deployed water temperature loggers from 1 June to 31 August at two locations on the lower Henry's Fork, one immediately downstream of a that has little interaction with shallow groundwater and a second 5 km downstream, in a reach where the river is well connected with shallow groundwater. We statistically compared mean daily temperature difference between the two locations.

We used the Idaho Department of Water Resources' Enhanced Snake Plain Aquifer Model Version 2.1 (ESPAM2.1) to assess response of streamflow in a 75-km study reach of the Henry's Fork to MAR at an existing site 8 km from the river, as well as to hypothetical MAR at other locations. This regional, finite-difference flow model is configured with a single aquifer layer, monthly temporal resolution, and 1.6-km grid cells. We used steady-state simulation to calculate the fraction of total recharge that in affects streamflow in the target reach from recharge in a given model cell and transient simulation to calculate the modeled timing of streamflow response in the target reach. We modeled response to a single one-month recharge event and to a 150-year series of annual one-month recharge events.

We assessed physical and administrative availability of water for MAR in the upper Snake River basin within Idaho's prior appropriation system of water rights, relying primarily on a formal review of Idaho's MAR program conducted for the Idaho Water Resource Board. In addition, we reviewed the state's water rights database, water-rights accounting manual and water rental procedures.

Mean daily water temperature over the period 1 June 2010 to 31 August 2010 was 0.6°C cooler at the downstream location influenced by shallow groundwater, and this difference was statistically significant. At steady state and for recharge immediately adjacent to the river, ESPAM2.1 predicted that >90% of recharge is realized as increased streamflow in the study reach. However, the response fraction decreased fairly rapidly with distance between the river and recharge location. The model predicted that 35% of the volume of water delivered to the MAR site will increase streamflow in the Henry's Fork, and the balance will benefit other river reaches in the basin. For the MAR site as a whole, the immediate benefit of a single recharge event is small; the first month's benefit is little more than 0.5 percent of the recharge volume, and the twelfth month's benefit is only 0.3 percent of the recharge volume. With a continuous series of annual recharge events, the monthly average rises to nearly three percent of the annual recharge volume, and sums to 35% across twelve months.

There are 84 decreed, permitted, or pending water rights for MAR in the upper Snake River basin, with a combined diversion rate of up to 725 m^3/sec. Diversion of only 0.59 m^3/sec is allowed under water rights with priority dates preceding 1980, in a system where the majority of the irrigation rights have priority dates preceding 1910. During irrigation season (1 April to 31 October), only water delivered to a designated, off-canal MAR site can be accounted as MAR, but during the winter, canal seepage also accounts as MAR. Storage water can be rented from a pool held in one of the upper Snake River storage reservoirs and applied anywhere in the basin for MAR. Water rented in a given administrative year (1 November to 31 October) must be delivered by December 1 and cannot be carried over into the subsequent year. Entities that do not hold water rights, including most conservation groups, cannot participate directly in rentals and other water transactions, including those to facilitate MAR.

The limited temperature data we analyzed show that river reaches receiving groundwater inputs during the summer can be over 0.6 °C cooler than reaches that do not. To cool summertime water temperature enough to have a positive effect on cold-water species in a warming climate, MAR volumes will likely need to offset declines in recharge from irrigation seepage that have already occurred over the past few decades from increased irrigation efficiency. This volume, around 250 Mm^3, exceeds the physical capacity of the existing MAR site but could be attained if recharge occurred year-round, so that wintertime canal seepage also contributes. Modeling showed that gains in the study reach from nearby MAR decline slowly enough that MAR conducted in the springtime will contribute to streamflow during the middle of the summer. However, only 35% of the total MAR at the Henry's Fork recharge site returns to the study reach, so the benefits to summertime streamflow must be weighed against the negative effects of withdrawing a larger amount of water from the river at other times of year.

The one-month temporal resolution of ESPAM2.1 limits its ability to predict streamflow response during specific time periods. Furthermore, the model cannot distinguish the difference in effect between increasing stream reach gain and decreasing reach loss, the latter of which has a much lower effect on temperature. Due to hydrogeologic variability, temperature-moderated groundwater returns may occur in specific locations that act as thermal refugia for fish. These can be identified only through field observation.

While improved modeling, detailed field work, and expanded infrastructure can increase the physical potential for MAR to benefit summertime habitat for trout, numerous administrative hurdles must be overcome for implementation. The most basic of these is the junior priority dates of water rights for MAR. In the Henry's Fork watershed, water for MAR is available in only half of all water years and then generally between mid-May and early July, when the existing canal system is already near its capacity delivering irrigation water. Additional canal capacity could alleviate this limitation during years of high water supply, but the cost of the additional capacity would not contribute to additional MAR in the other half of years. Because MAR rights are junior, rented storage water and other exchange mechanisms may offer greater potential to conduct MAR during the fall, winter and spring.

Ideally, conservation groups could facilitate incentive-based irrigation demand reduction, rent the saved storage water for MAR, and keep that water in reservoirs all summer, reducing negative effects of reservoir drawdown. The rented storage could be diverted for MAR in the winter, when natural stream reach gains can support diversion without physical delivery of storage water. The separation of physical and administrative water that makes this possible is routine under current administrative procedures. Physical capacity to deliver water for MAR is greater in the winter, when canals are not also delivering irrigation water, but changes to rental rules are needed to allow storage water rented in one administrative year to be diverted for MAR beyond the current one-month carryover period into the next year. Finally, to fully capitalize on the high value anglers place on upper Snake River fisheries, new administrative and "market" mechanisms are required to allow conservation organizations to participate directly in water transactions. Such mechanisms already exist in some western states and could greatly increase the effectiveness of MAR to benefit cold-water ecosystems in a changing climate.

Acknowledgments: Collection of water temperature data was funded by U.S. Department of Agriculture grant 2008-51130-19555 to RVK. CM received support from National Science Foundation Grant No. 1633756.

Paper for ISMAR10 symposium. ***Topic No: 2 (152#)***

Exploring the long-term impact of MAR in Southern California

Doris E. Wendt[1*], Anne F. Van Loon[1] and Bridget R. Scanlon[2]

[1]University of Birmingham, Birmingham, United Kingdom
[2]Bureau of Economic Geology, Austin, United States
*Correspondence: dew637@bham.ac.uk

Abstract: Continuous groundwater use in overexploited aquifers can jeopardise groundwater management strategies. The Central Valley in California is a well-known example for continuous groundwater use to meet the agricultural demand. The majority of groundwater basins is overexploited, especially in Southern California. Managed Aquifer Recharge (MAR) was introduced as a new groundwater management strategy in 1966 to sustain the agricultural demand and increase groundwater storage locally. In theory, continuously applied MAR could reverse declining groundwater levels and relieve overexploited aquifers. However, it remains unknown how continuous MAR affects groundwater storage regionally. Hence, this study explores the long-term impact of MAR in Southern California. Groundwater observations were used to identify regional patterns using cluster analyses. The spatially coherent clusters show generally three patterns in the groundwater time series. The first pattern confirms the overexploitation of the aquifer, as the clusters show declining groundwater levels over time. The other two patterns indicate the opposite. Rising groundwater levels are found for observation wells located in MAR facilities and in the southern part of the aquifer. The clustered time series show an increase in groundwater storage that confirm the positive influence of continuously applied MAR in Southern California. The regional increase of storage highlights the potential of management strategies, such as MAR, in relation to sustainable groundwater use in overexploited aquifers.

Keywords: Managed aquifer recharge, overexploitation, sustainable groundwater management.

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1. Introduction

Continuous groundwater use can jeopardise groundwater sustainability, since groundwater abstractions might not be in balance with groundwater recharge [1-3]. A well-known example is the Central Valley in California, where the majority of groundwater basins is critically overexploited [4-7]. Continuous groundwater abstractions exceed groundwater recharge, which results in falling groundwater levels and changes in regional groundwater flow in the Central Valley [6,7]. Regional groundwater flow used to sustain large lakes (Kern and Tulare Lake) in the topographically-closed aquifer, but these lakes dried up in 1900 due to large-scale agricultural groundwater use [7, 8]. Another permanent consequence of the sustained groundwater loss is subsidence in Southern California that reduces the storage capacity of the aquifer [6,9].

Management techniques to increase groundwater recharge are reviewed as potential to reverse declining groundwater levels in Southern California [10]. Managed Aquifer Recharge (MAR) was initiated in 1960 to meet the agricultural demand locally and reduce dependency of imported surface water [11,12]. MAR projects were designed to overcome short dry periods and potentially secure water supply when applied continuously [12-14]. An increase in groundwater storage is found by modelling studies that analysed one MAR project operating for 50 years [10,11], although the combined influence of multiple MAR projects requires a new research approach.

This study aims to quantify the regional influence of continuously applied MAR in Southern California. The research focusses on one of the most critically over-drafted groundwater basin in the Central Valley: Tulare basin (Figure 1). MAR facilities have been recharging the groundwater since 1960, and over 10 facilities are operational since 1990 (marked in blue in Figure 1) [11, 12]. In addition to the MAR facilities, a dense monitoring network is present that is used to analyse groundwater level time series in Tulare basin.

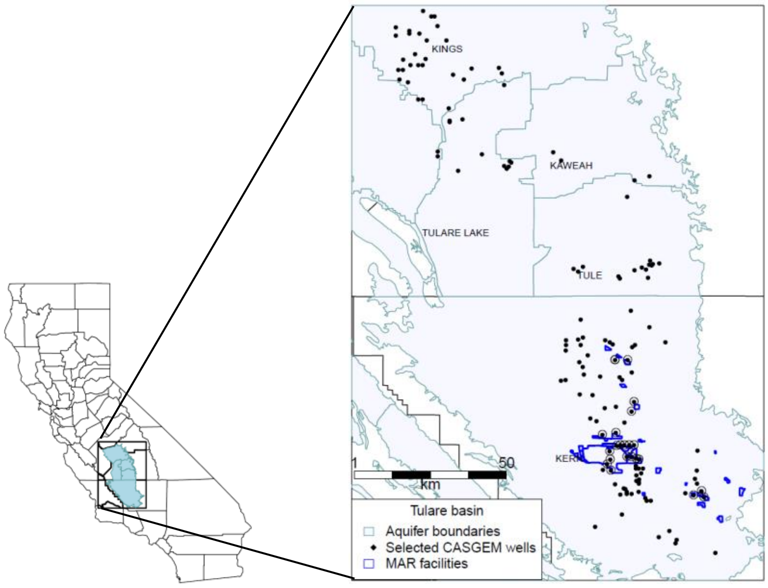

Figure 1: Study area in Southern California. The selected groundwater observation wells are indicated by the black dots, MAR facility boundaries are indicated in blue. Annual recharge and recovery volumes were obtained for the following 10 MAR facilities [10-12]: Arvin-Edison, Kern Water Bank, City of Bakersfield, Pioneer, Kern River Channel, West Kern, Semitropic, Berrenda Mesa, Rosedale, and City of Fresno.

2. Data and methods

2.1 Data

Long records of groundwater observations were obtained from the CASGEM groundwater dataset [15]. Groundwater is recorded on biannual basis in over 12,100 wells [15]. Wells with at least 35 years of data were selected (1980-2015). These time series were further screened for missing data, which were filled in case of minor gaps (< 3 observations) [16, 17]. Time series with longer sequences of missing data were excluded, resulting in a selection of 149 wells (see Figure 1). Amongst the 149 wells, 20 wells were located inside MAR facility boundaries [11]. These 20 wells were therefore flagged as 'MAR observation wells' (marked with a ring in Figure 1) and used to analyse the direct influence of MAR [10,11].

Precipitation data were obtained from the gridded Daymet dataset [18]. The 1km^2 grid cells were matched to groundwater well locations and precipitation data was extracted for all 149 wells. These precipitation time series were trimmed to meet the 35 year time frame (1980-2015).

Finally, we used reported annual recharged (infiltrated) and retrieved (extracted) volumes for 10 MAR facilities in Tulare basin. These volumes were converted to feet per year using the size of recharge basins at the time of infiltrating [12]. Data for three MAR facilities was available for (almost) the whole 35 year time period: Arvin-Edison (1966-2015), Kern Water Bank (1968-2015), and City of Fresno (1985-2014). A shorter dataset was available for the other seven facilities: City of Bakersfield (1981-2010), Pioneer (1995-2011), Kern River Channel (1981-2010), West Kern (1988-2010), Semitropic (2005-2010), Berrenda Mesa (1983-2011), and Rosedale (1989-2011).

2.2 Methods

The quality-checked groundwater level time series were converted into standardized groundwater indices (SGI) using the method of Bloomfield & Marchant [19]. The SGI values of 0 represent the long-term mean, groundwater levels above the long-term mean are positive and groundwater levels below the mean are negative. The SGI time series were compared to standardized precipitation indices (SPI). These SPI time series were calculated from the precipitation data using the method of Mckee [20].

Next, the SGI time series were clustered using two different unsupervised clustering techniques: kmeans and Ward's minimum. Kmeans is a partitioning clustering technique that minimizes the total distance between all objects into a number of clusters based on a common mean (linear discretization). Ward's minimum applies a quadratic reduction of distance between objects, and visualizes this distance reduction in a dendrogram of all objects. Using both techniques on the same dataset gives a better indication of the stability of a certain cluster composition [21,22]. The optimal number of clusters for kmeans was determined by a numerical reduction of the sum of squared error between the clusters. These kmeans clusters were verified using Ward's minimum clusters. We chose the final clusters based on consistent results between the two clustering techniques [22].

3. Results

The optimal number of k-means clusters was 2, 7, 13. Out of these three options, most consistent results for both clustering techniques were obtained for seven clusters, as the composition of clusters was similar for 85% of wells. In Figure 2, the similarities are evident in the north of the basin (sub-basins Kings, Kaweah and Tulare Lake). Both cluster compositions allocated 45 wells in the same cluster (C1 in yellow). Another identical cluster is found in two southern sub-basins Tule and Kern (C6 in purple). Smaller variations are observed for clusters 3, 4, 5 and 7 for which a couple of wells differ between the two techniques (C3 in black, C4 in red, C5 in light blue, and C7 in blue). The largest variation between cluster groups is found in sub-basin Tule and Kern for cluster 2 (C2 in green).

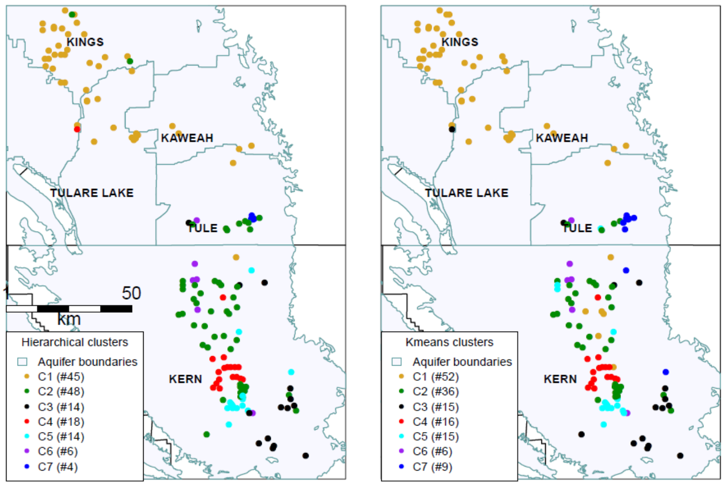

Figure 2: Cluster composition for 149 CASGEM wells in Tulare basin. Standardized time series are clustered using Ward's minimum (left plot) and kmeans (right plot).

The identified seven clusters represent the main groundwater level variation in Tulare basin (Ward's minimum clusters are shown in Figure 3). Time series of clusters C1, C2, and C5 show a gradual decline. This decline seems stronger in the cluster mean of C1 compared to C2 and C5. In C1, the decline starts in 1990 and ends in 2012, whereas the decline starts and ends later in C2 and C5 (2000-2015). The other four clusters show a contrasting pattern to the declining time series. The cluster mean of C3 and C6 rise from 1985 onwards, indicating a positive tendency in long-term groundwater level. C4 represents a pattern of both rising and falling SGI without a tendency for either positive or negative long-term groundwater level variation. The four remaining wells in C7 represent a distinct pattern that is found in one location only.

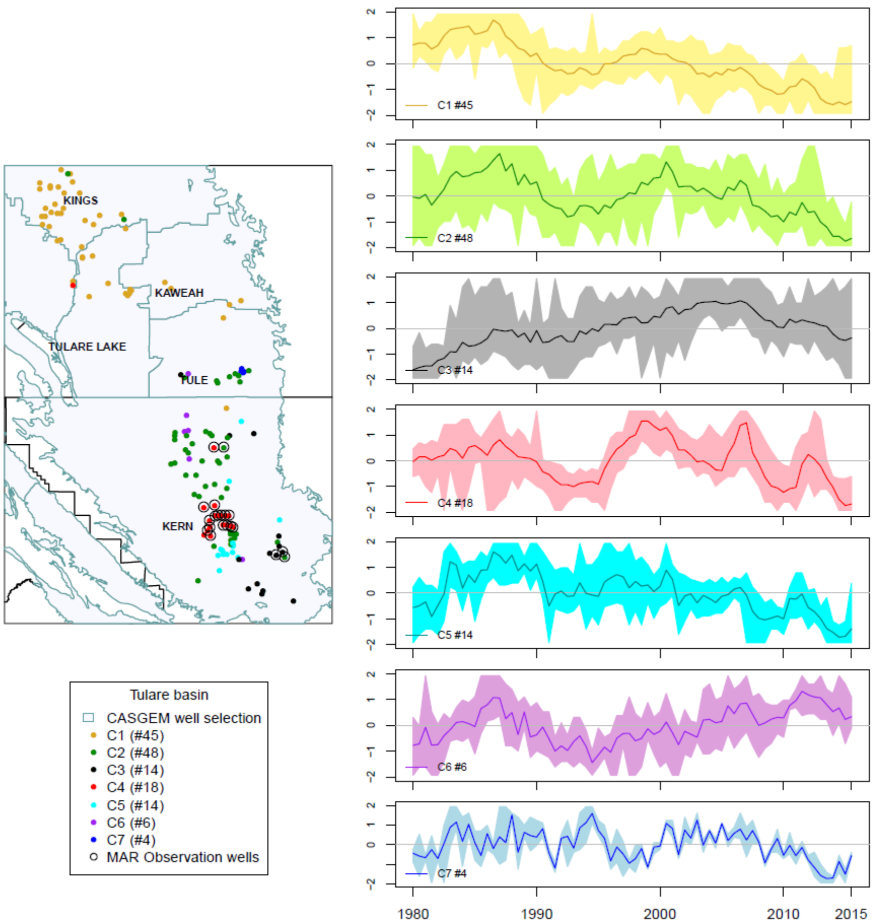

Figure 3. Spatial and temporal results of the Ward's minimum cluster analysis for 149 wells in Tulare basin. The map on the left shows the location of the seven clusters. On the right, the SGI time series are shown for each cluster. The cluster mean is indicated with a thick line and the range is represented by the shaded area.

The majority of 'MAR observation wells' (16 out of 20) is included in C4, for which clustered SGI time series are relatively similar given the narrow range. The peaks in the clustered time series also synchronize with the peaks in total recharge volumes in 1998-99, 2005-06, and presumably in 2010-11, see Figure 4. Due to data limitations, recharge volumes were incomplete in 2010-2015. However, it is likely that the total recharged volume in 2010-11 is comparable to that of 2005-06. The middle panel of Figure 4 shows two example wells, representing C4 and C2. The SGI of C4 exceeds the SGI of C2 in 1997-2015. A remarkable result, as the precipitation was similar for the two example wells. The peaks in the SGI time series, representing C4, suggest that additional MAR recharge reflects in higher groundwater levels.

4. Discussion and conclusion

Three main patterns are identified in the clustered SGI time series. The first pattern is represented by three clusters that show a decline in groundwater level, mainly present in the north of Tulare basin (C1, C2 and C5). These clusters confirm the falling groundwater levels in the Central Valley due to overexploitation of groundwater [5, 6, 17]. The second pattern is opposing the general trend, as SGI time series of C3 and C6 rise almost continuously in 1985-2015. The rising SGI time series confirms the results of modelling studies [10, 11], but the clusters have a larger spatial extent than previously assumed. The last pattern highlights gradual peaks and falls in the SGI time series (C4) that coincide with the recharge years of MAR facilities. The direct influence of MAR is evident when the SGI of C4 wells is compared to other wells nearby. From 1997 onwards the SGI in the MAR sites is consistently higher, which illustrates the direct and long-term influence of MAR on regional groundwater levels. This is also the case in C3, located in the southern tip of the aquifer. Groundwater used to accumulate here before flowing from Kern towards Tulare Lake (prior to 1900) [7] and C3 now shows an accumulation of groundwater level, as a consequence of continuously applied MAR.

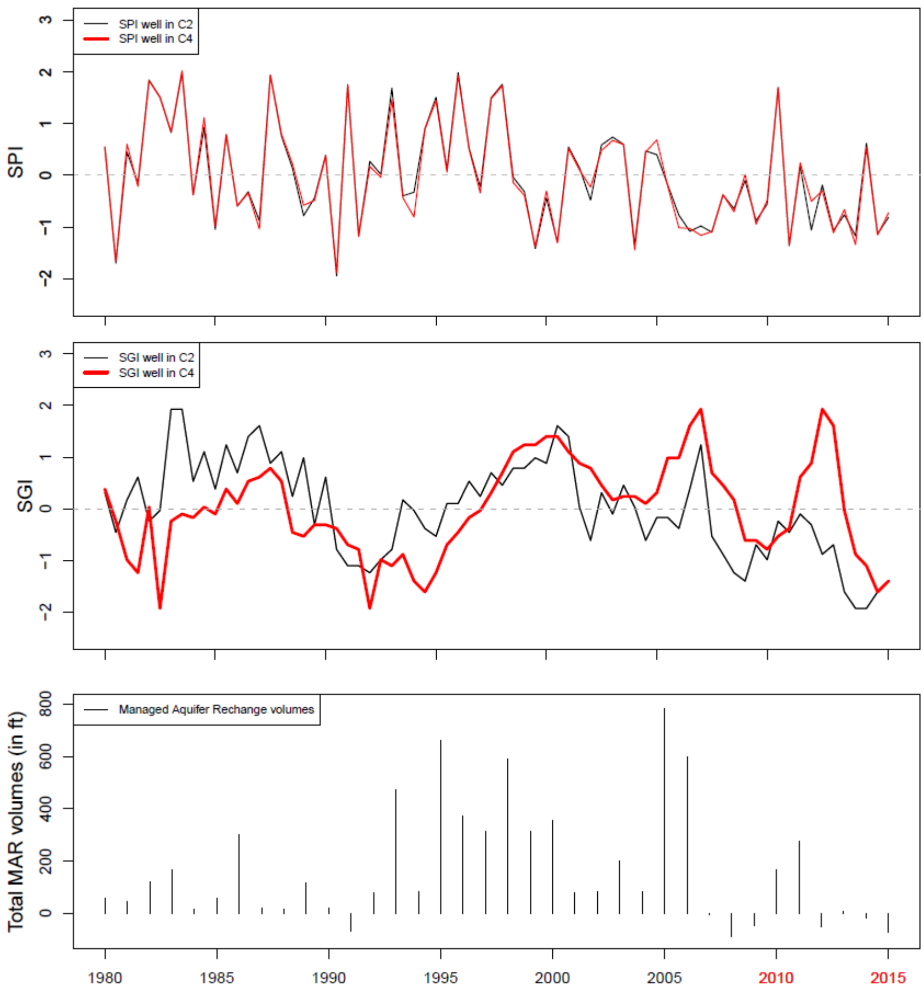

Figure 4. Two example wells representing clusters C2 and C4, of which the well in C4 is located within the boundaries of a MAR facility. In the top and middle panel, the SPI for both well locations and the SGI for both wells are shown in black (C2) and red (C4). The bottom panel shows the total recharged and retrieved MAR volumes. Limited data was available in 2010-2015 (therefore marked in red; see Data 2.1).

The findings demonstrate the positive influence of continuously applied MAR on declining groundwater levels. This emphasises the potential of active groundwater management in largely over-drafted aquifers, as Tulare groundwater basin is viewed as critically overexploited [4, 8, 17]. The positive influence of MAR on groundwater storage confirms the work of Thomas & Famiglietti [23], who investigated groundwater trends in Coachella Valley. Even though groundwater trends are not investigated in this study, the clustered SGI time series show increased groundwater storage in relation to continuously applied MAR. MAR could thus contribute to sustainable groundwater use, even in largely over-drafted basins as the Tulare basin. However, more research is required to quantify the regional influence of MAR on declining groundwater storage and specifically during droughts.

Acknowledgments: DW would like to acknowledge the provided funding by CENTA NERC and BGS. A research visit was organised within the IAHS Panta Rhei network, working group "Drought in the Anthropocene". DW would like to thank Amir AghaKouchak and his research group at University of California Irvine and the Bureau of Economic Geology at University of Texas for hosting in October 2017.

Author Contributions: DW, BS and AVL conceived and designed the study. BS contributed the data. DW performed the analysis and wrote the paper, supervised by AVL. All authors contributed to the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Extended abstract for ISMAR10 symposium. ***Topic No: 2 (221#)***

Sites and indicators of MAR as a successful tool to mitigate Climate Change effects in Spain

Jon San Sebastián Sauto[1]*, Enrique Fernández Escalante[2], María Villanueva Lago[3] and Rodrigo Calero Gil[4]

[1]Tragsatec; jsss@tragsa.es
[2]Tragsa; efernan6@tragsa.es
[3]Tragsatec; mvillan2@tragsa.es
[4]Tragsa; rcalero@tragsa.es
*Correspondence: jsss@tragsa.es; Tel.: +34 91 322 66 61

Keywords: Managed Aquifer Recharge, Climate Change, water management, mitigation measures, indicators, Spain.

EXTENDED ABSTRACT

1. Introduction

Beyond overexploitation of water bodies, it is mandatory to build models that consider the current effects of CC, especially in those countries with a Mediterranean or Arid Climate, where the annual rain scarcity overlaps with punctual extreme precipitations. These accepted phenomena get worse indeed according to the prevailing CC models.

The main manifestations of CC shown in this paper that could be influenced by MAR techniques are: average temperature increase, annual precipitation decrease, extreme weather regularity and sea level rise [1].

The key problems and impacts of CC whose figures are globally rising are evaporation rate, water demand, fire risk, and extreme run-off while decreasing figures are found in water supply, wetland surface, and Hydro-electric energy production [2].

Managed Aquifer Recharge (MAR) can provide a large array of technical solutions to mitigate those adverse CC effects, not only managing groundwater, but showing an integrated view of water resources and their related ecosystems, following the EU Water Framework Directive approach [3].

2. Materials and Methods

Main objective of this paper is to collect numbers and examples that can illustrate that MAR, as well as its combination with other techniques, can fruitfully contest the effects of CC by adaptation and mitigation.

The methodological approach is the problem and solution pairing. Main CC impacts are going to be matched with the available MAR techniques that can be used to mitigate them. Results follow those four groups according to adaptation or response against main CC effects.

1. Examples of technological solutions to palliate rising temperatures (3.1).
2. Examples of technological solutions to palliate decreasing annual precipitation rates (3.2).
3. Examples of technological solutions to manage extreme phenomena (3.3).
4. Examples of technological solutions to reduce sea level rise (3.4).

3. Results

3.1. Examples of technological solutions to palliate rising temperatures

3.1.1 Underground water storage (Canal del Guadiana, Castilla-La Mancha)

The high temperatures, over 40ºC in August, that can be found in the historic record [4] and the shallow streams multiply the evaporation rate during summer in Castilla-La Mancha Region. A net of wells close to the canal of Guadiana was built by the Guadiana River Water Authority (CHG) for rural development and mitigation of the overexploitation of the groundwater body known as aquifer #23 [5]. This MAR system can increase the total recharge in 48 supplementary Mm^3 per year.

3.1.2. Temperature reduction (Palma de Mallorca, Illes Balears)

A good example of SUDS (Sustainable Drainage Urban Systems) [6] is found in Parc Bit (Palma de Mallorca) where the vegetated roofs, fed by rain collection, are able to reduce the air temperature in a range of 1.5 to 6ºC. Thermographies can establish a clear and quick difference in the pattern of colours when areas with or without canopy are compared [7]. A square meter of green cover can evaporate more than half a liter per day.

3.1.3 Soil humidity increase (Gomezserracín, Castilla y León)

Los Arenales aquifer in Gomezseracín provides an example of increased soil moisture and a rise in the phreatic surface brought about by underground storage through a system of canals and streams. Artificial recharge operations, initiated in 2003, have resulted in an average rise in the phreatic surface of more than 2m. This additional storage in the unsaturated zone has increased soil moisture by 15-20% [8].

3.1.4. Reclaimed water Infiltration (Alcazarén, Castilla y León)

This MAR system began to recharge in 2012 win an estimated volume of 0.4 Mm^3 for the last 3 years [9]. Those resources come from an advanced secondary treatment of the WWTP of Pedrajas de San Esteban. Some subsequent treatment is advisable (as filtering beds, reactive filters or desinfectants) to improve the quality of the recharge so any hazard to the environment or Public Health is avoided as final water use is horticultural irrigation.

3.1.5. Punctual infiltration (CYII, Madrid)

Canal de Isabel II, the public entreprise in charge of water purification and wastewater management in Madrid has built a system of deep injection in a semi-confined aquifer under the city. This MAR device is mainly used during drought alerts for potable water supply, increasing resources in the city of Madrid with up to five Mm^3 per year [10].

3.2 Examples of technological solutions to palliate decreasing annual precipitation rates

3.2.1 Self-purification (Santiuste, Castilla y León)

The inadequate WWTP system of Santiuste consists of four connected lagooning ponds that spill its discharge into the East recharge channel of this MAR demo site. First kilometre stretch of the canal is permeable while the next 1.5 km is not. The combination of sunlight, water depth and flow and vegetal and bacteria growth play main roles in the stagnation and purification process, especially when no recharge from Voltoya River is flowing into the MAR so dilution does not happen. NO_3 concentration may decrease in a 30%, turbidity in 34% and cupper in 60%. Once treated, water pours back to the MAR canal [11].

3.2.2 Off-river storage (Santiuste, Castilla y León)

Aquifer storage does not occupy any additional space and has no evaporation issues except random inner losses to deeper strata. Santiuste MAR demo site is a pioneer system after 14 years of effective work. The annual authorization of abstraction of 8.5 Mm^3 from December to May has implied a total recharge of 42.12 Mm^3 [12]. Recharge rate has been increasing from 37 to 98%. That means all that volume has not stopped the river flow over the weir and it has not supposed a significant loss of irrigated surface during storage. An average of 2.62 Mm^3 stored per year would mean 43 times the volume of the abstraction dam in Voltoya River and around 2.5 ha dedicated to 5-6 water reservoirs.

3.2.3 Restoration (Santiuste, Castilla y León)

In Santiuste area, the alkaline pools near the village of Villagonzalo de Coca have such a peculiar water composition that their protection is linked to a botanic and bacterial diversity with a very limited extension in Europe. La Iglesia has been restored using part (5% recharged volume) of the diverted water from Voltoya through the West Canal. Water runs over the terrain so the low EC water from Voltoya, captures biochemical compounds so the alteration of the lake conductivity is far compensated by the upsurge of water into the basin [11].

3.2.4 Gravity flow water distribution (El Carracillo, Castilla y León)

El Carracillo recharging water distribution works by gravity using 40.7 km of pipes and ditches that dispense the water to different villages, where infiltration reservoirs are placed. That way, the infiltration, though extensive, occurs mainly in certain spots on the aquifer so every area receives its share. Up to 21 infiltration ponds recharge the aquifer covering the nine main town centres. Management has been transferred to those sharing points that can receive equitably the water from the Cega weir. Irrigation area covers 3,500 ha in a total cultivated area of 7,865 ha [13].

3.2.5 Energy efficiency through Artificial Recharge (El Carracillo, Castilla y León)

The recharge in El Carracillo contributes to the rise of watertable and affords energy savings for irrigators, since farmers pump less deep groundwater. Monitoring of the pumping consists of 314 pumps, with average extractionvolume of 9,957 m^3 per well per annum, and the rise in the average phreatic level, after several artificial recharge cycles, represents a mean rise of +2.30 m. The saving in kW-h of power is 36%, the equivalent of 3,000€/annum [14]. Consequentely, the volume of CO_2 emitted by the year in the Carracillo irrigation community has gone down 10,780 kg.

3.3 Examples of technological solutions to manage extreme phenomena.

3.3.1 Infiltration of extreme flows (Arnachos, Valencia)

The "Arnacho" deep borehole is located just a few metres from the pond of the Tarragó Irrigation Community in Losa del Obispo (Valencia). In 2014, it was used twice to recharge the aquifer, absorbing a volume of intense precipitation in Lliria of almost 1,000 l/s for a period of 14 h (0.0504 Mm^3), a significant quantity of water that would have worsened the devastation caused by the flooding [15].

3.3.2 Forested watersheds (Neila, Castilla y León)

An example of mechanical soil preparation for increasing the infiltration rate is located in Neila, Burgos, where a canal channels water from a road towards a forest adequately managed for this purpose. This forest can retain 15-40% of the volume of surface runoff [16].

3.3.3. Multiannual management (Santiuste, Castilla yLeón)

According to TRAGSA Group data [17], the agrarian activity in the area could be supported for three consecutive years with no rain just on the base of the average reserves achieved by a single recharging season.

3.4 Examples of technological solutions to reduce sea level rise

3.4.1 Intrusion barrier wells (Llobregat, Cataluña)

One of the most emblematic examples of water barrier against sea intrusión is in the surroundings of the city of Barcelona. A system of recharging wells injecting water from El Prat WWTP. According to the mathematical models, the recovery of preoperational state before the sea intrusion should take around 30 years [18].

4. Conclusions

CC effects and their associated problems have been related to 15 succesful MAR solutions in Spain through a series of indicators (Table 1) that let us value the eficacy and efficiency of MAR tecnique as a tool that can simultaneously achieve several purposes.

The list of CC effects in Spain has been accompanied by several efficacious cases of artificial recharge. The data associated with these monitored sites have enabled the establishment of status indicators, whilst demonstrating the efficiency and effectiveness of MAR as a multi-purpose technique that can carry out several functions at the same time that can be achieved depending on little design or management changes of the same MAR device.

Management schemes featuring aquifer recharge provide guarantees with respect to future water supply and constitute an important set of CC adaptation measures too. Some of them also serve to palliate the adverse effects of CC.

Table 3. Relations between CC problems and MAR solutions with their site locations and indicators of positive achivements against CC.

CC ISSUES	MAR SOLUTIONS	SITES	INDICATORS
Evaporation ↑	Underground water storage	*Santiuste (CyL)*	+0,4-12 hm³ (+230ha irrigated crops)
	Temperature decrease	*P. de Mallorca (I. Baleares)*	-1,5-6°C of air temperature
Evapotranspiration ↑	Soil humidity increase	*Gomezserracín (CyL)*	+15-20% soil moisture
Water demand ↑	Reclaimed water infiltration	*Alcazarén (CyL)*	+0,4 hm³
	Punctual infiltration	*Canal Isabel II (Madrid)*	+5 hm³/year
	Directed Infiltration	*Canal del Guadiana (CLM)*	+48 hm³/year
Water availability ↓	Self-purification	*Santiuste (CyL)*	+/-12-53% in water q parameters
Run-off ↓	Off-river storage	*Santiuste (CyL)*	+2,62 hm³/year out of Voltoya River
Wetlands ↓	Restoration	*Santiuste (CyL)*	-5% recharge vol. (Alkaline lake)
Hydro Electric Power ↓	Gravity flow water distribution	*El Carracillo (CyL))*	+40,7 km of canals and pipes
	E savings / Lower emissions	*El Carracillo (CyL)*	-36% E costs (-10,780 kg CO_2)
Floods ↑	Infiltration of extreme flows	*Arnachos (Valencia)*	+0,05 hm³ in 14 hours
	Forested Watersheds	*Neila (CyL)*	-15-40% of diverted flood volume
Droughts ↑	Multiannual management	*Santiuste (CyL)*	Supply for 3 years with no rain
Saltwater intrusion ↑	Intrusion barrier wells	*Llobregat (Cataluña)*	30 years to regain water table

A full paper has been submitted to the MDPI journal *Water* that provides more detailed information. If this is accepted it will be published at:
https://www.mdpi.com/journal/water/special_issues/ISMAR10_2019.

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Paper for ISMAR10 symposium. ***Topic No: 2 (246#)***

Insights from groundwater level measurements over a managed aquifer recharge site in Central Morocco

Younes Fakir[1*] and Houssne Bouimouass[1]

[1]Faculty of Sciences Semlalia, Cadi Ayyad University, Marrakech, Morocco
*Correspondence: fakir@uca.ac.ma; Tel.: +212 5 24 434649

Abstract: The Haouz plain (Tensift basin, central Morocco) is experiencing a severe depletion of groundwater. To enhance the groundwater recharge at the upstream area of the plain, a managed aquifer recharge (MAR) system consisting of concrete and masonry bunds was placed across the streambed of Ourika wadi in 2012. The objective was to spread the water in the streambed and to enlarge the infiltration surface during high-flow events. However, the overall hydrologic impact of this system was unknow. To have over that MAR site a first view of groundwater fluctuation during a hydrological cycle, 2 groundwater level measurement campaigns were held in September 2017 (dry conditions) and in March 2018 (wet conditions). Within this period, the groundwater level rose by 01 m to 3.5 m. However, the groundwater fluctuation showed clearly that recharge outside the streambed was higher than recharge beneath the streambed. This was explained by streamflow diversion for irrigation, as deduced from the analysis of the land cover of the area and from stream data. These results along with a first analysis of the environmental impact of the bunds call into question the pertinence and efficiency of such a MAR system in our context.

Keywords: streamflow; irrigation; groundwater fluctuation; recharge; Haouz-Tensift.

1. Introduction

Northern Africa is one of the most sensitive regions of the world with respect to the likely climatic changes that are predicted as a result of human activities [1,2]. Despite the uncertainties in projections, the anticipated reduction of renewable water resources could be as high as 50% within the next 100 years affecting water resources sustainability and food security. Groundwater is a vital resource especially during dry seasons and drought periods. However, in Northern Africa generally groundwater resources are decreasing under high pumping and low recharge [3]. Managed Aquifer Recharge (MAR) can help address overexploitation and water scarcity challenges [4]. One of the techniques used in Southern Mediterranean countries is the installation of bunds in streambeds to increase streamflow infiltration to groundwater. This technique could be classified as an in-channel modifications method [5]. It requires low levels of technology and can be (and have been for centuries) implemented with little engineering knowledge [5]. For instance, it has been implanted in Tunisia [6], Kenya [7], India [8], Jordan [9] alongside with other techniques.

In the Haouz plain (Tensift basin, Central Morocco, NW Africa), which is already experiencing a severe depletion of groundwater [10, 11], bunds were placed in 2012 upstream in the piedmont area to enhance streamflow infiltration beneath the Ourika wadi. Despite that this method is the most used in Morocco thanks to its simplicity, no adequate monitoring was carried out before to assess its performance. In this study, measurements of groundwater fluctuation during a hydrological cycle were performed to check the magnitude of groundwater variation over the area covering the MAR site. Field observations around the MAR bunds were also made to assess some of their environmental impacts. The aim is to provide a first analysis of this experience.

2. Materials and Methods

2.1. The study site and the MAR plant

The managed aquifer recharge (MAR) site on Ourika wadi is located in the upstream area of the alluvial aquifer of the Haouz plain, in the piedmont of the High-Atlas mountain (Figure 1). The regional piezometric contour map of the alluvial aquifer (Figure 1) shows, as indicated by groundwater gradients, that the upstream area transmits recharged groundwater from the piedmont towards the center of the plain.

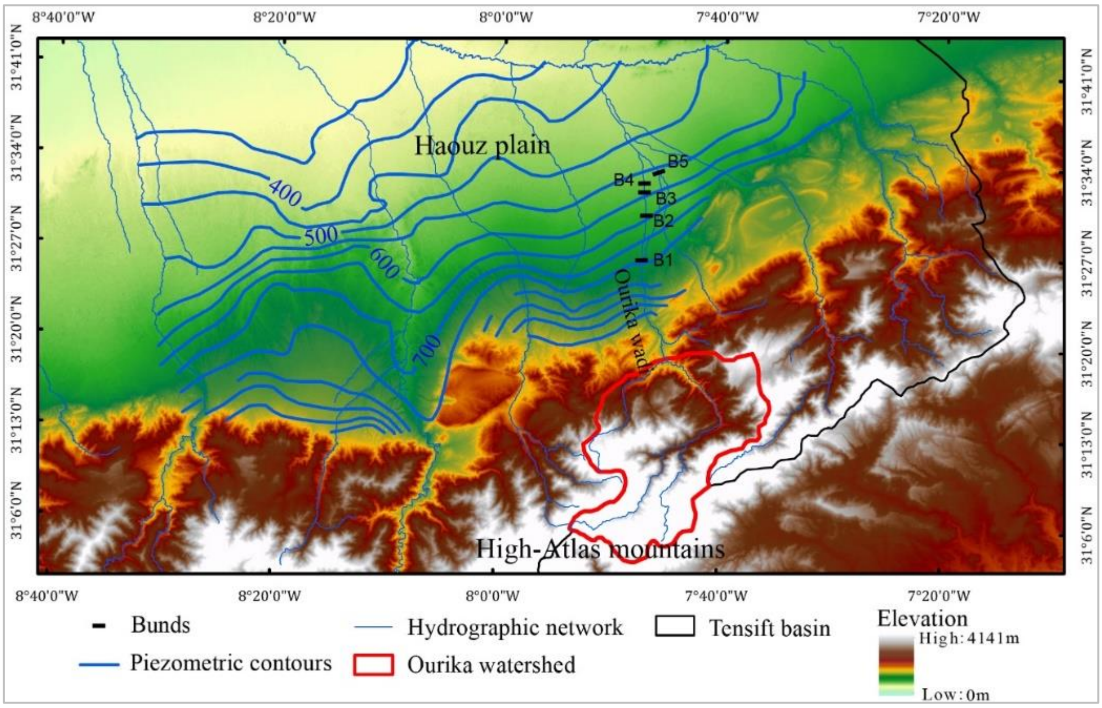

Figure 1. Piezometric map (2011) of the alluvial aquifer of the central Haouz plain and location of the managed aquifer recharge site (bunds1 to 5) on the Ourika wadi.

The MAR site of Ourika consists of 5 concrete and masonry bunds placed across the Ourika streambed (Figure 2) and operating since 2012. The objective of this installation is to spread the water from floods across the streambed and to enlarge the infiltration surface and therefore increase the infiltration volume to the underlying groundwater. Water spreading technique is applied in cases where the unconfined aquifer to be recharged is at or near to the ground surface [5]. Recharge would be achieved by infiltration through permeable material at the surface.

The Ourika wadi is one of the main tributaries that originate from the High-Atlas and cross the Haouz plain from South to North. The Ourika mountain watershed is 1070 km^2, culminating at 4001 m. Annual precipitation (snow and rainfall) in the watershed is around 600 mm, contrasting with the plain with an average rainfall of about 250 mm. The average interannual flowrate is 5 m^3/s. Floods could be violent with high flowrate.

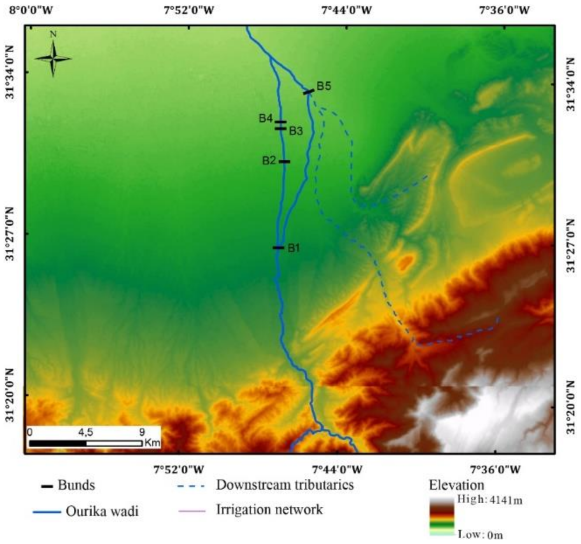

Figure 2. Location of the bunds (1 to 5) along the Ourika wadi (on the left). The Image (on the right) shows a bund crossing the *wadi* and on the background the first hillslopes of the High-Atlas mountain.

2.2. Groundwater level measurements

Two piezometric campaigns were carried out to analyze principally the groundwater fluctuation and locate the distribution of the groundwater variation over the MAR site and surrounding area. The first campaign was carried out on the first week of September 2017 representing dry conditions and the second on the first week of March 2018 representing wet conditions. 54 wells are common to the 2 campaigns.

2.3. Streamflow occuurrence, agriculture area and environemental field observations

Satellite images showing the soil moisture and the agriculture within the area during the study period were acquired from Sentinel-2 Data Hub website: https://apps.sentinel-hub.com/sentinel-playground/. Through the soil moisture index images, we expected to determine the presence of flows within the Ourika streambed during the study period. With agriculture images the objective was to show the extent and the location of irrigated areas.

Furthermore, environmental observations were made during field visits of the MAR site, aiming to collect qualitative information about the environmental impact of the bunds.

3. Results

3.1. Groundwater variation

Over the MAR site area, in September 2017 when the groundwater was low, the water table depth varied from 9.5m to more than 35m (Figure 3). The thick unsaturated zone indicated a consistent storage capacity of the alluvial aquifer.

From September 2017 to March 2018 the water-table rose by 0.5 m downstream of the MAR site to 3.5 m upstream (Figure 4). This witnessed a consistent groundwater recharge in the area. However, the remarkable here is that the maximum groundwater elevation did not occur beneath the streambed. The maximum was recorded on the left side of the wadi where the recharged area extended several kilometers from the wadi. Therefore, the groundwater recharge outside the streambed is more important than beneath the streambed. This could be explained by large amounts of recharging water were spread over the lands surrounding the wadi.

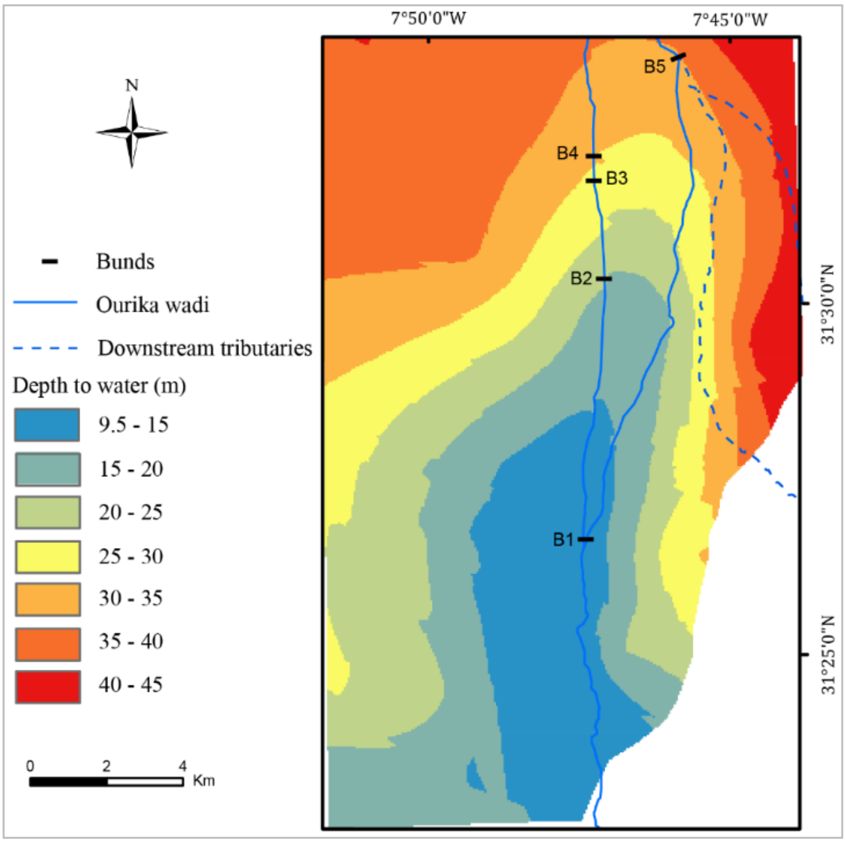

Figure 3. Groundwater depth in September 2017, in dry conditions.

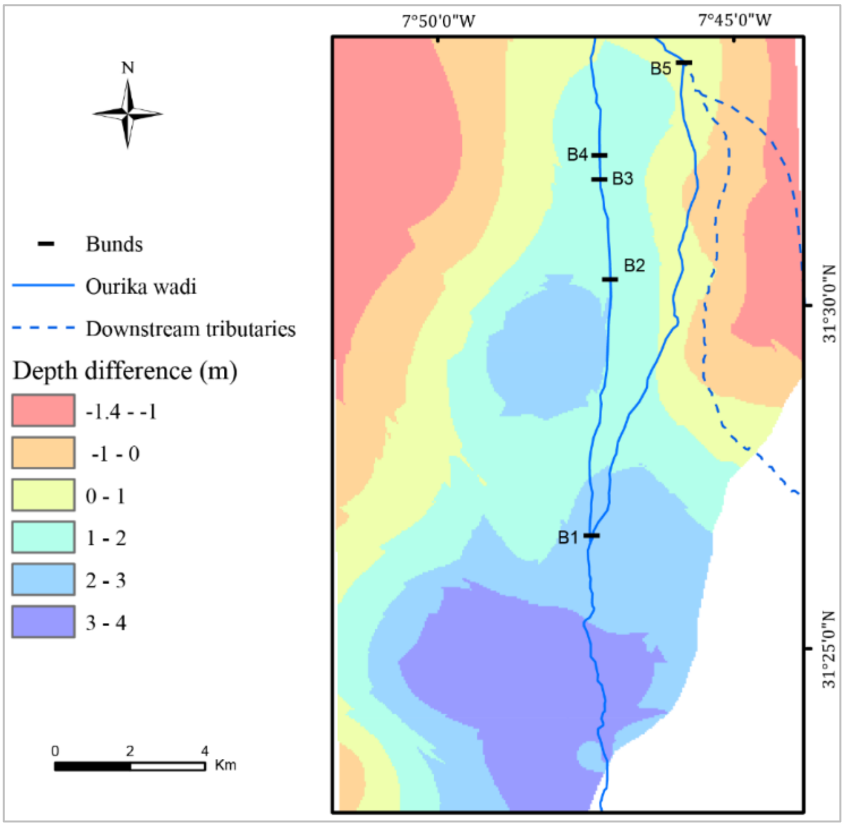

Figure 4. Groundwater variation from September 2017 (dry season) to March 2018 (wet season).

3.3. Irrigation and Streamflow

In the study area, agriculture is dominated by olive trees and irrigated by a network of irrigation channels diverting streamflow on both sides of Ourika wadi. In order to observe the extent of the irrigated crops, a satellite image of Sentinel-2 of September 19th, 2017 was used; at this date representing the end of the summer only irrigated crops would have developed. As clearly shown on the image (Figure 4), irrigated crops were extended from the mountain border and covered all the area down to the plain. The image disclosed in addition that the irrigated surface on the left side of the *wadi* was far larger than the right side. Therefore, more streamflow would have been diverted to the left side resulting in more groundwater recharge.

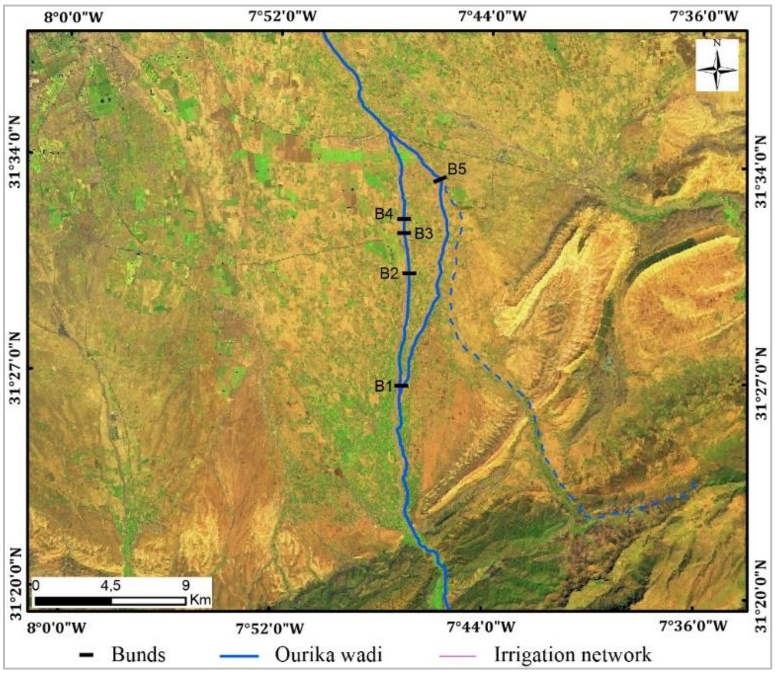

Figure 5. Satellite images (Sentinel-2 Data Hub website) indicating the extent of irrigated crops (in green) in September 2017.

In addition, the observation of the moisture index images allowed to detect the presence or absence of flow in the streambed over the study period. During 09 months, from May 2017 to January 2018, the images indicated that streamflow which was present in the mountain area, had generally not flown significantly across the MAR site (Figure 5). The streamflow reached the MAR site only starting February 2018 (Figure 6). Therefore, the streamflow produced in the mountain watershed was diverted by channels at the entrance of the wadi to the piedmont, for irrigating crops during several months. Streamflow reached the MAR site only in case of water excess in the wadi with respect to irrigation.

The diversion of streamflow for irrigation during several months resulted in that the amounts of streamflow transiting across the MAR site are reduced. This certainly reduced the recharge potential beneath the streambed and increased it underneath the irrigated areas. Groundwater recharge from irrigation returns were more important than recharge by streamflow losses.

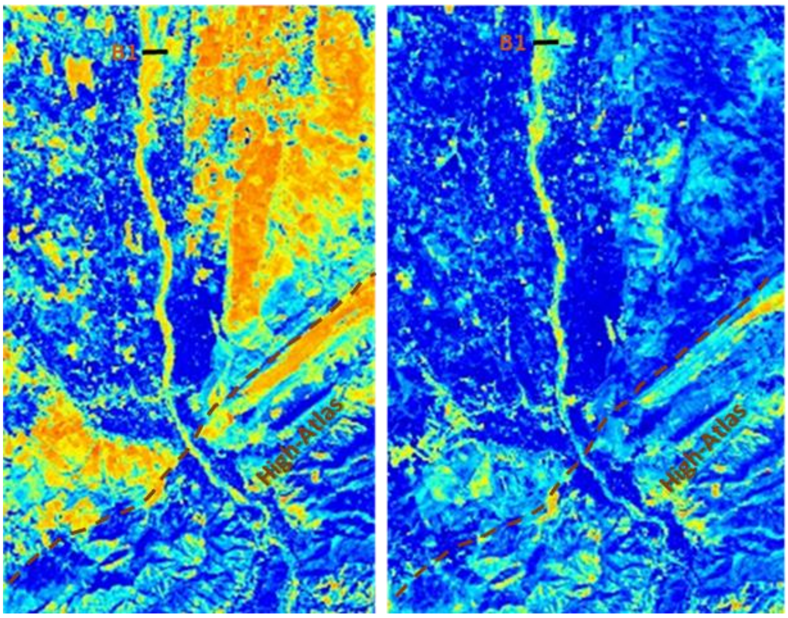

Figure 6. Moisture index images (Sentinel-2 Data Hub website) indicating in the upstream of the MAR site conditions of dry streambed in September 2017 (on the left) and wet streambed in February 2018 (on the right). This was explained respectively by the absence and presence of streamflow. It is noted that in the High-Atlas Mountains, streamflow was present in both cases.

3.4. Environmental imapcts observations

Field observation made around the bunds allowed reporting that: (i) the bunds have not behaved similarly regarding sedimentation or erosion. At the foot of a bund, a deep and narrow channel was dug by streamflow erosion (Figure 7a). It seemed that in that situation the bund caused a channeling of streamflow rather than its spreading across the streambed. (ii) the bunds have behaved as a trap of fine sediments that could likely reduce infiltration in the streambed (Figure 7b). All the bunds are filled with deposits in their upstream. (iii) The buds are currently pathways for crossing the streambed and an area of solid waste deposits of different types (Figure 7c & 7d).

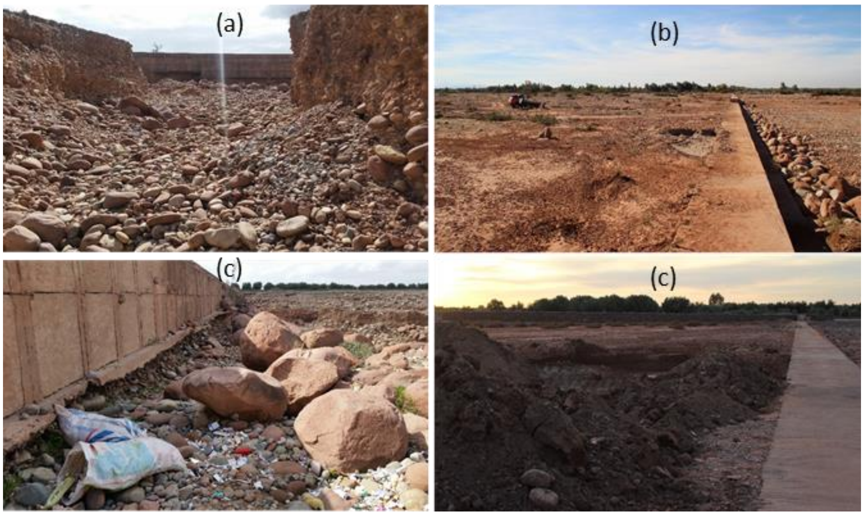

Figure 7. Some environmental impacts of the bunds: (**a**) A channel was dug by streamflow erosion at the downstream site of a bund. (**b**). Fine sediments were deposited on the streambed surface near the bund. (**c**) Solid waste dumped over both sides of a bund.

4. Discussion

MAR is considered as an appropriate management measure to enhance the groundwater recharge and help restoring the groundwater resources. Several favorable conditions to MAR projects exist in the studied area. Indeed, there is a large alluvial aquifer with good hydrodynamic properties [12] and a thick unsaturated zone. The overlooking snowy High-Atlas mountain provides freshwater through several streams under a snow influenced regime [13,14,15].

The MAR project of the Ourika wadi was expected to generate more groundwater recharge beneath the wadi. However, our study showed that the streamflow was diverted for irrigation during a long period of the year. Consequently, a substantial groundwater recharge occurred beneath the irrigated crops, over a wider area than streambed surface. This incidental recharge, which is not included in the water management system and occurs as unplanned side effect of irrigation [16], would be more important and a primary source of recharge.

Regarding these first results, a focus should be made on the management of this irrigation induced recharge. The study area is characterized by the abundance of traditional agricultural practices. People use natural fertilizers (e.g. animal residues) rather than chemical products. Currently groundwater has generally a good quality and does not show serious signs of nitrates contamination [11]. In this context, the emphasis should be made on the prevention of soils and groundwater from pollution, leaching of salts, chemicals from fertilizers, pesticides and other products [17,18] that could be used in agriculture. Maintaining and improving the current traditional agricultural practices, introducing ecologic agriculture and conducting farmers awareness, are management actions that should be applied.

In addition, field observation of the environmental impacts of the bunds has shown various disturbances. Decision-makers should be aware of the importance of taking into account the environmental concerns in the planning and management of MAR sites.

5. Conclusion

All these results call into question the pertinence and efficiency of such a MAR system in our context. Detailed and multidisciplinary studies must be carried out at the site scale but also at regional scale. Understanding of the groundwater system and its recharge sources, assessing accurate water balances, analyzing human-ecosystem interactions should be performed in order to make successful and performant MAR projects.

Acknowledgments:

This research was conducted within the GEOHYD laboratory (Cadi Ayyad University) and he International Joint Laboratory TREMA (http://trema.ucam.ac.ma). Funding were provided by PPR program (SAGESSE) funded by the Moroccan Ministry of Higher Education, Grant agreement no: PPR/2015/48). We thank the ABHT (Agence du Bassin Hydraulique du Tensift, Marrakech) for its collaboration.

Conflicts of Interest: No conflicts of interest.

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Topic 3. NEW REGIONAL CASE STUDIES

Paper for ISMAR10 symposium **Topic No: 3 (017#)**

Groundwater Hydraulics. Computing Groundwater Inflow/outflow at Lake Qarun, Egypt

Rania Abd-El-Baky*1 and Mohamed Abd-El-Mooty2

1 Ph.D. student Faculty of Eng.Alex.Univ, Egypt. Rania.abdelbaky@yahoo.com.
2 Prof. Faculty of Eng.Alex.Univ, Egypt. Mooty431@yahoo.com.
* Correspondence: Rania.abdelbaky@yahoo.com; Tel.:+00201222626258

Abstract: All over the world MAR (Managed Aquifer Recharge) projects play an extremely important role in addressing water scarcity. Obtaining water for MAR is not always easy and depends on many factors including the local water cycle and human activities. A study of Lake Qarun, in the North of the Western Desert (Egypt) water budget was conducted for MAR assessment purposes. The lake ecosystem has a unique natural biological diversity. Lake Qarun also provides humans with a drainage reservoir, a fishery and also is a source of touristic income. In addition, it is considered one of the oldest lakes in the world. Assessing a hydrologic water budget balance for lakes requires an understanding of interactions between the inflows and the outflows. All water budget values for the lake are estimated based on technical approach, but inflows and outflows of groundwater volumes are the most difficult components to be measured or estimated in the equation. Most of the previous studies have assumed that the residual term of water budget equation was groundwater flow. Thus, a study to estimate the groundwater towards the Lake Qarun Qarun was developed based on Darcy's law. In addition, groundwater analysis included flow-net analysis conducted for El-Fayum depression region which acts as the lake's watershed. This analysis shows that the direction of most groundwater flow is towards the lake from the El-Fayum depression region. Consequently, Lake Qarun receives approximately 47.92 MCM of groundwater per year so the lake water level increases annuallyand so depression area does too. The aquifer absorbs the water excess from the irrigation drainage by recharge from gradual infiltration.

Keywords: Groundwater, Lake Qarun , MAR, Out/inflow water, Water budget.

1. Introduction

MAR is one of the measures that can be implemented to secure the water supply. The groundwater comes from the immediate vicinity agricultural lands of lakes. In many cases, there are several reasons which make the groundwater measurements inaccurate or very difficult to achieve. Limited data about the water table levels, very low hydraulic gradients or significant diversity in soil texture have been observed in the study region.

Actually, most of MAR project required accurate groundwater measurements .There are some previous studies that have used the water balance equation to estimate groundwater inflow or outflow of lakes Mostaz, for instance, determined the leakage value for Lowry sand hill lake in central of Florida, USA, as a residual in the water budget equation [1]. Over 200 km in the northern section of the Tonle Sap Lake in Cambodia –the largest freshwater lake in SE Asia–were surveyed by using a customized system that measures natural (radon), temperature, conductivity, GPS coordinates, and water depth [2]. Those results showed that there were portions of the lake with significant enrichments in radon, indicating likely groundwater inputs.

This paper presents sufficient calculation using Darcy's law [3] and some properties related to soil texture, water table level, hydraulic gradient and topography of catchment basin to estimate the magnitude of groundwater flow into or out the Lake Qarun . Also, the rest of the water budget components have been calculated to check the water balance of the lake to be used for MAR purposes.

2. Study area: Lake Qarun

2.1 Location

Lake Qarun is one of the closed saline lakes located in the North of the Western Desert of Egypt. It is the only significant natural lake in Middle Egypt (Figure 1).

Figure 1 Satellite image Lake Qarun located in the Fayaum Depression (inset) in Northern Western Egyptian Desert. Source: Google Earth.

The lake is an important place for fishery, salt production, tourism and migratory birds in the autumn and winter seasons. Therefore, Qarun area was declared as a natural protected site according to the provisions of Law 102/1983, by Prime Ministerial Decree No. 943/1989 [4].

Lake Qarun covers 240 km^2 and is situated in the lowest part of the Fayoum Depression with an elevation of ≈ 43 m below sea level. It is located between the longitudes of 30° 24′ & 30° 49′ E and latitudes of 29° 24′ & 29° 33′ N. Its catchment is arid with a long hot dry summer and a short winter. Consequently, the climate has low rainfall and a high evaporation rate. The annual rainfall is approximately less than 15 mmThe mean minimum and maximum annual temperatures are 14.5 °C and 31 °C, respectively, and the annual mean relative humidity varies between 44 and 68%. The cultivated land slopes steeply towards the lake which makes it a natural store for agricultural drainage water. The main sources of drainage water recharge to the lake are El-Batts and El-Wadi drains.

3. Materials and methods

Determination of a water balance is an important factor in the management of water supplies. The water budget was computed by measuring or estimating all of the lake's water gains and losses by means of monitoring the corresponding change in the lake volume over the same time period. One of the major problems is the estimation of all water budget components. Investigations of water budget are increasing rapidly, because of the dependence of human life on aquatic ecosystem.

The hydrologic water balance for lakes can be expressed as:

Change in storage = Inflow – Outflow

$$\Delta S = P + R + Qi - E \pm Qgw - Qo$$

Where ΔS is the change in water body storage, P: the precipitation over a lake surface, R: the runoff to a lake from drainage, Qi: groundwater inflow (e.g drainage water), Qgw: the groundwater discharge, Qo: the outflow water from the lake, and E: the amount of evaporated water.

Estimations of groundwater are determined by several factors such as, thickness of the unsaturated zone, size and topography of catchment basin, depth of the lake, water table level, the head in the upper aquifer and soil texture and its permeability coefficient - which is affected by particle size and shape, properties of pore fluid, void ratio of soil, degree of saturation, and dissolved impurities in water. These factors affect timing and magnitude of the groundwater flow. The flow-net analysis (Graphical Construction used to calculate groundwater flow through soil. Comprised of Flow Lines and Equipotential Lines) has been thoroughly tested as a useful method of solving field problems and presents a closest prediction for water paths under the soil.

The water table level and lake stage specially affected the ground water flow and the interaction between groundwater and lake water. Thus, the difference between two levels plays an important role in the volume of water flow in and out of the lake. When the water table level is below the lake surface, the lake leakage replaces the ground water inflow. Leakage is also increased because, due to the decreased inflow, more of the lake bottom is available to leak [5].

The Aquifer Boundary Condition (The head of the aquifer) is also greatly affected by the size of the ground-water catchment and the magnitude of exchange water between groundwater and lake. The higher head in the Upper aquifer increases the ground-water inflow, widens the catchment size and reduces leakage from the lake basin.

3.1 Groundwater flow estimation (Qgw)

The groundwater measurements are related to the water flow under the ground. A few previous studies used the water balance equation to estimate ground water inflow or outflow of Lake Qarun . This paper presents sufficient calculation using Darcy's law and some properties related to soil texture, water table level, hydraulic gradient and topography of the catchment basin to estimate the magnitude of ground water flow into or out the Lake Qarun . This law gives the discharge per unit time (rate of flow). Darcy's law is considered the fundamental relation governing steady-state flow in porous media. There are many assumptions that must be taken into account when using Darcy's law, such as that the soil is saturated, the flow is laminar, continuous and steady... Additionally, the total cross section of the area is considered. Darcy's Law can be expressed as:

$$Q_{gw} = k \times i \times As$$

Where Q_{gw}: discharge per unit time (rate of flow), As: the cross-sectional area through which the seepage to and from the lake occurs, i : Hydraulic gradient =Δh/ΔL, Δh: differential head of water($h_1 - h_2$) where h_1 and h_2 are hydraulic heads, L: interval length, K: Permeability coefficient.

3.2 Topography and aquifer media for catchment area (El-Fayoum depression) of Lake Qarun

In groundwater systems, topography is the main factor that affects the groundwater measurements. The degree of slope and soil texture will determine the ability of surface water to infiltrate and the extent of runoff. In El-Fayoum depression, there is a gradual decrease of slope. Based on the topography contour map (Figure 2), ground level varies between 37 m at the southern extreme to about -49 m in the northernmost area.

An aquifer media is defined as either consolidated or unconsolidated geological formations where water is contained and allowed to move naturally. It includes the pore spaces and fractures of the media where water is stored. The characteristics of the aquifer media have a significant impact on the route, path length and amount of groundwater flow. The path length is important in determining the flow rate. The route of water (influenced by fracturing, porosity and openings) may provide preferential paths for groundwater flow.

The upper aquifer in the study area consists of sand, clay and loam. The soil texture has a significant influence on the amount of recharge which can infiltrate to the water table. EL-Fayoum Depression has a unique character. It is considered an oasis mainly recharged by water coming from the Nile River that enters the Fayoum depression through a waterway called Bahr Yousef. The presence of fine-textured materials, such as silts and clays, reduce the soil permeability and restrict the water flow capacity. The lake is surrounded in the northern part by a desert, where huge volumes of sand are transported by the wind. This sand deposits inside the lake causes a notorious bottom level rise, thus, this natural process reduces the capacity of the lake to store water. The soil data has been extracted from the main physiographic map (Figure 3) of the El-Fayoum depression [6]. This area comprises lacustrine plain, alluvial–lacustrine plain and alluvial plain representing 12.22%, 53.58%, and 34.20% of the total area, respectively. The water table depth is shown in Figure 4.

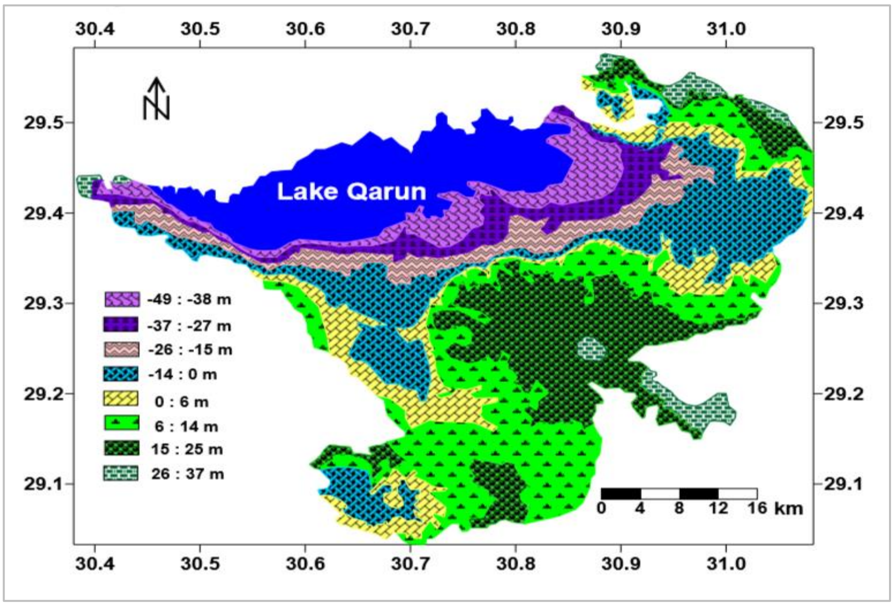

Figure 2 .Topographical intervals map for El-Fayoum depression in relation to the sea level.

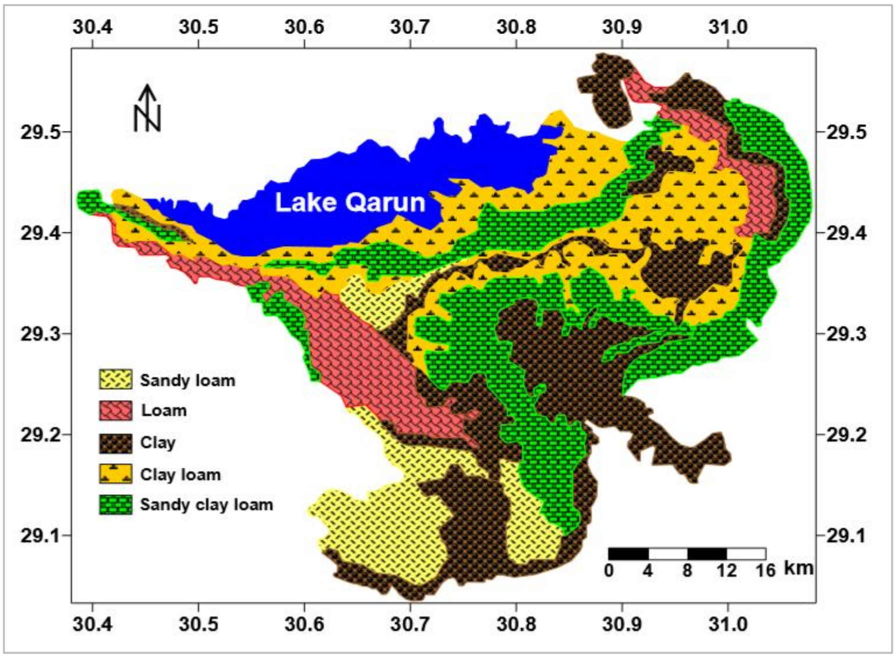

Figure 3 .The soil texture and classification within El-Fayoum depression.

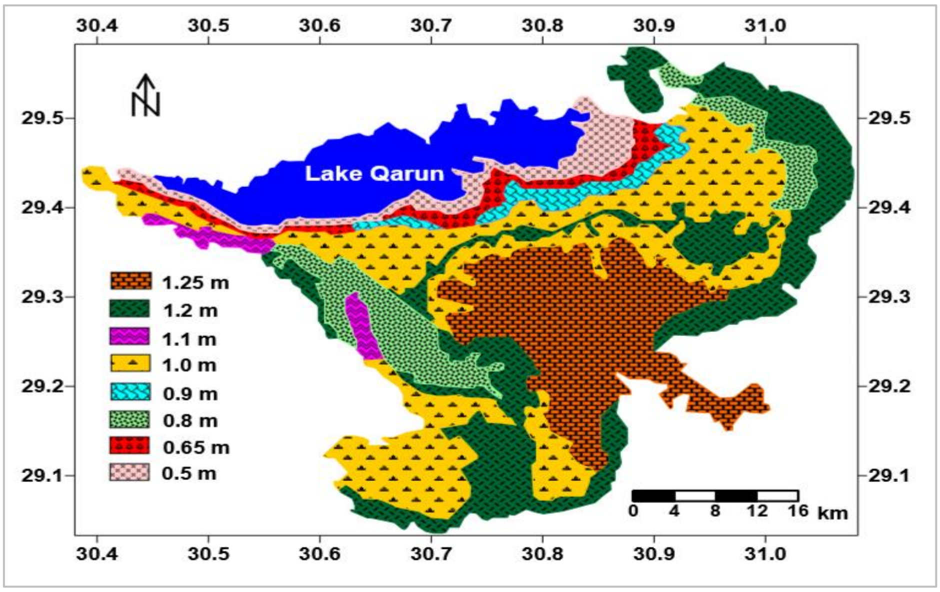

Figure 4. Water table depth map for the aquifer beneath El-Fayoum depression.

The water table level depends on the amount of water that penetrates the ground surface and reaches the upper aquifer and then flows underground through different flow paths to get finally into the lake Qarun. The flow-net analysis has been recognized as an effective method to predict the closest flow paths for water under the ground. Figure 5 gives an assumed form of the flow net patterns for water after filtration process. Authors assume that the groundwater flow is two-dimensional and the groundwater flows into the lake through the entire lake bed. The flow net patterns are used as a tool for mapping groundwater.

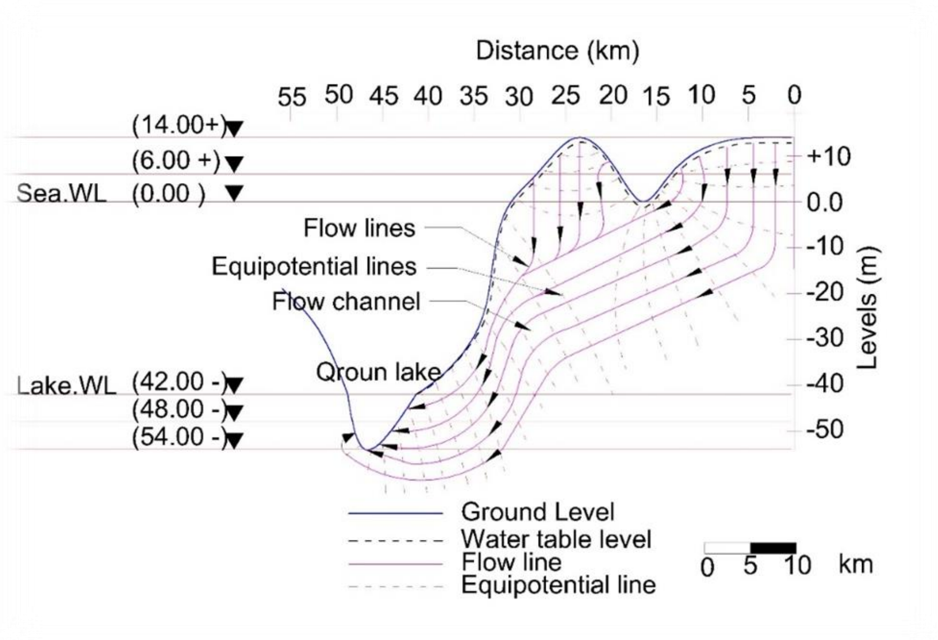

Figure 5. Groundwater flow patterns beneath El-Fayoum depression.

4. Results and discussion

The annual ground-water inflow rate was calculated from the flow-net analysis and from modeling results as 47.92 MCM/year.

The environmental and climate changes play an extremely important role in water basin management. The climate changes are closely connected to hydrology changes in the Lake Qarun. Therefore, the decrease of rainfall and runoff and increase of air temperature have a dramatic impact on the quality and renewability of groundwater. Thus, there is a compelling need to form accurate understanding of the other environmental parameters, particularly water budget components, e.g. evaporation, rainfall, runoff, outflow/inflow discharges, etc.

The evaporation rate (E) has been estimated by using meteorological data for year 2017 and Bowen Ratio Energy Budget (BREB) method. The results show that the annual evaporation rate equals 404.5 MCM.

Approximately 19.09 MCM/year have been discharged from Lake Qarun to The Egyptian Salts and Minerals Company [7].

The rainfall (P) estimation is, according to the metrological data for study region, 15.17 MCM/year. The excess water from rainfall can be entirely considered as evaporated and the runoff usually ignored for water balance calculations. The lake receives agricultural and sewage drainage water (Qi). The monthly water discharges, via El-Batts and El-Wadi drains range between 13.10 MCM in January and 48.89 MCM in September, with net annual water of 419.56 MCM. The residual amount of the water balance equation is 59.06 MCM/year. This amount resulted in increasing the water level annually by 25 cm and meanwhile increasing the surface water area (see Figure 6 and Table 1). Figure 7 shows the threatened area which will be affected by increasing water level.

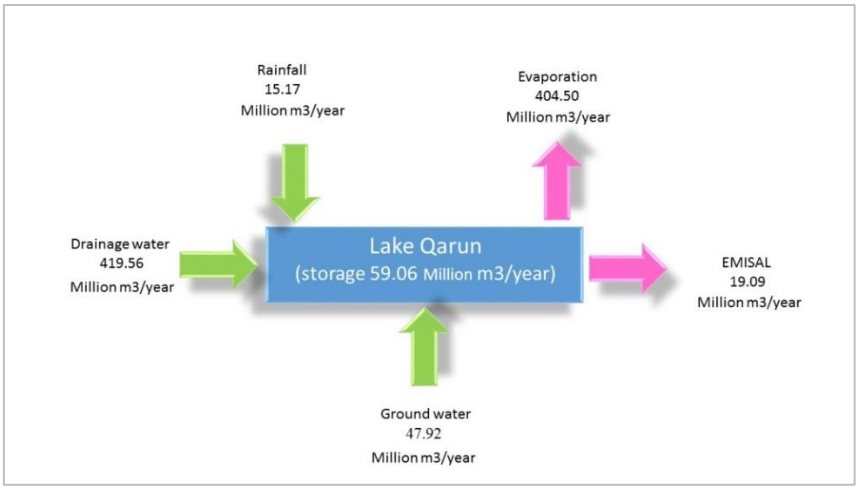

Figure 6 .Schematic diagram for the water balance for the modeled area.

The main common sources of water for MAR are river water, storm water, and treated wastewater. The irrigation system in El-Fayoum region depends on the recharge water from the Nile River. Most part of this water flows into lake Qarun as a groundwater in-flow. However, due to water scarcity, we could overcome this problem by using the treated lake water as a secondary source of irrigation water, taking into account that the Reusing of drainage waters in agriculture has some general limitations because of the high salinity, nitrate concentration and (semi-) metal and pathogen content [8].

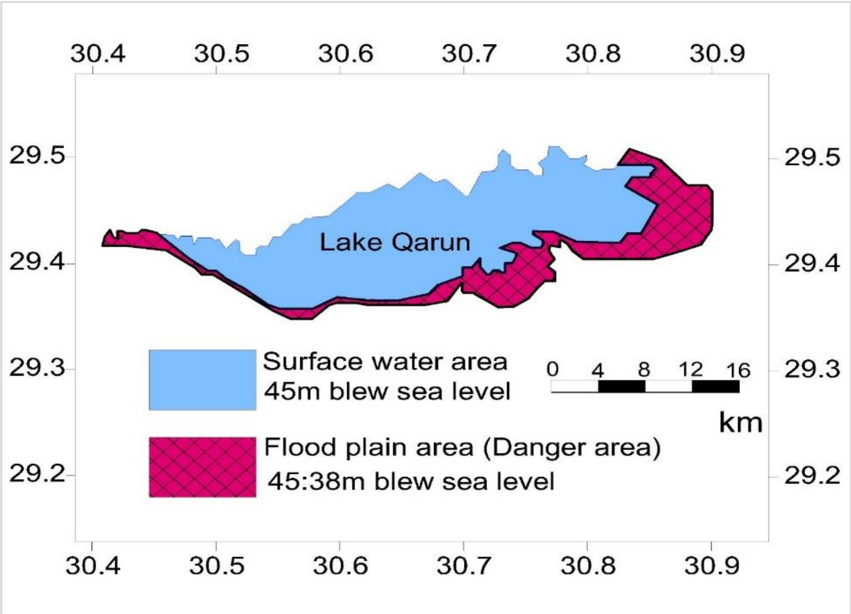

Figure 7. The threatened area will be affected by flood plain.

Table 1 .The percentage of the components for the in/outflow water balance of Lake Qarun.

Water budget component	Discharge (MCM/yr)	Inflow (%)	Outflow (%)
Drainage Inflow Water	419.56	87.0	---
Rainfall	15.17	3.0	---
Groundwater	47.92	10.0	---
Evaporation	404.50	---	95.0
EMISAL ponds	19.09	---	5.0

5. Conclusions

Nowadays, the aquifer of El-Fayoum Depression can be considered more an unintentional recharge system (from River Nile) than a true MAR system. Nevertheless, Lake Qarun has proved that it could become a MAR system for El-Fayoum Depression by using the water in the lake for irrigation after an adequate treatment. The irrigation water excess penetrates the ground surface and reaches the upper aquifer. Using treated lake water as recharging water for El-Fayum depression aquifer has many benefits not only to compensate the aquifer extraction but also to protect and conserve the water from evaporation in the lake and renew the surface and underground water stores. Then MAR is defined as the purposeful recharge of water to aquifers for subsequent recovery and/or for environmental benefits [9]. The issue is that present recharge is not planned jet but is totally leaving the cleaning of water to natural and passive infiltration processes within the aquifer.

The knowledge of the actual water balance has helped to understand the various paths and volumes of the inflow and outflow volumes. Nowadays, irrigation drainage threatens flooding the plots in the southern bank of the lake. Nevertheless, Climate change is an important factor for the future of the Nile basin, as the quantity and quality of available water resources in the river will be affected by changes in precipitation and increasing evaporation due to rising temperatures. The exact consequences are uncertain, however, and the discussion on appropriate adaptation measures within the cooperative water resource management of the Nile riparians is still at the beginning. MAR system should be considered in order to develop a sustainable Water Plan within El-Fayoum Basin.

Real and future water balance could be studied within a MAR system conception to analyze the sustainability of different interests that merge into the basin exploitation.

Aquifer recharge could be fed by the water from the agricultural drainage with and adequate treatment and balance conjunctive use of surface and groundwater resources to sustain water supplies and achieve other water management objectives such as the protection of ecosystems. Many efforts should be done to mitigate hazardous flow events, adapt to more extreme and more prevalent drought episodes while optimizing surface and underground water resources to fulfill the different need of uses (agricultural, urban and ecological) in the basin,.

6. References

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Paper for Proceedings of ISMAR10 ***Topic No: 3 (101#)***

Managed Aquifer Recharge at a Farm Level: Evaluating the Performance of Direct Well Recharge Structures

P. Soni[1], Y. Dashora[2], B. Maheshwari[3], P. Dillon[4] and P.K. Singh[2]

[1]Vidya Bhawan Krishi Vigyan Kendra, Udaipur, India; prahladsoni.baif@gmail.com
[2]Maharana Pratap University of Agriculture and Technology, Udaipur, India; dashora.yogita@gmail.com;
[3] Western Sydney University, Penrith, New South Wales, Australia; b.maheshwari@westernsydney.edu.au
[4]CSIRO Land & Water, and NCGRT, Flinders University, Adelaide, Australia; pdillon500@gmail.com
*correspondence: prahladsoni.baif@gmail.com

Abstract. A field study was carried out in the Dharta watershed, situated in semi-arid hardrock region of Udaipur district, Rajasthan, India during 2016 to 2018. In this study, we evaluated the performance of a new MAR approach that involves the use of direct well recharge structures (DWRS) to achieve local groundwater recharge. Basically, DWRS involves directing runoff from field to a nearby dug well, filtering it for suspended sediments and then discharging it directly into a well. A total of 11 DWRSs were constructed at farmers' field and in each well the discharge volume from DWRS, depth to water level in well and water quality (viz. pH, EC, TDS, Turbidity, Fluoride and *Escherichia coli*) of were monitored during the monsoon season. For each well in which rainwater was discharged from DWRS, two nearby dug wells, called control wells, were also monitored for the depth to well water level and water quality. The study shows that the turbidity of runoff was quite high for first two rain events but decreased significantly for the subsequent rain events after the establishment of vegetation. The volume of water recharged through DWRS into individual wells during the monsoon season varied with rainfall amount and intensity and ranged between 6 kL to 177 kL per well. The rise in well water levels at the end of monsoon season was higher in wells with DWRS when compared nearby control wells. The water quality analysis results showed that due to the direct and natural recharge the values of pH, EC, and TDS decreased as monsoon progressed in DWRS and control wells while the turbidity of well with DWRS slightly increased. The values of *E. coli* of water for well with DWRS were higher compared with control wells but the values were under the permissible limit. Overall, the DWRS were found to be beneficial in augmenting local groundwater supplies and can be used by small farmers with investment in the range of INR 3500 – INR 7000 (US$ 50 to US$ 100).

Keywords: Groundwater recharge; Water quality; Water level monitoring; Recharge performance; and Rainwater harvesting.

EXTENDED ABSTRACT

1. Introduction

Water scarcity has become a major problem especially in most arid regions of the world it ultimately affects food security, natural ecosystems, plant and human health (Seckler et al., 1999). Water scarcity arises due to the various anthropogenic factors and one of them is the depletion of groundwater resource. Many states in India, such as Rajasthan and Gujarat, are currently experiencing overuse of groundwater due to growing demand for irrigated agriculture and industrial use (Massuel et al., 2014) As a result, wells are being further deepened in search of groundwater. The advancement drilling technologies and irrigation pumps as well as easy access to finance have considerably contributed to the overuse of groundwater. To cope with lowering, managed aquifer recharge has become important to cope with groundwater scarcity. Managed aquifer recharge can particularly help in maintaining groundwater supplies in overexploited areas and reduce the effect of lowering groundwater level on water quality.

Groundwater supplies in hardrock areas are relatively localised when compared with alluvial areas. Managed aquifer recharge at micro-watershed level can benefit farmers at village level (Cavelaars et al., 1994). The MARVI project, Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention, has demonstrated that it is important to monitor and manage groundwater at village level, particularly in hardrock areas of India (Maheshwari et al, 2014; Jadeja et al., 2018). The overall aim of this study is to understand the effectiveness of direct well recharge structures (DWRS) to improve groundwater supplies and quality at local level. The main function of DWRS is to direct runoff from field to a nearby dug well, filtering it for suspended sediments and then discharging it directly into a well. The runoff thus discharged add to the local groundwater storage and provides additional recharge.

2. Study area

The study was carried out in Dharta watershed, which is situated in Bhindar block of Udaipur district of southern Rajasthan, India. This area lie**s** between 24° 30′ to 24° 37′ N latitude to 73° 05 to 73° 15′ E longitude. Four villages were selected i.e. Badgaon, Dharta, Hinta, and Varni for evaluating the performance of direct well recharge structures (Figure). Topography is often undulating with slope up to 2.7%. The ground elevation of the area is 465 m above the mean sea level. The average annual rainfall of the area is about 665 mm (Dashora et al. 2018) and the temperature ranges from 19° C to 48° C in summer and 3° C to 29° C during winter season. The major crops grown in the area are Maize, Wheat, Mustard, Cluster bean (Guar), Chickpea and Barley. About 25% of the total land area in the watershed is irrigated mainly by open wells and tube wells.

3. Methodology

The study was carried out during 2016-18 in four villages of the Dharta watershed, viz., Badgaon, Dharta, Hinta, and Varni. These four villages are adjoining and are within the area covered by radius of 4 km. The key steps followed in this study are as follows:

Selection of the dug wells

With a view to evaluating the performance of the direct well recharge at a farm level, a number of dug wells were selected and marked with the code numbers for identification. In the year of 2016, a total 18 number of wells were selected and out of which, six wells were selected for direct well recharge (Table 1). In 2018, 13 additional wells were selected, and out of these 5 wells were used as a recharge wells (Table 1). Thus, in 2018, there were total 11 wells used as a recharge wells and 20 wells as control. All the control wells were close in the proximity to their recharge wells.

Identification of suitable location for pits

It was considered important that the recharge pit was located close to the recharge well to reduce the cost and it was located such that the runoff can easily flow towards the pit. For this, the important consideration was the general slope of the runoff contributing area. We also had to construct a channel (0.2 m x 0.2 m) to guide the runoff towards the pit.

Pits construction and pipes installation

The pit digging work near to the recharge wells was done with the help earth moving machinery. The size of the pit varied slightly and was decided based on the runoff contributing area of the field. The average length, width, and depth of the pit were kept 1.6 m wide, 1.6m long and 1.1 deep. Once the pit was dug to the required dimensions, the masonry work was done on the four sides of the pit walls to maintain stability of pits. The bottoms of pits were cemented using the stones from a local quarry. The pit was divided into two sections by a brick wall constructed in the middle along the width of pit and the height of this middle bricks wall was kept about 2/3 of the pit depth. This division was done to allow extra deposition time of sediments in pit. To discharge runoff water from pit into recharge well, HDPE pipes were placed between pits and the wells. The pipes were installed about 0.2 – 0.3 m above from the bottom of the pit to minimize clogging of the pipe lines.

Reducing sediment discharge into wells

The runoff often carries suspended sediment particles throughout the rainy season although the concentration tends to be higher at beginning of the rainy season. It is therefore important to prevent the discharge of sediments into recharge well, otherwise they are more likely to clog fractures in wells and increase the turbidity of the well water. A simple and cost effective filter system in which we placed bricks and stone aggregates on the bottom of pit and covered it with net cloth to make sediments settle into the pit.

Installation of flow meters

Flow meters were installed between the pit and recharge well to monitor discharged water into wells. Flow meters with 50 mm diameter size were used to measure the total volume of the runoff water discharged. A total of 5 flow meters were installed in 2018. To protect the water meters from any clogging due to plant debris in runoff water, iron wire meshes were placed at the inlet of pipes. Schematic diagram of field settings of components of recharge structure are shown in Figure 2 (a) and photos of two structures are shown in Figure 2 (b).

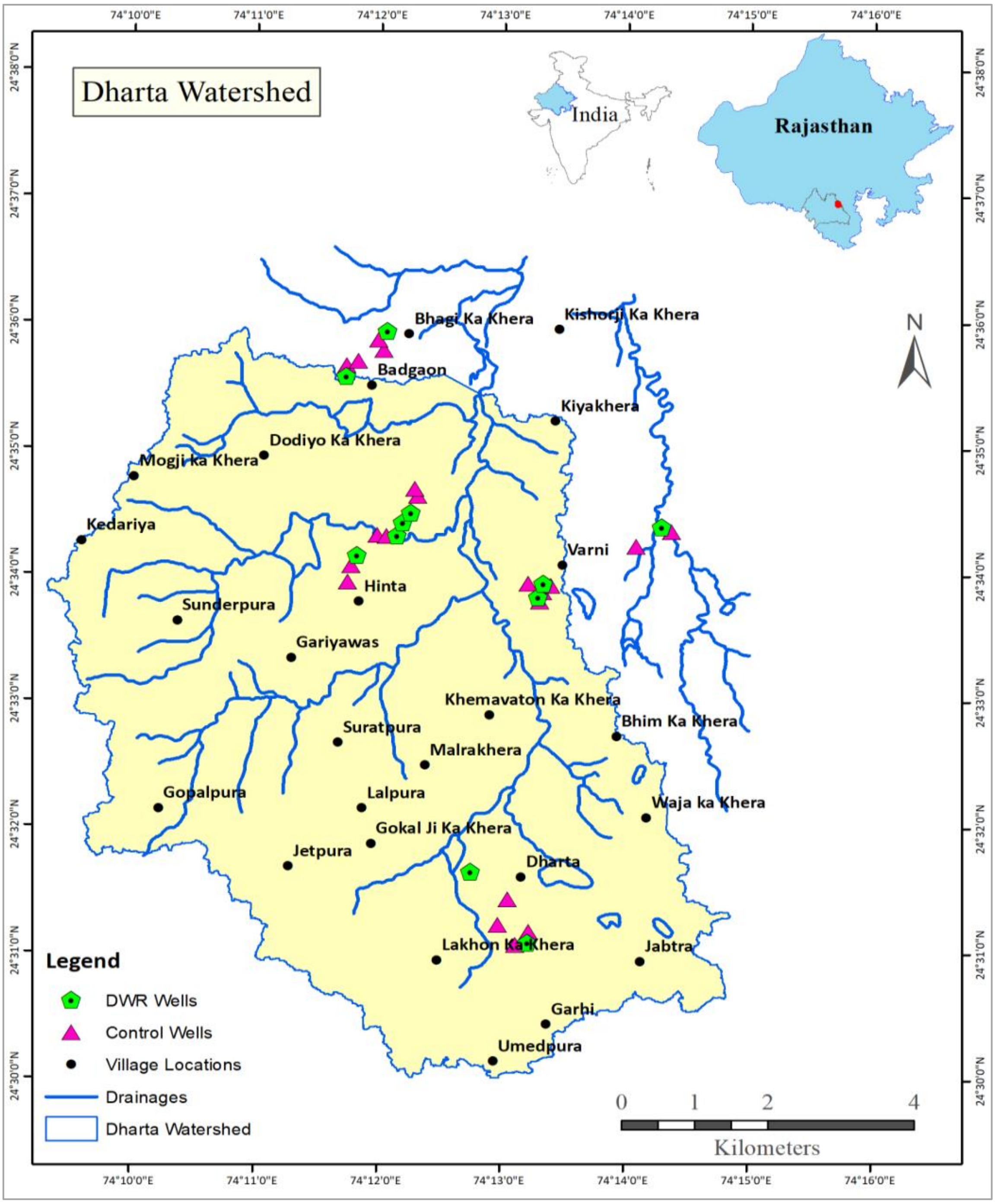


Figure1. Location map of Direct Well Recharge Structures sites at Dharta watershed.

Cost of construction

The cost of construction of the recharge pits varied depending upon the location and material used. Locally available construction material was used and well owners engaged throughout the construction process. All the cost components starting from digging pit to installing water-meter and outlet pipes was recorded. The cost of construction and installation was reliant on reachability of site, distance between pit and recharge well, construction of runoff collection field channel (wherever applicable necessary). The site specific average estimate of cost for installing DWRS is given in table 2.

Water level monitoring

The water level monitoring was done at weekly interval and was commenced a few weeks before monsoon and was continued till the end of the monsoon season (Table). Ordinary measuring tape with a float at its end was used for monitoring the water level in open wells. The dial pad reading of the flow meter was recorded at the time of installation, and subsequently after every runoff event. The water level data obtained during weekly monitoring were used to plot the different trend graphs, water level fluctuations and other analyses.

Water quality monitoring

Collection of water samples

The water samples were collected at weekly interval basis to analyse pH, EC, TDS, Turbidity and Fluoride, whereas for *E. coli* samples were collected at monthly interval basis. First five parameters (pH, EC, TDS, Turbidity, and Fluoride) were tested at field site, while the testing of *E. coli* was done in the laboratory.

Instrument used for water quality monitoring

Aquaread instrument was used to test pH, EC, TDS, and Turbidity, whereas HACH Dr890 instrument was used to test Fluoride content, and MacConkey Agar (MAC) method was used to grow *Escherichia coli* bacteria. For the bacteriological analysis, standard lab procedure was used, the MAC flasks, spreader and petri-dishes were sterilized in autoclave at 120 ℃ at 15 psi for 15 minutes, after which spreading of field samples was done under laminar flow conditions. The MAC was poured into sterilised petri dishes on which e-coli water cultured. This agar provides solid medium on which selected bacteria are able to decompose agar. MAC is a selective and differential medium designed to isolate enteric based on their ability to ferment lactose. It contains bile salts and the dye crystal violate, which inhibit the growth of gram positive bacteria and select for gram negative Organisms present in ground water samples of DWRS wells and control wells were tested for organisms which will ferment lactose to produce end products which reacts with the pH indicator **neutral red**, and will produce a pink colour colony (Microbiology lab tutorials).

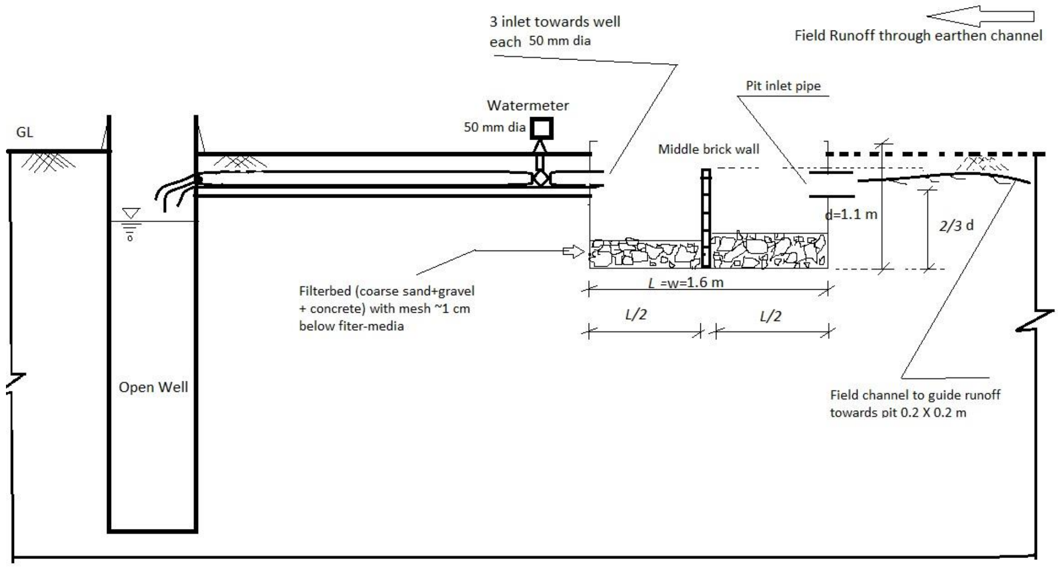
Rainfall monitoring

To evaluate the effect of the runoff on the water level fluctuation of the wells, rainfall monitoring was done on daily basis. In all four villages, rain gauges were installed, and centrally, automatic weather station was used to take daily rainfall readings and the other weather parameters. The rainfall data obtained were used to correlate with the water table level and the influence of the recharge pit at specific rainfall event.

Table 1. Design details of DWRS pits.

DWRS code	Length, m	Width, m	Depth, m
H6	3.35	1.9	1
B21	1.15	1.2	0.7
B40	2.3	2.3	1.1
H21	0.9	1.35	1.15
H22	1.2	1.4	1.1
H23	1.4	1.55	1.2
D1	1	1.37	1.22
D14	1.34	1.13	1.22

V28	1.4	2.4	1.3
V43	1.9	1.9	1.2
V47	1.9	1.8	0.85



(a)

(b)

Figure 2. View of DWRS installed in the study: (a) A cross-sectional view of DWRS (not to scale); and (b) Photographs of two sample structures constructed in the study area.

Table 2. Total well depths of Recharge and Control wells.

Year	**DWRS well**	**Total well depth, m**	**Control well (1)**	**Total well depth, m**	**Control well (2)**	**Total well depth, m**
2016 –17	H6	19.6	H4	24.5	H5	17.65
	H21	28.9	H30	29.2	H10	25.4
	B21	20.5	B22	23.2	B44	20.6
	B40	18.45	B41	23.2	B50	27.9
	V43	30.45	V44	35.8	V45	33.1
	V47	27.1	V48	28.45	V49	30.1
2018	H22	21.2	H30	29.2	H10	25.4
	H23	18.3	H25	24.3	H26	21.8
	V28	19.2	V29	19.1	V30	22.7
	D1	32.1	D11	18.95	D20	19.6
	D14	31.2	D13	22.8	D15	31

Table 3. Installation cost of a DWRS structure at field site.

Items	Quantity	Cost, INR
Hiring cost for earth moving equipment	1 hour	800
Stones	1 trolley load	1,300
Coarse sand	¼ trolley load	600
Cement bag	2	600
Bricks for partition	50	250
Stone aggregates	¼ trolley load	300
Pipes (m)	3	600
Builder and labour	1+1	1,600
Total		**6,550**

4. Results

The results of the performance evaluation of DWRS at a farm level are presented and discussed as below.

Head rise comparison between direct recharged (DWR) and control wells

The comparison between the ratio of head rise in DWRS wells and mean head rise in control wells was done, before and after construction of the DWRS. Figure 311 revealed that DWRS wells show the significant increase in the head rise. The difference in the ratio of head rise in DWRS varied from -0.07 to 1.74 over the mean of the controls. The maximum head rise observed in the DWRS V28 (1.74) followed by D1 (1.08), D14 (0.84), and V47 (0.78). The DWRS H6, H23, and H22 showed 0.51, 0.53, and 0.54 found no major head rise difference between them. DWRS V43 indicated 0.44 ratios of head rise and next to this B21 showed 0.11. While on DWRS B40 and H21 observed negative ratio of head rise 0.07 and -0.33, shows that these two DWRS were not benefited by the DWRS structures.

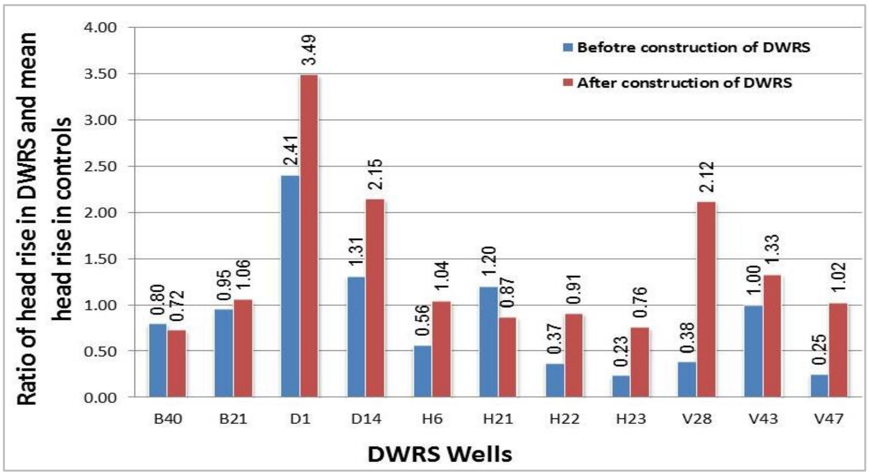


Figure 311. Ratio of head rise in DWRS wells and mean head rise in control wells before and after construction.

Flow meters were also installed on five DWRS structures in year 2018. The V28 DWRS of Varni village, captured maximum volume of water (176 kL), followed by H23 (Hinta) and D14 (Dharta) which is presented graphically in figure 4 for better understanding.

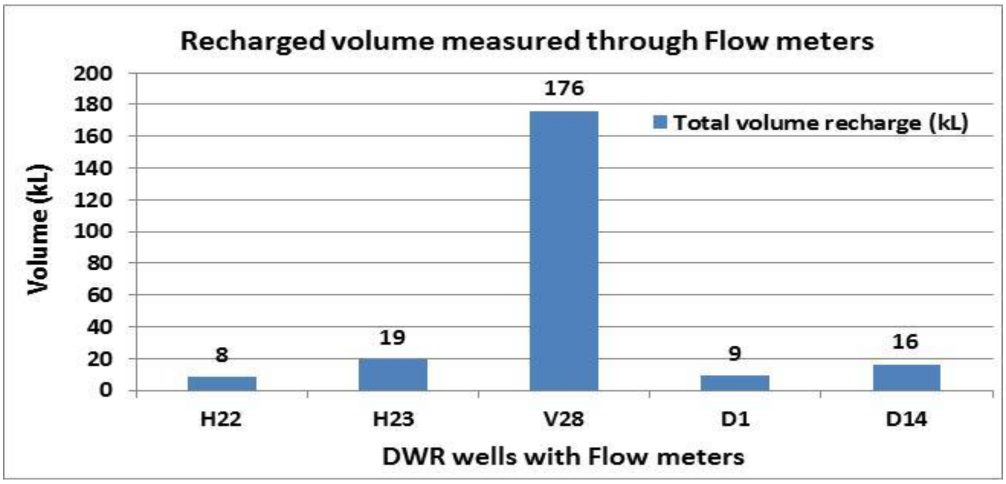


Figure 4. Direct Recharge volume measured by flow-meters.

Table 4. Mean of water quality parameters Recharge and Control wells in study villages.

	Badgaon		Dharta		Hinta		Varni	
Parameters	**R[a]**	**C[b]**	**R[a]**	**C[b]**	**R[a]**	**C[b]**	**R[a]**	**C[b]**
No. of wells	*2*	*3*	*2*	*4*	*4*	*6*	*3*	*6*
pH	8.06	7.90	8.00	8.18	7.95	7.99	8.05	8.04
TDS , mg/l	1751	2671	1675	1892	2493	2214	2672	2227
Turbidity, NTU	33	51	48	66	65	63	30	29
Fluoride, mg/l	0.96	0.86	0.77	0.94	1.13	0.83	0.75	0.87

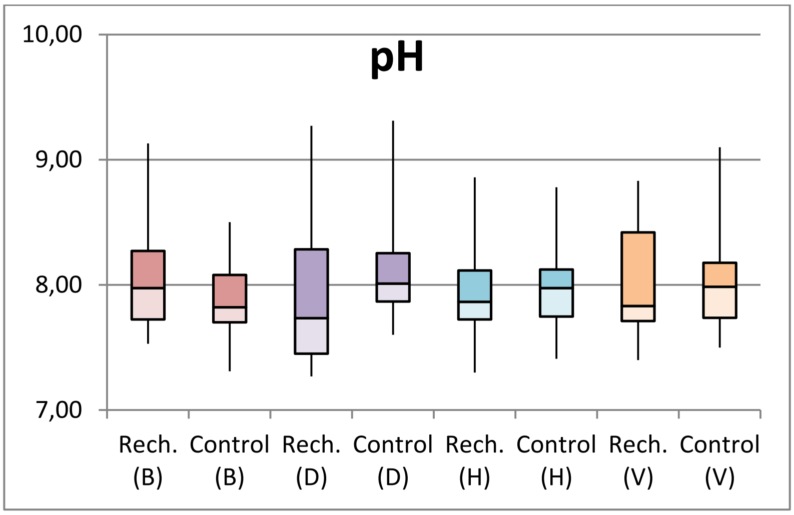
R[a]- Recharged well; C[b]- Control well

Water quality

pH

The box plots pH values are presented in 5 (a) with overall values for recharged and control wells of each village. The varying shape of the box plots for each villages are example of variation in data set with median values of pH 8 for recharge wells (Badgaon), control wells of Dharta, Hinta, Varni whereas remaining villages have median values of pH less than 8. The mean pH values of all the DWRS and their controls were found below the permissible limit (7.5-8.5) of BIS (Bureau of Indian Standards).

Figure 5 shows the percentage of samples meet the BIS criteria. For DWRS and control wells, the range of the BIS criteria was 27% to 100% and 25% to 55%, respectively. The DWRS meet 100% while in control only 55% samples were meet the BIS criteria in June 2015 and Oct 2018. In 2017, the % of meeting criteria was close to the same in both of the DWRS and controls.



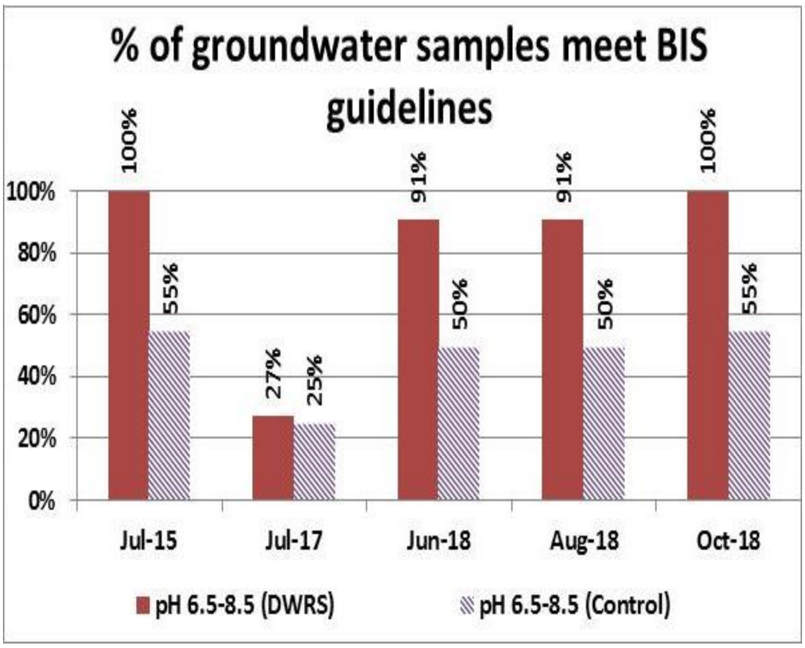


Figure 5. Box-plots of pH village wise and per cent of samples meet BIS guideline.

TDS

The overall values of TDS in 2015, 2017 and 2018 are represented by box plots in Figure 6(a) of all the DWRS and control wells for each village in mg/l respectively. In July 2015, about 82% samples met BIS criteria for TDS but there number reduced to almost half in June 2018. In the month of August 2018 the higher number of wells (both DWRS and Control) was within BIS limits, but as the discharge started in *rabi* season, the TDS values in both DWRS and control wells increased. This resulted in reduced samples approaching BIS criteria (45% in DWRS and 35% in control wells) (Figure 6(b)).

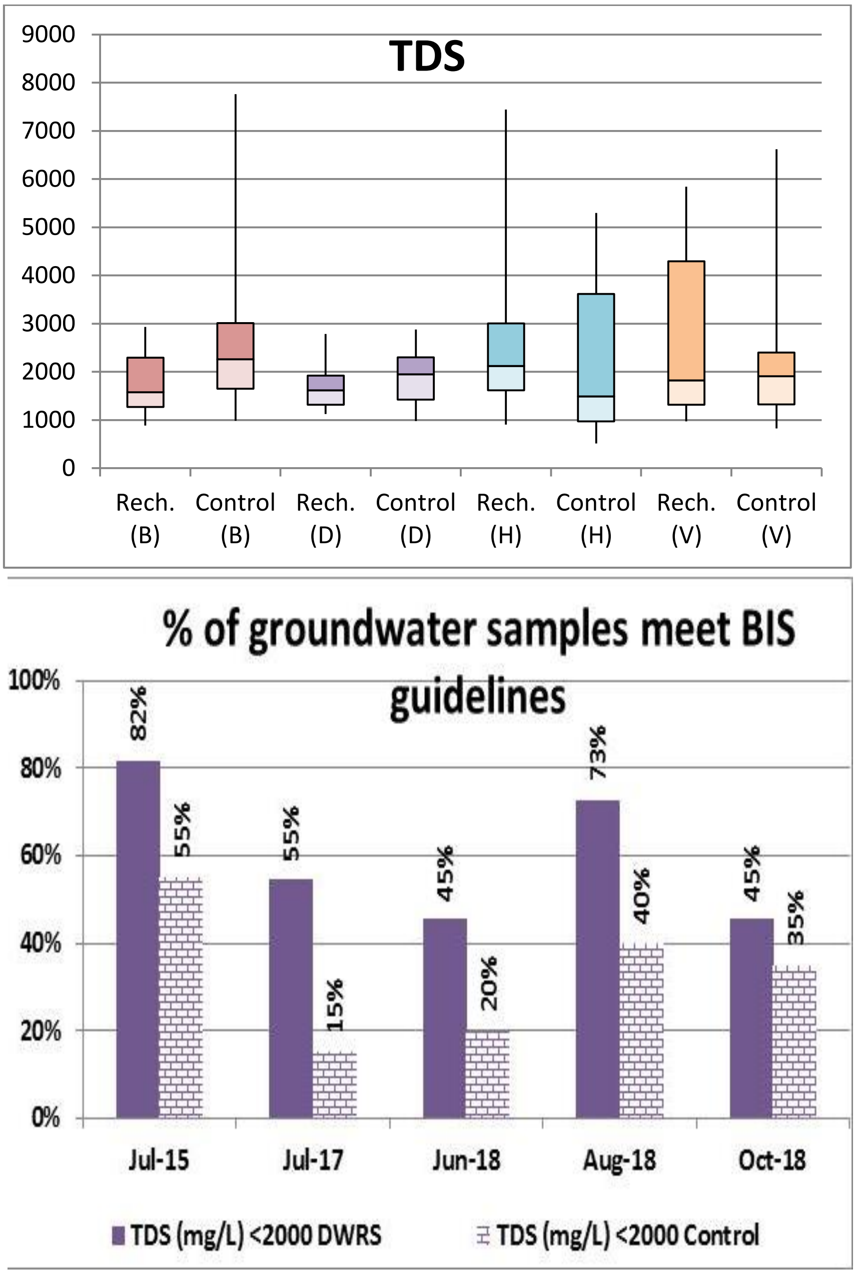


Figure 6. Box-plots of TDS and % of samples meet BIS guideline.

Turbidity

The overall values of Turbidity in 2015, 2017 and 2018 are represented by box plots in Figure 6 Figure 7(a). As recharged wells of Badgaon (shown as Rech. (B) in graph); both type of wells of Varni, (Rech. (V)); Control (V) are showing high level of agreement with each other, respectively. From the Table 4, it can be seen that the mean values of the Turbidity of DWRS and control wells ranged from 30 to 65 and 29 to 66 NTU respectively. As illustrated in Figure 7 (b), from year 2015 to 2018, none of the samples met the BIS criteria except in June (DWRS 27% and control 20%) and October (control 10%) 2018.

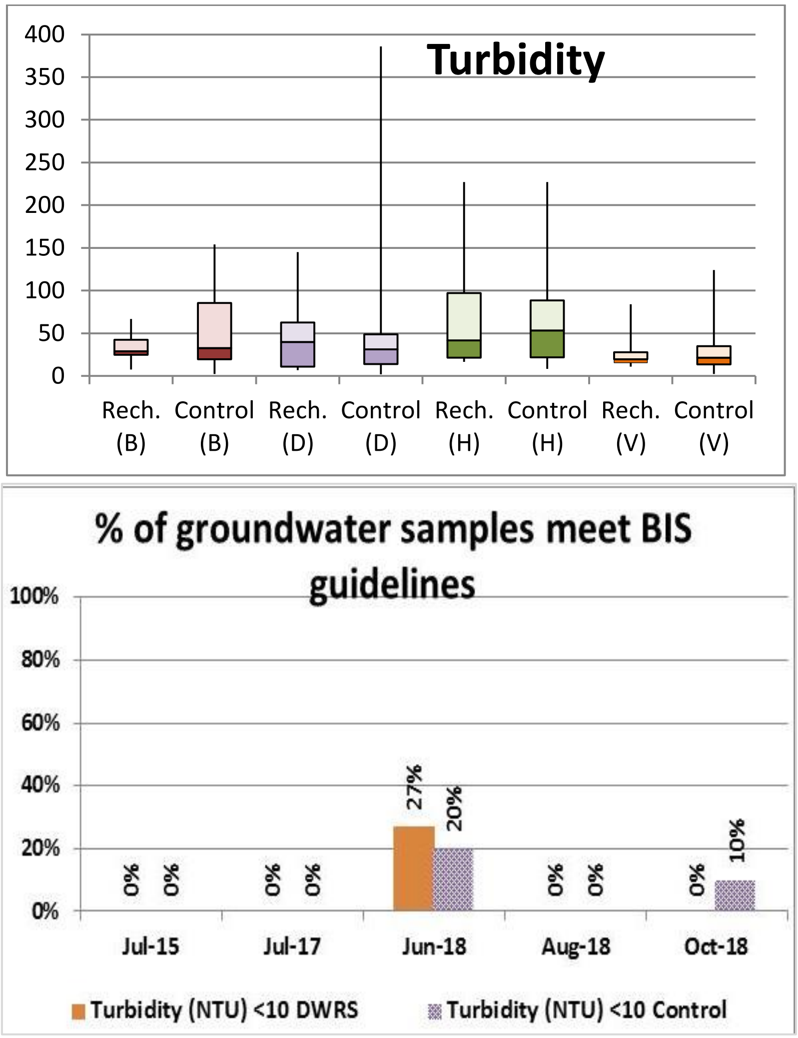


Figure 7. Box-plots of Turbidity and % of samples meet BIS Guideline.

Fluoride

From the Table 4 and Figure 8, it can be seen that the average values of Fluoride of DWRS and control wells ranged from 0.75- 1.13 mg/l and 0.83-0.94 mg/l respectively. Box plots of Fluoride present in recharge and control wells varied hugely which indicated close to permissible limit value (1.4). The % meet criteria of DWRS was 73% in 2017, and slightly increase up to 82% in June 18 and found 100% at the end of the monsoon in 2018; while in case of control only 55% and 50% samples met the BIS criteria in 2017and 2018 respectively.

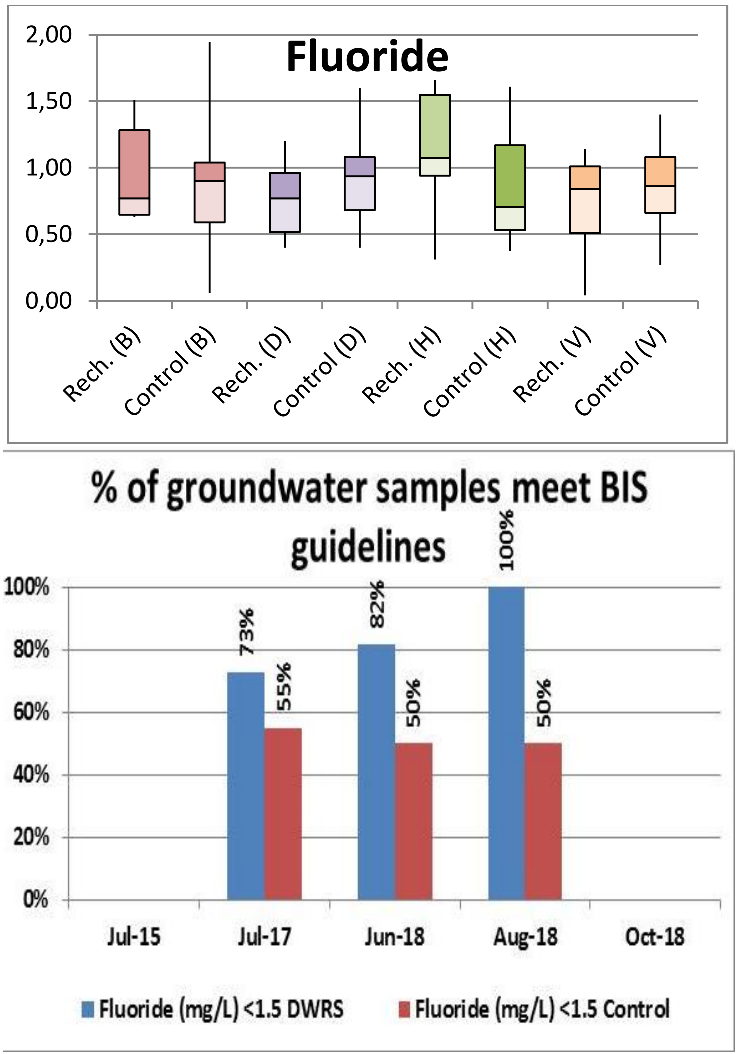
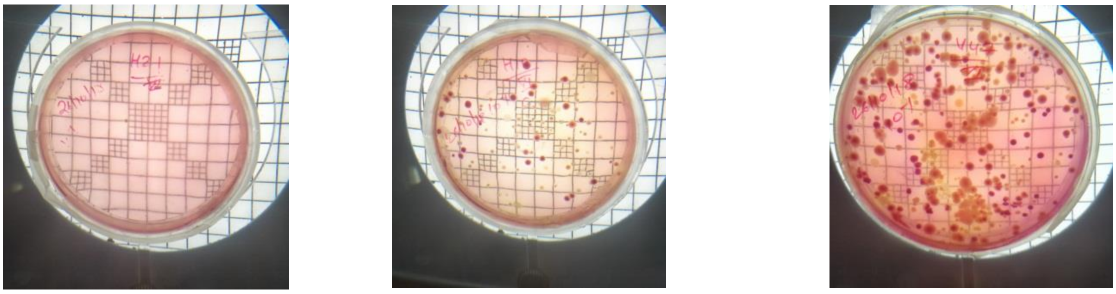


Figure 8. Box-plots of Fluoride and % of samples meet BIS guideline.

E. coli

The presence of *E. coli* bacteria in the drinking was indicates that the water was contaminated. In Figure 9 (i, ii & iii) shows different samples poured in petri dishes, growth on the plates indicates the organism, is not inhibited by bile salts and crystal violate and is a gram-negative bacterium. The pink colour of bacterial colonies (Figure 9) indicates *E. coli* is able to ferment lactose as discussed in methodology section. The laboratory test was done to identify either the wells which were recharged with DWRS were influenced by the *E. coli*. The water samples for both DWRS and control wells were tested and found that not only the wells which were recharged but also control wells has shown the presence of the *E. coli*.



(i) No E. Coli colonies (ii) Few number of E. coli colonies (iii) Severe number of E. coli colonies

Figure 9. Presence of *E. coli* (CFU/ml) in different petri dishes.

0 clearly shows that initially in the month of August, only 9 % DWRS well samples were found free from the bacteria. Later on, in the month of September all the DWRS samples were found contaminated by the *E. coli* bacteria. During the month of September all DWRS well samples were infected. And gradually after monsoon 82 per cent samples were free from the bacterial colonies. Initially, it was predicted that the water samples of the control wells would be free from the bacteria but the water samples of these control also shown the presence of the *E. coli*. Initially 40% control samples has not shown the bacterial presence, in the next test found only 5% samples were free from the contamination. At the end of the monsoon 80% samples were found contaminated by the Escherichia coli in control. The BIS Standards for Drinking Water (2012) for *E.coli* are "these shall not be detectible in any 100mL sample".

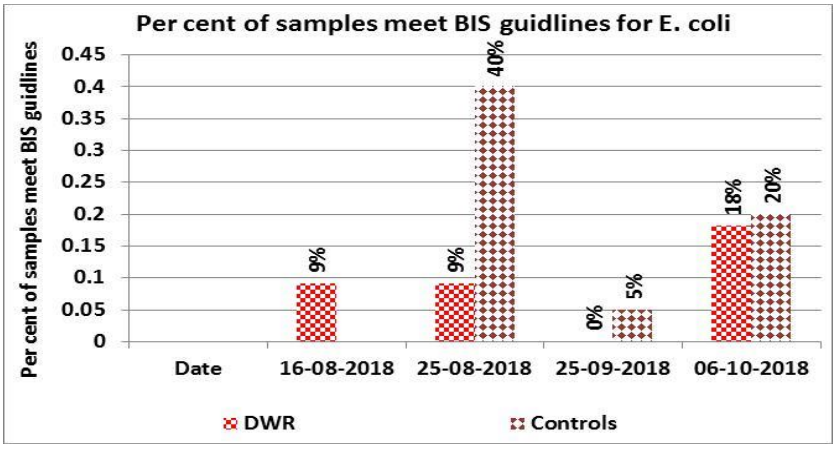


Figure 10. Percentage of GW samples that meet BIS guidelines for *E. coli.*

Figure 12 shows the box plots of *E. coli* log_{10} CFU/ml variability in bacterial growth and found that the range of infestation in all DWRS and control wells was 2.77 to 3.22 and 2.35 to 3.10, respectively. The data revealed that both DWRS and control well were found infected by the E.coli and it was also noticed that the control wells which does not have well-constructed parapet, influenced by the bird droppings, rotten plant debris etc. create the possibility of the *E. coli*. As Furthermore, there is evidence in the literature that the survival and transport of *E. coli* in the subsurface is controlled by various factors, such temperature, rainfall, soil type, porosity, and soil water content (Federle et al. 1986).

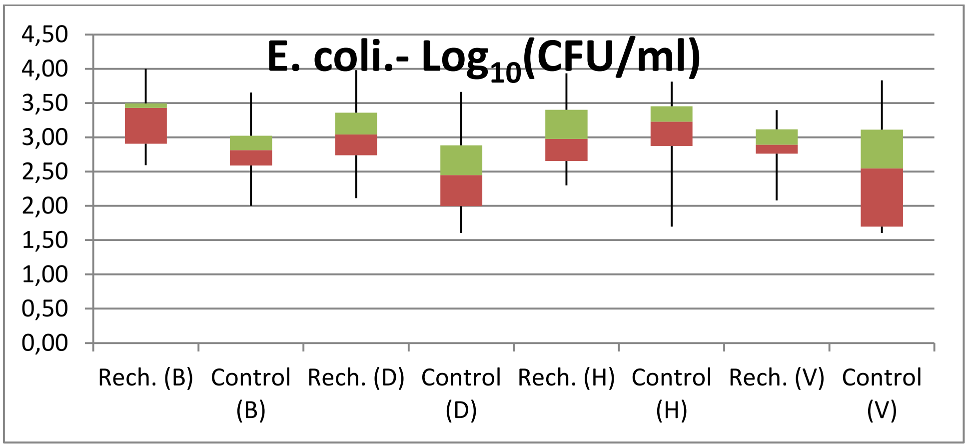


Figure 12. Box-plots of *E. coli* Log_{10} (CFU/ml).

Clogging

The runoff water was filtered before redirecting it in to the recharge well was done to reduce the blockages of fractures (Figure12), to retain suspended sediments outside and to improve the groundwater quality. In the study it was observed that initial two to three shower of the rainfall the surface water carries suspended fine silt particles and other organic plant materials including rotten leaves and plant debris with it. The coarse sand and gravels retained the suspended silt and iron wire mesh kept rotten plant debris outside. It was also observed that timely manual cleaning of the pit viz. removal of the silt; plant debris was an important thing to reduce any clogging of the pipe lines.

According to Dillon and Pavelic 1996 in Australia, where stormwater has been seasonally injected into aquifers, pathogen attenuation rates in aquifers are adequate for irrigation use and generally also meet local requirements for potable use of recovered water.

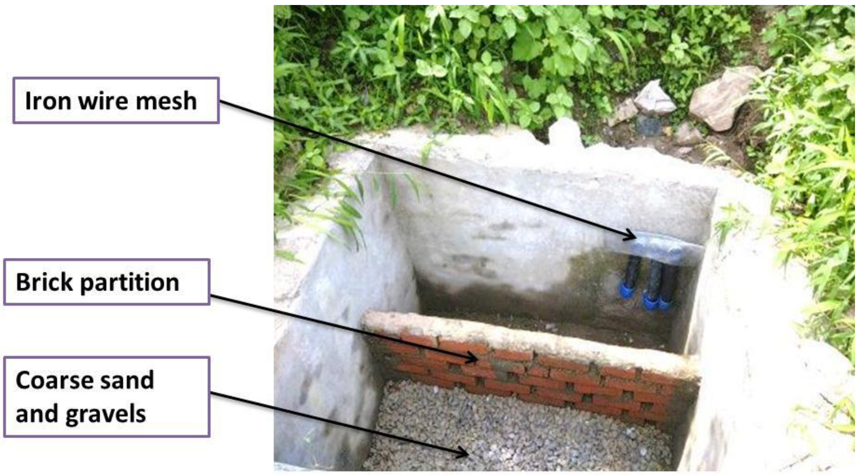


Figure 12. Recharge pit with filters

Dillon and Pavelic (1996) and Dillon et al. (1997) suggested that in Australia stormwater runoff and treated municipal waste-water effluent are injected into brackish aquifers to produce water for irrigation by pumping from the same wells. Clogging is then alleviated by a combination of low-cost water treatment and well redevelopment, and groundwater quality is protected. Baveye et al. 1998 reported that the main problem in infiltration systems for artificial recharge of groundwater is clogging of the infiltrating surface (basin bottoms, walls of trenches and vadose-zone wells, and well-aquifer interface in recharge wells), and resulting in infiltration rates. Clogging is caused by physical, biological, and chemical process. For surface infiltration systems, clogging is controlled by periodically drying the basins or other infiltration facilities, thereby letting the clogging layer dry, decompose shrink, crack, and curl up. This removal is done mechanically with scrapers, front-end loaders, graders, or manually with rakes.

6. Conclusions

In this study, we evaluated the effect of Direct Well Recharge Structures (DWRS) on the water level variation and quality of recharged water in wells as compared to nearby control wells. Direct Well Recharge Structures as a part of managed aquifer recharge technique at micro scale (farm level) was evaluated for the first time in semi-arid region of Rajasthan state which is facing problem of groundwater over-exploitation. Total 11 structures were constructed, six in 2016 and additional five in 2018 to capture runoff that overflowed from farms, and after filtration this runoff was discharged into well using plastic pipes.

The study reveals that wells with DWRS have shown increase in water level when compared with control well water levels. Turbidity values in both types of wells were above the permissible limit of BIS standards and control wells had higher turbidity recorded more as compared to DWRS wells. This shows that the filter system used in DWRS was effective.

The study shows that the turbidity of runoff was quite high for first two rain events but decreased significantly for the subsequent rain events after the establishment of vegetation. The volume of water recharged through DWRS into individual wells during the monsoon season varied with rainfall amount and intensity and ranged between 6 kL to 177 kL per well. The rise in well water levels at the end of monsoon season was higher in wells with DWRS when compared nearby control wells.

The water quality analysis results showed that due to the direct and natural recharge the values of pH, EC, and TDS decreased as monsoon progressed in DWRS and control wells while the turbidity of well with DWRS slightly increased. The values of *E. coli* of water for well with DWRS were higher compared with control wells but the values were under the permissible limit. Overall, the DWRS were found to be beneficial in augmenting local groundwater supplies and can be used by small farmers with investment in the range of INR 3500 – INR 7000 (US$ 50 to US$ 100).

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Paper for ISMAR10 symposium. ***Topic No: 3 (192#)***

Tunisian experience in managed aquifer recharge by hill dam water release: case of some groundwater flow systems in North of Tunisia

Anis Chekirbane[1,*], Dorsaf Aloui[1], Insaf El Euchi[1], Sabrine Mejri[1], Samia Khadhar[1], Fethi Lachaal[1], Maki Tsujimura[2], Adel Zghibi[3] and Ammar Mlayah[1]

[1] Laboratory of Georesources, Water Research and Technologies Center, Borj Cedria Technopark, Tunisia;
[2] Faculty of Life and Environmental Sciences, University of Tsukuba, Japan
[3]. Faculty of Sciences of Tunis, University of Tunis El Manar, Tunisia
*Correspondence: a.chkirbene@ecopark.rnrt.tn ; Tel.: +216 23 482 882

Abstract: In addition to their agricultural role, Tunisian hill dams provide important water volumes for Managed Aquifer Recharge through water release in wadis such as the cases of Wadi Khairat in Sousse prefecture. The aim of this study is to evaluate the Tunisian experience in MAR throughout assessing the efficiency of water release from hill dams for the artificial recharge of the shallow stressed aquifers. Frequent field observations were conducted between 2013 and 2016, and during them, physical and geochemical parameters of stream, dam and well waters were measured. MAR efficiency is firstly assessed basing on WTF method. Furthermore, based on the geochemical and isotopic data, PCA and EMMA model were used to calculate the flux exchange between stream and aquifer. Results show that dam water release is playing an important role in aquifer recharge and its contribution exceeds 70% in some locations. Recharge amount is clearly depending on the released volume, climatic conditions and wadi lithology and morphology. The present MAR method is more efficient in Wadi underlying aquifer. This concept is strongly encouraged to be applied in stressed aquifers where an excess of surface water might exist during rainy periods in order to guarantee the sustainability of these resources.

Keywords: Managed Aquifer Recharge; MAR; hill dam; Tunisia.

1. Introduction

As the water demand is continuously increasing with increased population, water availability is becoming a crucial concern. Thus, understanding the complex interactions between the different components of the water cycle is necessary in order to regulate and control their flux exchange, to cope with their rarity and to ultimately insure their sustainability. In arid and semi-arid regions, surface water bodies and groundwater are interacting in a variety of geographic landscapes. Aquifer sustainability is crucial and induced recharge is the most important method to increase groundwater sustainable yield [1-2]. Managed Aquifer Recharge (MAR) as intentional storage and treatment of water in aquifers [3]. MAR can constitute in arid and semi arid regions an effective mean to increase groundwater reserves and an economic and social feasible solution for sustainable management of water resources [4]. Dam water release into rivers is one of the commonly used techniques of groundwater artificial recharge. Discharged dam water into dried river beds or *wadis* penetrates the permeable layers and replenishes shallow alluvial aquifers [5].

Several authors studied the groundwater recharge efficiency of released dam water in rivers and wadis. Martin-Rosales et al. [6] quantified recharge by estimating the infiltration capacity of the river bed by infiltrometer tests in south-eastern Spain Alderwish [7] quantified groundwater recharge from wadi in Yemen using simple water balance approach. Zammouri and Feki [8] computed the river reach water balance to deduce the infiltrated water amount throughout wadi bed in Ogla and Essahel watershed in northeastern of Tunisia. Dahan et al. [9] used a geophysical method (flexible time domain reflectometry probes) to measure the temporal variation in vadose zone water content as indicator of aquifer recharge in hyper arid zone in Namibia. Scanlon [10] used chemical and isotopic tracers to qualitatively assess the role of river water in groundwater recharge. Although the diversification of these methods, exact quantification of recharge from hill dam water release is still a scientific and technical challenge.

In Tunisia, groundwater artificial recharge has become a priority in water management plans since 1970s. Since this date, several techniques are adopted and most of them are using different setups to infiltrate surface water into aquifers. The commonly used techniques are dam water release, check dams, injection wells and recharge basins. The total recharge amount in Tunisia is estimated to range between 14 and 66 millions m^3/yr in the period 1992-2015 [11]. In addition to their agricultural role, hill dams provide important water volumes for MAR (36%) [11] through water release in wadis such as the cases of Wadi Khairat in Sousse prefecture. Khairat aquifer is subject of intensive exploitation for irrigation and drinking purposed of Enfidha region, Sahel of Tunisia. As tentative remedy, artificial recharge strategy was implemented since 2002 basing on water release from the hill dam of Wadi Khairat. Previous studies have focused only on qualitative assessment of this recharge technique impact on groundwater resources [12-13].

This study was carried out to demonstrate the impact of hill dam water release as a method of MAR in improving the groundwater quantity, quality and livelihood, and also to present a case study (pilot Tunisian case of MAR by hill dam water release) from Wadi Al Khairat watershed, where a quantitative approach of recharge amount was performed.

2. Materials and Methods

2.1. Study area

This study was conducted in Khairat Watershed in Enfidha region, Sahel of Tunisia. The Khairat River has an ephemeral water flow and it is located in the eastern flank of the Tunisian Dorsal between latitudes 36°5′ and 36°10′N and longitudes 10°10′ and 10°28′E (Figure 1). Its elevation ranges between 110 m in upstream and 0 m in downstream coastal region and a mean average precipitation (2003 to 2016) of 354 mm [19]. The geology of this area is dominated by tertiary and quaternary deposits. A hydraulic threshold subdivides the reservoir in two units (Figure 2): (1) Ain Garci (upstream) and (2) Enfidha (downstream). Ain Garci unit constitutes an underflow aquifer mainly composed of alluvial deposits, sand and clay with a thickness reaching 100 m. The transition zone (threshold) shows limited thickness of the aquifer (less than 25 m) due to the ascent substratum composed by Vindobonian marls [14]. Enfidha unit consists of a multilayered system composed of a first shallow horizon of alluvium, then a second horizon of sands, pebbles and gravel and finally a third layer which constitute the substratum composed by clay and marls [15].

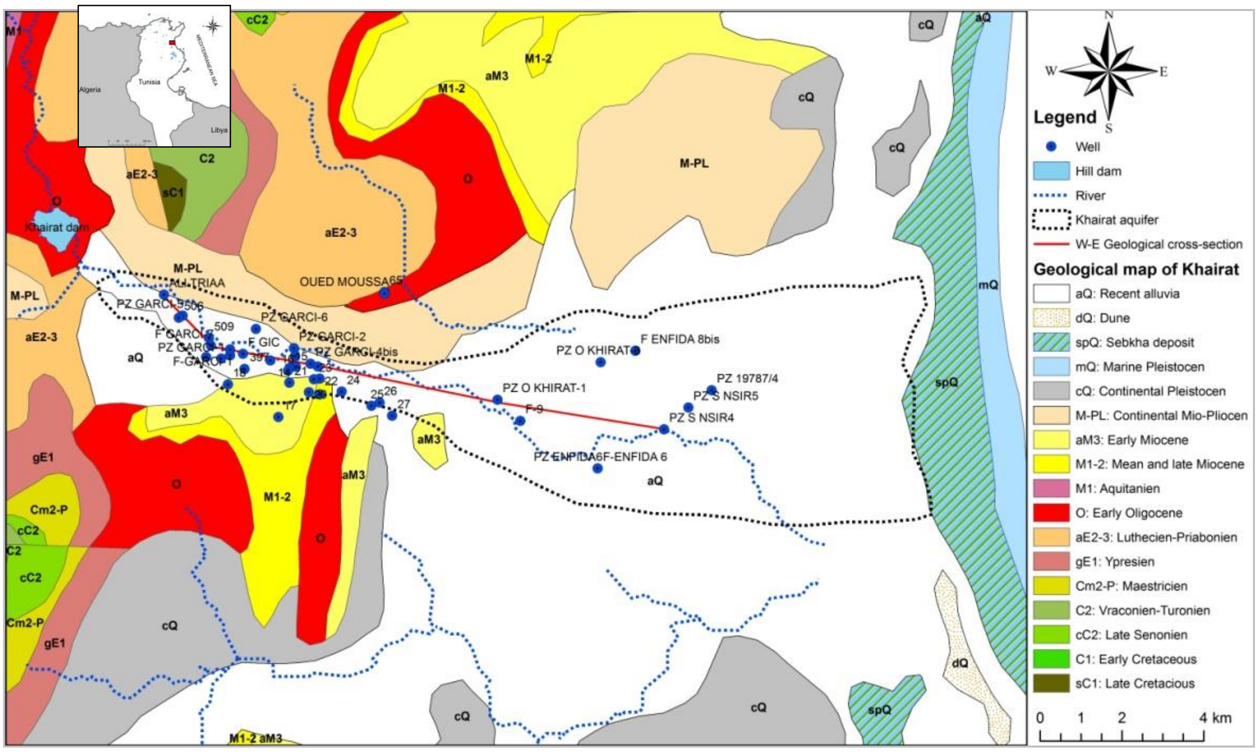


Figure 1. Study area location and its geological settings.

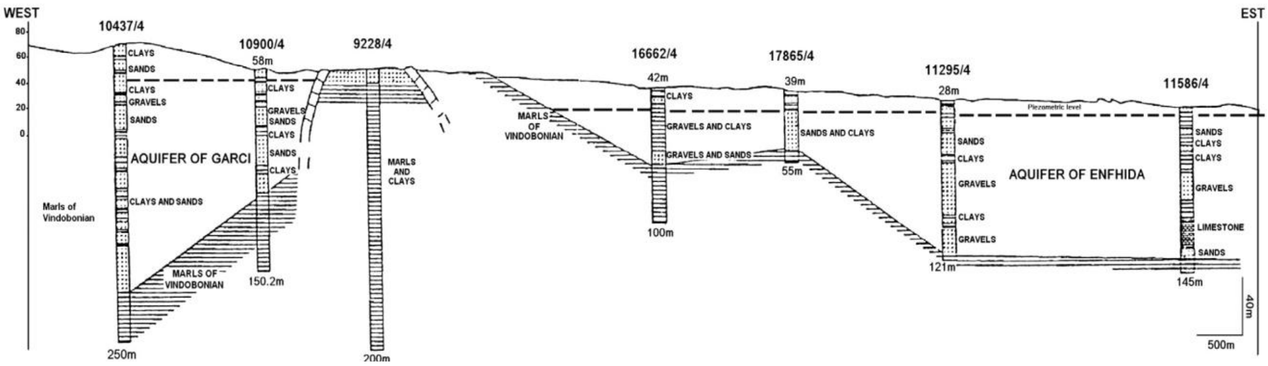


Figure 2. Hydrogeological W-E cross section through the aquifer of El Khairat [14].

The total renewable resource of Khairat aquifer is estimated to 7 Mm^3/yr [14] primarily used for drinking water supply and secondly for irrigation. MAR was implemented after the construction Khairat hill dam in 1991. Dam water is directly released in the stream bed where a succession of small check dams is established along the wadis to enhance the water infiltration.

2.2. Field monitoringand data acquisition

Frequent field observations and monitoring were conducted from 2013 until 2016. During the field surveys, physical and geochemical parameters of dam, Wadi water and groundwater were measured. The non-conservative and physical parameters (pH, temperature, electrical conductivity and groundwater level) were measured in-situ. Wadi water velocity was measured using field current-meter. Water samples from Khairat dam, river and wells were taken. Major anions have been analyzed by ion liquid chromatography and major cations were analyzed by ICP-MS. Stable isotopes (^{18}O and ^{2}H) were analyzed using an isotopic liquid water and vapor water analyzer at the Terrestrial Environmental Research Center of Tsukuba University, Japan. Stable isotopic compositions are reported in the usual δ notation in which δ is equal to (Rsample /

Rstandard – 1) 1000, where Rsample and Rstandard represent the ratio of heavy to light isotopes of the sample and standard, respectively.

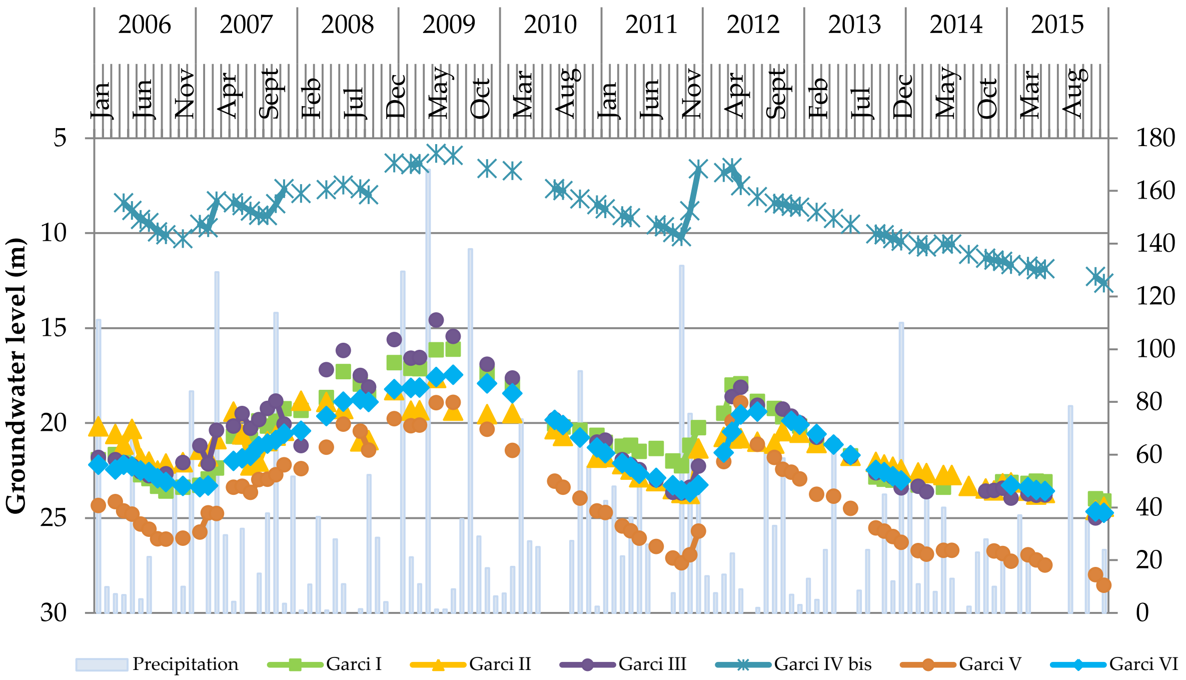
3. Results and discussion

3.1. Use of WTF to asses MAR impact

The water-table fluctuation (WTF) method provides an assessment of groundwater recharge by analysis of water-level fluctuations in observation wells. The method is based on the assumption that a rise in water-table elevation measured in shallow wells is caused by the addition of recharge across the water table [16]. Ten years (2006 – 2016) observation data including Khairat aquifer piezometric fluctuation and records of the Khairat hill dam water release are used to assess the recharge efficiency. MAR operation has started in early 2007 with a total released volume of 7.9 Mm^3. Most of the piezometers (Garci 1, Garci 2, Garci 4bis, Garci 5 and Garci 6) have registered a rise between 1.6 and 4.1 m by the end of 2007 (Figure 3).

The period of 2008 – 2009 is characterized by a general groundwater level increasing between 1.2 and 2 m. This rise is due to the conjunctive effect of MAR and precipitation. However, from the second half of 2009 until 2011, there is a period of rainfall deficit associated with a cessation of releases, causing a long period of piezometric decline with a uniform rate and amplitude almost identical for all piezometers (-4 m). After the floods of October-November 2011, a piezometric increase is observed which reached 2 m during just two. This rise was the combined result of the dam water releases and important rainfall amounts registered by the end of 2011.

In 2012, MAR operation has been stopped due to the irreparable damage in check dams during the flood of October 2011. Since that period MAR is ensured by simple dam water release in the bed of the wadi. Since May 2012 until 2016, a continuous drawdown around -4.5 m is registered in all monitoring points. During this period the volume released from El Khairat Dam is estimated to 16.3 Mm^3. However, it is much lower than the total aquifer exploitation which was evaluated to 23.8 Mm^3.



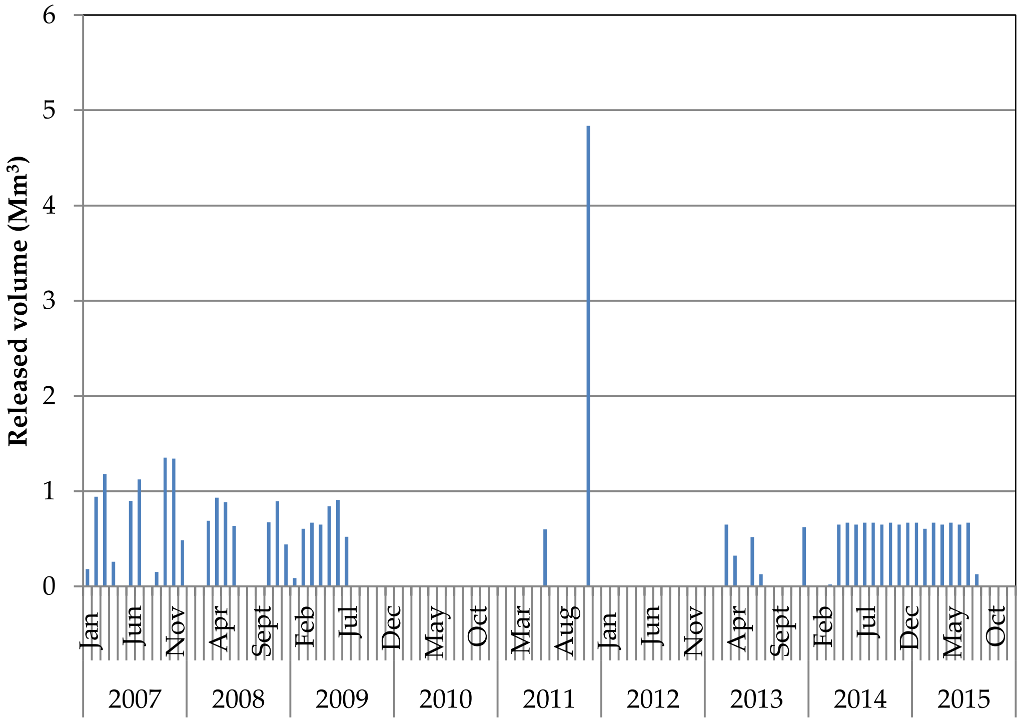


Figure 3. WTF record of Khairat aquifer.

3.2. Use of geochemical and isotopic tracers to quantify MAR impact

A prior comprehensive hydrogeochemical study using major chemical elements and stable isotopes [17] demonstrated that shallow groundwater in the target zone is a mixture of three end-members: (1) dam water, (2) left bank recharge zone (*LB-RZ*) represented by k8 sample and (3) right bank recharge zone (*RB-RZ*) represented by k6 sample (Figure 4). The concentration of a target sample in both Garci and Enfidha units (*target . well*) is the result of a mixture of the above mentioned three end-members characterized by two tracers (D: deuterium and Cl^-: chloride).

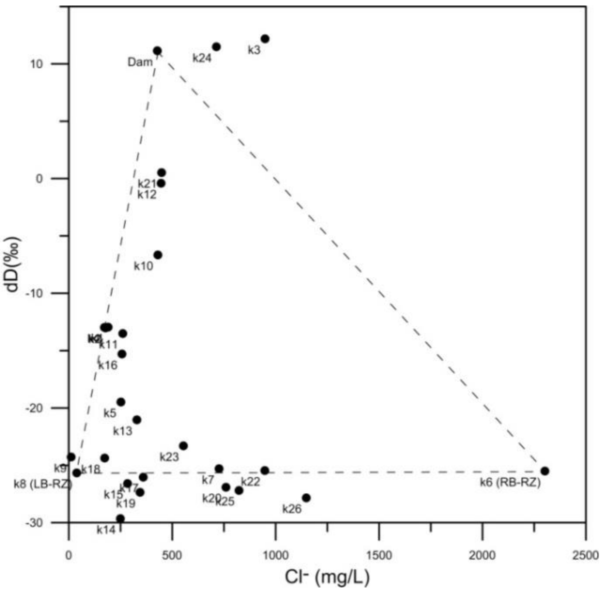


Figure 4. End-members and tracers used to quantify recharge in Khairat aquifer.

The contribution fraction (*f*) of every end-member can be determined by solving a system of simultaneous equations described by the following matrix:

$$\begin{vmatrix} 1 & 1 & 1 \\ \delta D_{Dam} & \delta D_{LB-RZ} & \delta D_{RB-RZ} \\ Cl^{-}_{Dam} & Cl^{-}_{LB-RZ} & Cl^{-}_{RB-RZ} \end{vmatrix} \cdot \begin{vmatrix} 1 \\ f_{LB-RZ} \\ f_{RB-RZ} \end{vmatrix} = \begin{vmatrix} 1 \\ \delta D_{t\arg et.well} \\ Cl^{-}_{t\arg et.wel} \end{vmatrix}$$

EMMA results show that most of the samples located in Garci unit are enriched in dam water which represents a fraction ranging from 12.5% (k13) to 77.5% (k3) (Figure 5). These results confirm that recharge is more efficient in Garci unit due to the role of the geological threshold (Figure 2).

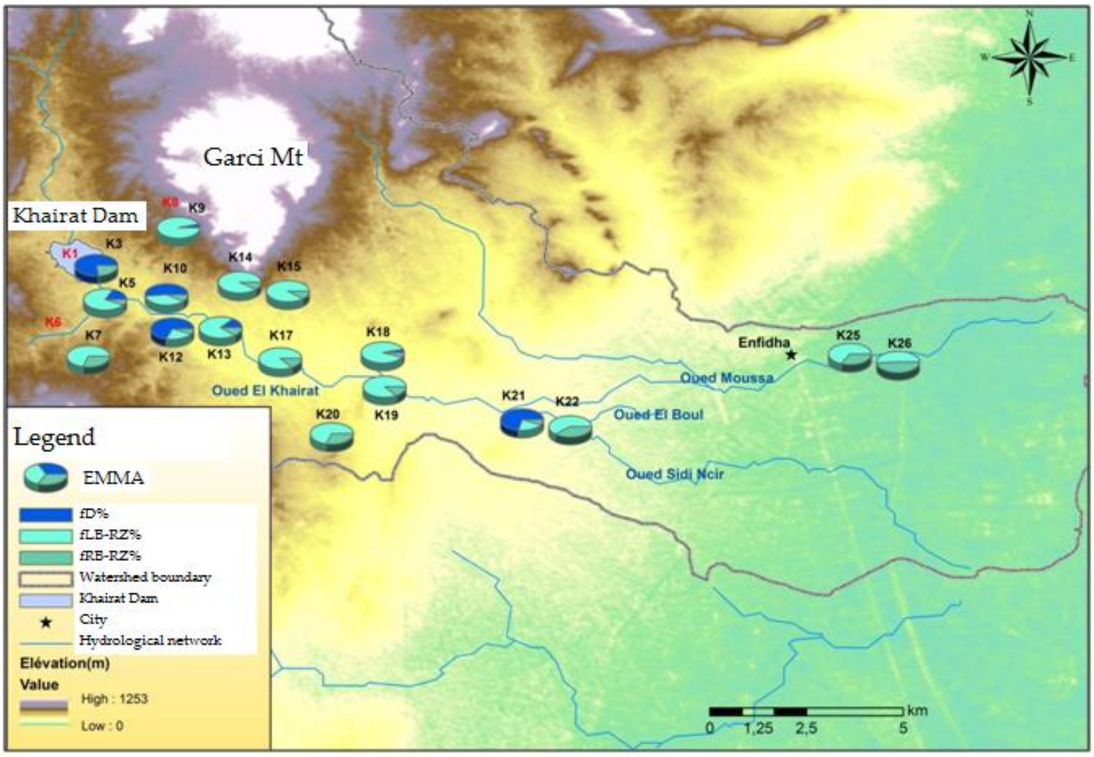


Figure 5. End Member Mixing Analysis results.

4. Conclusions

Dam water release for MAR is widely used in Tunisia to restore stressed aquifers equilibrium. However, it is practiced without scientific and technical optimization tools. Its effectiveness is depending from a combination of diverse parameters. MAR in Khairat watershed is a typical case of artificial recharge of groundwater in Tunisia using dam water release.

MAR in Khairat watershed is more efficient in Garci unit because of the released water amounts and the local geological conditions. In fact, the coarse alluvial sediments of the wadi underflow in Garci unit facilitate the infiltration of the released dam water. EMMA shows that MAR is less efficient in Enfidha unit due to the intermittent and insufficient dam water release, the existence of the geological threshold which blocks the migration of the infiltrated dam water in upstream region and climatic conditions (especially evaporation).

To be more efficient in Tunisia, MAR using dam water release should use a stronger monitoring network, especially more piezometers and gauging stations equipped with sensors for long term records. Furthermore, comprehensive hydrogeochemical studies and numerical model can constitute an asset to optimize MAR and to guarantee the sustainability of water resources in Tunisia.

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ISMAR10 symposium. Extended Abstract **Topic No: 3 (205#)**

Use of Managed Aquifer Recharge to Improve Water Management in Arid and Semi-Arid Regions of Mexico

Mary-Belle Cruz A.[1]*and Sharon B. Megdal[2]

[1] PhD Candidate Arid Lands Resource Sciences, CONACYT-México Fellow, The University of Arizona, Tucson, Arizona, United States.
[2] Director and Professor, Water Resources Research Center, The University of Arizona, Tucson, Arizona, United States
* Correspondence: marybelca@email.arizona.edu

Abstract: In several countries, Managed Aquifer Recharge (MAR) using reclaimed water has been growing as an option to recycle treated wastewater. In Mexico, reclaimed water and stormwater are the major sources for MAR. Although scholars recognize that public policies for MAR are needed, analysis of the role that national policies have played in promoting or hindering MAR applications has been limited. We carried out a systematic literature review of peer-reviewed publications in English and Spanish languages, using such key words as MAR, Mexico, artificial recharge, and water recharge. We analyzed the Mexican framework regulating MAR to identify gaps or aspects that could be modified. Most MAR projects have been established in arid and semiarid regions of Mexico. We categorized three types of MAR efforts. The first group includes exploratory and suitability studies for MAR. The second group is composed of pilot projects. The third group includes MAR facilities that currently operate. Overall, MAR pilot projects and facilities have been planned with four objectives: restoring contaminated aquifers, reducing land subsidence, replenishing aquifers, and managing floods. We conclude that MAR as a viable option to increase water supply in Mexico and that improvements to the regulatory framework to incentivize the installation of MAR facilities should be considered.

Keywords: Mexico, Regulatory, Framework, Arid, Semiarid, MAR.

EXTENDED ABSTRACT

1. Introduction

Groundwater overdraft in Mexico is a serious problem. One hundred of the 188 most important aquifer dedicated to agriculture and human consumption are over-exploited, with several affected by seawater intrusion in coastal areas [1, 2] According to scientific models, climate change will affect regional rainfall patterns and weather. In some regions of the country there may be severe drought, while in others warmer conditions may lead to more hurricanes and tropical storms, which could impact coastal areas [3, 4]. Reusing water for agriculture and industrial activities is particularly relevant in arid and semi-arid regions. Therefore, it is important to examine policies and programs regarding reclaimed water and stormwater, which might be useful resources for mitigating droughts in the Mexican Northwest. Considering that Mexico relies on groundwater and that many aquifers are over-exploited [1, 5], it is important to develop a portfolio of alternatives to improve aquifer conditions.

In several countries, Managed Aquifer Recharge (MAR) using reclaimed water has been growing as an option to recycle treated wastewater, to replenish aquifers, and to stop seawater intrusion [6-10]. In Mexico, reclaimed water and stormwater are the major sources for MAR. Even though scholars recognize that public policies for MAR are needed [11-13], analysis of the role that national policies have played in promoting or hindering MAR applications has been limited.

Based on information available through a literature search, we describe selected water recharge projects that have been implemented in Mexico in the last 50 years, including their methods for recharge, water sources, geographical distribution, and the main project results. While not an exhaustive inventory of the MAR projects in Mexico, we present evidence of projects widely distributed throughout the country. We examine the regulatory framework for MAR and identify some challenges and opportunities associated with Mexico's regulatory framework. We consider how the implementation of soft path solutions, such as small-scale facilities for water recharge, and the participation of local governments would help to improve policies focused on replenishing groundwater.

2. Materials and Methods

We carried out a systematic literature review of peer-reviewed publications in English and Spanish languages, using such key words as MAR, Mexico, artificial recharge, and water recharge. Considering that in Mexico several studies for MAR have been conducted by universities and private consultants, the search also included grey literature and governmental reports. Additionally, we obtained information from publicly available conference proceedings and academic theses and reviewed the Mexican regulatory framework for groundwater and wastewater. Recharge projects were grouped based on whether reclaimed water or stormwater was the source water. We also consider each project's objectives. Finally, we analyzed the Mexican framework regulating MAR to identify gaps or aspects that could be modified.

3. Results

Overall, we categorized three types of MAR efforts. The first group includes exploratory and suitability studies for MAR; these studies have been mainly proposed by researchers. The second group is composed of pilot projects. In some cases, pilot projects have operated for a short period and later were stopped or canceled, and others are still operating. The third group includes MAR facilities that currently operate. Overall, MAR pilot projects and facilities have been planned with four objectives: restoring contaminated aquifers, reducing land subsidence, replenishing aquifers, and managing floods. Also, we found information regarding a MAR project that included maintaining environmental services in a riparian ecosystem as a key objective.

Most MAR projects have been established in arid and semiarid regions of Mexico, although there are facilities in Mexico City, a region with an average precipitation of 600 mm per year [1]. MAR projects have been primarily designed to replenish aquifers using two types of water: stormwater and reclaimed water. Stormwater is used in small-scale facilities, mostly in rural environments, whereas in cities reclaimed water is used. Regarding projects that use stormwater, currently we found four projects functioning; these projects are in the states of Chihuahua, Mexico City, Querétaro, and San Luis Potosí [14-17]. Although MAR facilities located in Toluca, Estado de Mexico, Iztapalapa, Mexico City, and San Luis Río Colorado (SLRC), Sonora recharged reclaimed water, only the SLRC project is still operating. Also, there is a pilot project located the city of Chihuahua that recharges reclaimed water [11, 18].

4. Conclusions

We conclude that MAR as a viable option to increase water supply in Mexico and that improvements to the regulatory framework to incentivize the installation of MAR facilities should be considered.

Acknowledgments: M.B.C.A. thanks the Mexican Council for Science and Technology (CONACYT) for support through a Ph.D. fellowship. She also thanks the Herbert E. Carter Travel Award Program, the Graduate & Professional Student Council Travel Grant Program, the Arid Lands Resource Sciences Program, and the Sol Resnick fund at the University of Arizona Water Resources Research Center for the travel support to participate in the ISMAR10 Conference.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Paper for ISMAR10 symposium. ***Topic No: 3 (216 #)***

The MAR system in Ica, Peru. Technical and social lessons learned from a mega-scale MAR system and improvement possibilities

Fernández Escalante, Enrique[1]; Navarro Benegas, Roberto[2]; Guerrero Salazar, Pedro[3] and Rojas Vega, Carola[3]

[1] Tragsa Group-WB, Madrid, Spain
[2] JUASVI, Ica, Peru. *rnjuasvi@gmail.com
[3] ANA, Lima, Peru
* Correspondence: rnjuasvi@gmail.com; Tel.: +51 947263548

Abstract

Ica is located on the South Coast of Peru and counts on the most advanced agro-industrial development of the country. Agricultural production depends on groundwater availability, and since 2012 The *Junta de Usuarios del Valle de Ica* (JUASVI) and the *Autoridad Nacional del Agua* (ANA) have implemented more than 800 infiltration ponds for intermittent use. So, it has become one of the largest scale MAR systems in America, and it is providing lessons beyond those acquired from small-scale pilot sites.
Water is taken from Ica River during the rainy season, stopped by specific constructions, retained in decantation ponds and later directed at infiltration ponds (*pozas*) interspersed along the aquifer.
Most of the technical and social lessons are about the integration of the different elements in a multicomponent scheme, with certain new canals, spillways, water transferences and more infiltration ponds as main improvement possibilities, apart from a wiser water management. Some alternative lines of action are based on the use of gravity dikes, underground dykes, river basin´s slopes treatment and SUDS. In seven years of operation it is surprising that clogging impacts are not as yet very significant (beneath the surface, which is regularly cleaned), infiltration rates have barely changed and cleaning and maintenance activity is inviting to new owners to provisionally loan their terrains for new infiltration ponds, as they are aware it is profitable for the whole community.
It is also worth to mention the support of local authorities and difficulties to reach agreements between the different agents within the basin (from the mountain to the sea) which have different interests leading to eventual water conflicts. Apart from the technical and social barriers, the total dependence of rainfall is forcing to seek new sources of water and alternative mechanisms, from Waste Water Treatment Plant (WWTP) to Sustainable Urban Drainage systems (SUDS) implementation.
MAR is in the Peruvians idiosyncrasy (Incans recharged intentionally from at least the XII Century). By means of single surveys, it is possible to find out new prospective areas for new "*pozas*".

Keywords: Ica; MAR; intermittent systems, flood MAR, pozas; IWRM; Peru; detention-infiltration system; retention-infiltration system.

1. Introduction

Ica MAR system is a good international example on how Managed Aquifer Recharge is used in an overexploited aquifer to seek a certain correction of the impact on the environment and pursuing a *safe yield* water management system for latter sustainability. It also seeks to satisfy a rising water demand for irrigation in the most agricultural profitable area of Peru. The source of water proceeds from Ica river during the rainy season (between January and May), being dry the rest of the year. Thus, the system is passive, intermittent and requires the combination of stopping devices, infiltration ponds and a wise water management scheme within an integrated approach. Ica River is the main source of water supply and apart from MAR, some surface reservoirs are filled during the rainy season to be used as deposits. Also the sub-alveus of the river has storage conditions for medium term extractions.

Ica Valley´s Association of users of groundwater (JUASVI) is in charge of management and monitoring, under the supervision of the Peruvian National Water Authorities (ANA). Apart from the initial aquifer characterization, specific lines of action to improve the system are under permanent development, such as:

- Structures to retain water from Ica River minimizing the volume finishing in the Ocean.
- Improve the predictive component for over-floods so as to reduce their devastation effect.
- Managed Aquifer Recharge (MAR) actions. It is a young recharge in which the involved technicians and the authorities are constantly learning from the actions carried out, integrating the activities and promoting communication among all agent s, in order to apply premises of circular economy.
- Aquifer knowledge and its behavior improvements, so as to set new infiltration ponds in the most suitable sites
- Creation of an integrated and interconnected water management system
- Monitoring network in real time (figure 1)
- Clogging reduction and highly efficient maintenance operations
- Search for alternative sources of water such as transferences, irrigation returns, springs, etc.
- Coordination and communication improvement among all involved agents.

Since 1998, some entrepreneurs with an agro-exporting vision enhanced the agricultural activity of the Ica Valley of lea, investing on high efficiency irrigation systems. Even so, groundwater demand increased, and water conflicts related to groundwater exploitation rose, confronting traditional users, new investors, informal users (association of farmers extracting groundwater without any permission or concession) and Authorities (ANA). Ica River´s resources are temporal (from May to June) and the rest of the year agriculture relies exclusively on groundwater and eventual water transferences from external river basins (either from the Pisco River basin or the Atlantic Basin, crossing the Andes though tunnels (Choclococha, Supramayo).

The "Plan for the management of the Ica aquifer and the Villacurí and Lanchas pampas" (ANA, 2012) sets out specific objectives to be achieved, through the proposal of six programmes:

1. Information, dissemination, awareness-raising and training.
2. Evaluation of the aquifer to determine the capacity, reserves and extraction potential.
3. Aquifer control and monitoring.
4. Groundwater consumption reduction by means of a higher irrigation efficient, change of cultivation for a lower water consumption crops and a higher profitability.
5. Increase of the recharge of the aquifer with surface water and the joint use of surface-subterranean water for irrigation and urban water supply.
6. Modernization of integrated water resources management schemes.

This Plan requires an urgent modernization.

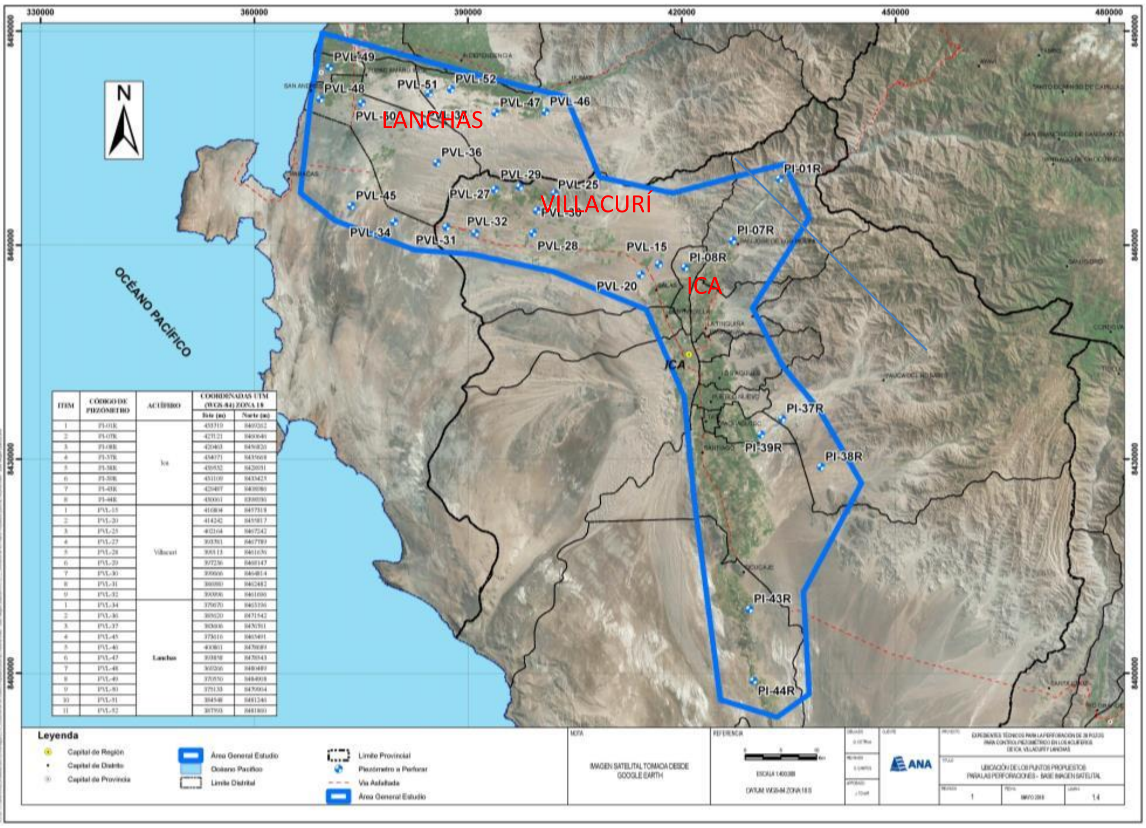

Figure 1. Ica aquifer and new monitoring piezometers to control groundwater levels and quality.

1.2. The Ica unconfined aquifer. Characteristics of the receiving medium

The depth of the groundwater level is very variable and changes from one sector of this unconfined aquifer to another (the aquifer is spatially divided in three horizontal areas: Ica, Villacurí and Lanchas, see figure 1). In the area of Ica it ranges between 5 and 50 m and in Villacurí from 60 to 90 m (JUASVI, 2016, with data scarcity for Lanchas area).

Between 1998 and 2005, the water table in the Ica valley dropped from 2 to 6.5 m (from 0.25 to 0.8 m/year as an average). In the Villacurí wells it fell from 1 to 19 m, (0.15 to 2.4 m/year as averaged drawdown). This trend monitored until 2005 has persisted until 2017 (due to the economic crisis some monitoring actions were importantly reduced and the data availability is more reduced).

Regarding the stratigraphy of the aquifer to be recharged intentionally, the Ica valley aquifer reservoir is made up of Quaternary unconsolidated fluvial-alluvial sediments, deposited essentially by the Ica River. The surface of the valley and its aquifer reservoir has an area of approximately 335 km^2. The depth of the aquifer bedrock is between 60 m and about 600 m. The thickness of the exploitable aquifer varies between 60 and 240 m and its saturated zone thickness from 20 to 190 m.

Regarding its hydrogeological parameters, horizontal permeability (K_h) varies from 0.98×10^{-3} to 2.70×10^{-3} m/s. The weighted storage coefficient varies between 0.1 and 9%, within the typical values for an unconfined sandy aquifer.

The groundwater equipotential lines for the Ica alluvial aquifer, after the Río Seco diversion, point towards the Ocean through its alluvial geological formation. Isolines are parallel to those for the underlying rocky aquitard. Both geological formations are drained, down the valley, towards the sea. The estimated residence time of the recharged water for the most superficial aquifer, between La Achirana area (heading of the La Achirana canal, see figure 5) and the area near the Ocean (Samaca Hydrological Station near Ocucaje District, see figure 7) is about 458 days (Navarro and Fernández, 2017). This entails a flow velocity for groundwater (either natural or proceeding from MAR infiltration ponds allocated near La Achirana area, e.g. figure 2a) across the alluvial geological formation of Ica River is about 208 m/day.

In respect to its hydrologic balance, the recharge is produced by seepage below the river bed and from irrigated areas (returns), and since 2012, due to MAR. The sustainable yield is estimated about 252.30 Mm^3/year or 8 m^3/s, which is the rationally exploitable volume of the aquifer determined by means of numerical modeling (ANA-WB, 2016). The actual exploited volume ranges from 321 to 326 Mm^3/year (=MCM). Therefore, the aquifer system is overexploited about 53 Mm^3/year, according to the most recent referenced calculation (ANA, 2019).

1.3. The Ica aquifer.Characteristics of the main MAR sytems

The ponds for MAR in Ica have become an emblematic worldwide example of "detention-infiltration" and "retention-infiltration" systems, for the stopping, diversion and infiltration of river and flood waters.

The recharging method is passive. Often, the same pond is used for decantation and infiltration, while others receive water from "upstream" located decanting ponds.

In the lower area of the river basin, once the Ica River has crossed Ica City, there are some small size infiltration ponds and wells.

It is often in the system the construction of wells with filtering galleries. The most usual are the horizontal galleries or filtering drainages buried in alluvial deposits, which functions as a draining trench (figures 2 e to g) or as a star well to drain in the vadose zone. This type of design is used for both, infiltration and extraction.

2. Objectives

The main objective of this technical communication is to describe the water management schemes used in the Ica aquifer, Peru's main agro-industrial zone, the water management so as to propose new schemes based on self-critical actions and the dissemination of those results that have achieved a certain technical success. These actions respond, partially, to the serious problem of overexploitation that affects the entire aquifer.

The main lines of action currently being carried out aim to overcome the complications encountered during the implementation of the integrated water management scheme, which are basically the improvement of the coordination and communication between the whole involved agents, the progressive knowledge of the physical environment improvement and an accurate assessment of the aquifer response, and finally, a proposal for technological solutions to combat the clogging impact and to achieve a greater maintenance effectiveness.

3. Materials and Methods

This study has a real, practical and pragmatic approach. The activities are the result of practice, consecutive essay and error attempts and a solid scientific support in form of models to foreseen results, results for monitoring networks in real time for water level, conductivity and temperature, flow meters installed in several important boreholes and a vast number of infiltration tests, improving the methodology for each MAR cycle and achieving more and more accurate specific parameters for Green and Ampt and Kostiakov interpretation methods.

A database gathering about 660 infiltration ponds or *pozas* extended along the aquifer were deposited in a publicly available store accessible on the Internet (see appendix 1). This inventory is under permanent review, as there are about 850 infiltration ponds when this paper has been submitted.

4. Results

The operability of the artificial recharge actions carried out in the area has an intermittent, temporary, seasonal or "of opportunity" character and is subjected to Ica River water surplus. This type of scheme is the most abundant for these environmental conditions, given that most rainfall is concentrated during a very short period of time, coinciding with the rainy season (January-March/April/May). These systems are "passive" as they operate by gravity without requiring electricity, taking advantage of the high slope of the basin.

The operationalization of the scheme begins in La Achirana dam (figure 2a), where water is stagnated and diverted to lateral canals (about 6 m^3/sg capacity) parallel to the Ica River, with interbedded decantation ponds, following the river until the Ocean. Some other smaller diversion dams are Macacona (2 m^3/sg capacity), Quilloay and Acequia Nueva (see figure 5), which also count on stagnation and decantation ponds, from where and across smaller canals, water is diverted to the Western part of the Ica Aquifer, Villacurí and Lanchas areas (see figure 1). It is important to mention that MAR technique is not applied in Lanchas due to the intense presence of salty and gypsum layers near the surface, which increase the salinity out of acceptable limits (conductivities exceeding 8 mS/cm). In this area they rely on superficial deposits, water transferences and deeper groundwater extractions.

Peruvian Water Authorities (ANA) authorize the use of surface water. The farmer´s association (JUASVI) is in charge of the construction of new infiltration ponds, negotiations with farmers to borrow their terrain for 5 year periods to increase the groundwater reserves in the aquifer, management, cleaning and maintenance of the structures. JUASVI is supported by the different agro-industries (exceeding 80) who contribute a share to support the activity.

Figures 2 a) to g). Aspects for managed aquifer recharge actions on the Ica River banks by means of infiltration ponds (*pozas*) (a to d), taken with drone during the 2017 MAR cycle; and wells with galleries (e to g). Photos e, f and g by courtesy of Manuel Augusto.

Some of the methodologies and lines of action already undertaken by the ANA and developed by either themselves or JUASVI (usually both) are the reduction of the volume of water flowing into the ocean by means of structural measures and small interception works; flood management with a predictive component to plan actions to be done; improvement of the aquifer knowledge and its hydraulic demeanor in order to locate the infiltration ponds in the most suitable places; creation of an integrated hydraulic infrastructure in which all the nodes are interconnected, improvement of the monitoring network and data collection in real time, greater efficiency in maintenance operations and the search for alternative sources of water for MAR (treatment plants, transferences between basins, irrigation returns, etc.).

The new water management schemes have developed and implemented up to eight different types of managed aquifer recharge method: infiltration ponds (*pozas*), wells, wells with galleries, canals, retention/infiltration dams, filtration through the river bed (RBF), infiltration fields (temporarily flooded areas) and Sustainable Urban Drainage Systems (SUDS). Most of these typologies are present in sectors of the middle basin, although the possibilities are much greater.

The analysis for alternative water intake possible sources takes into account the option of transferences of water from donating basins (PETACC project). At present, a request has been made to capture a 125 l/s flow from Casablanca springs for the artificial recharge of the aquifer. In this application MAR has been requested to be considered by Authorities as a single *"juridical person"* with rights and obligations. In the date of submission of this study, Water Authorities have initially denied the permission to "recarga artificial" (artificial recharge or MAR) as "juridical person", and an allegation has recently been made, still expecting resolution (Fernández and Navarro, 2019). JUASVI are willing to explore the possibility of proposing animated legal entities as juridical persons so as to acquire legal rights for the groundwater usage, especially in the cases when permits have been denied on the first attempt.

Notice the term "MAR" is not considered in the Peruvian regulations, so the applicants and even the authors must compulsorily use *"recarga artificial"* (=artificial recharge) when requesting permissions to be granted by local authorities, despite preferring the term "MAR".

4.1. Lessons learned, keys of success and barriers

Ica aquifer *hydro-managers* face two outstanding problems, which are conflicts for water use and the need to combat the aquifer overexploitation, generally by means of technical and social measures of general acceptance. Within the existing possibilities, the Ica regional government and JUASVI have adopted and implemented a series of measures based on the integration of water resources management, among which stand out:

- Water harvesting techniques in the Ica river basin headwaters are being applied from decades ago, with recent modern implementations (see ANA-WB, 2018 and ANA, 2019).
- The possibility of performing enhanced aquifer recharge activities with surplus water from water transfers (Choclococha project) is an option in development currently.
- The conjunctive use of surface water and groundwater by users should be better organized, avoiding groundwater pumping when surface water resources are available to cover the demand.
- The study of options for the reuse of reclaimed water not reserved for environmental purposes has become a reality, in spite of certain obstacles related to the purchase and sale of treated water and water banks. This option is contemplated with the expansion of waste water treatment plants and the existence of surplus volumes not adjudicated to specific users neither reserved by the government for theoretically "ecosystems restoration".
- It should be noted that during the seven-year duration of MAR activities, the flood resources used to recharge the aquifer have not seriously damaged the structures due to clogging by dragged solids. The rate of infiltration has barely changed in the ponds due to land movements and cleanups.

The Peruvian government declared a *Priority* the Execution of programs and projects to strengthen water management in the Ica River Basin, including a new one based on the construction of a dam in the next basin (Pisco River) and promoting artificial recharge actions with the rainy season´s surpluses.

In Ica and Villacurí valleys, new demonstration and experimental areas for artificial recharge by means of wells and temporary reservoirs are in permanent development, as a model to be exported to the rest of the country. It should be added that the project has had total social acceptance since its inception thanks to the dissemination efforts already done by ANA and JUASVI to create awareness that the region's economy depends on groundwater and the survival of more than 80,000 agro-industry employees, as well.

In addition to the technical barriers, some administrative problems entail significant difficulties, as different water management competencies reside in different authorities who manage surface and groundwater in a disaggregated manner, especially for the concession of licenses.

5. Discussion

5.1. Improvement actions in phase of implementation

The canals to transport water, either for irrigation, for surface storage or for MAR, follow the topography of the terrain and are, in general, highly effective due to the fact that they flow over a sandy substrate. They require an often maintenance, not always possible due to budgetary reasons. Local Authorities are studying how to externalize part of these costs, e.g. approving the renewal of licenses depending on the state of cleanliness of the canals. Dirty canals impede water to reach the infiltration ponds, and the final MAR volume depends much more on cleaning the channels than the technicians had initially thought. In this way, maintenance has become a key element for the success of MAR in Ica aquifer.

Possibilities of induced recharge from Bocachina WWTP are in study. This plant is located down Ica City in the river margin and in the vicinity of an alluvial channel where the underground flow emerges, due to a decrease of the alluvial *subalveum* thickness. In this sector, deeper managed aquifer recharge alternatives are being studied by means of wells or boreholes.

The new (improved) layout of La Achirana canal is improving some other lateral canals operations, which were abandoned, again within an integrated water management vision.

Figures 3 a) to c). Examples for "detention-infiltration", "retention-infiltration" and pure infiltration ponds in Ica MAR site, respectively.

5.2. Improvement of hydrogeological interpretation methodologies

Activities to improve the methodology recently applied or on going are:

- The installation of systems to calculate the evaporation rates in different areas of the aquifer (with especial attention on infiltration ponds)
- Infiltration tests from graphics automatically generated from instrumentation data gathered
- Study of improved methods specifically adapted for this area.

The final volume infiltrated from each pond is calculated from traditional hydrogeological equations from infiltration-time curves, determining empirical parameters for their interpretation. A percentage in the form of air trapped in the unsaturated and saturated zones are deducted from this volume. These procedures are improved each recharge cycle.

It is also necessary to install more gauging devices to quantify the aquifer inputs, lateral transfers and extractions, in order to be able to close detailed water balances. Once determined the order of magnitude of the water circulating in the alluvial of the Ica River, a new alternative progressively applied is the direct drilling of wells in the riverbed for direct extraction from the *subalveum*.

5.3. Redesign current "artificial recharge" systems

New designs entail actions on the following elements:

-Inventory of abandoned wells and tubular boreholes near water sources (such as canals, intakes, wells, treatment plants, reservoirs, etc.) that can be reused for enhanced recharge. The premise is "don't close a well, reuse it".

-Redesign of the new infiltration ponds. The most stable slope to support a high lateral pressure is 2/1. The bottom of the ponds is carved with furrows, to increase the infiltration rate and favoring the preferential sedimentation of clogging processes in the furrow-canals (thus facilitating their cleaning).

-Transverse dikes and intakes. This is an action with a high probability of technical success, both to divert the water to the reservoirs and to retain the flow through the alluvial reducing the "invisible" flow into the ocean.

- New water sources for artificial recharge. Water from transfers, desalination, purification and surplus water from the rainy season are contemplated. A resource used since 2018 has been the capture of the flow in springs. Its use requires an administrative permission that must be requested from the ANA, accompanied by a hydrological and hydrogeological study. In the case of Casablanca springs capture for MAR, an application has been recently presented, expecting final permission. The main arguments presented to the authorities have been that part of this water ends up in the sea, another part is taken by informal (unlicensed) farmers and only a fraction is used extracted from the subalveum-crossed galleries (the whole volume from the spring is infiltrated in less than a kilometer from the "*ojos de agua*" (water eyes).

Figures 4 a) and b). Casablanca springs. New intake source for managed aquifer recharge of the Ica aquifer, which application has been presented to water authorities in 2019 and expects resolution.

5.4. Integrated water management (surface and groundwater combined schemes)

The IWRM scheme for Ica Valley considers the combination of several connected canals diverted from the river Ica, spillways and infiltration ponds to ensure the water availability in most of the irrigation area. New pozas are placed every year and the project plans the construction of linking canals, especially in the Northernmost and Easter areas (Figure 5). A water transfer from the Atlantic watershed is also used (Desagüadero tunnel).

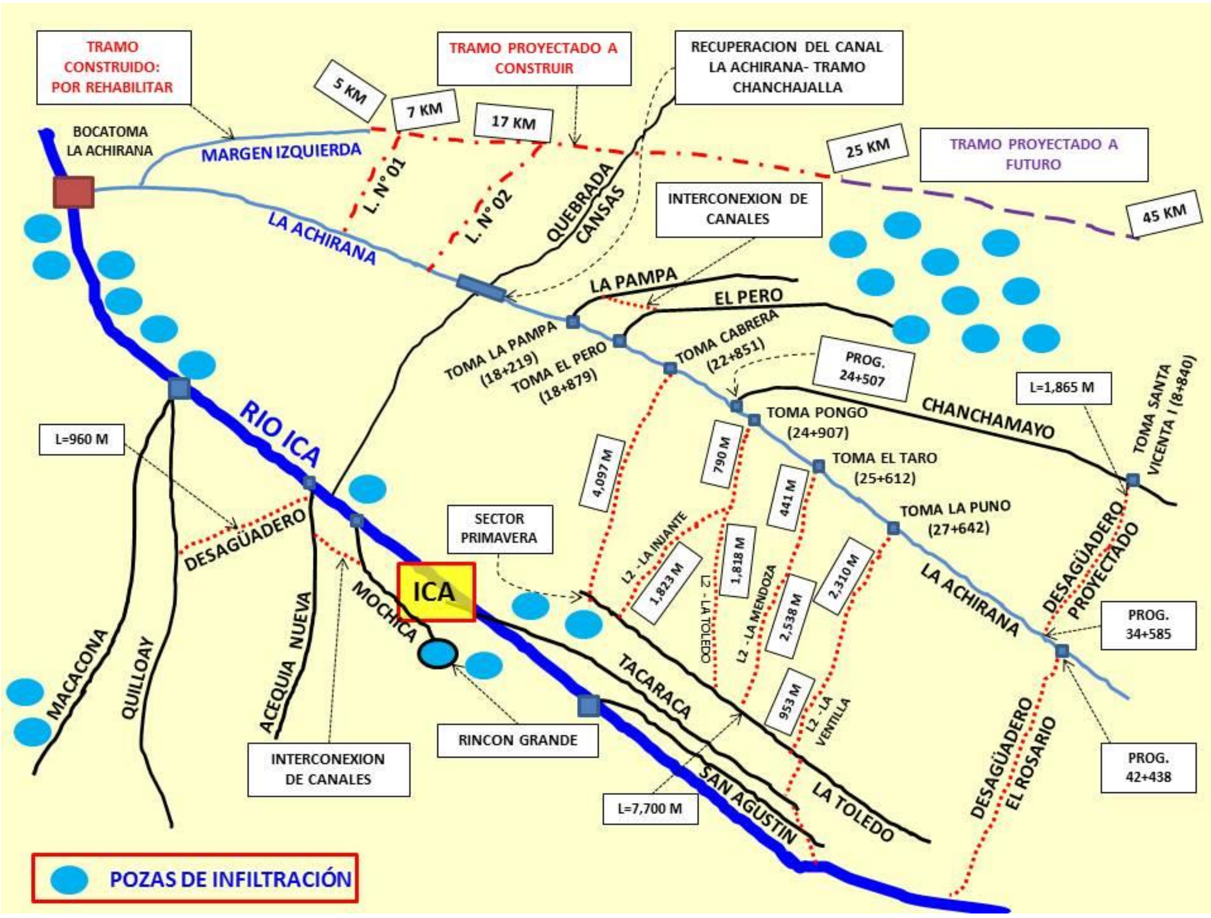

Figure 5. Integrated water resources management in the Ica River Basin mock-up. It combines transport and infiltration channels, wells and ponds from Ica river flow and water transferences. Modified from Navarro, 2015 and ANA-WB, 2015.

5.2. Proposal for new technical actions

5.2.1. Structural measures and constructions

- Construction of subsurface dams: In 2018, 19 Mm^3 have flowed into the Pacific Ocean, and a large part of this volume could have been used for recharging the aquifer after legal impediments. In this regard, some structural actions are required to facilitate an earlier decision making regarding water management. The next constructions have been proposed:

- Rehabilitation of a former canal at Achirana left margin (km 0 to 5).

- Construction of a 15+20 km canals at Achirana left margin (km 5 to 25 and 25 to 45) and either in-pipe buried or surface connections with the infiltration ponds in the main recharge area.

- Construction of a 200 meter filtering gallery in the Achirana area. This option has been studied and apparently has guarantees of technical success, although it requires the corresponding permits from surface water authorities.

- Protection and deterrent measures, due to the fact that in 2018 April a child who swimming was drowned in an infiltration pond.

5.2.2. Non-structural actions

In addition to structural actions, administrative, legislative and social measures have been proposed and are in the process of implementation. It is worth to remark:

- Improving the cartography of the aquifer to define the areas of greatest receptivity for artificial recharge operations. To date, site selection has been carried out "by opportunity", using as many hectares as possible. Currently, and after a campaign of geophysical prospecting of the aquifer located below the alluvial of the river Ica performed in 2017, the degree of knowledge has increased and the most productive areas have been defined, either recharging the alluvial (horizontal permeability between 0.98×10^{-3} and 2.70×10^{-3} m/s, with a maximum storage coefficient of 9%) or the aquitard. The maps of distribution of vertical permeability and storage coefficient of the aquifer are currently in draft phase (ANA, 2019).

- Dissociate good artificial recharge ponds from those on a poorly active receiving medium. Among the about 840 infiltration ponds implemented by JUASVI until 2019, some have been successful, while others seem to be located in areas with low infiltration rates, according to the cartographies developed by ANA for iso-permeability, iso-transmisivity and iso-storage cofficients (ANA-WB, 2016). It is necessary to generate a tool to increase the number of infiltration wells in the most appropriate zones, closing those already deployed of very low efficiency.

- Mayor coordination and communication between all the agents involved. Based on the experience gained during seven years of artificial recharge, it is necessary to optimize and specify the coordination with both, water Authorities and associations of users, especially for Surface Water, due to the fact that there are still some difficulties to overcome, such as:

- Updating the "Plan for the management of the Ica aquifer and the Villacurí and Lanchas pampas" (ANA, 2012).

The approach to solve the overexploitation of the aquifer, apart from technical, has a social tinge: the technology has the disadvantage of benefiting both, the users with their legalized water capture systems and the "informal" ones, who will benefit from the artificially recharged volumes without having participated in the implementation costs of this action. This task would require the participation of a multidisciplinary team for its proper implementation, including sociologists and experts in mediation with the indigenous population. So the “mediators” figure is becoming key within the IWRM modern scheme, so as to avoid potential water conflicts.

Among the socialization strategies, the organization of workshops focused to end-users and the population in general is an asset. These workshops should expose a comparison between two scenarios: the probable aquifer situation without MAR activities *versus* the current one for 2019, year in which 26 Mm^3 have been infiltrated into the aquifer by means of MAR, about a 50% of the overexploitation figure.

Figures 6 a) and b). MAR ponds in Ica River margins. Photographs taken with drone at Los Molinos District (24/04/2016). Appearance of the reservoirs in full operation. Most of this land is privately owned, and landowners have lent some plots for this purpose, aware of the advantage they can acquire, on the condition that the lands should be returned in perfect state of cleanliness after the cessation of activity. Drone video: https://www.youtube.com/watch?v=2TKSMj7rn-A

6. Conclusions

Recharge ponds and some combinations wells-galleries have become a key element for groundwater irrigation in the Ica valley. As MAR is an idiosyncrasy of Peruvians, it is feasible to find out new areas susceptible to implement MAR additional devices simply by surveying local experts.

Existing elements such as canals, spillways, water transferences and more infiltration ponds should be more applied as main improvement possibilities, apart from a wiser water management.

The integrated project proposed by ANA-WB and JUASVI (who collect the opinion of experts and from the general population) contemplates some lines of action to be added to those of the previous section:

1. Possibility of building gravity dams.
2. Possibility of building subterranean dikes/curtains to retain or slow down the groundwater flow across the *subalveum*.
3. Treatment of slopes and water harvesting techniques at the head of the basin (ditches, afforestation…).
4. MAR in urbanized areas through SUDS.

The IWRM scheme should count on the voice of the general population, so as to avoid a top-down proposal of solutions. The responsibility is shared and water user must be still more aware of the importance of this resource for over 80,000 people living from agroindustry in the area.

It should also be added that the package of measures to be applied includes the strengthening of a Management and Surveillance Committee, exploitation plans and automatic monitoring of the new observation piezometers network, at least.

The proposed series of measures is in the process of permanent improvement, on a technical basis and several years of studies, providing knowledge willing to be applicable to other overexploited aquifers or at risk of being so, especially in Andean countries.

Acknowledgements

Most of the activities presented in this paper have been developed by JUASVI engineers, who wish to thank the help of the Peruvian National Water Authority (ANA) for taking measures to combat overexploitation of the aquifer, especially Engineers Máximo Hatta and Wilfredo

Echevarría. ANA was also supported by the World Bank, thanks to the help of the Engineers Erwin de Nys and Martin B. Albretch. JUASVI engineers Alfredo Sotil and Aníbal Huaranca contributed providing data to the preparation of the article, as well as Eng. Benjamín Cillóniz from AGRO ICA. Special thanks to Mr. Francisco Masa for his help in the dissemination of the activity and Mr. Javier Gallegos, Regional Governor of Ica, for his support and confidence in MAR as an appropriate alternative to manage water. Finally, our deep gratitude for two reviewers from ISMAR 10 Scientific Committee, who did an intense effort very appreciated by authors.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

JUASVI has developed an inventory of reservoirs to retain water from floods during the rainy season to be used for MAR. The list is available on the Internet: "Implementation of more than 500 artificial recharge ponds for the sustainability of irrigation in the Ica aquifer (Peru)", from the publication "Manejo de la recarga de acuíferos: un enfoque hacia Latinoamérica", IMTA, 2017: goo.gl/SbBGpG

Appendix A

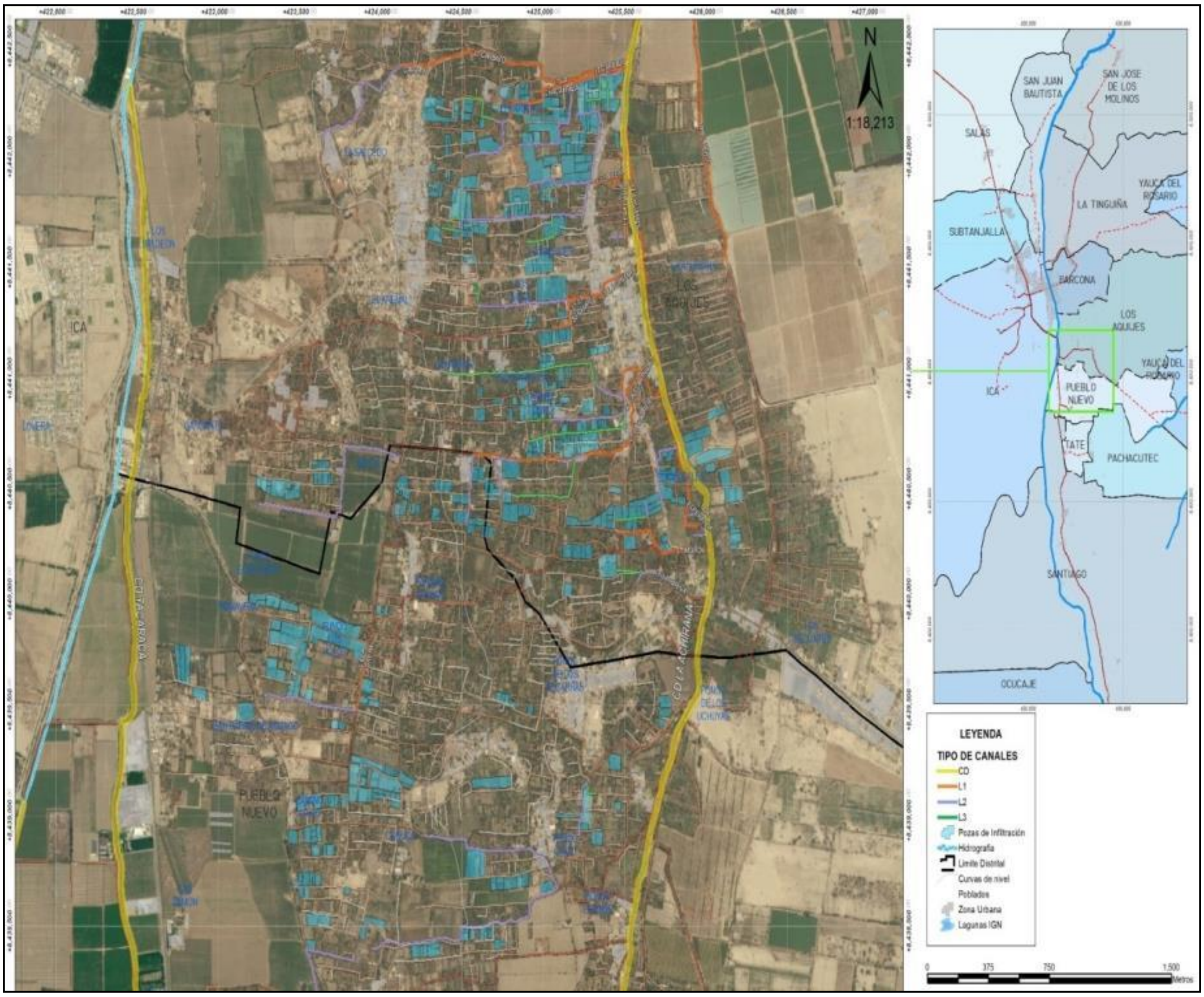

Figure 7. Location of the main infiltration ponds for MAR in the valley of Ica in 2016, with 70 ha used as reservoirs at Pueblo Nuevo and Los Aquijes Districts (polygons in light blue color). The distribution of the Districts is on the right margin legend. Source: Navarro, 2015 (JUASVI).

Paper for ISMAR10 symposium. ***Topic No: 3 (243#)***

Competitiveness and sustainability in agricultural irrigation areas in the Irrigation District No. 041 at the Yaqui River (Sonora, Mexico)

Víctor Manuel Olmedo Vázquez[1]; Emilio Camacho Poyato[2]; Juan Antonio Rodríguez Díaz[2]; Ma. Leticia Hernández Hernández[1]

[1] Universidad Autónoma Chapingo-Centro Regional Universitario del Noroeste, Ciudad Obregón, Sonora México.
[2] Escuela Técnica Superior de Ingeniería Agronómica y de Montes. Departamento de Agronomía. De Campus Rabanales. Edificio Leonardo da Vinci. Universidad de Córdoba. Córdoba, España.

Abstract: The gradual complexity of the issues that affect the competitiveness and sustainability of irrigation District No 041 at the Yaqui River, located in the South of Sonora, Mexico, manifested by a lack of indicative strategies, contributing to develop a planning according to its needs.
The research was carried out using the logical framework; which establishes actions and necessary projects for the good functioning of the district; using the methodology of strengths, opportunities, weaknesses, and threats (SWOT).
The objective of the study was to determine the importance of the efficient use of irrigation water for competitiveness and sustainability, as a determinant indicator of permanence of the agricultural activity in the irrigated areas of the irrigation district.
The results allowed corroborating the hypothesis raised of disengagement between actors (users – producers, and directors), establishing overall organization strategies, integral planning, competitiveness, and productivity, derived from main objectives, while the specific problems allowed to structure projects and actions referred to each of them.
The logical framework allowed to identify that the most irrigation modules present a potential improvement; admitting the articulation of efforts of all actors in the different stages of the development of the strategic plan.

Keywords: SWOT, MAR, streamflow; irrigation.

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1. Introduction

A fundamental management for competitiveness and sustainability in the irrigated agricultural areas of Irrigation District No. 041 Rio Yaqui will prosper by developing strategic planning, which consists of multiple factors to attend. Goodstein, L., Nolan, T., and Pfeiffer, J. W. (1998), indicates that, 1) the strategy is a coherent, unified, and integrative decision-making pattern; This means that the strategy is consciously, explicitly, and practically developed; 2) the strategy allows to establish an organizational purpose according to the long-term objectives, action plans and location of its resources; 3) the strategy is the definition of the action scope with which it is intended to be more prosperous; 4) the strategy is a response to internal strengths and weaknesses, external dangers and opportunities to achieve a competitive advantage; 5) the strategy becomes a logical system to differentiate the functional levels and position in the structure of managerial tasks and the operatives and the roles that each one must have in the organization, and 6) the strategy is a way to define the contribution which it makes to the interested parts, it's "its reason to be". Considering the importance of planning, this research projects the elaboration of a Strategic Plan for the district and its 42 irrigation modules, located in the south of the state of Sonora, Mexico.

In developing a solid and consistent strategy planning, it will generate competitive and sustainable advantages in the efficient use of irrigation water and other actions related to agricultural activity; using the Logical Framework Methodology (LFM) originally elaborated by León J. Rosemberg and Lawrence D. Posner (1979); which considered five stages in this research: the first was to identify the actors and develop a diagnostic of the irrigable area; the second was to identify and prioritize problems, establishing causal relationships; the third stage was to establish objectives for each and every one of the problems considered; the fourth stage was to propose a solution model generating concrete projects (strategies to be followed) by elaborating a matrix of indicators; and the last stage would be the evaluation and monitoring of strategic planning (short term), in order to identify goals and follow up the indicators to evaluate if they are being obtained (Martínez Pellegrini, S.E., Hernández D., Durazo, E., Barceló Aguilar J. G. 2010).

The imperative of greater competitiveness and sustainability in the growing complexity of today's world, have revealed the limitations of traditional planning tools. In the midst of this reality, it has become an urgent need for societies and governments to put into practice management tools that allow them to combine a strong leadership and a lasting long term with a short-term operational framework. All this generates new management tools such as strategic planning in which regional and local groups become strategic actors of development, identifying some indicative strategies to: 1) facilitate the articulation of already consolidated actors in production (irrigation modules); 2) to allow the experiences of the successful irrigation modules serve as experience to those who require it and 3) to identify the main problems faced by the modules in order to advance in the areas of organization, training, infrastructure, financing, competitiveness and sustainability.

With indicative strategies, the aim is to detonate a planning discipline to build a support instrument capable of mobilizing the endogenous resources of the region; since sustained growth in productivity requires an economy to be continually improved Porter E. Michael (1990). Collaboration and cooperation among the various actors is an essential requirement for establishing the new model of inclusive development and generating competitiveness and sustainability in the irrigation district.

The logical framework method responds to three common project problems (Ortegón, E., Pacheco J. F. y Prieto A. 2005), (a) planning of projects lacking of precision, with multiple objectives that are not clearly related to project activities; B) projects that are not executed successfully, and c) there is no clear picture of what the project is like if it were successful.

In the mid-1960s, the Financing for Development Agencies promoted the creation of new methodologies to guide the implementation of projects and programs. Among the solutions proposed, the most attractive was the one that was called Logical Framework or Log frame, developed in the United States by Practical Concepts Inc.

Beginning in the early 1970s, the United States Agency for International Development (USAID) formally began to use the Logical Framework in the planning of its projects. From then on, the methodology expanded first in the community of international development agencies, and then in the various academic and management fields (Aldunate. y Córdoba, 2011).

Some researches that refer to the logical framework methodology are: Strategic planning model based on the logical framework system. Application case "Tree of Hope Foundation" (Bedon Martínez, M. A. 2012), which lies in linking those involved in the diagnosis process (through tools such as the involved matrix and the problems tree) and in strategic addressing (

Through the objectives tree and the logical framework matrix). The application of this process has allowed to have clear the strategic direction to its managers and their collaborators. (Conza Salas, B. A. 2003) in its research "identification model, formulation, and evaluation of sustainable development projects applied to water supply in marginal areas: the logical framework system", determines that the use of the log frame system facilitates understanding among actors and those who promote the project development. In addition, it articulates the efforts of all in the different stages of the elaboration of the projects, derived of the conscious and real analysis of the problematic of the development.

In the research called Assessment through the Logical Framework of the Project: Soil Conservation in Degraded Areas in Tlacotepec Plumas, Oaxaca, mentions that the logical framework approach is important because it helps the planning of a project, formulating its thoughts better and expressing them in a clear way, and it does not pretend more than that. It is no more than an instrument to improve the planning and execution of a project or program and it does not guarantee efficiency in doing so. The implementation of the project will depend on the company responsible for execution and the beneficiaries, assuming responsibility for carrying out the activities satisfactorily with the guidelines specified in the project (Vázquez Morales A. L., 2013); Finally (Montiel, V. M., 2016) in the research Contributions of the logical framework methodology for the integration of university projects, indicates that the logical framework has tools for the diagnostic phase of the project, which can provide facility to identify, systematize, and present orderly and understandably all key information about a project proposal for approval or rejection on a firm base of decision. So, as to identify the project involved from this early phase of the project and involve them opportunely.

The purpose of this work was to develop strategies to analyze the efficiency of irrigation at the module level and that can be applied in other irrigated areas of Mexico. All of the above allowed us to answer questions and confirm the following hypothesis: The district and the irrigation modules present conditions of disengagement of actors and resources that diminish their efficiency and competitiveness in the use of irrigation water. Therefore, the objective was to determine the importance of the efficient use of irrigation water for competitiveness and sustainability, as a determinant indicator of the permanence of agricultural activity in the irrigable areas of the irrigation district.

2. Methodology

The methodology of the logical framework establishes a series of steps to reach the prioritization of actions and projects, given their characteristics will cover the following stages:

Identification of actors and elaboration of the diagnostic: the key actors participating in the study were: district directors; irrigation modules managers, producers, users, ditches (irrigation water distributors) and irrigators. It was necessary to carry out a systematized information search process to better define the environment in which the district's agricultural production is recorded at the regional, national, and international levels to define the main challenges. The research with the obtained information in the field tour is summarized in the matrix that presents the Strengths, Opportunities, Weaknesses, and Threats for the project (SWOT Matrix).

Identification and prioritization of problems: in the interviews carried out during the research, the main problems and windows of opportunity for the development of the agricultural sector were identified, according to the participants' perceptions. The problems identified as fundamental were taken as guiding of the objectives and actions.

Goal setting: General or global objectives were defined, which define the purpose and scope of the long-term strategic plan. This goal is understood as the great vision of the district. It also refers to the specific objectives of those that reflect the changes that competitiveness and sustainability hope to achieve in the medium and short term.

The hierarchy of objectives by importance and temporality makes explicit the line of action of competitiveness and sustainability. Figure 1 shows the relationship between the types of mentioned objectives and the scope of each of them.

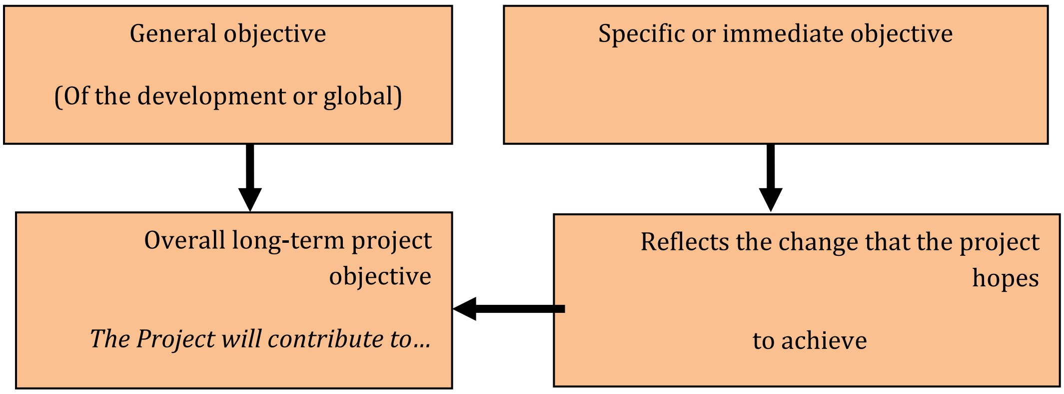

Figure 1: Logical structure of objectives.

Solution Model: To achieve the established specific objectives in the strategic plan (derived from the general objective) were formulated strategic lines for which were necessary to establish defined results. Each strategic line had a general objective and specific objectives that guide the projects that integrate the strategic line.

Evaluation and Monitoring: on the basis of the expected results, indicators should be established to allow assess if these have been achieved or not; As well as perform a task of monitoring the activities to know how far they move away or approach the objectives.

3. Characteristics and climate in the irrigable areas of the irrigation district.

The irrigated agricultural areas in No. 041 Rio Yaqui Irrigation District are located southeast of the state of Sonora, Mexico; Which has an area of 227,224 hectares of irrigation; This region is located between the parallels 26°45' and 27°40' North Latitude and between the meridians 109°37' and 110°37' west longitude of the Greenwich Meridian, bordering the north with the Yaqui River and the south with the Mayo River, the east limits with the Técali and Baroyeca mountains zone, and to the west with the Gulf of California, comprising the towns of Cajeme, San Ignacio Río Muerto, and Bácum; as well as part of Etchojoa, Navojoa, and Benito Juárez. The district forms part of the coastal plain in northwest Mexico.

The predominant climate is the group of very dry climates, subtypes BW(h')hw very warm, warm, with summer rains and a winter precipitation percentage between 5 and 10.2%. In the northeast portion of the area there is a BSo(h')hw very warm and warm climate. The average annual temperature is 20.03 °C, it has an average annual rainfall 281,6 mm / year and a potential evaporation of 2,061,51 mm (Comisión Nacional de Agua, 2003).

With regard to agricultural production in the district for the 2010-2011, 2011-2012, 2012-2013 and 2013-2014 crop years; the importance of the activity in the region is shown (Table 1).

Table 1. Annual agricultural production in the 041 Irrigation District at Yaqui River.

Crop Year	Surface		Production (ton)	Production Worth ($)
	Planted (ha)	Harvested (ha)		
2010-2011	217.501	217.201	1.719.427	4.714.358.286
2011-2012	218.029	217.065	1.604.022	5.757.256.951
2012-2013	217.502	216.519	1.779.748	7.149.649.646
2013-2014	220.500	217.584	1.924.376	9.008.696.540
Average	**218.383**	**217.092**	**1.756.893**	**6.657.490.355**

The main problem of the region is to face a drought, which is a very complex phenomenon that is originated from meteorological anomalies, which reduce the levels of precipitation below the average and, when it lasts during an agricultural year or for longer periods, makes rainfall insufficient to meet the demands of different water users and the environment. This precipitation deficit can manifest in very short periods, the steady and slow evolution of the drought causes that sometimes its effects can take months or even years to manifest it adversely affecting the water runoff in the river, the levels of storage in the dam system and even groundwater levels.

It is not easy to determine when a drought begins and ends, and today most of the irrigation districts in Mexico do not have the criteria to decide when a drought has started and when has finished. Another factor complicating the confusion in a reality or not of a drought is the absence of a precise and universally accepted definition of it. The definition of drought responds to the characteristics of the affected region, since the sequences are regional and each region presents climatic characteristics and specific and different infrastructure.

Given the conditions of hydro-agriculture infrastructure in the Yaqui basin (storage dams and deep wells), drought is considered not only a physical phenomenon that can only be defined by climate, as most people assume, so that in this basin drought can also be caused by an increase in the demand for available water during periods of average runoff or even during dry periods. In this way the drought in the Yaqui basin can be seen as a balance between available water and water demanded by different users.

Considering that competitiveness and sustainability implies improving the living conditions of the producers of the district, they establish permanent goals in the different agricultural activities that they develop to obtain a greater productivity in their activity and to be more competitive with respect to the conditions that prevail in national and international level. In this respect, it is observed that the development of the district inevitably implies the existence of a process of economic development, which involves describing a model that contributes to improving the conditions of agricultural activity.

In every innovation approach of the regional-local systems as developed by the district, an endogenous development process is determined that leads to the gain of competitiveness. (9) Indicates that competitiveness has become one of the cardinal concerns of the government and companies of each and every nation. It mentions that the only significant concept of competitiveness at the national level is national productivity. A rising standard of living depends on a country's ability to achieve high levels of productivity and increase productivity over time. Sustained productivity growth requires that an economy continually improve.

With regard to the above, it is considered the diamond of Porter, from the perspective of water resources, through the Mexican government; Where this government must act as a catalyst and competitor; In order to support the Irrigation District (which is a limited responsibility society, created by productors for their own service, it is committed to contribute to the sustainable development of the community, concerned with solutions to solve the needs of positive water, but also compromises to take care of the needs of future generations); and at the same time, to the irrigation modules with the purpose of making them more competitive, as shown in figure 2; in addition to all those involved have a proactive influence by the same government; where: The customers are persons or companies receiving the good, service or product (in this case water resource) in exchange for money; the complementers are considered as competence, expanding the market with reciprocal benefit; The Suppliers provide what is necessary for a purpose, and competitors are considered as competence where economic agents are free to offer goods and services in the market.

Once the intervention of the actors in the competitiveness has been achieved, they must specialize and improve dynamically; with the aim of achieving sustainability in agricultural production, with the premise of developing it socially fair, economically profitable and ecologically friendly with the environment. As a society we have a commitment to deliver the district's agricultural area to future generations in a sustainable manner over the time.

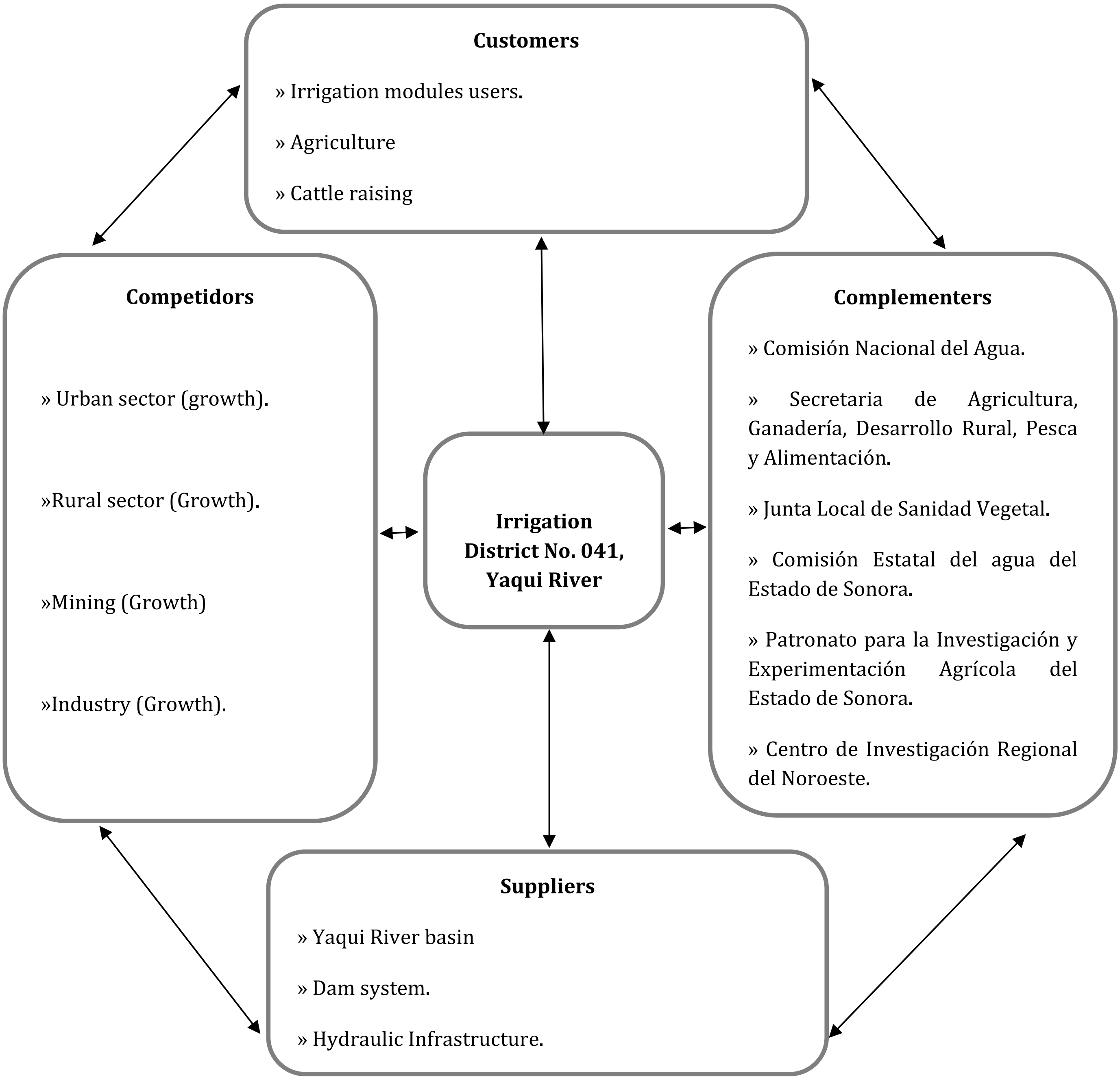

Figure 2. Porter Diamond adapted to the Irrigation District No 041, Yaqui River.

4. Results and discussion

4.1. Situation of agricultural activity and alternative solutions

In recent years, in the state of Sonora, unusual weather conditions have been present, influenced by the presence of extraordinary meteorological phenomena, causing problems in the collection of water in the different storage systems.

The current critical situation with respect to the high incidence of rent of the agricultural area, shows that more than 85% are rented between user (owner of land) and producer (lessee) in the region, which has not been duly sized by both governments and users, as these effects are beginning to present and there are insufficient alternatives to reduce them, causing social and economic problems of a structural nature for the region; because the plots are being eroded or simply agricultural activity is no longer profitable for those who produce; in addition to this problem, the increase in pest population levels, the establishment of diseases, high production costs, late government support for the production, and merchandizing of basic grains, health regulations for exports, among other. Finding the following environment in the research:

There is an evident need to adapt agricultural production in the irrigation modules to the conditions of their resources and to the current commercial opening framework.

The irrigation modules have been very marked economic dependence, due to monoculture (wheat up to 75% of the area sown).

In recent years there have been even more problems such as: reduced prices, high production costs, and lack of care in the management of the water resource by the irrigation modules and the same district.

With higher incidence of pests and diseases, the ecological damage increases.

In case of a phytosanitary emergency, such as that occurred with leaf rust in previous cycles of wheat, the region is very susceptible to losses due to the scarce crops diversification and activities, and the insufficient availability of equipment and products for prevention.

The problems of harvesting, transport, gathering, and marketing of grains are exacerbated in a very short period of harvest.

Opportunities that provide the productive reconversion oriented to export crops have been missed, depending on the regional economy of a single crop. A reconversion agriculture has the following advantages: Saving of natural resources and less pollution, diversification of production and activities, improvement of productivity and competitiveness, consolidation of a new productive culture, use of top technology and integration of productive chains that can reactivate the model of economic and social development of the district and greater contribution to the integral development of the modules and the district of irrigation.

The Table 2 shows the main findings of the analysis of the agricultural environment in the irrigation district, in the internal and external domains, in order to know the its Strengths, Opportunities, Weaknesses and Threats (SWOT).

Table 2. Strengths, Opportunities, Weaknesses, and Threats (SWOT).

Strenghts	Opportunities
1. Competitive agricultural activity. 2. Appropriate natural environment. 3. Irrigation modules legally constituted and formed by an administration board. 4. Own facilities with all the services for the operation. 5. Volumetric water supply per irrigation module. 6. Machinery for working (coating, leveling, drainage, others). 7. Well-structured channel network and measurement sockets. 8. 9.4% channel network coating. 9. Conservation, modernization, and lining of canals. 10. Investment in projects. 11. Timely irrigation scheduling. 12. Appropriate groundwater.	1. Conversion of more profitable crops. 2. Economic valuation of the water resource. 3. Export products. 4. Institutions for agricultural research and education. 5. Own forms of organization existence. 6. Enough resources for taking care of the environment. 7. Sustainability of the water resource in the dam system. 8. Improvement of modernity in irrigation modules. 9. Technological irrigation. 10. Technification with automated gates (Rubicon FlumeGate Type). 11. Recovery of rented land by the users (owners of the plots). 12. 90.6% Coating in the channel network.
Weaknesses	**Threats**
1. Inadequate management in some irrigation modules (excessive use of water per hectare). 2. Lack of continuous training in irrigation management.	1. Prolonged droughts. 2. Low profitability of agriculture and possibility of leaving the activity of most producers. 3. Increase of the quota per thousand of water.

3. Lack of control in the water sale to the user. 4. Inefficient use of water conduction. 5. Lack of short-term vision in pollution, degradation and health in natural and human resources. 6. Labor shortages. 7. Poor productive infrastructure (communications). 8. Poor social infrastructure (insecurity). 9. Decrease of up to 90% of production users. 10. Dependence of 75% of a single crop (wheat).	4. Degradation of soils from inadequate crops (castor oil plant). 5. Multiple opinions of management and operation. 6. Land concentration in few producers. 7. Absence of complementary activities in the agricultural area. 8. Inadequate management of irrigation water. 9. State and federal support cutbacks. 10. Greater transfer of water from one dam to another. 11. Basin pollution.

Establishment of Problems and Objectives

From the diagnostic in the study area, main problems and general objectives were identified and they are projected in Table 3.

Table 3. Key issues and main objectives.

Main Problems	**General Objectives**
Poor reconversion of agricultural activity and lack of profitability in the activity.	Development of competitive and sustainable agricultural activity.
Little articulation between irrigation modules to generate a common and operative project.	Establishment of an integral planning framework that allows the implementation and follow-up of a long-term development project for the irrigation district.

Specific problems:

Direct work with the involved (irrigation modules) in the agricultural activity allowed to detect the following specific problems that in some cases are causes and in other, results of the central problems.

Strategies Formulation

The general strategies were derived from the two central objectives, while the specific problems allowed structuring the projects and actions contemplated in each of them.

STRATEGY 1: ORGANIZATION.

General Objective: In the short term, to give immediate follow up to the actions that is proposed by each of the irrigation modules with the purpose of creating spaces of unity and equality. In the medium term, to establish permanent training mechanisms and organizational capacity that allows a sustained improvement of the competitiveness of the productive activities undertaken in the irrigation modules. In the long term, to detonate a development model capable of incorporating all the users of the irrigation modules so that the agricultural activity really works as initially proposed and do not concentrate the activity on few producers.

PROJECTS: 1.

Strengthening of Directors Board.

Objective: To review the existing normative framework that affects agricultural activity, proposing initiatives to improve the normative context and that intervene in the monitoring and evaluation of projects in the agricultural sector (Table 4).

Table 4. Actions and results to follow for the strengthening of the management board.

Actions	Results
Strengthening of the directors board structure, its functions, and financing sources for the irrigation modules.	Having a document (tracking plan).
Development of a long-term strategic plan.	Having a guiding document for the development of the agreed irrigation modules and identification of those responsible for pushing the proposals.

STRATEGY 2:

INTEGRAL PLANNING.

General Objective: In the short term, ensure the completion of already undertaken projects and the start of complementary projects. In the medium and long term, to follow up on the regulations that contributes to the competitive and sustainable development of the irrigation modules in balance with their productive vocation and socioeconomic needs.

Projects:

1. Ecological and territorial management (agricultural vocation of the region).

Objective: To establish territorial ordinances those ensure respect for the productive vocation of the region, as well as the most appropriate use of land to ensure the competitiveness and sustainability of the area development. These management tools will provide the framework for integrating environmental conservation with the development of productive activities in the area (Table 5).

Table 5. Actions and results to be followed in the environmental and territorial management.

Actions	Results
Elaboration of the region ecological order.	Establishment of optimal land uses and natural resources census.
Development of specific management plans for the urban and rural areas of the region.	Having the urban and rural planning of a development plan for infrastructure and services in these areas.

2. Implementation and Monitoring of the Strategic Plan.

Objective: To have a strategic plan (Table 6) that integrates and orders the different actions undertaken in the irrigation district to achieve:

The establishment of an integral planning framework that allows the implementation and follow-up of a long-term development project.

The Development of agriculture activity and related activities.

Table 6. Actions and results to be followed for the strategic plan.

Actions	Results
Identification and consensus discussion of priority projects of the Strategic Plan of the irrigation district.	Cooperation agreements and securing financing for the projects development.
Follow-up of cooperation projects and agreements.	Objectives achievement and the carried out projects goals, project evaluation.
Strategic Plan review: carried out projects review, their results, and adjustment of the plan according to the achieved, the pending, and the problems detected.	Plan updating, progress evaluation, and new proposals every two years.

3. Review of agreements and long-term sustainable water use plan.

Objective: In the short term, to regularize the existing situation with respect to previous agreements on the use of water. In a medium- and long term horizon, based on a hydrological diagnostic of the area, to establish a sustainable water use plan to guarantee the resource supply in the irrigation district in the future. (Table 7).

Table 7. Actions and results to be followed in the water use.

Actions	Results
Update and / or completion of the hydrological study of the region and elaboration of a plan for the sustainable use of the resource.	Hydrological study of the area and proposal of sustainable use of the resource.
Renegotiation of existing water supply agreements.	Updating information on water use and initiatives for irregular uses regularization (El Novillo dam).
Implementation of the contemplated actions in the sustainable water use plan.	Incorporation of sustainable water management to all the regulations applicable to the area. Regulatory control measures according to normativity.

STRATEGY 3: COMPETITIVENESS AND PRODUCTION.

General Objective: Increase competitiveness through actions on aspects related to all stages of production. This strategy seeks to diversify the activities and try to articulate some productive chains in the irrigation modules. This strategy is closely related to the results obtained from the study on the value chain for the sector that is in progress.

PROJECTS:

1. Agriculture growth.

Objective: To ensure that the technology used in each of the stages related to the agriculture production can achieve efficiency and quality standards (Table 8).

Table 8. Actions and results to be followed for the agriculture growth.

Actions	Results
Carry out an agriculture value chain analysis.	Opportunities estimation to improve productivity.
Generate of an information network on innovations and technology by stages of the productive processes.	Leveling of long-term production standards and between different producers.
Development of a basic aspects training program.	Leveling of production standards (medium term).

2. Production Increase.

Objective: To increase the importance of agriculture in the economy of the region in added value and employment terms. (Table 9).

Table 9. Actions and results to be followed to increase production.

Actions	Results
Conclusion of the value chain study.	General diagnostic of the production process and problems detection.
Studies and hydrological plan.	Establishing of the potential crop activities growth.

5. Conclusions

Through the developed analysis and based on the logical framework as a central methodology, focused on the district and the irrigation modules, it was determined that the set out hypothesis in the research was met; as there is a decoupling between actors (users-producers and managers) that diminish their efficiency and competitiveness in the use of irrigation water and complementary activities.

The logical framework allowed identifying that most of the irrigation modules present a potential improvement; which should be done correcting a series of actions that develop internally and externally wrong. Although all modules have a management structure, most of them do not work as such, since they leave the responsibility for execution to a single person who represents the three main actors in each module.

In most irrigation modules, there should be greater linkage between the landowner (user), the same irrigation module, the producer, and the irrigation district; that allows to carry out successfully the projects in common with those that are counted, such as: increase in the canals lining, land leveling, rescue of salted soils, profitable agricultural production with the purpose of starting with the redemption of land rents, and that really allows to benefit the 22,659 users that conform the pattern of the district and do not concentrate the production in few producers.

The Logical Framework allows the understanding between the actors (users-producers) and those who promote the development of agricultural activity (managers of all dependencies). Likewise, it admits the articulation of efforts in the different stages of the strategic plan elaboration.

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Topic 4. MAR MAPPING

Extended abstract for ISMAR10 symposium. ***Topic No: 4 (033#)***

Suitability maps for managed aquifer recharge: development of web-tools

Sallwey, Jana[1]; Schlick, Robert[1]; Bonilla Valverde, José Pablo[2]; Junghanns, Ralf[1]; Vásquez López, Felipe[3] and Stefan, Catalin[1]

[1] Technische Universität Dresden, Dresden, Germany
[2] Instituto Costarricense de Acuedcutos y Alcantarillados, San Jose, Costa Rica
[3] INERCO Consultoria, Bogota, Colombia
*Correspondence: Jana.sallwey@tu-dresden.de

Key Words: Managed aquifer recharge, webGIS, multi-criteria decision analysis, suitability mapping.

EXTENDED ABSTRACT

Suitability maps for managed aquifer recharge (MAR) are increasingly utilized (Sallwey et al., 2018) and hold the potential to be integrated into sustainable groundwater management plans, filling a void in missing strategic MAR site planning. Their advantage for water management plans lies within the spatial display through maps, quickness and simplicity of the analysis, possibility to include projections of climate scenarios, population growth or land use changes as well as assessment of different MAR techniques and their location.

However, the quality of the maps strongly depends on input data quality as well as expertise of the decision maker. Maps are commonly derived through GIS-based multi-criteria decision analysis (GIS-MCDA). This procedure is undertaken by combining and weighting geospatial data based on the study's objectives (Malczewski, 1999). To date, there is no common understanding on how suitability mapping should be conducted, as there is considerable variability concerning used GIS data and MCDA methodology (Sallwey et al., 2018).

To display the development as well as the state of the art of GIS-MCDA in the context of MAR suitability mapping, we retrieved information on used criteria and methodologies from 66 related studies. Findings from this review indicate a trend in MCDA methodology applied for MAR suitability mapping. It comprises a workflow including constraint mapping, suitability mapping by using pairwise comparison as a weighting method, and weighted linear combination (WLC) or analytical hierarchy process (AHP) as decision rule and less often a subsequent sensitivity analysis. Pairwise comparison is a weight assignment method where weights are calculated through matrix-based comparison of pairs of criteria (Saaty, 1980). WLC is the most commonly used decision rule, combining standardized datasets and their respective weights. It has been developed further to AHP, a more structured approach that categorizes GIS maps before

weighting them (Malczewski and Rinner, 2015). The retrieved database was compiled into a web-based query tool making the information easily accessible.

Based on the most commonly used practices in the assessed studies, we conceptualized and implemented an online tool that comprises a simplified web GIS as well as supporting tools for weight assignment and standardization of criteria. It is an open-source web tool embedded into the INOWAS online platform (https://inowas.com). The INOWAS platform is an open-source collection of analytical and numerical web-based models focusing on the planning, management and optimization of MAR applications. The INOWAS platform and the tools are accessible with any state-of-the-art web browser.

The structure of the GIS tool follows the workflow introduced by (Rahman et al., 2012) but excludes the steps of problem statement and sensitivity analysis. The process starts with a) choice of GIS criteria, and continues with b) weights assignment, c) data upload, normalization and reclassification, d) additional global constraint mapping, e) the suitability mapping and f) results visualization. We included several weight assignment methods so that next to pairwise comparison, the decision-maker can utilize rating and ranking method as well as multi-influence factor method (MIF). While we kept those methods for their simplicity or advantage in visual decision-making, the combination of pairwise comparison with AHP must be highlighted as the methodology with the highest increase in usage and the most benefits. All steps are supported by documentation explaining the functionalities of the tools and the underlying methodology. Tools are designed to be very intuitive, e.g. the multi-influence factor methods tool allows the user to visually draw connections of different intensity between the GIS criteria sets. Those connections are then automatically translated into weights (Figure 1).

The developed tool was verified with a standard desktop GIS system producing the comparable results. Advantage of the web tool over the standard GIS systems is its ease of use and intuitive guiding through the MCDA process. Especially the weight assignment process is much more user-friendly and visually appealing. Users don't have to take care of the underlying calculations, which fasten the decision-making process and avoids possible mistakes. The option to perform multiple weight assignments methods and compare them, offers the unique opportunity to efficiently implement different scenarios or quickly change parameters of the MCDA process. Result data for each scenario can be downloaded, compared and used for further GIS analyses.

The web tools and the underlying review will help planners of MAR sites to engage in the MCDA in a more structured way. It enables referencing of previously conducted studies as well as application of GIS-MCDA for MAR suitability assessment through a user-friendly web GIS. The clearly outlined process of map generation enforces standard methodology and will help to generate maps that are comparable due to the common methodological approach. While the tools can outline the map generation process, they cannot standardize one of the main sources of uncertainty- the datasets and respective weights assigned. Data availability and quality are a major constraint and the problem statement and specifics define the importance of a GIS dataset for each case study. In conclusion, the tools at hand standardize and simplify the MAR suitability mapping process but cannot substitute the decision-makers expertise in choosing relevant datasets and their importance for the specific study.

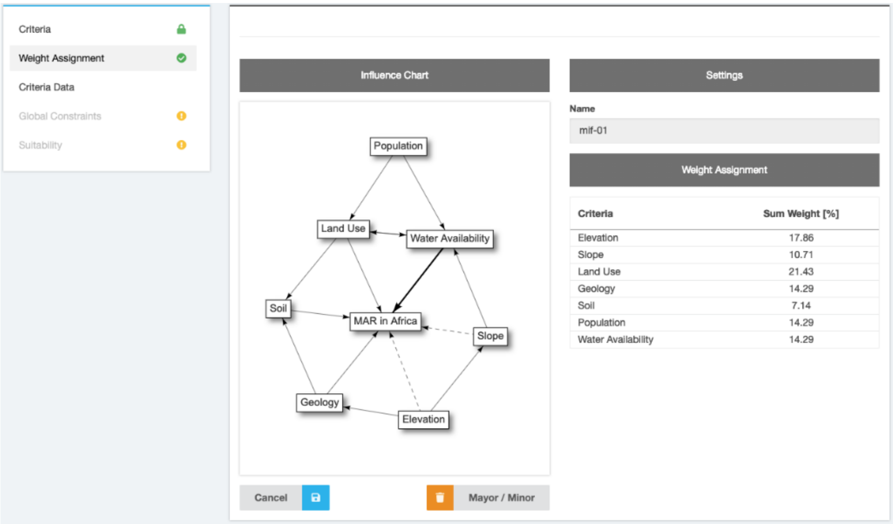

Figure1. Interface of web-GIS tool, with workflow display on the left and the weight assignment tool multi-influencing factor method where the user can define major and minor influences between the criteria

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Extended abstract for ISMAR10 symposium. **Topic No: 4 (045#)**

Specific types and adaptability zoning evaluation of managed aquifer recharge for irrigation in the North China Plain

Shuai Liu[1], Weiping Wang[1]*, Shisong Qu[1], Yan Zheng[2] and Wenliang Li[1]

[1] School of Water Conservancy and Environment, University of Jinan, Jinan 250022, China; 15053130651@163.com
[2] School of Env. Sci. & Engr., Southern University of Science and Technology, Shenzhen 518055, China; yan.zheng@sustech.edu.cn
* Correspondence: stu_wangwp@ujn.edu.cn; wangweipingwwp@126.com; Tel: +86-139-5316-2318

EXTENDED ABSTRACT
The North China Plain is the main grain production district with a large area of well irrigation resulted in a large groundwater depression cone. In the 1970s and 1980s, a variety of small-scale MAR projects were developed to increase the amount of shallow groundwater, playing an important role in ensuring stable and high yield of crops. Characteristics of MAR as a component of irrigation and drainage system are small scale, short service life, low investment as well as fixed irrigation water sources and crop planting structure. Considering these characteristics and the relationship between surface water and shallow aquifer, MAR is divided into three types of water spreading, well recharging and combination of both. MAR can be further divided into 10 forms through the specific farmland water conservancy projects. So far, the conjunctive use of well-canal irrigation has been widely used in the Yellow River Irrigation District of Shandong Province for nearly 40 years, in which the canal has multiple roles of transporting, storing the Yellow river water or local surface water, recharging groundwater and irrigating by pumping water in canal. Meantime, it also solves the potential clogging problem of aquifer resulting from high silt concentration by desilting basin at head works and canal silting where the sediment can be dredged. Moreover, the new developed open canal-underground perforated pipe-shaft-water saving irrigation system further expands the scope and amount of groundwater recharge and prevents the system clogging through three measures. Methodology of integrating MAR into agricultural facilities to form a farmland water conservancy system of diversion, storage, infiltration, water-saving, irrigation and drainage is proposed in order to achieve the goal of comprehensive control of drought, flood and salinization as well as groundwater overdraft. Finally, Liaocheng City of Shandong Province is selected as study area and an adaptability zoning evaluation system of water spreading is established, in which five factors of groundwater depth, thickness of fine sand in the vadose zone, specific yield of vadose zone, irrigation return flow, groundwater extraction intensity. It is concluded that the MAR is more adaptable for the western region than the eastern and central regions.

Key words: Types of MAR for irrigation; Yellow River Irrigation District; Adaptability zoning evaluation.

Paper for ISMAR10 symposium. **Topic No: 4 (086#)**

Mapping managed aquifer recharge potential in the tropical Mitchell River catchment in northern Queensland, Australia

Dennis Gonzalez[1*], Joanne Vanderzalm[1], Karen Barry[1] and Declan Page[1]

[1] CSIRO Land and Water; Locked Bag 2 Glen Osmond SA 5064, Australia.
* Correspondence: dennis.gonzalez@csiro.au; Tel.: +61-8-8303-8745

Abstract: Assessing managed aquifer recharge (MAR) potential at basin scale requires screening to identify sites for detailed investigation. In remote areas with limited hydrogeological information, landscape attributes form surrogates for hydrogeological data. Advances in probabilistic mapping of soil and geological properties e.g. depth of regolith and permeability, with coverage at scale provides additional information for MAR mapping; importantly including quantifying uncertainty. The 71,529 km^2 Mitchell River catchment in northern Queensland, Australia is sparsely populated and receives highly seasonal monsoonal rainfall that currently supports extensive grazing across 95% of the area. This assessment identified and prioritized areas to focus further infiltration-based MAR investigation to support high-value irrigated agricultural development. Initial constraints on hydrogeology, permeability, slope, regolith thickness and source water proximity indicated MAR potential for 9100 km^2 or 13% of the catchment. Further exclusion based on protected areas, proximity to source water and existing roads, and agricultural land versatility narrowed the area to 2,102 km^2 or 3% of the catchment. Suitability was scaled through a weighted linear combination of factors. Reliabilities of probabilistic data were integrated and scaled using a fuzzy membership function and weight sensitivities were analyzed. Of the 2,102 km^2 potentially suitable area, 436 km^2 (21%) had high reliability, 601 km^2 (29%) medium reliability and 1,064 km^2 (51%) low reliability. Considerations related to adequate aquifer storage space and water quality are discussed. Future site scale investigations are more likely to be successful if they target areas with higher suitability and reliability. Areas with lower reliability and sparse data require additional work to increase confidence in MAR suitability assessment.

Keywords: site suitability; GIS; digital soil mapping; constraint mapping; multi-criteria decision analysis.

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1. Introduction

The Mitchell River catchment in tropical northern Queensland, Australia is a remote and sparsely populated area that was among three key regions in northern Australia identified for comprehensive assessment of water resources and development potential [1]. Rainfall across the Mitchell River catchment is highly seasonal and is in deficit compared to potential evapotranspiration [2]. Potential for managed aquifer recharge (MAR) using infiltration methods to support agricultural development was assessed using a spatial multi-criteria analysis framework.

MAR has a long history in supporting agriculture with over 230 documented sites worldwide [3]. Of these documented sites, 84% apply infiltration techniques including in-channel modification, bank filtration and spreading methods [3]. Infiltration techniques generally produce water for a fraction of the cost compared to injection techniques so are favorable for providing cheap alternative water supplies for irrigation [4, 5]. At a screening level, in order to identify focus areas for detailed investigation of MAR feasibility, landscape scale attributes can be used to assess MAR potential across large areas with sparse hydrological and hydrogeological data [6, 7, 8]. Integration of data with differing levels of spatial, temporal and attribute accuracy and resolution also presents challenges to MAR assessments at scale. Weighted combinations of factors used to rank MAR suitability should be supported with clear rationale. This study identified and prioritized areas to focus further infiltration-based MAR investigation to support high-value irrigated agricultural development in the Mitchell River catchment and provides a range of weighted suitability maps, analyses weight sensitivities and quantifies reliabilities of probabilistic input data used in the assessment.

MAR feasibility and suitability assessment and mapping is a growing field of study and there are numerous international examples many of which are documented in the Global MAR Inventory [3]. All are subject to varying levels of data availability and most apply a geographic information system (GIS) multi-criteria decision analysis (MCDA) framework with examples in Costa Rica [6], Spain [7, 8], Australia [9], USA [10] and Greece [11]. The MCDA approach combines factors influencing MAR potential including hydrogeology, geology and lithology, topography, soil types and availability of source water, with the option of assigning weights to attributes according to their influence in determining MAR site suitability. Constraint mapping to exclude unsuitable areas (e.g. certain land uses, proximity to water source etc.) is appropriate in conjunction with MCDA [6, 10]. It is important to account for uncertainty in attribute values and sensitivity of weights due to their reliance on subjective value judgements relating to the relative importance of some factors over others [11]. Various studies have applied similar workflows for conducting assessments of MAR potential using GIS-MCDA approaches [6, 11, 12, 14]. The structure generally consists of:

1. Problem definition to describe the intended MAR technique, water source and end use
2. Constraint mapping to eliminate areas where MAR is unlikely to be feasible
3. Suitability assessment to rank feasible areas based on a combination of information layers
4. Sensitivity analysis on suitability criteria values and or weights

The current study assessed the potential for MAR to support irrigated agricultural development in the remote, sparsely populated Mitchell River catchment in Northern Australia through capture and sub-surface storage of surface water flows during the wet season for dry season recovery and use. Infiltration-based MAR using surface water is shown to produce water for about a third of the cost compared to well injection techniques, and about a tenth of the cost of using treated sewage [4]. This is an important factor when considering economical water sources. There is a growing body of knowledge around relevant parameters and thresholds for assessing MAR potential. Factors generally relate to technical, economic and environmental criteria [8, 12]. For infiltration based schemes, various studies have considered a topographic relief of more than 10% restrictive to infiltration-based MAR, a slope of less than 5% as most favorable and between 5 and 10% as possible [6, 9, 15]. Low permeability soils or soils with a high clay fraction (e.g. >10%) limit infiltration rates [6]. Economic considerations include distance from water source and associated pumping and power supply costs, accessibility, land suitability for use of recovered water, and land acquisition costs. Environmental criteria generally relate to avoiding ecologically important areas such as nature conservation reserves, and changing the hydrology of a natural system such that the risk of impacts on dependent ecosystems are increased.

With the exception of freely available global digital elevation data (e.g. from the Shuttle Radar Topography Mission) from which slope and surface hydrology can be determined at acceptable resolution for regional scale analyses, data at a regional scale are often derived from soil cores, bore logs and water levels measured at sparsely distributed or clustered point locations. Recent developments in soil mapping techniques and statistical methods for interpolation have produced a range of new data sources in Australia [16, 17]. The Soil Landscape Grid of Australia provides a suite of soil property maps including estimates of regolith thickness derived using consistent data mining and interpolation methods combined with regional mapping information where available, across Australia at 3 arc second (~90m) resolution [16]. Soil permeability and agricultural land suitability and versatility, among other soil attributes, was recently produced at similar resolution for selected areas in northern Australia based on advanced statistical interpolation techniques, use of environmental covariates and a database of historic and recent field based observations [17]. These digital soil maps apply a probabilistic approach that provide information of the variability and uncertainty of predictions.

The objective of this study was to assess suitable areas in the Mitchell River catchment in northern Queensland, Australia for MAR using infiltration techniques to recharge surficial aquifers with wet season runoff. Area elimination and weighted linear combinations of factors were used to rank suitable areas at a resolution of ~90m. The study incorporated recent probabilistic digital soil mapping and lithological datasets including reliability metrics to identify areas with higher potential and greater reliability within which further site-specific investigations could be targeted.

2. Materials and Methods

2.1 Site description

The Mitchell River catchment in northern Queensland, Australia covers an area of about 72,000 km^2 the majority of which is classified (Koppen) as tropical savannah with highly seasonal monsoonal rainfall and a distinct dry season. Almost 90% of the mean annual rainfall of 1000 mm occurs during the wet season from November to April, potential evaporation is also highly seasonal and totals 1800 mm per year [2]. The catchment is very sparsely populated (<6000) and largely limited to the main towns of Chillagoe, Dimbulah and Kowanyama (Figure 1). The area currently supports extensive cattle grazing on native grasses and shrubs across 95% of the catchment and very little irrigated agriculture. Overlapping some of this area, protected areas including nature conservations, forest reserves, bird sanctuaries and national parks together occupy 26% of the catchment (Figure 1).

The catchment drains from highest elevations around 1300 m in the east near Dimbulah to the western coast towards Kowanyama. There are four main rivers, the Palmer, Walsh, Lynd and Mitchell (Figure 1). Flow diverges across an alluvial fan in the lower part of the Mitchell River catchment draining to sea from a number of channels. Mitchell River mean annual flow measured downstream of confluences with the other main rivers is 8×10^9 m^3 [18]. National scale runoff data at ~5 km resolution was used to estimate accumulated annual flow in ungauged watercourses [19].

The majority of the higher elevation and higher slope areas in the eastern part of the catchment feature outcropping fractured basement rocks consisting of igneous intrusive and metasedimentary rocks including those within the Hodgkinson Formation (Figure 1). Aquifers within this area are highly heterogeneous with little to no surficial cover of unconsolidated deposits. The Rolling Downs Group includes mudstone and siltstone formations that generally act as aquitards for the underlying Gilbert River Formation [20]. The sedimentary aquifers of the Gilbert River Formation, Bulimba Formation and Wyaaba Beds are generally unconfined and sub-artesian where they outcrop and consist of sandstones and limestones. Bore yields of 5 L/s to 30 L/s are reported for these aquifers. Unconsolidated Tertiary and Quaternary alluvial aquifers are most extensive in the western part of the catchment closely associated with river channels and floodplains. Little extraction occurs from these aquifers and little hydraulic data exists. There is a history of localized use for community, stock watering and irrigation supply. The alluvial aquifers are thought to be largely unconfined with variable transmissivities [20].

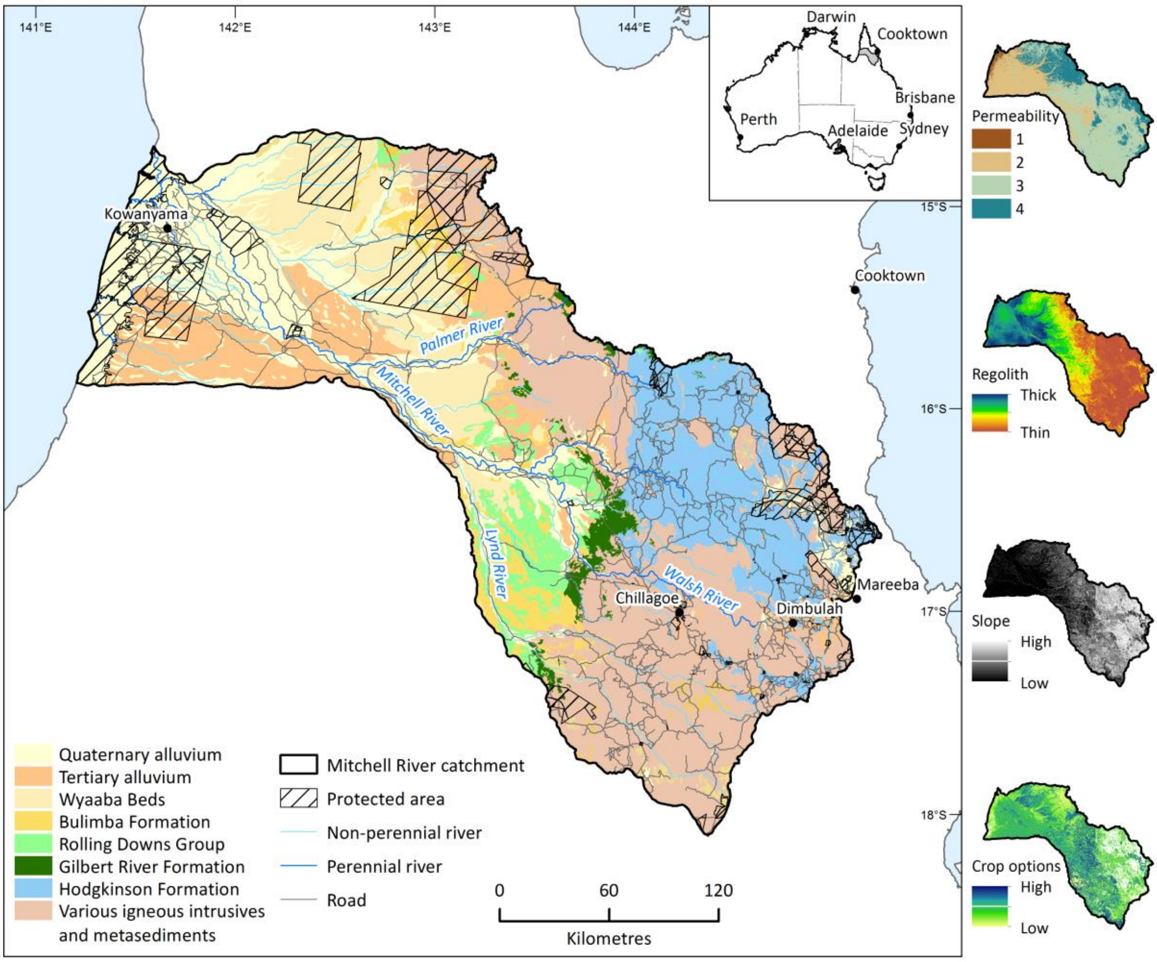

Figure 1. Location, major aquifers, protected areas, drainage and roads in the Mitchell River catchment. Side panels show soil permeability, regolith thickness, slope and spray and drip crop options.

2.2 Spatial assessment framework

The spatial assessment framework included constraint mapping, suitability assessment through weighted linear combination of factors, and reliability assessment of probabilistic data and is shown diagrammatically in Figure 2. All data were resampled to a common grid using bilinear interpolation for continuous data and nearest neighbor assignment for categorical variables. The specific problem definition for the assessment was to identify suitable areas for infiltration-based MAR using surface water during the wet season. The assessment considered a minimum recharge volume of 10^6 m^3 per year for a scheme to be viable and this was to be recharged over 100 days during the wet season over an area of up to 2 ha. Constraint mapping removed unsuitable areas from further analysis. The suitability assessment rescaled data uniformly using a fuzzy membership function before applying weight factors and aggregating values using an additive function. Reliability metrics associated with probabilistic mapping layers were combined using a fuzzy function and classified into three classes to represent areas of low, medium and high certainty.

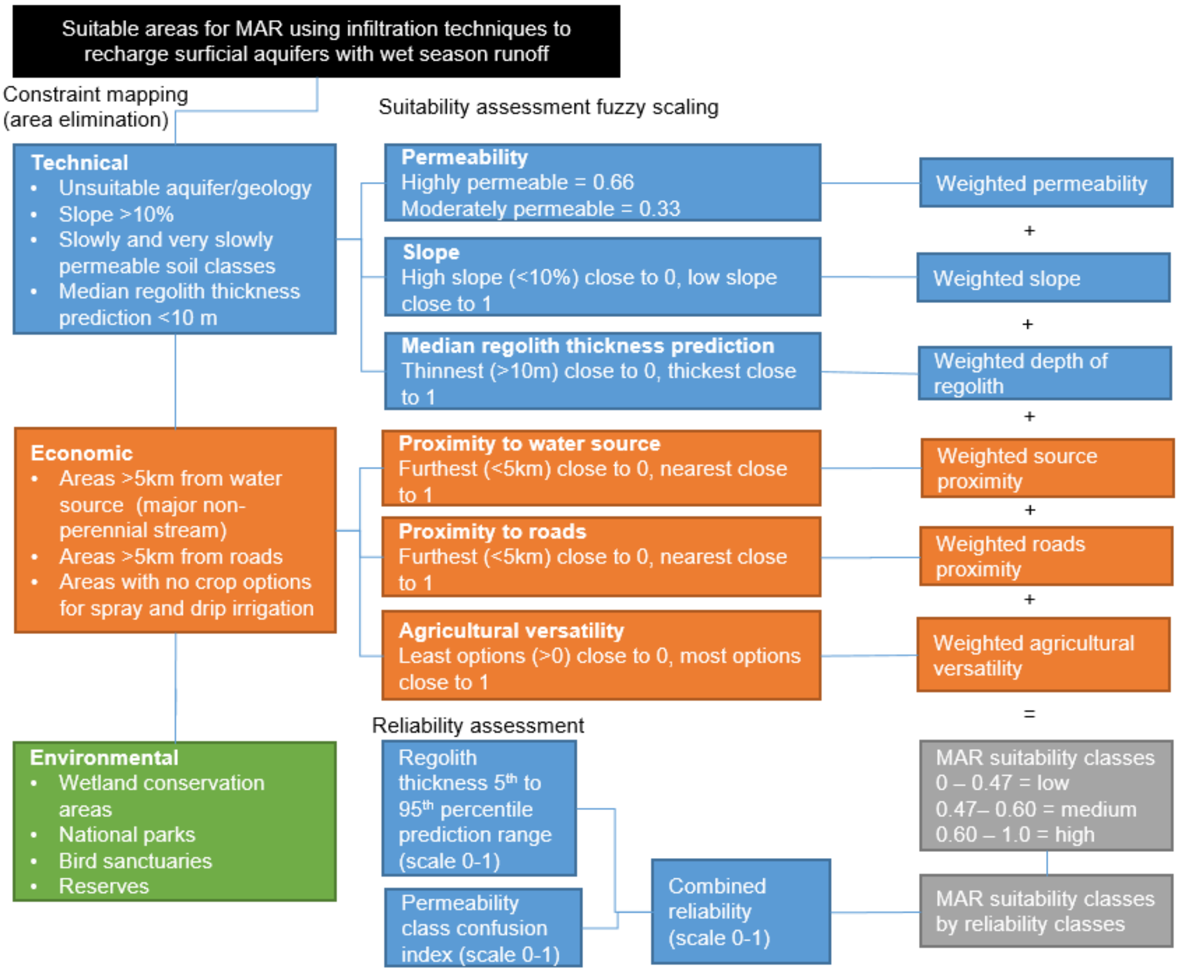

Figure 2. Spatial assessment framework.

Aquifer boundaries were determined from regional surface geological data (2012 edition of the 1:1 million scale Surface Geology of Australia http://www.ga.gov.au/) and suitability for MAR using infiltration techniques was assessed based on reviews of hydrogeological descriptions and data [20]. Constraint mapping removed highly heterogeneous fractured rock aquifers within the Hodgkinson Formation and various igneous intrusives and metasediments. Low transmissivity mudstones and siltstones of the Rolling Downs Group were also excluded. Aquifer units considered feasible for MAR in the area were within unconsolidated Quaternary and Tertiary alluvial aquifers and sedimentary sandstones and limestones of the Wyaaba Beds, Bulimba Formation, and Gilbert River Formation (Figure 1).

Median regolith thickness predictions made at national scale and 90 m resolution [16] were used as an indicator of the thickness of the selected aquifer types. The depth of regolith product is designed to represent an estimation of the combined depth of pedolith, transported regolith, saprolite and slightly weathered bedrock (saprock) encompassing the extent of alluvium, sandstone and limestone aquifers. A median depth of regolith prediction of less than 10 m was considered a constraint for MAR as this indicates a low chance of intersecting an aquifer of sufficient thickness. Regolith thickness (>10 m) was scaled using a fuzzy function where thinner sections received values close to zero and thicker parts received values closer to 1.

Slope was calculated based on a 30 m DEM (Shuttle Radar Topography Mission 1 Second Digital Elevation Models Version 1.0, Geoscience Australia http://www.ga.gov.au/). Areas where slope was greater than 10% were excluded. A fuzzy function was applied to scale slope (<10%) where high slope approached zero and low slope approached 1.

Based on a nominal MAR scheme size of 10^6 m^3 per year recharged over a 100-day period across 2 ha, the required infiltration rate is 500 mm/day. Estimates of permeability from digital soil mapping [17] contained four classes following the Australian standard [21]:

1. Very slowly permeable: less than 5 mm/day, generally clay or silty clay, no pores visible with hand lens.
2. Slowly permeable: 5 to 50 mm/d, generally clay or silty clay, few pores visible with hand lens.
3. Moderately permeable: 50 to 500 mm/d, moderate grade soils, pores very visible with hand lens.
4. Highly permeable: greater than 500 mm/d, texture usually sandy, unless soil is very well structured and so textures can be medium (e.g. loam) or fine textured (clays).

Constraint mapping eliminated permeability classes 1 and 2. Class 3 (moderately permeable) was likely to contain areas with marginal permeability for MAR purposes but was retained due to prediction uncertainty and potential to apply larger infiltration areas or use trenches or bores to bypass lower permeability layers. Classes 3 and 4 were reclassified as 0.33 and 0.66 respectively.

Environmentally sensitive areas including wetland conservation areas, national parks, bird sanctuary zones and reserves were excluded through constraint mapping.

Proximity to non-perennial watercourses was preferred as the likelihood of retaining enhanced recharge is increased. Generally perennial flows in this region are due to groundwater discharge meaning any additional aquifer storage is likely to be short-lived. For the purposes of this assessment it was considered that distances greater than 5 km from major (second order or higher) non-perennial streams would not be economically viable. Availability of source water was not considered with respect to existing water management plans. Access in the remote Mitchell River catchment was considered an economic constraint further than 5 km from existing roads. A fuzzy function was used to scale road proximity (within 5km) where low proximity approached 0 and high proximity approached 1.

Land suitability for irrigated agricultural development in the Mitchell River catchment was previously assessed [22]. Areas with crop options for spray and drip irrigation on a wide range of soil types with adequate infiltration potential were considered the most relevant for support through MAR. A constraint was set to remove areas with no crop options for spray and drip irrigation and a fuzzy function was used to scale agricultural versatility (number of crop options) where least options (>1) approached 0 and most (up to 64) approached 1.

Six factors were involved in the suitability assessment, three related to technical and three to economic factors (Figure 2). A range of weights were applied ranging from even weighting to greater and lesser weighting of technical and economic factors (Table 1). The total suitable area remained equal throughout, only the suitability index values varied spatially. A linear additive function was applied across the weighted layers resulting in a combined suitability index score on a scale of 0-1 where higher values indicated greater suitability. MAR potential was classified into low medium and high categories using tercile values as class breaks based on normally distributed evenly weighted suitability index results (Figure 2).

Table 1. Suitability assessment factor weights.

	Objective	Even	Economic weight	Technical weight
Technical	Slope	0.167	0.067	0.267
	Regolith thickness	0.167	0.067	0.267
	Permeability	0.167	0.067	0.267
Economic	Source proximity	0.167	0.267	0.067
	Road proximity	0.167	0.267	0.067
	Agricultural versatility	0.167	0.267	0.067

2.3 Reliability and sensitivity

Reliability was quantified for regolith thickness as the range between 5th and 95th percentile predictions, higher range indicating higher uncertainty. The permeability mapping product provided an uncertainty metric termed a 'confusion index'. Permeability classification used an ensemble learning method to generate 500 realizations from random forest models. The confusion index (on a scale of 0-1) is the ratio of the probability of the most probable class and the second most probable class, higher values indicating less reliability [17]. The 5th to 95th percentile regolith thickness prediction range was rescaled using a fuzzy membership function (higher values indicating lower reliability) enabling combination with the permeability confusion index values and inverted to form a combined reliability index (0-1) where higher values indicate greater reliability. Tercile class breaks were used to create low, medium and high reliability categories (Figure 2). Weight sensitivities were assessed for each suitability factor iteratively by increasing the weight of the test factor by 10% (from 0.167 to 0.184) and comparing with evenly weighted results.

3. Results

3.1 MAR suitability and reliability

Initial constraints on aquifer type, soil permeability, terrain slope, regolith thickness and source water proximity indicated potential for infiltration-based MAR across 9,100 km^2 or 13% of the catchment. Further screening of protected areas (conservation reserves and parks), proximity to non-perennial rivers, proximity to existing roads and agricultural land versatility narrowed the area to 2,102 km^2 or 3% of the catchment.

The suitability assessment revealed the most promising areas were located near the center of the catchment due to lower slope, higher soil permeability, and greater regolith depth in this area and this pattern was consistent across all weightings (Figure 3). Lower lying areas near the coast around Kowanyama were generally unsuitable due to low permeability soils. Applying a greater weighting to economic factors lowered the suitability of areas further from non-perennial rivers and roads (Figure 3b) while weighting towards technical factors reduced suitability of areas with lower permeability higher slope and thinner regolith thickness near the Walsh and Lynd rivers (Figure 3c).

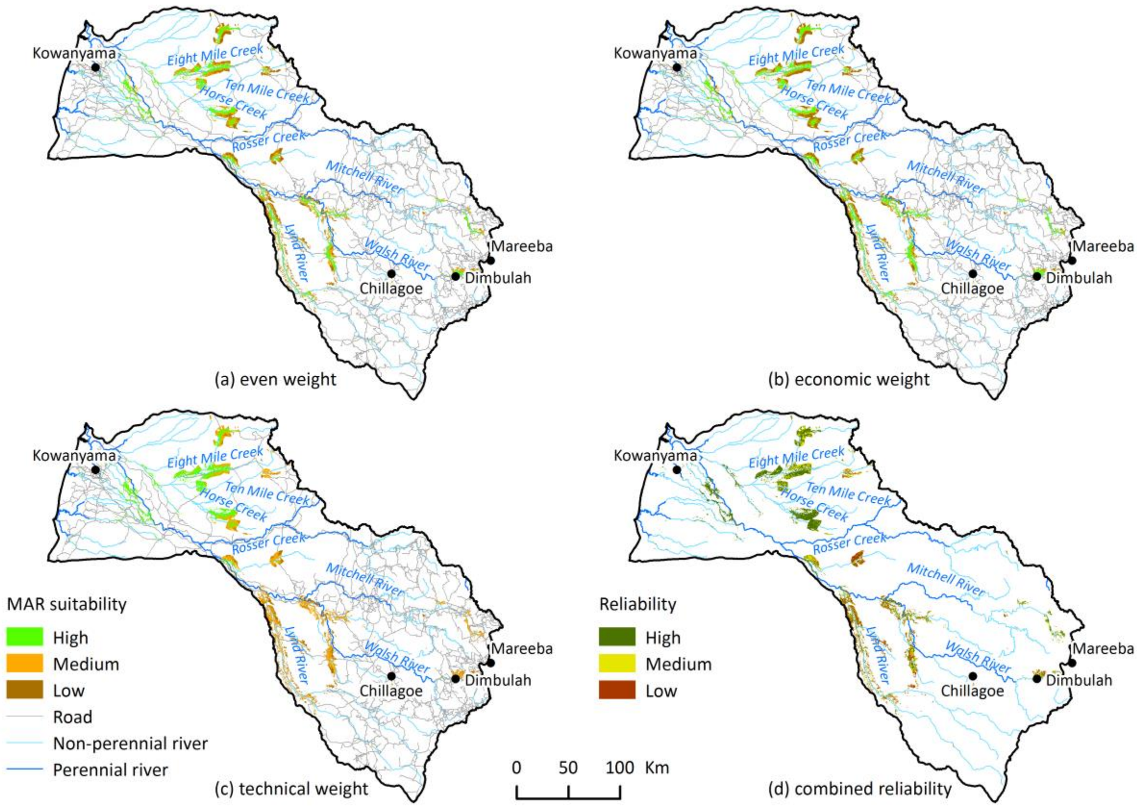

Figure 3. MAR suitability (a) evenly weighted; (b) weighted towards economic factors; (c); weighted toward technical factors; (d) combined reliability from regolith thickness and permeability predictions.

The combined reliability map based on regolith thickness and permeability class prediction error, indicated greatest reliability around Eight Mile Creek, Crosbie Creek (above Eight Mile), Ten Mile Creek and Horse Creek, and least reliability along Rosser Creek, Brown Creek (off Walsh River), and Lynd River (Figure 3d). Of the 2,102 km^2 potentially suitable area, 436 km^2 had high reliability, 601 km^2 medium reliability and 1,064 km^2 low reliability. Generally, higher reliability areas coincided with higher suitability.

3.3 Sensitivity analysis

Increases of 10% in factor weights resulted in between 0.1% and 6.1% change in area within suitability categories (Table 2). Overall, the suitability assessment showed reasonable stability as 10% perturbations in weights did not substantially change the areas within each suitability class.

Table 2. Change in suitability class areas from increasing each test factor weight by 10% compared to even weight.

	Suitability class percent area difference		
Test Factor	**High**	**Medium**	**Low**
Agricultural versatility	-0.2	-0.7	0.9
Permeability	-2.6	1.7	0.9
Regolith thickness	-4.3	0.5	3.7
Road proximity	0.0	-1.2	1.2
Slope	4.6	1.5	-6.1
Source proximity	-0.1	-1.8	1.9

4. Discussion

The suitability assessment revealed the most suitable areas for MAR were located near the center of the catchment around Eight Mile, Crosbie (above Eight Mile), Ten Mile and Horse Creeks due to lower slope, higher soil permeability, and greater regolith depth in this area (Figure 3a, 3b and 3c). Regolith thickness and permeability classifications were also more reliable in this area (Figure 3d). From a technical perspective, these areas could be considered optimal targets for subsequent local scale detailed investigation of MAR feasibility and viability. Flow estimates for these tributaries based on national scale runoff model data [19] indicated accumulated annul runoff volumes of >10^7 m^3. This is sufficient to supply a 10^6 m^3 scheme if conservatively assuming flow capture of 10%.

For MAR in unconfined aquifers the depth to water table is an important consideration. There should be sufficient freeboard available to allow additional recharge without increasing the risk of water logging, soil salinization and salt damp (particularly in urban areas) [15, 23]. Adequate thickness of the unsaturated zone (e.g. >5 m) is also important in achieving water quality improvements particularly during wastewater infiltration [11, 12, 24]. The Australian MAR guidelines recommend a minimum water table depth of 4 m in rural areas and 8m in urban areas where property risks are inherently higher [23]. There were limited water level data available for the Mitchell River catchment area. The few records that existed indicated depth to water was generally >4m in the areas more suitable for MAR higher in the catchment along Eight Mile, Ten Mile and Horse creeks and Walsh River [25]. Depth to water was <4m lower in the catchment in the floodplain of the Mitchell River however as this area is a low energy depositional environment it coincided with lower permeability soils and low MAR suitability.

High salinity of native groundwater can be limiting for MAR development where mixing in the aquifer leads to too saline recovered water for intended uses [26, 27]. Various factors affect tolerable salinity levels including the required water quality (e.g. crop and soil salt tolerance), mixing rates and source water salinity. For the crop options with most potential for spray and drip irrigation assessed in the Mitchell River catchment [22], salinity tolerances were unlikely to be challenged as the groundwater of the sedimentary aquifers was generally below 1000 mg/L TDS [20, 25]. These included cotton, sorghum, Rhodes grass, mango, banana and cucurbit crops that generally accept 1000 mg/L TDS or more in moderate draining loamy soils [28].

The greatest uncertainty for weight-based ranking systems in GIS multi-criteria analyses originates from the assignment of weights and consequent impact on results. There are a variety of methods available to determine weights, each have advantages and disadvantages but ultimately a degree of subjectivity exists. There are examples of pair-wise and multi-influencing factor comparison methods for ranking objectives and computing weight factors according to their relative degrees of importance as applied to MAR potential mapping [6, 11]. Analytical hierarchical process frameworks have also found applications that similarly provide structures for organizing priorities of factors in relation to the objective and to each other [12, 14]. However, as for the simpler rating and ranking methods of weight determination, these methods all rely on decisions to be made concerning the degree to which one factor influences MAR site potential and the degree of influence one factor has on another [13]. Rationales behind these decisions often rely on qualitative literature interpretations of, for example, landscape, hydrological, pedological and geological processes, or expert knowledge. Their application becomes challenging when considering numerous factor combinations.

It is important that whatever MCDA method is applied is transparent and interpretation of results includes recognition of sensitivities and uncertainties. The approach taken in this study did not attempt to determine a correct series of weights, instead it presented three alternatives to allow decisions makers to determine which factors and set of results were most relevant from their own perspective. For example, what may be important in terms of technical capacities to successfully install and operate a system may be different to socio-economic considerations. The remote nature of the Mitchell River catchment and the vast distances involved means that it is likely that any MAR system, along with associated agricultural development would most probably be located within reasonable proximity of existing population centers regardless of the existence of remote areas with higher technical suitability. Weight-based MCDA assessments would be well served as dynamic, interactive decision support tools allowing users to experiment with different influencing factors.

Acknowledgments: This manuscript was developed on the basis of work conducted for the Northern Australia Water Resource Assessment project funded by the Australian Government Department of Infrastructure, Regional Development and Cities. The Northern Australia Water Resource Assessment is an initiative of the Australian Government's Developing Northern Australia and the Agricultural Competitiveness White Paper, the government's plan for stronger farmers and a stronger economy. Aspects of the Assessment have been undertaken in conjunction with the Northern Territory Government, the Western Australian Government, and the Queensland Government.

Author Contributions: Dennis Gonzalez led the development of the methods, wrote most of the manuscript and produced the figures and tables. Joanne Vanderzalm contributed to the method development, helped scope the study, and provided editorial assistance. Karen Barry contributed to method development, data compilation and analyses. Declan Page contributed to scoping and provided editorial assistance.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI: Multidisciplinary Digital Publishing Institute
DOAJ: Directory of open access journals
MAR: Managed Aquifer Recharge
GIS: Geographic Information System
MCDA: Multi-Criteria Decision Analysis
DEM: Digital Elevation Model
TDS: Total Dissolved Solids.

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Paper for ISMAR10 symposium. **Topic No: 4 (125#)**

Site selection for underground dams using spatial multi-criteria evaluation in the semi-arid region of the state of Alagoas, Brazil

Daniel Webber*, Flávio Marques, Manuel de Oliveira Neto, Alexandre Hugo and Maria Sonia da Silva

Brazilian Agricultural Research Corporation.
*Correspondence: daniel.webber@embrapa.br; Tel.: +55 - 813-198-7840

Abstract: A spatial multi-criteria evaluation is proposed to identify suitable locations for underground dams (UD) in the semi-arid state of Alagoas, Brazil. This is a strategic program, which involves a national agency, Embrapa, and the State Government of Alagoas. Suitable areas are identified by combining spatial information on topography, hydrography, pedology, and geology. The topography (slope) and hydrography line vectors were extracted treating a Digital Elevation Model. The pedological data were classified using soil attributes including salinity and sodicity. The geological data were classified according their origin and structural/tectonic factors. The pluviometry data from 78 stations were classified and, subsequently, interpolated. Each map following a basic Geographic Information System analysis was divided into three categories. The "High suitability" category was given to locations that contain ideal conditions; the "Moderate" category indicates suitable regions, but may require further analysis focused on the element which indicated a low rating note, and finally, the "Low Suitability" category, indicates environmental limitations under the criteria presented here, although may still be considered if a more detailed investigation is performed. The methodology proved to be accurate for the scale of investigation as the results coincided well with the areas where the most efficient UDs are already in operation.

Keywords: Underground Dam; Site selection; Geographic Information System; Multi-criteria Evaluation

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1. Introduction

The Brazilian semi-arid region has a severe scarcity of water, reaching 200mm to 800mm of rainfall per year and irregular frequency, possibly showing a lack of rainfall during 2 or 3 months in sequence. These climate conditions results put at risk the success of many agricultural and livestock activities and the live standard of rural families. Consequently, this situation enhances migration to the big cities or to other regions causing a social problem. Nevertheless, the region has a potential to capture 3,780 m^3 / habitant / year, which is equivalent to 400 water trucks / habitant / year [1]. Thus, the problem, at least in some locations, may be overcome through a proper management of water resources.

Rainwater harvesting during the drought period became a priority when designing and implementing public policies. In order to promote the efficient use and maintenance of water resources, the governmental programs and private initiatives have been increasing the deployment of social technologies for rainwater harvesting. Some examples include underground dams, little dams, cisterns for human consumption, cisterns for food production and watering (boardwalk cistern and storm cistern), "barreiro" trenches, stone tanks, among others.

The UDs offer capturing and rainwater storage in the ground. They consist mainly of a dam body (cut-off wall), which is constructed on a relatively impermeable formation under the ground in the transverse direction of descending water. Thus, a groundwater flow in the porous medium is restrained and as the groundwater level rises, it increases a volume of water stored underground. The structures proved to help the local communities with water provision enabling regular and permanent production of crops and livestock and, consequently, offering the resilience of the families to the adversities of the climate, and contributing to the sovereignty, nutritional and food security of the agricultural families of the region [2-4].

There are many advantages of the UDs in comparison to the conventional surface dams, such as, (a) evaporation losses are low; (b) there is no reduction in storage volume due to silting and absence of the accumulation of sediments in reservoirs; (c) the stored water is less susceptible to pollution and health hazards due to mosquito breeding; (e) the land above the underground dam can be utilized as it was before the construction of the dam; (f) potential disasters caused by the collapse of dam walls are non-existent; among others [5].

The Brazilian Agricultural Research Corporation - Embrapa has been researching UD (submersible model) for agricultural purposes in the Brazilian semi-arid since 1982. The Embrapa has been developing agricultural research projects and technology transfer actions among universities, the State Government of Alagoas, Articulação do Semiárido Brasileiro (ASA Brasil), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ), Banco do Nordeste, and Institutos Federais de Educação, Ciência e Tecnologia.

The region classified as semi-arid covers 45% of the territory of the State of Alagoas (1,258,000 hectares) and encompasses 38 municipalities with approximately 30% of the state's population [6]. Data from ASA Brasil point out that there are more than 70 UDs constructed in the semi-arid region of Alagoas [7], which is a significant quantity and a great opportunity for the validating process of the site selection methodology. Identifying suitable locations for the construction of UDs is necessary for its success and requires a multi-criteria evaluation, including pedological, geological, climatic, hydrographic and geophysical data. Since there is a robust number of geospatial data from the semi-arid region of State of Alagoas, available on the 1:100000 scale, Embrapa and the State Government of Alagoas joined efforts to identify which areas have the required characteristics to build sustainable UDs. This contribution proposes a low-cost site selection method for the construction of UDs in the semi-arid of Alagoas using a spatial multi-criteria evaluation.

2. Materials and Methods

2.1 GIS Data Collection

Primary and secondary data of the study area were collected from Brazilian Government [8-13] and from NASA sites [14]. All layers (vectors and raster) were imported to ArcGIS, adopting SIRGAS 2000 as the reference system.

2.2 Exclusion areas

The reservoirs, lakes and urban areas were manually digitalized and vectorized using 5-meter resolution images (GeoEye and other satellite images from ArcGIS basemaps) and, then, converted to raster. Those have reached 1.5% of the total semi-arid region of Alagoas, being defined as exclusion areas in this site selection methodology.

2.3 Evaluation of Slope for UD Construction

A mosaic was created from 30-meter SRTM elevation raster images collected from NASA website using Mosaic to New Raster Tool and, subsequently, converted to the 1.100000 scale (pixel size of 20m). Topography (contour) were extracted from a Digital Elevation Model (DEM) and hydrography line vectors were extracted from a Hydrologically Consistent Digital Elevation Model (HCDEM). The HCDEM is a DEM whose flow direction defines expected flow of water over the terrain (the drainage pattern).

Since there wasn´t a significant number of elevation points available for the study area, a Digital Terrain Model (DTM) could not be created. However, a Triangular Irregular Network (TIN) was built using Delaunay triangulation from contour lines and stream lines in order to get more homogeneity to the model. TINs are a form of vector-based digital geographic data and are constructed by triangulating a set of vertices. The vertices are connected with a series of edges to form a network of triangles.

The outliers (data that was too high or blank) were detected with "Locate Outliers tool" and, after, excluded from TIN. TIN was converted to a raster image (TIN to Raster Tool) and, subsequently, a slope percentage was calculated (Slope Tool). Finally, the slope was classified using a Embrapa method [15], where data from 0 to 3% as "High Suitability" category, 3 to 8% as "Moderate Suitability" and, upper 8% as "Low Suitability".

2.4 Evaluation of Soil-water Conditions for UD Construction

The drainage system was configured to extract pixels that value greater than or equal to 100 considering that many headwater streams or streams in semi-arid regions sometimes run dry. Spring points were identified at the vertices of all tributaries and, after, received 50 meters circular buffers according to the premises of the Brazilian Environmental Laws. These areas were classified as "Low Suitability". As UDs are not recommended to operate on soils with high salinity and sodicity, other buffers measuring 80 meters were defined around the whole drainage system in order to clip this attributes from soil layer.

The pedological data from Embrapa [8] were classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories using soil attributes, such as, effective depth of soil or lithic contact, presence of stony, rocky, erosive and texture. The layer was then merged using 80-meter buffer of the drainage system that contained soil salinity and sodicity.

2.5 Evaluation of Geology for UD Construction

The geological data from CPRM [10] were classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories according to their origin (sedimentary, igneous or metamorphic) as well as structural / tectonic factors, including the presence of faults, fractures and foliation. Hydrogeological conditions require that dams should be located in water transmissive sediments overlying a poorly-permeable formation. For example, permeable fractures in the underlying formation may cause preferential groundwater flow resulting in a risk that the water stored in an UD escapes.

2.6 Evaluation of Climate Conditions for UD Construction

Climate conditions were also included in the multi-criteria evaluation through the pluviometry data, once rainfall is the main source of water recharge in semi-arid regions. Spatial-temporal analysis of pluviometric scenarios are necessary for the identification of areas suitable to the construction of UD. In the present study, 78 pluviometric stations – only those with historical rainfall series over 20 years – were interpolated in three different seasons (dry, rainy and interseasonal) and, classified as "High Suitability", "Moderate Suitability" and "Low Suitability" categories. The dry season represents the years where the total rainfall accumulated in the three consecutive rainy months was equal to or less than the value corresponding to the probability of 25%. The rainy season represents those years whose total precipitation, accumulated in the three consecutive rainy months, is higher than the value corresponding to the probability of 75%. The inter-seasonal records refer to years that were not classified in the two previous categories. Areas presenting total annual rainfall over 600 mm were classified as “High Suitability”, those presenting less than 300 mm were classified as “Low Suitability” and, areas presenting between 300 and 600 mm were classified as “Moderate Suitability”.

2.7 Spatial Multi-criteria Evaluation for UD Construction

The raster maps obtained were submitted to basic operations using the GIS raster calculation tool. The numerical grids of each matrix file were multiplied between them. Pixels classified in the “High Suitability” category were represented by the integer number “2”, “Moderate Suitability” category pixels by the integer number “1” and; “Low Suitability” category pixels by the integer number “0”. It is worth mentioning that any number multiplied by zero equals to zero. In the sense of spatial relations, all “Low Suitability” categorical areas of any of the five thematic evaluations will overlap “High Suitability” and “Moderate Suitability” categorical areas that are in the same position. An exception was configured to the spring evaluation which had “High Suitability” category pixels represented by the integer number “1”, considering that this kind of natural resource requires only one restriction area for the structure constructions.

Finally, the map resulted in six products coming from the programmed combinations using a multi-criteria evaluation. As usual, the values were classified into the three categories – “High Suitability” from 5 to 16, “Moderate Suitability” from 1 to 4 and, “Low Suitability” for 0 values of final raster´s pixels. This final raster was converted to a feature (polygon) and symbology of all categories has been chosen according to the following colors: dark green for “High Suitability”, light green for “Moderate Suitability” and, beige for “Low Suitability” areas.

In our approach, the “High Suitability” categorical areas are dedicated for those polygons that contain ideal natural conditions for UD construction. The “Moderate Suitability” categorical areas are suitable, but may require further analysis on variables which low evaluation rates were recognized. The “Low Suitability” categorical areas have natural limitations for the construction of UDs, however they are not prohibited since environmental studies did not indicate any technology that could provide water source in these areas.

In order to check if the site selection methodology and the current strategy of UD construction were matching, the layer of UDs in operation was imported to the GIS project where spatial analyzes could be made with all suitability categorical areas.

3. Results

3.1. Slope Suitability for UD Construction

The slope obtained from TIN showed an adequate homogeneity to the suitability map considering the limitations of SRTM Radar (Shuttle Radar Topology Mission) to penetrate in vegetation (not until the ground). The polygons resulted from the slope evaluation have reached an average size of 63.36 hectares. Table 1 presents some statistics of the areas by classes.

Table 1. Slope classes and respective areas (average and maximum).

Classes	Average Size (hectare)	Max. Size (ha)
High Suitability	84.07	688,750.03
Moderate Suitability	2.23	2,328.88
Low Suitability	103.79	15,893.56
Average	63.36	235,657.49

In the slope evaluation, 67.18% of the study area was classified as “High Suitability” (844,695 hectares), 17.02% as “Moderate Suitability” (213,956 hectares) and, 15.80% as “Low Suitability” (198,662 hectares). Considering that around 84% of the study area presents less than 8% of slope

(Moderate to High Suitability), the state shows adequate slope conditions for the construction of UDs (Figure 1).

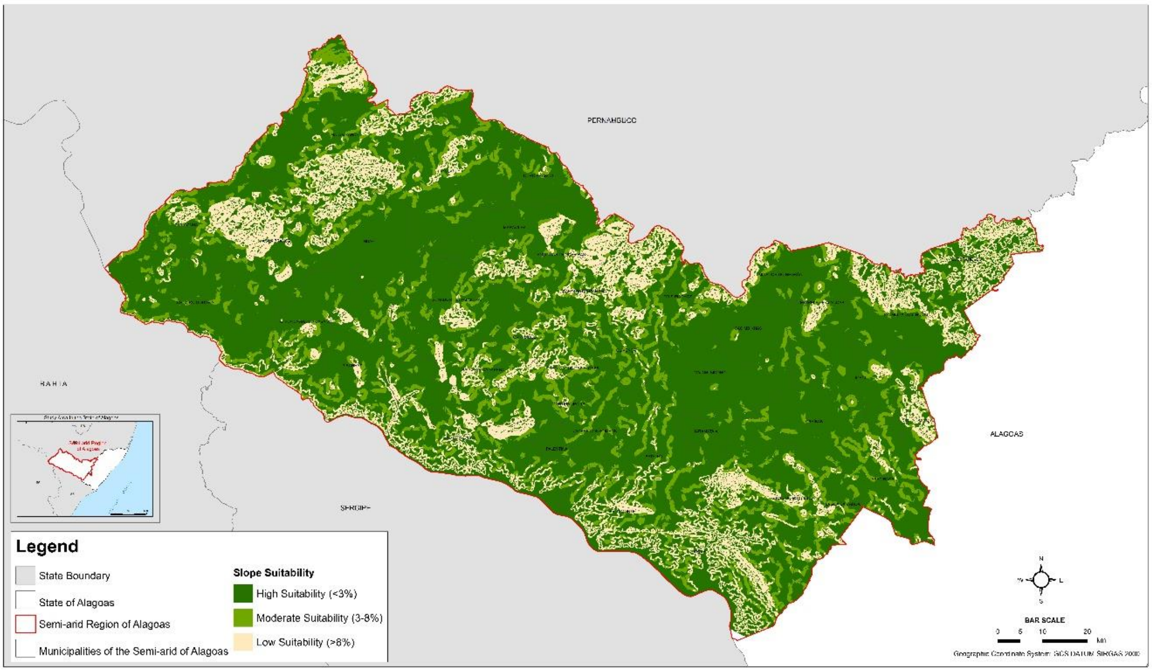

Figure 1. Slope Suitability Map.

3.2. Soil-water Suitability for UD Construction

The evaluation of soil-water conditions was essential to identify more areas with "Moderate" and "High Suitability" classes compared to the isolated pedological classification (Table 2).

Table 2. Classes of Pedological and Soil-water suitability, respective areas and percentages.

Classes	Pedological		Soil-water	
	Area (hectares)	**Area (%)**	**Area (hectares)**	**Area (%)**
Low Suitability	866,721.13	68.89	796,429.88	63.31 ↓
High Suitability	261,713.69	20.8	274,889.99	21.85 ↑
Moderate Suitability	109,069.66	8.67	166,185.27	13.21 ↑
Water bodies	11,333.8	0,9	11.333,80	0.9
Urban Zones	9,233.09	0,73	9.233,09	0.73
Total	1,258072.03	100	1,258072.03	100

The "High Suitability" and "Moderate Suitability" areas were better distributed throughout the semi-arid region from the soil-water point of view than in the single pedological one. It could be noticed clearly in the hinterland region (Figure 2), where the analysis of soil characteristics did not contain conditions conducive to the construction of UD. When overlapped by the soil-water layer, it was possible to identify "High Suitability" and "Moderate Suitability" categorical areas in the surrounding areas of streams where soils do not present salt or sodium.

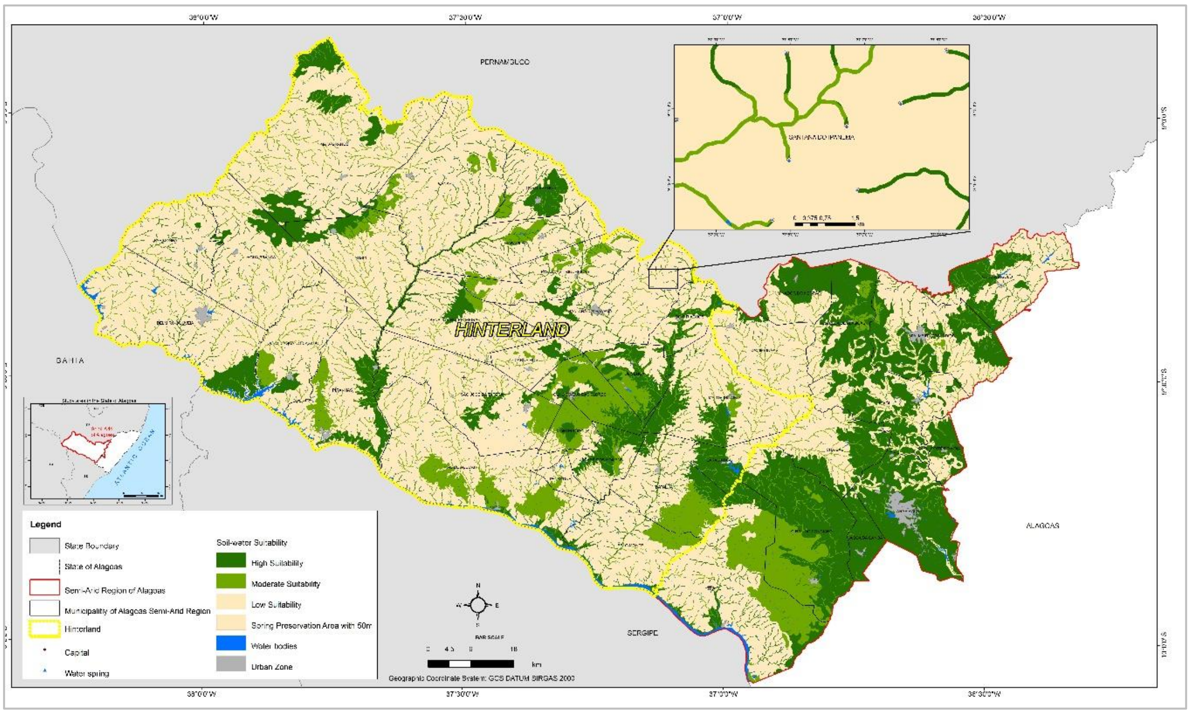

Figure 2. Soil-water Suitability Map.

3.3. *Geological Suitability for UD Construction*

In the evaluation of lithologic units the "High Suitability" categorical areas were predominant, occupying more than half of the entire semi-arid region of Alagoas (62.06%), followed by the "Moderate Suitability" (28.18%) and "Low Suitability" (9.75%) categorical areas (Figure 3).

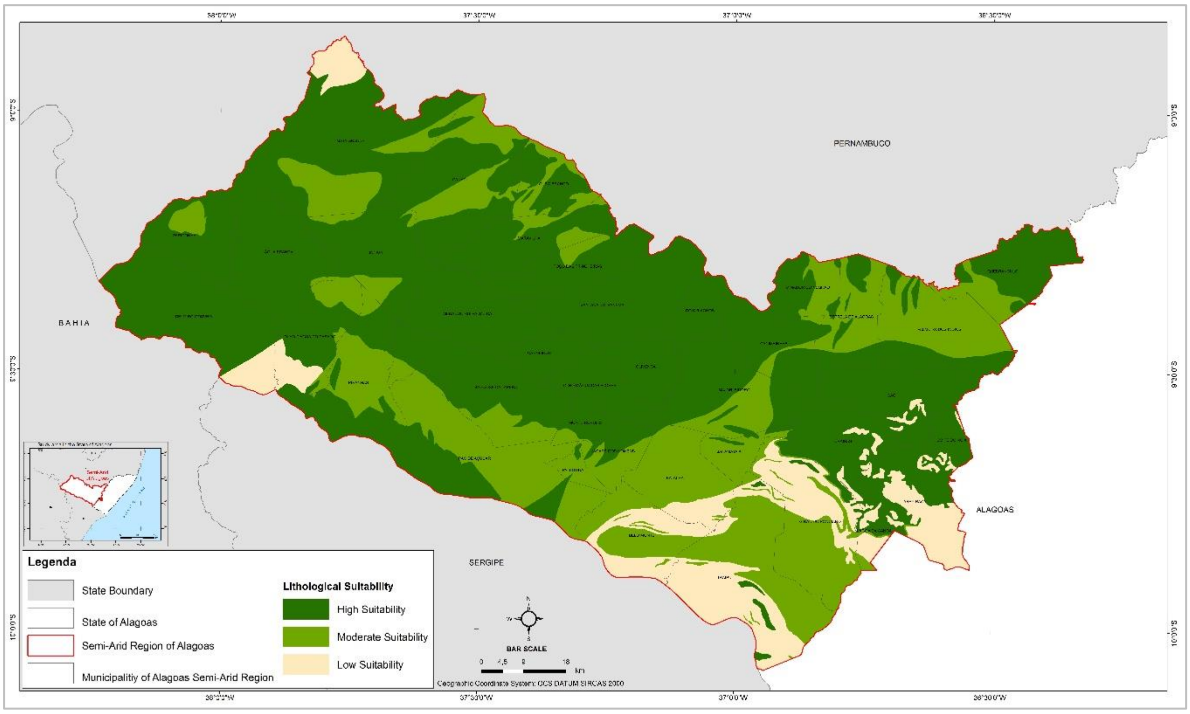

Figure 3. Geological Suitability Map.

3.4. Climatic Suitability for UD Construction

Considering the pluviometric scenario of dry years as the most restrictive among the other two (rainy and interseasonal), it was used for the multi-criteria evaluation. During this period the climate conditions for water recharge are limited, with annual rainfall around 300 to 600 mm. Only three small isolated areas were classified as "Low Suitability", with annual rainfall totals lower than 300 mm, which means there is enough rainwater to guarantee at least one period with stored water (Figure 4).

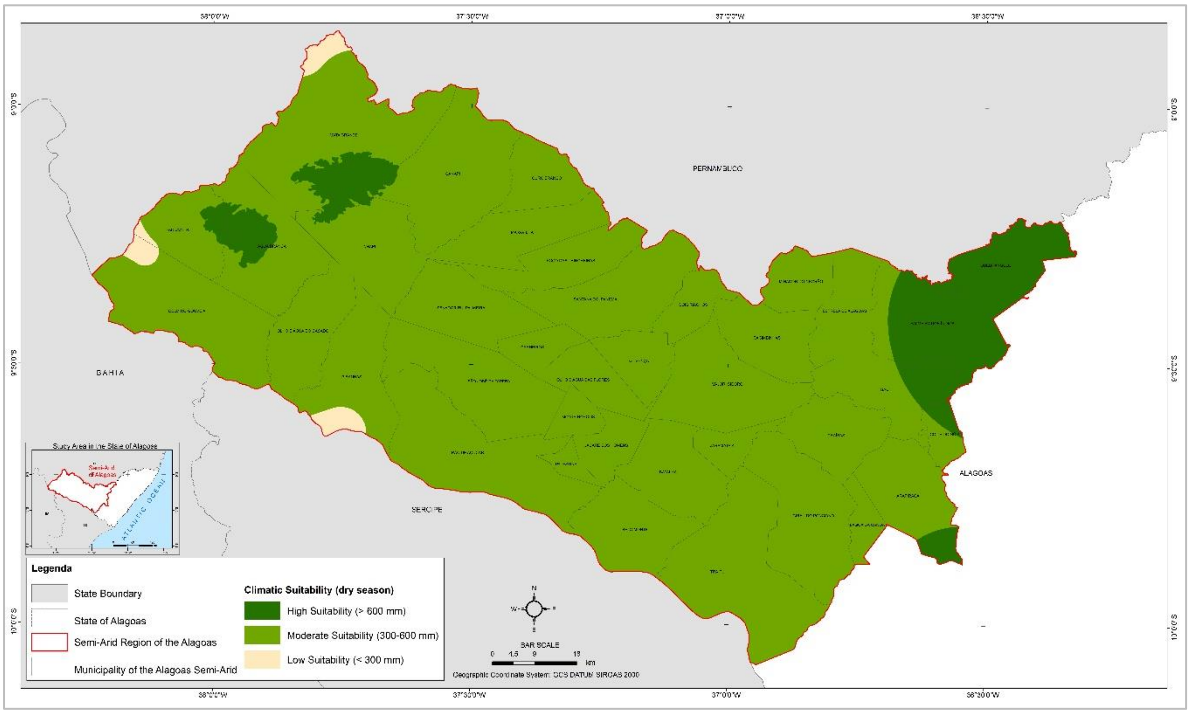

Figure 4. Climatic Suitability Map.

3.5. Site selection for UD using spatial multi-criteria evaluation

The methodology could point out the best sites for UD construction considering five different environmental characteristics in a multi-criteria evaluation. The result of all GIS operations is a layer containing each value of these variables and its respective category. Therefore, it´s possible to identify not only the multi-criteria suitability category, but also analyze which characteristics (geological, slope, climatic and soil-water) were responsible for this condition.

Homogeneous polygons were obtained in the proposed methodology, which are concentrated around the drainage system or along the semi-arid in a set of polygons closely arranged. Average size of high and moderate suitability categorical polygons is 18 ha. This average size of polygon areas is enough to build an UD for agriculture purposes, which is generally two ha.

Visually analyzing the suitability map overlapped by some of the UDs in operation (Figure 5), it´s possible to notice compatibility between the results of the proposed methodology and the current ASA strategy for UD construction. Even so, it´s still not possible to quantify the resulting suitability areas neither do make any statistic with UD´s in operation, once the validation process has not started and changes in the current configuration might happen.

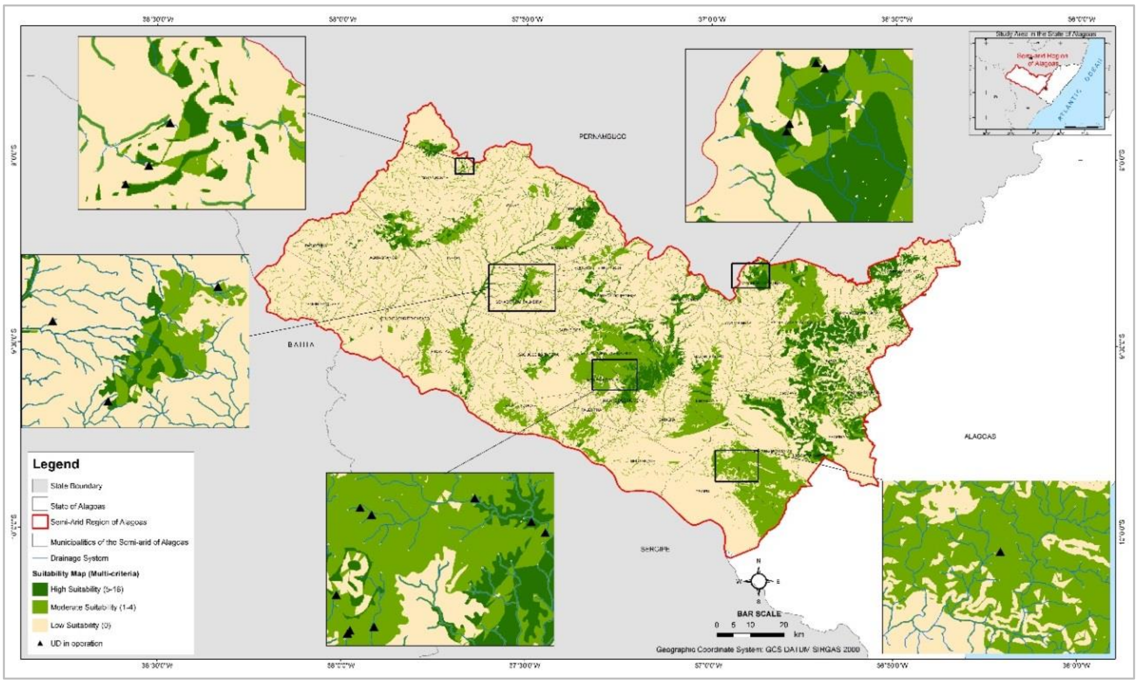

Figure 5. Suitability Map (Multi-criteria) and UDs in operation.

Indeed, this analyzes will be a consistent contribution to the validation map process, which will include survey with farmers, technicians, non-governmental organizations and, rural extension agents, in order to improve and complement the suitability map. It will help decision makers of Embrapa and the State Government of Alagoas to identify potential areas for the construction of pilot technologies and to orient future R&D projects, as well.

4. Discussion

The spatial multi-criteria methodology adopted for underground dam's site selection is simple, but innovative and effective, since existing areas obeyed satisfactorily the multi-criteria evaluation. However, the methodology cannot be replicated in other semi-arid regions since most of them has less accurate cartographic basis, especially in Brazil.

Despite the fact the scale level used in this work (1:100,000) is not the most appropriate for the construction of local structures, this was the most detailed possible considering the cartographic bases available for the Brazilian semi-arid. In addition, the pedological data from Agro Ecological Zoning of the State of Alagoas [8] is the only in 1:100,000 scale which is updated to the Brazilian system of soil classification. Even though, some secondary spatial data used in the multi-criteria evaluation were not in the project target scale (1:100,000), the cell size resample tool and the vectorization process could improve the accuracy of the multi-criteria suitability map. It´s worth mentioning that the geological data used in this study is the most detailed (1:250,000) among the Brazilian states.

It was possible to associate some UDs in operation with their respective categories obtained from the suitability map. These analyses (links) can be considered a reference for the validation process. As soon as the validation process finishes, the suitability map for the UD construction will be available for decision makers from the State Government of Alagoas and other companies in order to select the best areas of the semi-arid to define public policies to this water technology. A detailed investigation is warranted in the selected areas before constructing any kind of hydraulic structure.

Since there are no official procedures of the construction of UDs in the semi-arid of Alagoas, and there is a large number of UDs already in operation, the suitability map becomes an important and strategical tool and should be used as a guidance document to construct and manage UDs.

Acknowledgement

We wish to thank the following organizations for granting important data to our research: Embrapa, Secretaria de Estado do Meio Ambiente e dos Recursos Hídricos de Alagoas, Articulação do Semiárido Brasileiro, Companhia de Pesquisa de Recursos Minerais, Superintendência de Desenvolvimento do Nordeste, Agência Nacional das Águas and USGS-NASA.

Special thanks should be given to Dr. Antonio Gomes Barbosa, coordinator of the P1 + 2 program and other social programs which ASA Brasil is involved, and Dr. Wilton José Silva, Progestão coordinator from Secretaria de Estado do Meio Ambiente e dos Recursos Hídricos de Alagoas for their valuable technical support on this project; Dr. Konrad Miotlinski, professor of Universidade Federal de Santa Catarina, for reviewing and helping to translate this paper.

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Extended abstract for ISMAR10 symposium. ***Topic No: 4 (166#)***

A GIS approach to evaluating bank-filtration occurence and potential in the province of Quebec, Canada

Patenaude, Marc*; Baudron, Paul; Masse-Dufresne Janie; Pontoreau, Coralie and Dion, Gabriel.

Polytechnique Montréal, Montreal, Canada
*marc.patenaude@polymtl.ca

Key words: Bank Filtration, geographic information systems (GIS), Province of Quebec, Canada.

EXTENDED ABSTRACT

1. Background

In reviews of the international use of bank filtration (Dillon et al., 2019; Stefan & Ansems, 2017), Canada and the province of Quebec in particular are completely overlooked. As of this point in time, no inventory of bank filtration sites exists and the extent of its use throughout the province remains unknown. There is however a high probability that induced bank filtration (IBF) is widely used. Indeed, Quebec is a province rich in both surface water and groundwater with 22% (MDDELCC, 2014) of its surface covered by water either in the form of lakes, rivers, or wetlands. It is estimated that Quebec contains 3% of the Earth's renewable freshwater resources (Boyer, 2008). In addition, Quebec was settled through its waterways which have had long term effects on its population distribution. These two factors mean that there is high probability that pumping wells are located in close proximity to surface water. The process of IBF is thus likely to be occurring in many of the municipalities throughout the province. Current regulations and guidelines exist in Quebec for protecting surface water and groundwater extractions from contamination but there is no regulation specific to hybrid groundwater-surface water systems(Act, 2019). Existing IBF sites are therefore necessarily treated as standard groundwater extractions. This means that even if the groundwater wells are located within a few meters of a water body, there are no protection guidelines for the nearby surface water. The objective of this study is to present a GIS method of quantification of IBF sites in the province of Quebec, where there is a crucial need for improved characterization and comprehensive management guidelines.

2. Material and methods

There are two main factors that will determine whether a well is pumping a mixture of surface water and groundwater. First, a hydraulic connection between the surface water and the aquifer is necessary. Second, since groundwater naturally discharges into surface water in the study region, it is necessary to pump a sufficient volume to reverse that natural gradient and draw surface water toward the pumping well. In the existing databases, this information is not available.

In order to estimate the number of sites with the limited information available, a series of steps were taken in order to calculate their distance from surface water bodies and use this to infer whether the two conditions are met. A database obtained from a series of regional studies (PACES) which integrated data from multiple sources (MELCC, 2009-2015) was used for the individual wells to perform a series of steps in QGIS. In order to calculate the distance between each well and the nearest water body, a cleaned version of the database was used with duplicate wells removed. The waterbody files for smaller zones within the province were converted from multipart to single part files in order for the conversion of lines to points to work properly. The waterbody outlines were then converted to points with a 2-meter spacing. The distance from each well was calculated for each of the waterbody zones. This generated multiple distances for each well corresponding to each of the zones that were then merged into a single file that was used to calculate the minimum value for each well. Once the minimum value had been calculated, it was possible to join the resulting file to the additional files containing pertinent information (i.e. aquifer type, waterbody type, etc.)

3. Results and discussion

The PACES database contained a variety of information including the type of aquifers exploited for certain wells (granular vs fractured). Of the roughly 181000 wells in the PACES database, only 10179 were reported as granular aquifers and 45649 in fractured aquifers, and the majority had undocumented aquifer type. By looking at a provincial map of the aquifer type, certain areas where there are very few or no wells exploiting granular aquifers were identified. This distribution could indicate that the aquifers are either not productive enough or that the granular deposit thickness is not sufficient to support a well. With this in mind, two main conclusions can be drawn. First, municipal wells that are in these areas and far from a lake or river are likely drilled in a fractured aquifer. Second, wells in these areas that are close to surface water bodies could be drilled there for the increased productivity associated with the alluvial deposits around those water bodies and the rapid recharge from the nearby waterbody.

Furthermore, a more detailed look at the distribution of wells versus the distance from surface water bodies, suggests that the highest density of wells is found in the first 250m near surface water bodies. After the 250m mark there is a gradual decrease in the number of wells. This could be related to two main possibilities. Firstly, as was mentioned previously, individuals are often settled near water bodies, either due to the town they live in being founded in those locations or the fact that there is a preference for waterfront properties for homes and cottages outside of the major metropolitan areas. Secondly, the spatial distribution of wells in the first 250m could be related to the sheer number of surface waterbodies throughout the province. In any case, we can conclude that there is likely some individuals who are also pumping a mixture of surface water and groundwater and inducing recharge of the aquifer through the banks of lakes or rivers.

4. Conclusions

Looking at individual wells provides some insights into the types of aquifers and the distribution of wells in proximity to surface water bodies. In addition, it can be used to target specific areas where aquifer conditions are more favourable for IBF. However, these individual wells are much less likely to be pumping large volumes and the probability of IBF prevalent in these wells is less likely than in municipal wells where much larger volumes are pumped on a consistent basis. The study should therefore be repeated on municipal wells, although limited availability of data is expected.

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Paper for ISMAR10 symposium. ***Topic No: 4 (223#)***

Determining the Potential for Managed Aquifer Recharge (MAR) for the Bengal Basin, Bangladesh

Faneca Sanchez, Marta[1]; Zahid, Anwar[2] and Oliemans, William[1]

[1] Deltares, Utrecht, Delft, The Netherlands
[2] Bangladesh Water Development Board, Dhaka, Bangladesh
* Correspondence: Marta.faneca@deltares.nl, Tel.: +31-652-41-78-47

Abstract: In Bangladesh, many communities depend on groundwater for drinking water and small scale irrigation. Particularly during the dry season when rains have ceased, safe and reliable groundwater supply is key to the livelihoods and socio-economic development of a large part of the rural population. The shallow and main aquifers in the country can yield large quantities of water however these aquifers are not all suitable for further development due to the already occurring declining water tables and deteriorated water quality. This paper summarizes the method used to generate potentiality maps for artificial recharge techniques in Bangladesh. The method consists of analysing key variables that contribute to the Physical Potential (PP) and the Demand Urgency (DU) for the aquifer systems in Bangladesh. The variables describing these two aspects are analysed and reclassified according to a set of criteria. Each criterion is then assigned a "suitability score"and the final total potentiality is calculated. Following this method, the potential of a number of MAR techniques are mapped. According to the results, the techniques "infiltration well" and "artificial reservoir" have the highest potential in Bangladesh.

Keywords: Managed aquifer and recharge; physical and demand potential; hydrogeological condition; artificial recharge; infiltration well.

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1. Introduction

Artificial recharge i.e. the augmentation of infiltration into groundwater by different technologies like recharge basins, recharge wells, induced infiltration by injection wells etc. of treated safe and fresh surface water or harvested rain water is now a days very much accepted worldwide for overstressed aquifers. Managed Aquifer Recharge (MAR), also referred to as Artificial Recharge and Recovery (ASR), is a well-tested and viable technique, with applications in developed countries from as early as 1948 in Berlin, Germany, France from 1959, and California, from 1962 onwards. The Orange County groundwater recharge project in California that started in 1975 and expanded in 2008 to serve some 600.000 people, is a particularly well known example [3]. Much of this experience is well documented and tested. The knowledge of the potential and application of MAR in a developing country such as Bangladesh is however limited.

In general, artificial recharge is an attractive option however, it comes with several prerequisites that are often hard to meet [1]. They include having sufficient water for recharge, good quality or pretreatment of the water in order to avoid contamination or public health issues, land availability for recharging facilities and/or a sustainable stream of funding to pay for energy costs in the case of recharge by injection; easy recovery of the recharged water [4].

A range of techniques has been developed for artificial recharge. The infiltration well is currently the most common aquifer storage and recovery technique used in Bangladesh. It is mostly meant for domestic water supply and less meant for irrigation. There are several studies researching the potential of this system and monitoring its benefits, however there is no concluding study yet on its impact. There are other techniques which could also enhance the rainwater harvesting during the wet season to make water available during the dry season. Some of them might be more interesting for irrigation purposes and other for domestic water supply. There are many experiences about these techniques, but most of them have not been piloted in Bangladesh yet.

In this study the potential of four aquifer storage and recovery techniques has been mapped using the method described in the next section. The four systems were defined by experts of the BWDB in Bangladesh:

- Infiltration well: in this case the rain water is collected in the roof-tops and injected through a well at a certain depth in the aquifer.

- Infiltration pond: this system consists of building a pond in a sandy area where water can infiltrate easily. The pond has a permeable bottom to allow water to infiltrate and recharge the aquifer. The pond should collect rain water directly, or surface water conducted to the pond as diversion of rivers. This system has been applied in several countries and has proofed to work.

- Recharge basin connected to the aquifer: this system consists of creating an artificial pond by digging out the surface impermeable material and replacing it by sandy material in order to bring the new sand in contact with the aquifer and enhance the recharge of it. This system is at the moment conceptual and its potential still needs to be tested.

- Artificial reservoir disconnected from the aquifer: similar to the previous system, this one consists also of digging out some clay and fill it with sand. In this case the clay thickness us such that the new sand does not come in contact with the aquifer. This technique might be useful to create shallow surface water lenses disconnected from a deeper aquifer that might be contaminated by saline water or arsenic rich water.

In order to illustrate well the method, the steps to create the potentiality map for an Infiltration Well fed with Rain Water is extensively presented.

2. Materials and Methods

The method used for this study is based on a previous method designed by Deltares and the Rain Water Foundation [8] which has been complemented with Expert Knowledge from the Bangladesh Water Development Board (BWDB). The method consists of analyzing various variables that contribute to the Physical Potential (PP) or the Demand Urgency (DU) for a given technique. The different variables describing these two aspects are analyzed and reclassified according to several criteria defined by experts with specific knowledge on the climate, hydrology, hydrogeology and socio-economic aspects of Bangladesh. Each class is then assigned a "suitability score" equal to 0, 0.5 or 1 depending on its correlation to the PP or DU. Once the score is ready, the scores for the variables related to the PP are combined and so are the ones defining the DU. Finally, the result for these two groups is added up giving a final score per spatial unit. All calculations have been done with gridded data at a resolution of 2x2km.

The identified variables that define the Physical Potential are:

- Precipitation intensity and duration

- Evaporation loss
- Surface geology
- Thickness of the aquitard
- Groundwater depth below the surface in the middle of the Monsoon (June)
- Wells contaminated with Arsenic
- Inundation land type.

The variables that define the Demand Urgency are:

- Population density
- Depth of the groundwater table below the surface at the driest month (April)
- Poverty
- Absence of perennial rivers close by
- Irrigation demand.

2.1 Variables related to the Physical Potential

2.1.1 Precipitation

The criteria used to classify precipitation are the following: areas with high precipitation intensity and long duration of the precipitation are most suitable than areas with low precipitation as rainwater needs to be harvested for infiltration. We consider that for rain water harvesting, a minimum of 100mm/month during at least 4 months is required. The justification of 100mm/month is related to the fact that this are considered household systems with an efficiency of $10m^3/150$ days [3]. Considering a roof-top of 5x5 meters, the systems can store about $2.5m^3$/month which is more than the $10m^3/150$days. With this, the system can supply water to at least a family of 4 members, each with 20l/day during 4 months. The dry season can vary but it can be as long as 7 months, so when the precipitation is higher than 100mm/month during at least 7 months, the suitability of the area and therefore the physical potential related to precipitation, is considered 1. The data used is decade precipitation per station from 1948 to 2014. A total of 33 stations were used

Suitability classification:

- The precipitation is 100mm/month or more during less than 4 months = suitability 0
- The precipitation is 100mm/month or more during 4 to 7 months = suitability 0.5
- The precipitation is 100mm/month or more during at least 7 months = suitability 1.

2.1.2 Evaporation loss

Areas with a high evaporation loss are less suitable than areas with a low evaporation loss. The data used is average daily evaporation per station from 1983 to 2011. A total of 14 stations were used.

Suitability classification:

- Evaporation loss > 50% = suitability 0
- Evaporation loss > 40 and < 50% = suitability 0.5
- Evaporation loss < 40% = suitability 1.

2.1.3 Surface Geology

Hard rock areas are not suitable for the Infiltration Well technique, while sedimentary materials are. According to the geological map of Bangladesh, tertiary hills are hard rock and therefore not suitable for this measure, Pleistocene uplands, flood plains and deltas are suitable for this system.

Method:

Suitability classification:

- U/H2O/lake/QTdd/Tba/Tb/Tt/QTg/Tbb/QTdt/QTdi= suitability 0
- afo/afy/asd/rb/asl/asc/ppc/ac/rm/ava/dsl/dsd/de/dt/csd/dm/dsw= suitability 1.

2.1.4 Thickness of the aquitard

If the thickness of the aquitard is less than 3 meters, Infiltration Wells are less suitable as water can infiltrate directly and there is no need for an infiltration well. If the aquitard has a thickness of more than 35 meters, drilling a well might require more sophisticated machinery. Therefore 3m and 35m have been used as thresholds to define the suitability of the area for this given technique.
Suitability classification:

- If thickness of the aquitard is less than 3 meters = suitability 0
- If thickness of the aquitard is between 3 and 5 meters or more than 35 meters = suitability 0.5
- If thickness of the aquitard is between 5 and 35 meters = suitability 1.

2.1.5 Groundwater Depth below surface after 2 months of monsoon

For areas where in June the groundwater table is still deeper than 1 meter, the Infiltration Well has more potential as there is still some space for infiltration and storage of water. If the groundwater table in June is shallower, the potential is less. The data used is the average groundwater depth from BWDB for the years 2000 to 2014 for May.
Suitability classification:

- If groundwater table <1m below surface = suitability 0
- If groundwater table between 1 and 3m below surface = suitability 0.5
- If groundwater table >3m below surface = suitability 1.

2.1.6 Arsenic

If the aquifer is contaminated with arsenic, the suitability of MAR is low as infiltrated water will mix with already contaminated water. In this case, the infiltration should be done at a deeper aquifer or other methods should be applied. The experts chose as threshold 20% of the wells contaminated or not contaminated by As.
Suitability classification:

- If > 20% of the wells contaminated by arsenic = suitability 0
- If <20% of the wells contaminated by arsenic = suitability 0.5
- If Arsenic safe = suitability 1.

2.1.7 Inundation land type

For low lying areas that get regular seasonal flooding or water logging and that lay at less than 3 m above sea level, the Infiltration Well is not suitable as the well would get often inundated and possibly clogged. Medium Land between 3 and 10m above sea level are better areas for this MAR technique. Highlands lying at more than 10m above sea level are the most suitable for the implementation of Infiltration Wells.
Suitability classification:

- Lowlands or very lowlands with regular seasonal flood or water logging = suitability 0
- Medium Land with high flood vulnerabilities = suitability 0.5
- Highlands or medium highlands without or less flooding = suitability 1.

2.2 Calculation of the Physical Potential

These variables have been combined in order to calculate the Total Physical Potential, which is the sum of all the suitability scores (SS) assigned to the different variables. The formula is as follows:

Total physical Potential = SS Precipitation + SS Evaporation Loss + SS Groundwater Depth + SS Surface Geology + SS Thickness of the aquifer + SS Arsenic contamination + SS Inundation Land Type.

2.3 Variables related to the Demand Urgency

2.3.1 Population Density

In areas with high density population, there is higher demand for such a MAR technique. We used the threshold of 500 and 10 inhabitants per km^2 to separate high and low suitability based on expert judgement.
Suitability classification:

- Areas with a population density <10 inhabitants per km^2= demand score 0
- Areas with a population density between 10 and 500 inhabitants per km^2= demand score 0.5
- Areas with a population density >10 inhabitants per km2= demand score 1.

2.3.2 Depth groundwater table below surface

For areas where in April (and the end of the dry season) [2] [6] the groundwater table has lowered below the pumping threshold (around 7m), the suitability is 1. If the groundwater table is below 3m but above 7, so half way the pumping limit of hand pumps, the suitability is 0.5, and if the groundwater table has lowered to less than 3m below surface, the experts do not consider that there is an urgency for such techniques as the groundwater table is still high enough for hand pumps to withdraw it.
Suitability classification:

- If groundwater table <3m below surface =demandscore 0
- If groundwater table between 3 and 7m below surface =demandscore 0.5
- If groundwater table >7m below surface =demandscore 1.

2.3.3 Poverty line

If the percentage of population below the Lower Poverty Line (LPL) is more than 20% the suitability is high, if it is between 20 and 5% the suitability is medium and if it is below the 5% the suitability is 0. The data used are poverty maps launched by the World Bank in 2014. The maps are for 2010. We used the Proportion of Population below the Lower poverty Line. The Lower Poverty Line corresponds to the extreme poor households whose total expenditures are equal to the food poverty line using the Cost of Basic Needs (CBN) method.
Suitability classification:

- If % of population below the LPL <5% =demandscore 0
- If % of population below the LPL is between 5 and 20% =demand0.score 5
- If % of population below the LPL >20% = demandscore 1.

2.3.4 Absence of perennial river close by

If there is a river at a distance less than 500 meters, the demand for another source of water will be low (suitability 0), otherwise the demand can be high (suitability 1). 500m is indicated by the WHO as the minimum radial distance for a water supply point as the minimum standard for water and sanitation.

2.3.5 Irrigation demand

We used irrigation demand instead of land use as we did not have trustworthy data on land use. The criteria are related to the irrigation demand. If there is a deficit in irrigation, then the technique is more suitable than if there is no is no deficit. We considered a deficit of 200mm/year as threshold based on expert judgement of the average irrigation requirement.
Suitability classification:

- If no deficit irrigation or surplus= suitability score 0
- If deficit irrigation 0-200mm per year = suitability score 0.5

- If deficit irrigation >200mm per year = suitability score 1.

2.4 Calculation of the Demand Urgency

These variables have been combined in order to calculate the Total Demand Urgency, which is the sum of all the demand scores (DS) assigned to the different variables. The formula is as follows:

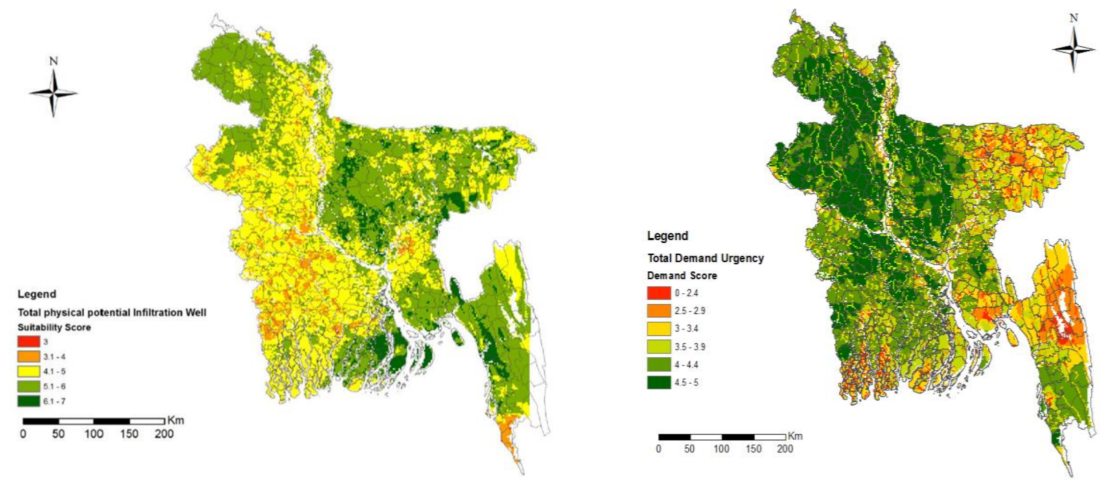
Total Demand Urgency = DS Population Density + DS Poverty + DS Groundwater Depth below surface + DS Existence of Perennial river + DS Irrigation Demand

2.5 Calculation of the total potential

The final total potentiality has been calculated by first normalizing the total physical potential and the total demand urgency, and then adding them up.

3. Results

The map of the Total Physical Potential (Figure 1, a)), shows that the highest physical potential is in the north west of Bangladesh (Barind area), and in the eastern side of the country. The western side still has potential but it is a bit lower. The most influential variables are the precipitation and the evaporation, which are higher in the east. The map of the Demand Urgency (Figure 1, b)) shows that mostly in the western part of Bangladesh there is a need for MAR techniques. These areas are highly populated, with high poverty, and as a distinctive fact, with a high irrigation demand and an irrigation deficit. The coastal zone, areas that one could also to have a high demand urgency, are also highlighted, however, due to a lower population density, the scores for DU are lower. In the eastern side of the country, the DU score results lower as there is less irrigation demand and less space for groundwater storage.



(a) (b)

Figure 1. Results of the potentiality maps. Total physical potential map for the infiltration well (a). Total Demand Urgency (b) panel

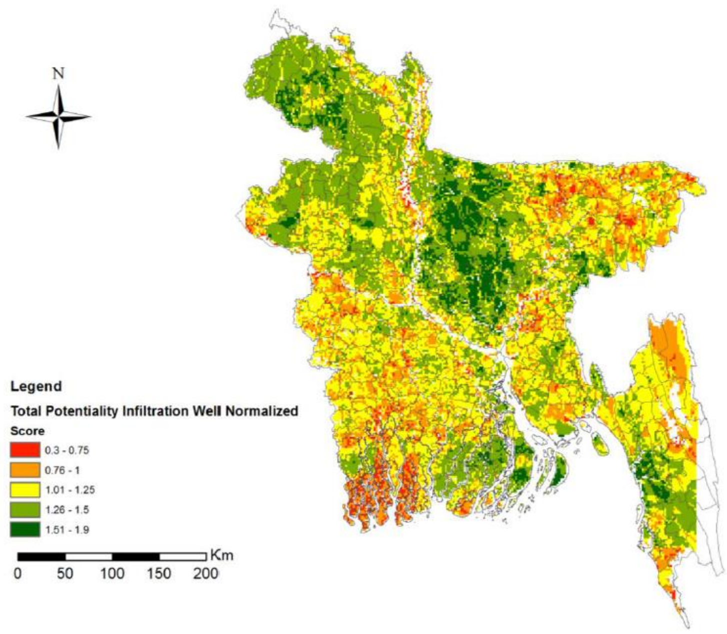


Figure 2. Results of the total potential

Combining the PP and the DU (Figure 2) shows that the total potentiality for an Infiltration well is clearly higher in the north west, Barind, and in the central north part of Bangladesh. Some parts in the coastal belt and the Chittagong are also interesting to consider MAR through infiltration wells.

The results of the maps generated for the other three techniques (which are not illustrated in this paper), show that the highest potential is for the already shown infiltration well and for the artificial reservoir.

4. Discussion

As shown in section 2, the method is a combination of data and expert judgement. Although strictness was applied when selecting the data, it was unavoidable to use data with different resolutions in time and space depending on what was available. Some information such as precipitation, groundwater depth or evaporation was available as point data and therefore interpolation techniques were used to obtain a map covering the entire country. This approach might lead to results uncertain in some areas were information is scarce. Even though these limitations need to be mentioned, the resulting map seems to reflect the expected potentiality areas by country experts.

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Topic 5. MAR AND ECONOMIC ASPECTS

Paper for ISMAR10 symposium. **Topic No: 5 (175#)**

The costs and benefits of managed aquifer recharge

Andrew Ross and Sunail Hasnain

Fenner School of Environment and Society, Australian National University
* Correspondence: a.ross@anu.edu.au

Abstract: Groundwater use increased by 300% between 1960 and 2010 and over 20% of the world's aquifers are overexploited. Managed aquifer recharge (MAR) is an important groundwater based natural infrastructure approach for improving groundwater recharge, maintaining aquifer levels and enhancing water security. Despite the numerous benefits and demonstrated advantages of MAR, uptake has been lower than expected.

The financial and economic performance of MAR is a key determinant of its global uptake but there are very few studies that demonstrate the financial performance or economic advantages of MAR. The economics working group of IAH MAR is carrying out a two-stage research program to address this deficit; to document the financial costs and economics of MAR, and to provide information on situations where MAR may produce the least cost water supply.

The first publication from this program included the development of a methodology for assessing the financial costs of MAR schemes, and a comparative analysis of recharge costs in 21 schemes from five countries. The costs of recharge vary substantially, with schemes using infiltration basins and untreated water having lower recharge costs than schemes using water that requires expensive water treatment infrastructure. Other factors that affect recharge costs include the range of scheme objectives, scale, operating periods and frequency of use, infiltration rates, recovery efficiency and well yields.

This presentation includes the results of a comparative analysis of costs of recharge and recovery for a wider range of 30-40 MAR schemes including from developing countries. The presentation also discusses methodology for the classification and assessment of the economic costs and benefits of MAR and provides examples of economic assessment of MAR and groundwater based natural infrastructure.

Key Words: Recharge, costs, benefits, natural infrastructure.

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1. Introduction

Managed aquifer recharge (MAR) is an important technique for improving groundwater recharge and maintaining aquifer levels. MAR can be defined as the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. MAR has a number of advantages compared to other forms of water storage. Aquifers are widely distributed and water can be drawn from them when it is required. Aquifer storage is relatively cheap to operate and there is little evaporative loss. Managed aquifer recharge can restore over used or brackish aquifers, protect groundwater dependent ecosystems, enhance urban and rural water supplies and water quality, reduce evaporative losses and improve water supply security (Dillon et al 2009). The application of MAR is sometimes limited by slow recharge and recovery rates and groundwater salinisation and pollution, and is typically used in conjunction with other supply options (IGRAC 2007).

Despite the numerous benefits and demonstrated advantages of MAR, uptake has been much lower than expected due to the lack of a well-established economic case for MAR. A global inventory of MAR schemes has been established to increase global knowledge about the implementation of MAR and to assist the planning and implementation of MAR schemes (Stefan and Ansems 2017), but the global inventory does not include financial and economic data. Although the financial and economic characteristics and performance of MAR are key determinants of the global uptake of MAR, there are few studies of the financial costs and benefits of different kinds of MAR or of the performance of MAR compared to other water supply options.

MAR schemes show a great diversity of type and scale. This diversity is reflected in the wide range of costs of different MAR schemes. The economics of MAR schemes are influenced by a wide variety of hydrogeological, socio-economic and legal and institutional factors. For example, aquifer geology and soil characteristics affect water recharge and recovery rates, socio-economic conditions affect the availability and cost of labour and capital and regulatory arrangements influence project set up costs (ASR Systems 2006, Dillon et al 2009).

This study includes an analysis of the costs and benefits of 30 MAR schemes using a standardised analytical approach, building on an earlier analysis of 21 schemes in 6 countries (Ross and Hasnain 2018). The study includes an analysis of costs in a larger number of cases and countries, and introduces a standardised conceptual approach for considering the benefits of MAR schemes. This conceptual approach is illustrated by presentation of results from 16 schemes. Although this data cannot by itself make the case for MAR, the data indicates the economic and other credentials of a wide range of MAR schemes.

This study contains two components:

1. analysis of cost data from 30 MAR schemes from 10 countries, including data on volumes of water infiltrated and recovered combined with capital and operating costs to estimate levelised costs per cubic metre of water infiltrated and/or recovered. The financial and economic analysis for many of the schemes is based on targets for infiltration and recovery which include assumptions about infiltration and recovery rates in lieu of long-term operational data;

2. analysis of estimates of benefits per cubic metre infiltrated or recovered and cost benefit ratios from 16 of these schemes. Benefits are estimated using a range of approaches including revenues from water, the costs of the next best alternative source of water or water treatment and the value of production using recharged water. Systematic analysis of external economic and environmental costs is not attempted because of lack of data.

The study proceeds as follows. In the following section materials and methods for assessing the costs and benefits of MAR schemes are presented. The capital and operating costs of 30 MAR schemes are analysed and key factors influencing cost differentials between schemes are identified. Benefits of 16 of these MAR schemes are analysed and cost benefit ratios are presented.

The paper ends with a summary of the main findings and suggestions for further research on financial and economic aspects of MAR.

2. Materials and methods for assessing the costs and benefits of MAR schemes

2.1 Classification and selection of MAR schemes

MAR schemes around the world serve many different purposes, and there are many different MAR methods and technologies. In recent years, there have been coordinated efforts to classify global MAR schemes (IGRAC 2007) and European schemes (DEMEAU 2014). The global inventory of MAR schemes has been developed by a working group of the International Association of Hydrogeologist's MAR Commission (IAH-MAR) and a team of European researchers and the International Groundwater Resource Assessment Centre (IGRAC 2016) (Stefan and Ansems 2017). In 2016 the IAH-MAR commission established a working group on financial and economic aspects of MAR. The first task of this working group is the collection and processing of financial and economic data on MAR projects. The group established a number of country contact points to coordinate the collection and analysis of cost information on MAR schemes.

The MAR schemes included in this study are listed in Table 1 based on the classification of MAR types in the global MAR inventory. These schemes represent three broad MAR types from 10 countries; wells (W) including Aquifer Storage and Recovery (ASR) and Aquifer Storage Treatment and Recovery (ASTR); Infiltration Basins (IB), including infiltration galleries (IG) and infiltration channels (IC); and Riverbank Filtration (RBF). The main source for 21 schemes is natural water (N), while 9 schemes are based on recycled water (R)[3]. Each scheme is given a codename - also used in subsequent tables -indicating MAR type, country and location.

Data was collected for each scheme on capital and annual operating costs, and physical measures for land, labour, electricity and water use. The physical measures allow estimation of unit costs. per cubic metre of water recharged, and cost per cubic metre recovered or recoverable. External costs of MAR schemes such as impacts on third parties, such as downstream groundwater users, and the environment were not included because of absence of data and/or inconsistent coverage and methods of estimation.

[3] Some schemes use both natural and recycled water. The source water classification for each scheme is based on the main water source.

Table 1: Managed Aquifer Recharge Schemes.

Scheme code name	Country	Name/ location	Source water	Scheme code name	Country	Name/ location	Source water
01-W-ASR-NL-FM	Netherlands	Freshmaker	N	16-IB-SP-LLO	Spain	Llobregat	N
02-W-ASR-NL-ND	Netherlands	Nootdorp	N	17-RBF-IT-SER	Italy	Serchio	N
03-W-ASR-NL-WE	Netherlands	Westland	R	18-IB-US-PMR	US-Arizona	Sahurita	N
04-IB-AU-IBWA	Western Australia	Mandurah, Geraldton	N	19-IB-US-AF	US-Arizona	Surprise	N
05-IB-NZ-HN	New Zealand	Ashburton	N	20-IB-US-SMR	US-Arizona	Queen Creek	N
06-W-ASR-NL-D	Netherlands	Dinteldorp	N	21-W-SAT-AU-AS	Australia	Alice Springs	R
07-IG-AU-PL	Western Australia	Perry Lakes	R	22-IB-ISR-MEN	Israel	Menashe	R
08-IC-IT-BRE	Italy	Brenta	N	23-IB-US-TD	US-Arizona	Tonopah	N
09-RBF-IN-HD	India	Haridwar	N	24-W-ASR-AU-BLSA	South Australia	Bolívar Adelaide	R
10-W-AS-MAL	Malta	Malta	R	25-W-ASR-US-EPWU	US-Texas	El Paso	R
11-W-ASR-US-FL	US-Florida	Florida	N	26-IB-WALA-JOR	Jordan	Wala	N
12-W-ASR-US-KR	US-Texas	Kerrville	N	27-IG-AU-BYWA	Western Australia	Beenyup Perth	R
13-IB/W-SP-ARE	Spain	Los Arenales	NR	28-W-ASTR-AU-AG	Australia	Anglesea, Victoria	R
14-IB-US-LSC	US-Arizona	Marana	N	29-W-ASR-US-SAWS	US-Texas	San Antonio	N
15-IB-US-HM	US-Arizona	Surprise	N	30-W-ASR-US-OR	US-California	Orange County	NR

The 30 MAR schemes have varying objectives. Many schemes involve seasonal or short-term recovery of water but some facilities are aimed at providing long-term/ future reserve storage. In these cases the recoverable capacity is the relevant metric[4]. Many of the schemes involve upgrades to existing facilities and/or facilities transitioning from pilot schemes to commercial projects. Although some of the schemes have not been operating at full commercial scale for a long period of time, it is possible to have some confidence in the cost and benefit estimates because they are based on operational experience.

2.2 Methodology for assessing costs and benefits of MAR schemes

Economic evaluation of projects is based on systematically balancing the predicted beneficial and adverse effects generated by a proposal. Benefits are the good or desired effects while costs are the less desired effects. The valuation of policy outcomes can be based on the concept of willingness to pay (Young 2005). Benefits are the sums of the maximum amounts that people would be willing to pay to gain outcomes they view as desirable; costs are the sums of the maximum amounts that people would be willing to pay to avoid outcomes that they view as undesirable (Boardman et al. 2001). Costs can also be expressed as the amount people would need to be compensated to accept outcomes they view as undesirable.

Appropriate valuation of costs and benefits is essential for choosing between different water supply and storage options, including MAR. Total economic value provides a framework for assessing the costs and benefits of MAR. The total economic value (TEV) of MAR schemes can be divided into three broad categories: extractive use, non-extractive values and option values

[4] The unit cost of recovered water may be relatively high but the cost of longer term storage measured by the cost per unit of recovery capacity is relatively low, which can justify the choice of ASR compared to alternatives such as desalination (ASR Systems 2006).

(Qureshi et al 2012). Increased aquifer storage results in an increase in the total volume of water available for later extractive benefits. Non-extractive values can be divided into in situ and natural discharge benefits. In situ benefits include protection of groundwater quality, avoidance of land subsidence and prevention of seawater intrusion. Natural discharge benefits include maintenance of springs and wetlands, and recreational and cultural values. Option values include maintaining aquifers and connected ecosystems for use by future generations.

The costs and benefits of MAR schemes are distributed between a range of direct beneficiaries and other affected parties. The direct costs and benefits such as water storage and recovery costs and additional water supplies (extractive values) are easier to account for and measure in monetary terms than indirect costs and benefits to third parties and the environment (non-extractive and option values). The range of valuation techniques used in the analysis of MAR schemes in this study is limited by the relatively small number of schemes, but includes several widely used methods.

2.2.1 Costs of MAR schemes

Following an earlier analysis of costs of 21 MAR schemes (Ross and Hasnain 2018) levelised cost was chosen as the preferred method to estimate and present the costs of MAR schemes in this study. Levelised cost is a widely accepted method of costing infrastructure projects. Levelised cost of a water supply project is defined as the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply. Levelised costs provide an effective means to compare the costs of water from alternative projects (Dillon et al 2009). It was not possible to calculate actual levelised costs for the MAR schemes included in this study because of data gaps, in particular lack of time series of operating costs, but an estimate of levelised cost could be calculated for each scheme assuming that schemes have a life of 30 years and that the present value of annual operating and maintenance costs does not vary over the lifetime of a scheme.

Water supply security insurance costs provides an alternative costing method for MAR schemes when they are primarily intended to provide a drought, emergency or highly seasonal supply[5].

The costs of MAR schemes are represented by the cost per m^3 water recharged, able to be recovered or actually recovered. The volumes recharged are adequate to meet scheme objectives allowing for infiltration and recovery rates, in other words they represent volumes that can be recovered. Scheme costs generally include all of the capital and operating costs but a few schemes have relatively low costs compared to other comparable schemes because some costs such as water treatment, land, conveyance or distribution are accounted separately and/or provided free or at subsidised prices. The costs of MAR schemes were processed and standardized in three steps:

1. Financial cost data (capital and operating costs) was collected for each scheme in local currency units (LCUs). External costs including water quantity and quality impacts on downstream water users and the environment were not included because of lack of data. These impacts are usually small for schemes less than 20,000 m^3 annual recharge CHECK which represent the majority (75%) of schemes included in this study. Estimates of some external costs in some schemes are included in the consideration of cost benefit ratios - see below.

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[5] This cost can be calculated by dividing the capital cost of the project by the daily supply capacity ($/$m^3$ per day). Water supply security insurance costs were not calculated for most of the schemes in this study because most of the schemes have the objective of maintaining aquifer levels and/or providing ongoing water supplies instead of, or in addition to drought and emergency supplies.

2. The capital costs of MAR schemes are available for different years ranging from 1965 to 2016. The capital cost of each scheme was converted to 2016 values by multiplying the cost by a GDP deflator which measures changes in prices of all domestically produced goods and services[6,7].
3. Local Currency Costs in 2016 were converted to US dollars in 2016. The local currency costs of each MAR scheme were converted to US dollars using exchange rate indices from IMF International Financial Statistics[89].

An indicative figure for the levelised cost of each scheme was calculated assuming an operating life of 30 years, a discount rate of 6.67% and a capital recovery factor of 0.0779. Further details of this calculation can be found are shown in Ross and Hasnain 2018, Table 4.

2.2.2 Benefits of MAR schemes

The valuation of economic benefits of MAR is complicated because of the general absence of a market price for stored or treated water. Drinking water and irrigation water prices often reflect what people can afford to pay, and what is politically acceptable rather than water scarcity, reflected in a market price. Some scheme costs are met by government grants or subsidies, and the system owner and water users may receive most or all of the benefits of the system while not having to pay the full costs. Many non-extractive benefits (and costs) of MAR accrue to third parties or the environment, and have to be estimated by surrogate measures such as increases in farm income owing to MAR, or from willingness to pay surveys.

In the absence of market prices a range of techniques have been established to value MAR schemes. These include best alternative cost of water supply or water treatment, avoided cost of alternative supply or treatment, or net value of production using recharged water (e.g. farm production). In situ groundwater values are estimated by the costs avoided because groundwater resources are protected by MAR - avoided costs include costs of pumping, saltwater intrusion and subsidence (Marsden Jacobs and Associates 2013, National Academies of Sciences, Engineering, and Medicine 2016). There are also various methods to value unpriced social and environmental benefits and to estimate the price people are willing to pay for services from MAR (Qureshi et al 2012, Maliva 2014). An example of the application of the analysis of willingness to pay for benefits from a MAR scheme can be found in Rupérez Moreno et al 2015. The choice of valuation techniques depends on the context and objectives and scope of MAR.

For example if the main benefit of a MAR scheme is additional water supply, the monetary value of additional supply (either annual supply or reserve supply for drought years) may be estimated by one of the following methods:

- volume of water recovered or supplied multiplied by the price of water. Theoretically this is the best way to estimate the value of additional water, but it is often impossible because water is supplied at rates that do not reflect its full economic value;

[6] A GDP deflator measures the change in price of all domestically produced goods and services by dividing an index of GDP measured in current prices by a constant price index of GDP. A GDP deflator is used instead of CPI because it is assumed that the inflation of MAR construction costs is related more closely to changes in GDP than to consumer price changes. GDP deflator values are taken from IMF website. See the link below. The GDP deflator for India was obtained from the Indian Reserve Bank website.
http://data.imf.org/?sk=5DABAFF2-C5AD-4D27-A175-1253419C02D1&ss=1409151240976

[7] It was not possible to standardise operating costs across the schemes because of incomplete information about the year or years in which operating costs were collected

[8] https://www.imf.org/external/np/fin/data/rms_mth.aspx?SelectDate=2017-03-31&reportType=REP

[9] An adjustment for purchasing power parity was made for the scheme from Haridwar, India A factor of PPP at time of construction of scheme was applied. Data for the factor was obtained from the following Link: https://alfred.stlouisfed.org

- the cost of recovering or supplying an equivalent amount of water of similar quality by the next cheapest supply option. This may be described as the alternative cost of production or the avoided cost of production. This method is used for estimating benefits of most of the schemes included in this study;
- In the case of water for agricultural or industrial use additional supply can be valued by the net benefit (revenue minus cost) of additional production made possible by the additional water supply.

If the main benefit is an improvement in water quality, to meet a specified standard, as might be the case in a MAR scheme using recycled stormwater or wastewater, the benefit can be valued by the costs of the next cheapest water treatment facility.

3. Results and discussion

3.1 Costs of MAR schemes

The table 2 shows the costs of 30 MAR schemes from 10 countries Australia, the USA, the Netherlands, Spain, Italy, New Zealand, Israel, Malta, India and Jordan. Scheme costs include total capital and annual operating costs adjusted for inflation and converted to US$, annual water recharged, capital and operating cost per cubic metre water recharged and estimated levelised cost (see Section 2.2.1). Operating costs are the most recently available annual cost figures[10].

Overall the main factors that determine the relative costs of MAR schemes are the type of aquifer recharge and recovery technology used in the scheme and the source of water, which is linked to the end use of the scheme and the consequent amount of water treatment required. Other significant factors that affect scheme costs include the range of objectives schemes have to meet, scale of the scheme, scheme frequency of utilization and operating period, life expectancy of schemes, and hydrogeological setting including soil and aquifer characteristics. The general level of income in the region where the scheme is located can also be a significant since many costs, especially operating costs, are determined locally. Further analysis of factors that affect the costs of MAR schemes can be found in Ross and Hasnain 2018.

[10] For Scheme 20 ASR-OR-US which has experienced several stages of development average annual operating costs were used.

Table 2 Costs of MAR schemes.

Scheme code name[11]	Capital cost (US$'000 2016)	Annual operating cost	000m³ recharge year	Capital Cost/ m³ recharge (US$ 2016)	Operational cost/ m³ recharge (US$ 2016)	Levelised cost/m3 recharge (US$2016)
01-W-ASR-NL-FM	56	6	6	9.33	1.00	1.72
02-W-ASR-NL-ND	67	6	15	4.47	0.40	0.75
03-W-ASR-NL-WE	293	13	56	5.23	0.23	0.63
04-IB-AU-IBWA	403	27	29	14.14	0.93	2.03
05-IB-NZ-HN	682	96	4,000	0.17	0.02	0.04
06-W-ASR-NL-D	949	70	300	3.16	0.22	0.48
07-IG-AU-PL	1,363	1667	1,825	0.75	0.91[12]	0.97
08-IC-IT-BRE	1,608	166	20,000	0.08	0.01	0.02
09-RBF-IN-HD[13]	2464	1980	220000	0.01	0.09	0.09
10-W-AS-MAL	2,635	696	1,000	2.64	0.69	0.90
11-W-ASR-US-FL	3,349	376	6,908	0.48	0.05	0.09
12-W-ASR-US-KR	3,393	0	3,661	0.93	-[14]	0.07
13-IB/ASR-SP-ARE	4,162	443	2,610[15]	1.59	0.17	0.29
14-IB-US-LSC	5,345	7495	51,800	0.10	0.14[16]	0.14
15-IB-US-HM	7,078	5910	43,200	0.16	0.14	0.15
16-IB–SP-LLO	9,180	382	11,600	0.79	0.03	0.09
17-RBF-IT-SER	10,529	1510	15,830	0.67	0.10	0.15
18-IB-US-PMR	14,459	5092	37,000	0.39	0.14	0.17
19-IB-US-AF	14,406	4100	30,800	0.47	0.13	0.17
20-IB-US-SMR	11,972	4309	30,800	0.39	0.14	0.17
21-W-SAT-AU-AS	11,608	1065	600	19.35	1.16	2.67
22-IB-ISR-MEN	20,922	1535	10,130	2.07	0.15	0.31
23-IB-US-TD	22,067	24434	185,000	0.12	0.13	0.14
24-W-ASR-AU-BLSA	25,137	2438	9,000	2.79	0.27	0.49
25-W-ASR-US-EPWU	38,037	3958	13,817	2.75	0.29	0.50
26-IB-WALA-JOR	71260	1231	6739	10.57	0.18	0.77
27-IG-AU-BYWA	91,753	12235	14,000	6.55	0.87	1.38
28-W-ASTR-AU-AG	154,513	5172	7,650	20.20	0.68	2.25
29-W-ASR-US-SAWS	269,147	1018	82,900	3.25	0.01	0.26
30-W-ASR-US-OR	722,667	18391	294,486	2.45	0.06	0.25

3.2. Factors influencing the costs of MAR schemes - MAR type and water source

An overview of the recharge costs of 21 MAR schemes classified into the two MAR types and two water source types is presented in Table 2[17]. Table 2 shows the capital and operating cost (in US dollars 2016) of recharging one cubic metre (m^3) of water under different MAR types and water sources. Some schemes use multiple recharge methods including both infiltration basins and wells. In these cases schemes are classified according to the largest cost component.

[11] Scheme details are shown in Table 1

[12] Operating and maintenance cost includes 1.25 million of Environmental monitoring program, 0.20m of maintenance cost. Therefore, operating and maintenance cost is more than Capital cost

[13] Estimates based on personal communication from T Grischek and C Sandu 2019

[14] Included in council costs, exclusive cost data not available

[15] For schemes 22-27 recharged amounts described as water outlows ie available for use. These and other numbers for these schemes taken from MARSOL WP 15 final project meeting report on financial results page 27.

[16] Includes water charges, hence, operating cost is higher than capital cost

[17] An average of costs from 11 MAR schemes in Florida is included and presented as a single scheme.

The costs of treating water prior to recharge and/or use is one of the largest cost elements of some MAR schemes. The two main factors that influence treatment costs of MAR schemes are the source of water recharged into aquifer storage and the end use of water abstracted from storage. Some of the highest cost schemes involve recharge or injection and recovery of recycled storm water or wastewater. Recycled water often requires additional treatment to meet standards for drinking and agricultural water use (NRMMC, EPHC, NHMRC (2009)) but these approaches can still be substantially cheaper than alternative water supplies.

The data presented in Table 3 shows infiltration basin and spreading basin schemes have lower costs per cubic metre of recharge and recovered than schemes using on recharge wells. Schemes using natural water have much lower costs than schemes using recycled water. Recharge wells using recycled water have the highest recharge costs. Infiltration structures and riverbank filtration schemes using natural water have the lowest costs.

Table 3 Average MAR scheme levelised costs in US$ per m3 recharged/recovered.

MAR Scheme Type/ Water Source	Infiltration structures	Wells and boreholes	River Bank Filtration
Natural water	0.15	0.25	0.15
Recycled water	0.52	1.07	-

These results must be treated with caution because of the relatively small number of schemes , but give some indication of the differential cost of recharge between some MAR types. Further analysis of factors that influence MAR scheme costs is provided in Ross and Hasnain 2018.

3.3. Benefits of MAR schemes

The following section presents a brief overview of the benefits and cost benefit ratios of 16 of the 30 MAR schemes included in this study. These schemes come from 6 countries; Australia, the USA, Spain, Italy, Israel and Malta. There is some variation in the methodologies used in the assessments of the Australian, US and European schemes, but there is sufficient similarity for broadly comparable estimates of costs and benefits to be presented.

A summary of the levelised costs, benefits and cost benefit ratios of the 16 schemes is presented in Table 4. The levelised costs were calculated as explained in section 2.1.1. The benefit estimates were drawn from the preparatory studies and reports on the 16 schemes.

Table 4 Levelised costs, benefits and benefit cost ratios of 16 MAR schemes.

Scheme code	000 m³ recharged per year	Levelised cost/m3 Recharged (US$ 2016)	Benefit /m³ Recharged (US$ 2016)	Main benefits included	BCR
04-IB-AU-IBWA	29	2.03	8.50	Avoided cost above ground storage, aquifer treatment	3.2
05-IB-NZ-HN	4,000	0.04	na[18]	Avoided costs of mitigation, reliability gains	4-17[19]
07-IG-AU-PL	1,825	0.97	2.0	Avoided cost maintaining wetland with potable water	1.9
08-IC-IT-BRE	20,000	0.02	0.11	Tree harvest, sale of water. WTP aquifer recharge	5.5
11-ASR-US-FLO	6,908	0.09	0.59	Avoided cost SW storage	6.5
12-ASR-US- KER	3,661	0.07	1.17	Avoided cost reservoir $US 30m	16.7
13-IB/ASR-SP-ARE	2,610	0.29	0.41	Increase irrigation supply and Ag production	1.4
16-IB–SP-LLO	11,600	0.09	0.40	Increased water supply for Barcelona	4.4
17-RBF-IT-SER	15,830	0.15	0.55	Increased municipal supply. WTP aquifer recharge	3.7
21-SAT-AU-AS	600	2.67	0.21-0.39	Avoided wastewater cost	0.10-0.18
22-IB-MEN	10130	0.31	0.50	Seasonal or occasional storage & supply (100Mm³)	1.7
24-ASR-AU-BLSA	9,000	0.49	2.51-3.71	Reduced discharge wastewater to marine environment	2.9-4.2
28-ASTR-AU-AG	7,650	2.25	4.10	Avoided costs wastewater, potable water, GHG emissions	1.2
27-ASTR-AU-BYWA	14,000	1.38	3.14	Avoided costs desalination	1.4
29-ASR-US SAWS	82,900	0.26	0.64	Avoided water right purchases US$600m	2.5
30-IB/ASR-US-OR	294,486	0.25	0.78[20]	Increased recharge and revenue, avoided costs of external water purchase[21]	3.2

The average levelised costs and benefits per cubic metre recharged/recovered, and estimated benefit cost ratios of the 16 MAR schemes are summarised in Table 5. The schemes are divided into five categories: infiltration using natural or recycled water, wells using natural or recycled water and riverbank filtration. The average unit costs and benefits are weighted by annual volumes of recharge/recovery[22]. There is significant variation between levelised costs, benefits and benefit cost ratios within each of the five MAR categories as well as between them.

[18] Benefits given in terms of hectares supplied
[19] Depending on water price (0.03-0.14/m³)
[20] Inferred from calculated BCR
[21] Unquantified benefits include: basin management flexibility, drought protection/reliability, seawater intrusion, higher GW levels, and permitted recharge of wastewater.

Table 5: Levelised costs and benefits per cubic metre of water recharged/recovered, and benefit cost ratios**.**

MAR type	Levelised cost $/m³	Benefit $/m³	Benefit cost ratio
Infiltration: natural water (4 schemes)	0.06	0.25	5.5
Wells: natural water (4 schemes)	0.25	0.79	3.2
Infiltration: recycled water (4 schemes)	0.52	0.72	1.7
Wells: recycled water (3 schemes)	1.34	3.37	2.0
Riverbank filtration (1 scheme)	0.15	0.55	3.7

The variation between the benefits and benefit cost ratios of schemes using wells, infiltration and riverbank filtration is broadly similar to variations in levelised costs. Schemes using infiltration with natural water and riverbank filtration have the highest benefit cost ratios, followed by schemes using wells and natural water. Schemes using recycled water have higher levelised costs and lower benefit cost ratios, although the three schemes using wells with recycled water have relatively large benefits per m3 recharged/recovered. Additional information is being collected to enable further improvements in these estimates including a wider range of countries and schemes.

4. Conclusions and priorities for further work

MAR schemes are highly heterogeneous with a wide range of types, objectives and sizes. Although this complicates comparisons between schemes it is still possible to draw some conclusions about major factors that affect scheme costs and benefits.

The costs and benefits of MAR schemes vary substantially between MAR types. Schemes recharging unconfined aquifers using infiltration basins with untreated water and riverbank filtration are relatively cheap and have good benefit cost ratios. Schemes requiring wells with substantial drilling infrastructure and or water treatment have relatively low albeit positive benefit cost ratios.

Even when water requires substantial and costly treatment before recharge and recovery, especially urban storm water and recycled water, storm water and wastewater recycling can offer substantial benefits together with positive benefit cost ratios, and sometimes offers lowest cost opportunities for improving water security and supplies when natural surface water and groundwater is scarce.

The costs and benefits of MAR schemes are also influenced by soil and aquifer characteristics which affect infiltration rates and well yields, scheme operating periods and frequency of utilisation, the range of objectives that schemes have to meet, the existence of legal and institutional requirements for recharge and recovery and community acceptance of MAR.

There are a number of areas for further analysis of the benefits and costs of MAR schemes in conjunction with increasing the number and range of schemes. Inclusion of a greater number of schemes from developing countries would give a more representative picture of global MAR schemes – including low-cost technologies and cheap water sources such as rainwater harvesting with untreated water and in channel modification. Inclusion of a wider range of MAR types and contexts would improve confidence in cost and benefit estimates, enable further investigation of the effects of infiltration rates and well yields, and legal and institutional requirements.

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Paper for ISMAR10 symposium. ***Topic No: 5 (217#)***

El Carracillo. An example of rural development and positive impact on the agroindustry thanks to MAR technique. Los Arenales Aquifer, Castilla y León, Spain

López Hernández, Manuel[1*]; Fernández Escalante, Enrique[1]; San Sebastián Sauto, Jon[1]; Navarro-Colmarena, Manuel[2]; Villanueva Lago, María[1] and Calero Gil, Rodrigo[1]

[1] Tragsa Group, Madrid, Spain.
[2] Ministry of Agriculture, Fisheries and Food, Madrid, Spain.
* Correspondence: mlopez@tragsa.es

Abstract: Since 2003, MAR has been used in the El Carracillo District, Castilla y León, Spain. This district is supported by important agro-industrial activities reliant on MAR and groundwater exploitation.

The increasing aquifer storage is having a direct impact on the economy of the area. Some specific indicators especially related to rural development and economic improvement have been designed and tracked by the association of farmers for more than 10 years.

The indicator database has provided important information. A specific benchmarking approach was applied, measured, tracked and charted, so as to evaluate the difference between areas with and without MAR activities integrated into their water management approaches.

Economic indicators have permitted the assessment of economic trends over a decade in time, demonstrating that MAR is contributing to several key economic factors including: the stability and even rise of the rural employment rate, a reduction in emigration from rural areas, greater crop production, energy savings due to the rise of the water table, guaranteed water supply for short drought periods, etc. El Carracillo has 4,000 new hectares under irrigation, an 80% increase in vegetable production of the whole province, 3,700 MAR related employment, 6% population increase, etc. and 23.8% of water used for irrigation comes from MAR.

The article also describes several constraints: how MAR is affecting the agroindustry agents, the sustainability of the aquifer and the agricultural activity or the relationships among farmers, authorities and some ecological groups who are against MAR activities in this area.

In short, the El Carracillo area has successfully employed MAR techniques with positive results compared to other nearby areas without groundwater resources and rain-fed crops.

Keywords: Managed Aquifer Recharge, indicators, economic assessment, rural development, El Carracillo, agroindustry, MAR.

1. Introduction and background

El Carracillo District stands out in the Spanish agriculture for its production of horticultural products. This region accounts for 80% of vegetable production of Segovia and 30% of Castilla y León. This area is the leading producer of leek and strawberry plant of Spain, and third in carrot. Also worth noting is the production of other vegetables such as onion, potatoes, garlic, sugar beet, sweetcorn, or lettuce among others.

Figure 1. Situation of El Carracillo District in Spain

The total area of the Irrigation Community in Carracillo reaches 7500 ha distributed in 11 municipalities; they are Arroyo de Cuéllar, Campo de Cuéllar, Chañe, Chatún, Fresneda de Cuéllar, Gomezserracín, Narros de Cuéllar, Remondo, Sanchonuño, Pinarejos and Samboal. 3,000 of those 7,500 ha are irrigated.

Table 1. Municipality list of Carracillo District. Source: Junta de Castilla y León, 2011.

Municipality	Irrigation Area (hectares)	Nº of holdings
Arroyo de Cuéllar	718,35	484
Campo de Cuéllar	1.032,31	862
Chañe	1.724,36	1.175
Chatún	557,9	518
Fresneda de Cuéllar	430,06	222
Gomezserracín	1.055,45	1.120
Narros de Cuéllar	754,61	569
Pinarejos	61,05	74
Remondo	450,8	242
Samboal	98,66	119
Sanchonuño	702,66	840
Total	**7.586,21**	**6.225**

The largest part of arable land is covered by cereals, especially wheat and barley, but only a small part is under irrigation systems (about 17%). The production of potatoes is remarkable As far as industrial crop is concerned; the mostly grown crop is irrigated sugar beet. With regard to vegetable production; farmers dedicate 30% of their agricultural areas to carrot (close to 700 ha), 20% to leek (approximately 500 ha), 5% onion (65 ha) and 4% garlic (48 ha).

Table 2. Distribution of agricultural areas in Carracillo in 2014. Source: Junta de Castilla y León, 2015.

	RAINFED	IRRIGATION	TOTAL
Cereals	2.750	588	3.338
Potatoes	228	205	433
Industrial crops	50	129	179
Forage crops	52	26	78
Vegetables	155	1.019	1.174

According to data from Junta de Castilla y León (Government Agency) there are approximately 200 ha of nurseries in the region where different vegetables and fruits are grown. Carracillo is well known for its production of strawberry mother plants, they hold the number one position of Spain production. About 600 hectares are cultivated, which produce about 60 million strawberry plants of four different varieties, which supply both the immense production nurseries that exist in southern Spain and producers in England, Germany, southern countries of Europe or Morocco. They also have an important later production of fruits, particularly strawberry and raspberry, to supply markets out-of-season products.

Due to favourable climate conditions, the good properties of sandy soils and the availability of water, this agricultural region presents high yields in the different existing crops, in particular in carrot, which is one of the highest in Spain.

Table 3. Yields in El Carracillo. Source: President of Carracillo Irrigation Community, 2015.

Crop	Yield (t/ha) or (nº plants/ha)
Potatoes	40-50
Carrot	70
Leek	40
Strawberry plant	550,000-600,000
Sugar beet	80

The topologic scheme for El Carracillo with the main water resources management components and structure is displayed in the figure 2. As this is an article for economic indicators and rural development, authors recommend interested readers consulting MAR technical-related references, such as MARSOL deliverables, WP 5, in http://marsol.eu/35-0-Results.html. As a brief summary, figure 2 contains the junctions and all the interconnected elements of El Carracillo scheme. The most remarkable characteristics are:

- River water source: Cega River surplus
- Maximum flow: 1,370 litres per second from January 1st to April 30th as far as this same outflow is measured in the river
- Annual maximum volume (irrigation use): 14.2 Mm^3
- Recharge amount: 31.47 Mm^3 (13 years)
- Water processed by MAR facility (unitary): 24.18 m^3/ha in·13 years
- Carracillo shield. What are concessions like?
- River basin civil servants supervise the gate to divert water from Cega river, managed by the irrigation community
- There is an specific allowance period revisable yearly
- An environmental minimum flow rate must be respected: 6,898 l/s (initial permission)
- Maximum diversion: 1,370 l/s from January to April (2nd allowance)
- The total flow rate minor than 22,4 Mm^3/year
- Flow meter controlled in real time by legal requirement.

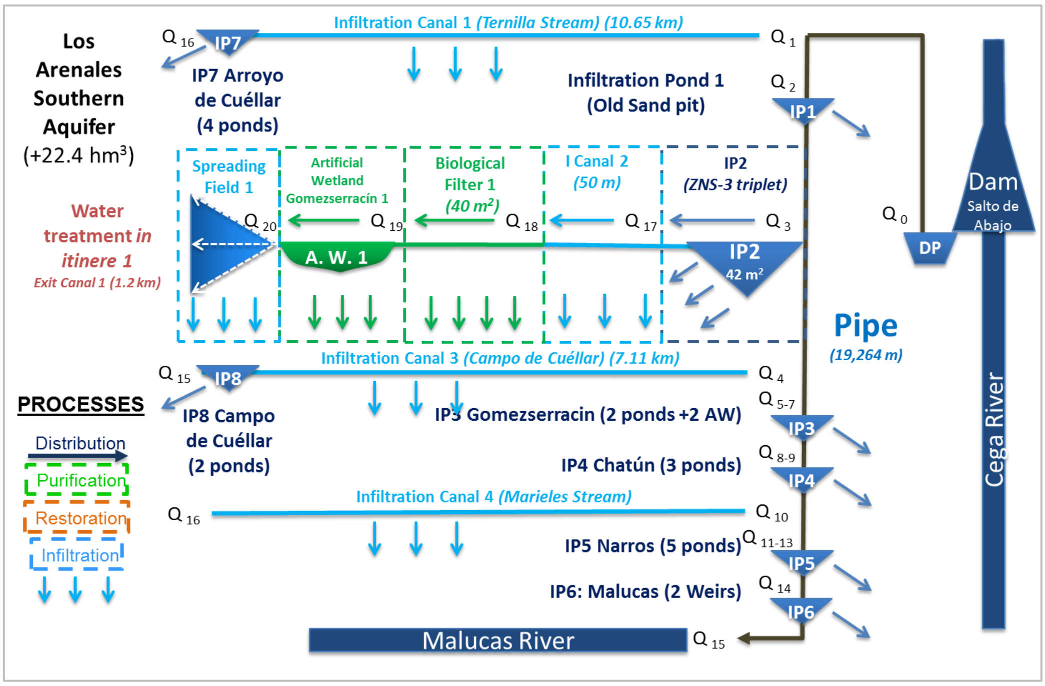

Figure 2. Operational sketch of El Carracillo MAR plant.

Volumes diverted from Cega River for MAR in El Carracillo since 2002 to 2015 are exposed in the fig. 3.

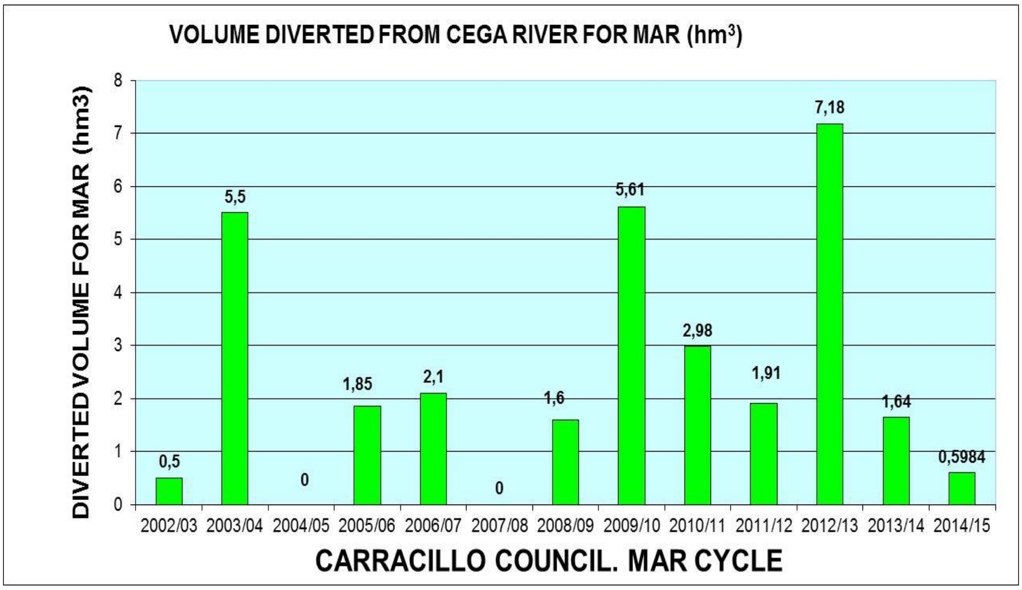

Figure 3. Histogram with the volume of water infiltrated in the aquifer by means of MAR technique since the activity began in El Carracillo area.

2. Materials and Methods

In this study, different sources of information have been gathered, in special from National and regional statistics analyses. Some surveys have been directly conducted to farmers and farmers associations by MAR to MAR-k€t working Group Technicians.

Results have been represented in graphics, studying their evolution as well as those specific indicators adopted for rural development.

The results comparison of each indicator and analyses of errors was done by the Normal Root Mean Square Error (NRMSE) criterion.

3. Results

3.1. Evolution of price paid to growers

Prices paid to suppliers in Segovia market have been tracked since 2002 to 2015. The evolution of the prices came down due to the economic crisis, with certain typical market fluctuations. The reduction of the prices was compensated with a higher production, in a certain measure thanks to MAR, as a technique to increase water availability for irrigation. Some selected examples to track the evolution of prices were carrot (figure 4), potato (figure 5) and sugar beet (figure 6).

Table 4. Price paid to farmers evolution: Carrot (€uros/100kg).

Price paid to growers evolution: Carrot (Euros/100kg)

2002	7,81	**2009**	9,17
2003	21,28	**2010**	18,51
2004	10,04	**2011**	9,83
2005	9,08	**2012**	14,30
2006	12,67	**2013**	16,01
2007	13,49	**2014**	9,77
2008	18,92		

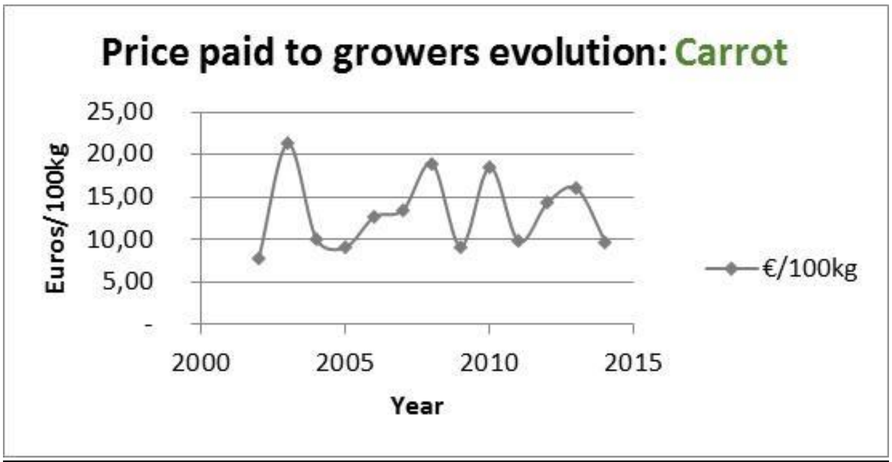

Figure 3. Price paid to farmers evolution: Carrot (€uros/100kg).

Table 5. Price paid to farmers evolution: Potato (€uros/100kg).

Price paid to growers evolution: Potato (euros/100kg)

2002	6,60	**2009**	6,40
2003	14,20	**2010**	16,41
2004	10,50	**2011**	9,83
2005	10,10	**2012**	17,30
2006	20,70	**2013**	21,22
2007	15,60	**2014**	7,21
2008	14,60		

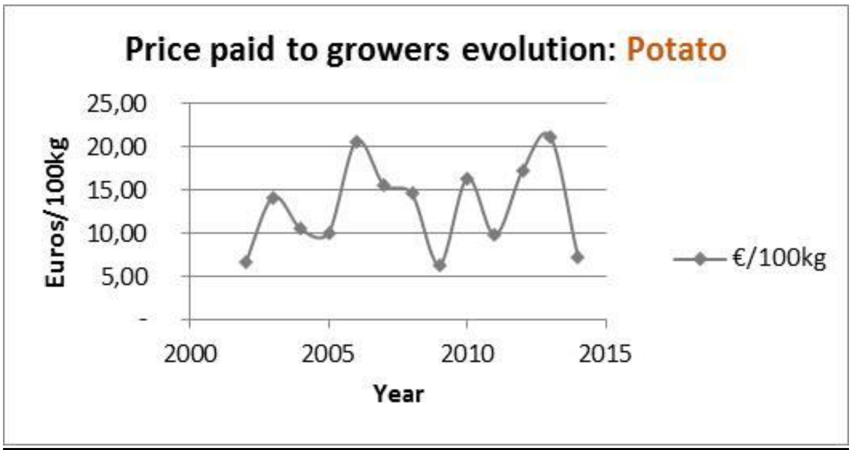

Figure 4. Price paid to farmers evolution: Potato (€uros/100kg).

Table 6. Price paid to farmers evolution: Sugar beet (€uros/100kg).

Price paid to growers evolution: Sugar beet (euros/100kg)

2002	4,90	**2009**	3,46
2003	6,10	**2010**	3,41
2004	5,40	**2011**	3,11
2005	5,60	**2012**	3,02
2006	4,00	**2013**	2,93
2007	3,40	**2014**	3,81
2008	3,40		

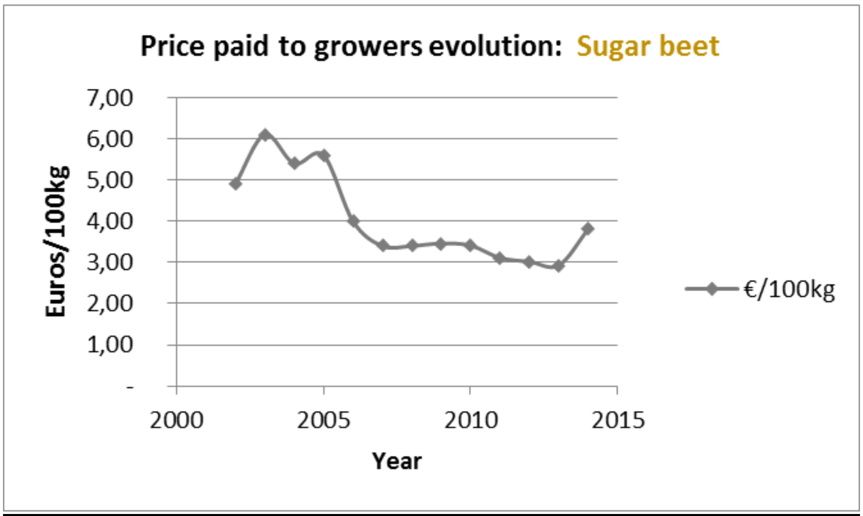

Figure 5. Price paid to farmers evolution: Sugar beet (€uros/100kg).

3.2. Agro industries

Agriculture and industry have traditionally been considered as two separate sectors both for its characteristics and its role in economic growth. However, they are closely related activities; Agribusiness or Agroindustry means processing products from agriculture, forestry and fishing sector, whether the processing of raw materials or intermediate products derived from these sectors.

In the region of Carracillo stands out horticultural industries; there are around 30 from the 40 existing in Segovia (approximately 75%), due to the significant production of these products that joins a high quality and the large investment in research and innovation to develop products of fourth and fifth range that best suit the needs of today's consumer. These products are prepared and packed by heat treatments that ensure its conservation while maintaining the texture, flavour and original aroma and retain all their nutritional properties. Also, they have a lifespan of up to six months from date of packaging. Although most are specialized in the preparation of carrot and leek, they also transform other products such as onions, sweet corn, red beets, beetroot and endive. Much of this production is exported to France, UK and Italy. The impact of the horticultural industry is so important that it has a turnover of roughly 50 Million €uros. In the following list are distributed the enterprises in the agricultural sector by municipality. Among them, Chañe, Gomezserracín and Sanchonuño have large cooperative societies, such as *Viveros Campiñas*, *El Pinar del Carracillo* or *Hijos de Teodoro Muñoz*, which are a reference in the horticultural sector. The agro-industries inventory list is included as Annex 1 at the end of the article.

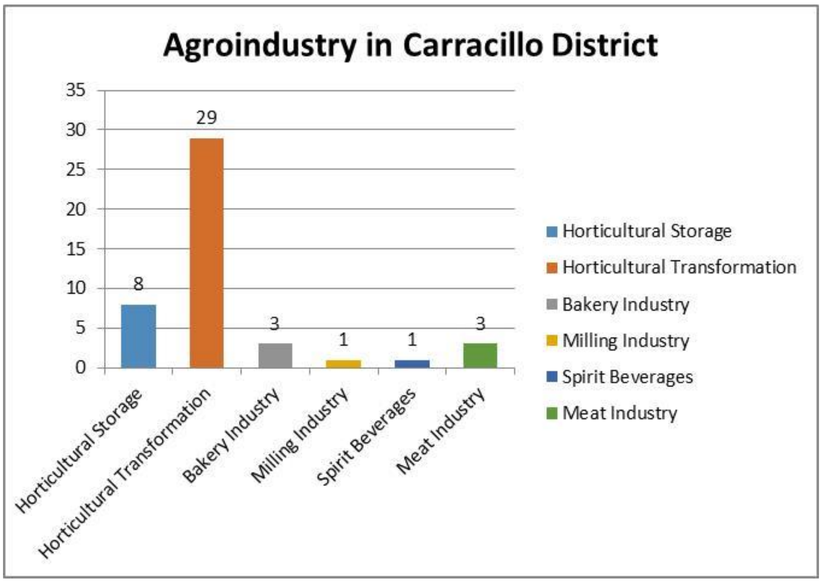

Figure 6. Distribution of Agroindustry in Carracillo District. Source: RGSEAA, 2016.

4. Discussion

4.1. MAR role in El Carracillo rural development

According to a report made by ITACYL (Agricultural Technology Institute of Castilla y León) the municipalities located in the Carracillo exceeded "broadly" the mean in terms of working age population of 20 to 64 years old. Thus, if in rural areas of Castilla y León 7.4 inhabitants are recorded between 20 and 64 per square kilometer, in the area of El Carracillo this ratio exceeds 17 older people per square kilometer. This indicates that employment opportunities in this environment are "far superior" to the average in the Region, a situation that is repeated if the density of workers referred to the area is analysed: "three times higher in El Carracillo than in the other rural areas of the region."

As for occupation; the jobs related to the activities of agriculture and industry is 3.5 times above the average for the region, which has an indirect impact on services sector. Thus, in Carracillo have been recorded 11.29 workers per square kilometer compared to a regional average of 3.73; 2.38 agricultural workers per square kilometer and 2.74 are achieved in industry, compared to regional averages of 0.67 and 0.81.

As reported by ITACYL, the number of companies in the area is 1.28 per square kilometer, while in rural areas of Castilla y León the average ratio is 0.46 companies per square kilometer, that is, almost three times less. "The data show that the effects of horticultural products and their transformation on labour, business and consequently the entire socio-economic activity in rural areas is very important, multiplying the possibilities in these settings" concludes the study.

It is estimated that the industries of strawberry and vegetables generate about 700 direct jobs and 3,000 indirect jobs in the region of Carracillo. High employment rates maintain the populations in their local rural areas. Since 2000 Carracillo´s population has increased by an average of 6%. There are cases with considerable increases. For example, since MAR began the municipality of Chañe has increased 28%.

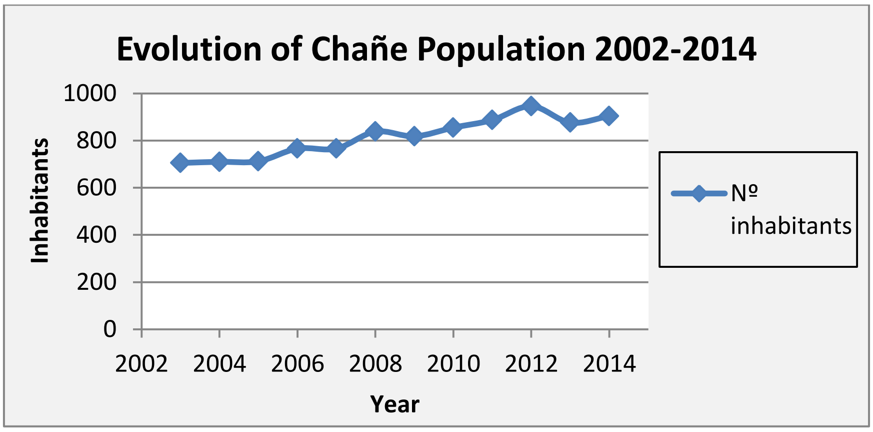

Figure 7. Evolution of Chañe population between year 2002 and 2014. Source: INE, 2014.

4.2. MAR benefits to agriculture

Regarding irrigation improved yields, MAR increases water availability allowing the transformation of dry lands into irrigated lands, which lead into greater productions. Yields per hectare are duplicated in most cases, and even tripling as observed for sweet melon.

Table 7. Crop yields in Castilla y León, 2014. Source: Junta de Castilla y León, 2015.

	Crop Yield (kg/ha)	
	Rain fed	Irrigated
Potato	28,472	48,431
Garlic	5,649	11,058
Melon	7,978	26,478
Wheat	2,977	4,610
Barley	2,446	3,654
Oats	1,906	3,413
Rye	1,789	3,272

4.3. Facts and figures related to MAR, agriculture and rural development in Los Arenales aquifer, El Carracillo District:

- MAR facilities construction. Initial cost (€): 5,273,999
- Hectares in irrigation: 3,500
- Hectares in irrigation before MAR activities began: 3,000
- Arable hectares: 7,586

- Number of commoners in each irrigation community: 713
- Total volume employed for MAR since intentional recharge began until 2015 (Mm^3): 31.47
- Years of operability until 2015: 13
- Ratio recharge/surface (m^3/ha) total: 24.18
- Average annual groundwater extraction (Mm3/year): 8
- Contribution for irrigation groundwater proceeding from MAR activity (m^3/ha): 314.3
- Percentage of water used for irrigation proceeding from MAR activity (%): 23.8%
- Rise of the average groundwater table thanks to MAR (m): 2.3
- Energy savings thanks to the raise of the groundwater table by MAR [(kW h (%)]: 36 kW h
- Total cost (including maintenance and operation) per m^3 of "MARed" water (€/m^3): 0.08.

5. Conclusions

- MAR has been a key factor to boost rural development as well as to combat the aquifer over-exploitation. MAR has increased water availability allowing the transformation of dry lands into irrigated lands and leading to greater productions (as an average, a double). Yields per hectare get duplicated in most cases, and even tripled for the sweet melon case. Also:
- MAR has positive effects on job creation and economic growth.
- MAR plays a vital role in avoiding rural depopulation.
- MAR improves yields and productions.
- MAR saves energy costs supporting farming incomes.
- According to the exposed figures, MAR has increased the number of hectares in irrigation, but more importantly has secured a good technique to combat the previous overexploitation of the aquifer.

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ANNEX 1. MAR SUPPLIED AGROINDUSTRIES IN EL CARRACILLO. INVENTORY.
Source: AECOSAN and MAR to MAR-K€t W.G., 2016.

	NAME	ENTERPRISE ACTIVITY
ARROYO DE CUÉLLAR	Patatas Dami, S.L.	Storage and wholesale of potatoes
	El Señorito De Arroyo, S. L.	Storage of fresh fruits and vegetables

	Arranz Nevado S.L.	Storage of tubers
	NAME	**ENTERPRISE ACTIVITY**
CAMPO DE CUÉLLAR	Hortalizas El Carracillo	Storage, packaging, preserving and wholesale of vegetables
	NAME	**ENTERPRISE ACTIVITY**
CHAÑE	Cultura De La Huerta, S.L	Washing and sale of potatoes and vegetable products
	Jose Luis López García	Production and bakery retail
	Juan Manuel Cocero Alonso	Wholesale of vegetables
	Mª Paz Gómez Laguna	Production and bakery retail
	Soc.Coop Del Campo Glus I	Storage of vegetables
	Viveros El Pinar, Soc. Coop.Ltda	Cultivation & wholesale of fruits, vegetables & strawberry plants
	Zanahorias El Manojillo, S.L	Preparation, preservation and wholesale of vegetables
	Horpin S.C.	Storage of fresh fruits and vegetables
	Hortícolas Bermejo Manso, S. L. N. E.	Storage of fresh fruits and vegetables
	Viveros Campiñas	Production, packaging and wholesale of fruit and vegetables
	NAME	**ENTERPRISE ACTIVITY**
CHATÚN	Hortafercar Sociedad Cooperativa	Storage of fresh fruits, mushrooms and vegetables
	NAME	**Enterprise activity**
FRESNEDA DE CUÉLLAR	Micronizados Acemar S.L	Production of grain mill products
	Piñones Gonzalez, S. L.	Distribution, packaging, transformation and storage of dried and dehydrated vegetable products
	NAME	**ENTERPRISE ACTIVITY**
GOMEZSERRACÍN	El Pinar Del Carracillo, Soc. Coop. Ltda	Washing, packaging and wholesale of horticultural products
	Fuente Pinilla, S.L.	Washing, packaging and wholesale of horticultural products
	Martín Cuesta, S.A.	Production and wholesale of meat products
	Luis Felipe Garcia García	Production and bakery retail
	Puerros Esperanza, S.L.	Storage of fresh fruits, mushrooms and vegetables
	C. B. Hijos De Clemente Gonzalez	Storage of fresh fruits, mushrooms and vegetables
	S. C. Hortalizas Los Claveles	Packaging of fresh fruits, mushrooms and vegetables
	Jose Antonio Muñoz Gonzalez	Packaging of fresh fruits, mushrooms and vegetables
	Hortigovia S.C.	Packaging of fresh fruits, mushrooms and vegetables
	Agrícola Villena, Coop. Valenciana	Packaging of fresh fruits, mushrooms and vegetables
	NAME	**ENTERPRISE ACTIVITY**
NARROS	Zanahorias Manojillo, Soc. Cooperativa	Packaging Of Fresh Fruits, Mushrooms And Vegetables
	NAME	**ENTERPRISE ACTIVITY**
SANCHONUÑO	Arranz Nevado, S.L.	Wholesale of seeds, phyto-sanitary products and potatoes for consumption and cultivation
	Hijos De Teodoro Muñoz, S.L.	Packaging, storing and wholesale of fruits and vegetables
	Soc. Coop. Del Campo De Glus I	Packaging and wholesale of cereals and vegetables
	Las Lagunas De Sanchonuño, S.A	Preparation and wholesale of vegetables
	La Flor Del Carracillo, S.L.	Wholesale of vegetables
	Ultracongelados Del Duero S.L	Processing and preserving of fruits and vegetables
	Sanchonar S.L	Processing and preserving of poultry products
	Huerta Castellana, S.A.	Packaging of fresh fruits, mushrooms and vegetables and production of frozen and deep-frozen vegetable products
	Hortalizas Las Adoberas, S.L.	Production of vegetables preserves and fresh vegetables import
	Sabor De Segovia, S.L.	Production of meat products
	NAME	**ENTERPRISE ACTIVITY**
REMONDO	Jose Antonio García García	Packaging and wholesale of vegetables
	Comercial Agrícola Del Barquillo Coabar Sociedad Limitada	Processing and preserving of fruits and vegetables
	Remondo De La Calle S.L.	Packaging of fresh fruits, mushrooms, tubers and vegetables
	Vegapiron, S. L.	Storage of tubers
	Enrique y Félix De Diego, S. L.	Storage of tubers
	NAME	**ENTERPRISE ACTIVITY**
SAMBOAL	Calle De Pablos S.L.	Production of spirit and spirit-based beverages
	Idealfruits, S.L.	Import and packaging of fresh vegetables

Extended abstract for ISMAR10 symposium. **Topic No: 5 (255#)**

Introducing economy into suitability mapping of MAR scheme

Maréchal, JC. ; Bouzit, M. ; Moiroux, F. ; Caballero, Y. ; Desprats, JF and Rinaudo JD.

BRGM, University of Montpellier, Montpellier, France
*Correspondence: jc.marechal@brgm.fr

Key words: Infiltration basin, cost function, capital cost, operational cost, spatial analysis.

EXTENDED ABSTRACT

During the first phase (desktop study based on available information and data collection) of the course of a MAR project implementation, an analysis of suitability maps is generally carried out in order to identify the most suitable location for a given MAR scheme. Most of the approaches found in the literature rely on the construction of suitability maps using spatial multi-criteria analysis (SMCA) and focus on the aptitude of the aquifer to store water, the infiltration capacity of soils, the distance from the targeted surface resource or the available space (derived from landuse) necessary for building such a MAR scheme. At this stage of the project, only physical parameters are considered and no economic analysis is ever carried out.

The objective of this study is to introduce an economical assessment in this first phase of a MAR project implementation by producing a map of total costs of an infiltration basin scheme. Both capital costs (water abstraction, transfer, land acquisition, basin construction) and operational costs (energy, maintenance, monitoring and water pre-treatment) are taken into account (Figure 1). For that purpose, information and data collection from previous engineering MAR projects have been gathered in order to identify cost functions for the various components of a MAR scheme (Figure 1).

In a first step, an objective of yearly volume to be recharged is defined. A cells grid (50 x 50 m size) is applied on the study area and, using a GIS tool, the following distributed data are extracted for each cell (Figure 2): (i) Distance *D* between cell and the nearest surface water point; (ii) Head change *H* between cell and the nearest surface water point (using Digital Elevation Model); (iii) the soil infiltration *i* rate on the cell (value obtained from permeability maps) and (iv) Land value *LV*. Other parameters are not distributed and are then fixed. In a second step, from these parameters and data, a cost function is developed to map the levelised costs of recharged water for a given operating life duration of MAR scheme and discount rate.

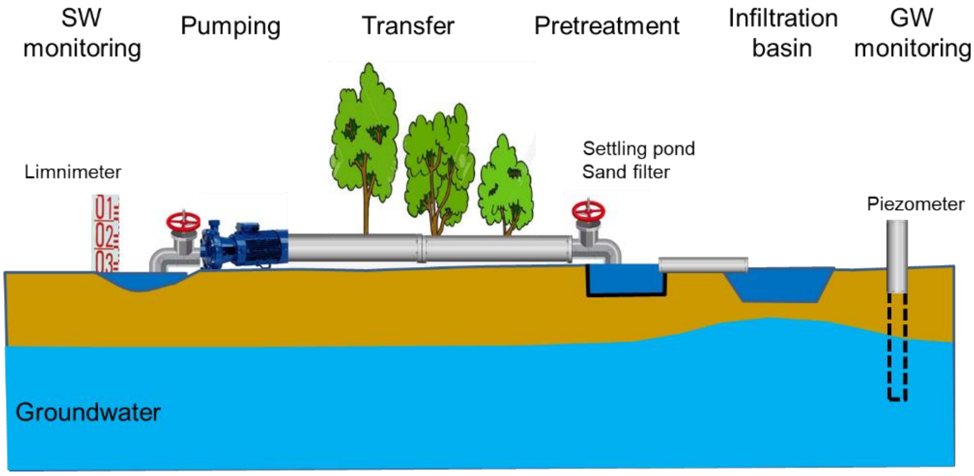

Figure 1: Engineering components of an infiltration basin scheme (SW: surface water; GW: groundwater).

The cost function is applied for all the surface streams that can be used for recharge purpose. Afterwards, the minimum cost is kept in order to build a map of minimum levelised costs (in €/m³ recharged).

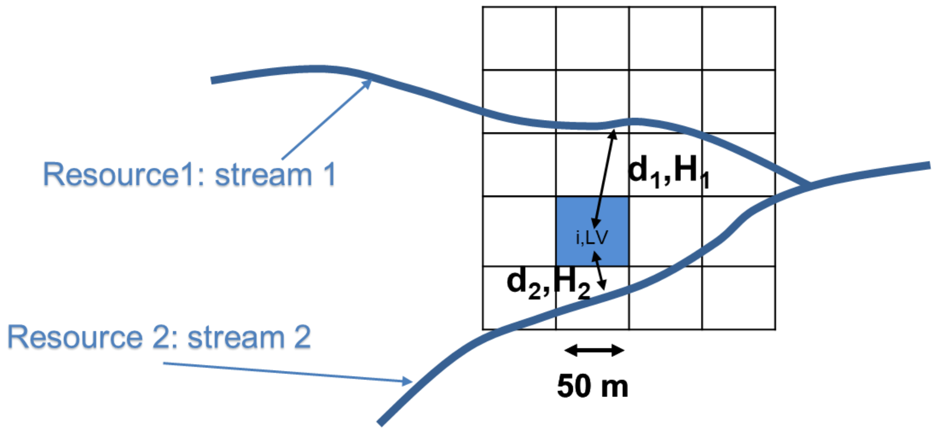

Figure 2: Calculation process of the distance between the grid cell and the surface water point for a case with two surface streams available for potential water abstraction (i: soil infiltration rate, LV: land value, d(-H): distance (-elevation difference) between the infiltration cell and the surface water resource).

The operational and capital costs have been estimated for all the engineering components of a MAR scheme. The annual average cost (€/yr) of the scheme has been computed using the following equation (Figure 3). Then, the levelised cost (€/m³) has been computed according to the yearly recharge volume.

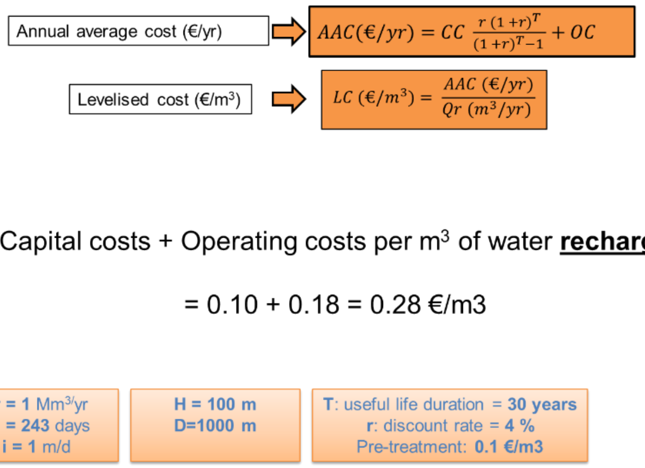

Figure 3: Calculation of the levelised cost for a reference case study (CC: Capital Cost; OC: Operational Cost; Nd: number of days per year of MAR operation).

The methodology has been applied to a case study located in South of France (500 km² area): the Vistrenque aquifer located south of Nimes city which is in an unbalanced state (Figure 4). Among several sources of surface water, the following solutions have been selected: the Vidourle River on the western part and the BRL surface water canal network elsewhere. The following conditions have been considered: annual recharged volume objective of 1 Mm³/yr, useful life duration of the scheme of 30 years, discount rate of 4 %, pre-treatment cost of 0.1 €/m³. Lowest levelised costs are observed at the western part with a free of cost surface water than could be abstracted from the Vidourle River. Into the rest of the study area, the levelised cost of recharged water fluctuates according to the infiltration capacity of the soil and the distance to the BRL canal network (Figure 4).

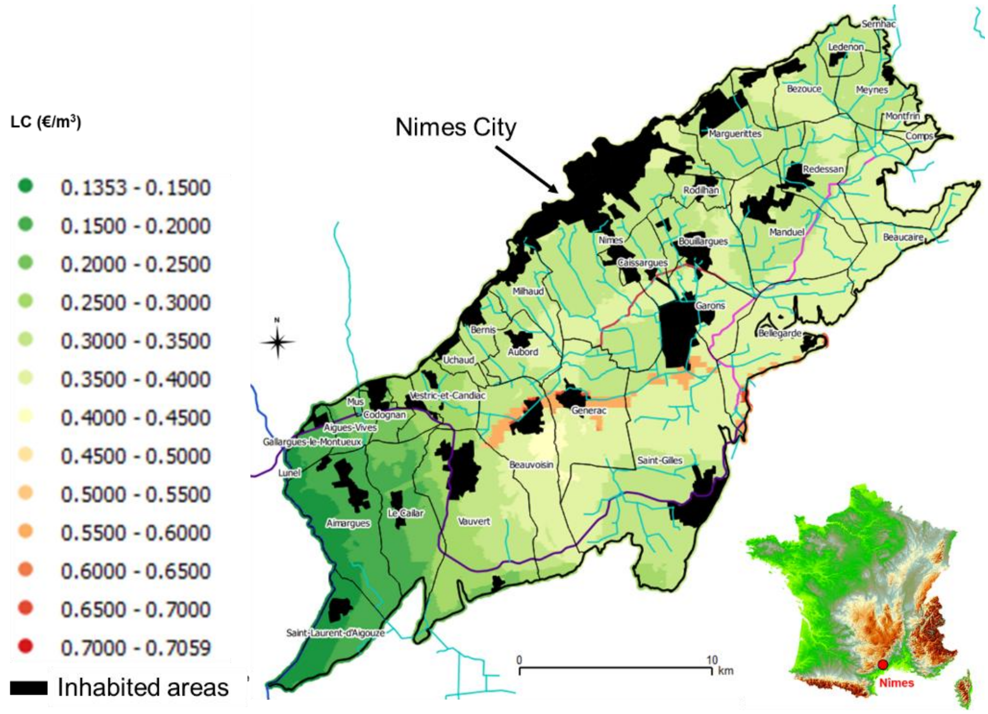

Figure 4: Mapping of levelised cost (€/m³) of recharged water through an infiltration basin on the Vistrenque aquifer case study. Black color corresponds to inhabited areas.

More generally, the cost function can be used in order to illustrate how the various parameters (distance from the surface stream, head difference, pre-treatment cost…) impact the levelised costs. Among other parameters, the water pretreatment and buying costs constitute the main costs. The levelised costs map can be mixed with other types of suitability maps in order to identify the most suitable location for a MAR scheme taking into account economic and financial aspects.

Apart from the cost analysis, the evaluation of benefits associated to a MAR project constitute another scientific challenge that should be overcome for identifying the real potential of such a management solution.

Topic 6. MAR to MAR-k€t & Topic 7. MAR and water reuse

Extended abstract for ISMAR10 symposium. **Topic No: 7 (016#)**

Managed Aquifer Recharge in the Reclaimed Water Master Plans

Ester Vilanova[1*], Begoña Martínez[2], Jordi Guimerà[1], Roger Mas[1], Pere Aguiló[2] and Albert Solà[2]

[1] Amphos 21 Consulting S.L., Barcelona. Spain
[2] Consorci Besós Tordera, Granollers. Spain
* ester.vilanova@amphos21.com; Tel.: +34-935-830-500

Abstract: The increasing water demands and the need for new and alternative water sources has evidenced the need of integrating reclaimed water in basin water management plans. In this context, managed aquifer recharge with reclaimed water is an alternative strategy that is being implemented in these programs to cope with water quality and water scarcity problems and to ensure a continuous water supply. Therefore, these master plans include the characterization of aquifers considering its proximity of water treatment plants, presence of extractive infrastructure for water use, transport structures and the demand of this water type.

This article presents the methodology developed for the Reclaimed Water Master Plan of the Besós-Tordera river basins. The methodology combines multiple ratios of different nature - distance to water sources, infrastructure, hydrological regime and storage capacity of the aquifers- that results in a scoring tool that it is a relevant tool for decision making. This master plan also includes the identification of the water quality requirements depending on the water final use and considering the additional treatment of the aquifer. Finally, the tertiary treatments to achieve these quality goals are designed and sized.

Keywords: reclaimed water; managed aquifer recharge, reclaimed water master plans.

EXTENDED ABSTRACT

1. Introduction

Water scarcity prompts to investigate alternative water resources to mitigate the balance between resources and demands in highly populated areas. In the last ten years, technologies for waste water treatment have evolved to the extent that reuse of reclaimed water is not only possible, but it is common practice. Despite the fact that the regulatory framework for water reuse is still different in different parts of the World, management practices in countries of long-lasting water scarcity are evolving due to the imperative needs to obtain additional sources of water – Europe, has not implemented yet a definitive framework directive of Water Reuse for the state members, only a recent proposal on minimum requirements for water reuse in agriculture (COM (2018) 337 final) - . Hence, programs for water reuse or for non-potable water exist and are being implemented in arid parts of the World, where alternative uses are given to reclaimed water.

Managed aquifer recharge with reclaimed water is an alternative strategy that is being implemented in these programs. Differently to conventional fresh water sources like river or rain water, reclaimed water needs to demonstrate a quality of water so that not only does not pose health threads to public, but also does not worsen the groundwater quality. Additionally, specific risk analyses have to be conducted considering the water final uses, the quality of recharged water and the media characteristics.

Under these circumstances, aquifers candidates to receive reclaimed water for either replenishment or store-and-recovery must have specific features in a context of proximity of water treatment plants, presence of extractive infrastructure for water use -namely extraction wells or users- and potential for water store. In addition, the distance of the potential injection or infiltration sites must be such that the residence times of recharged reclaimed water complies with the requirements of risk analysis.

2. Materials and Methods

2.1 Framework

This article presents the methodology developed in Besos-Tordera river basins to integrate the aquifer recharge with the reclaim water master plan (RWMP) to attain a most sustainable water basin management.

The RWMP has been developed in the municipalities where Consorci Besos-Tordera (CBT) is responsible for wastewater management being a total of 64 municipalities. Besòs basin is totally included in the analysis while in the Tordera basin only the upper part is considered.

This RWMP has included different tasks from the identification of reclaimed water demand and characterization of source waters from water treatment plants to the design of the most appropriate tertiary treatments. This RWMP has also designed the infrastructures to transport and to treat the reclaimed water.

Managed aquifer recharge (MAR) is considered as an environmental use of reclaimed water in the Spanish Water Reuse Royal Decree (RD 1620/2007). This Royal Decree establishes the legal regime to rule the treated wastewater reuse in Spain. It defines the uses for reclaimed water, quality criteria, control parameters and procedures to get reuse permits.

To identify the most favorable areas to implement MAR with reclaimed water two parallel activities have been conducted: a) the identification of reclaimed water demands and the water available sources and b) the aquifers characterization.

2.2 Reclaimed water demands and sources

The demands of the whole basin have been classified following the 5 main types that the RD1620/2007 identifies for reclaimed water: urban, agricultural, industrial, recreational and environmental uses.

The urban demands have been estimated by means of personal interviews with each city water manager (mainly council towns). These demands include municipal gardening and streets cleaning, urban orchards, … Industrial demands have also been approached using specific surveys including the quality requirements of their needs. Recreational water demands have been facilitated by main users (mainly golf courses), council towns and the Catalan Water Agency (CWA). Agricultural demands have been calculated using the specific water demand of each crop type. Finally, environmental demands have been considered using different information sources. From one side it has been taken into account the environmental river flows defined by CWA and the environmental needs pointed out by local council towns. From the other side, CWA and the aquifers study have also identified those areas with higher pressure over groundwater resources.

	Volume (m^3/y)
Urban demand	3.080.680
Industrial demand	3.821.155
Agricultural demand	6.456.642
Recreational demand	533.692
Environmental demand	8.628.732
TOTAL	**22.520.901**

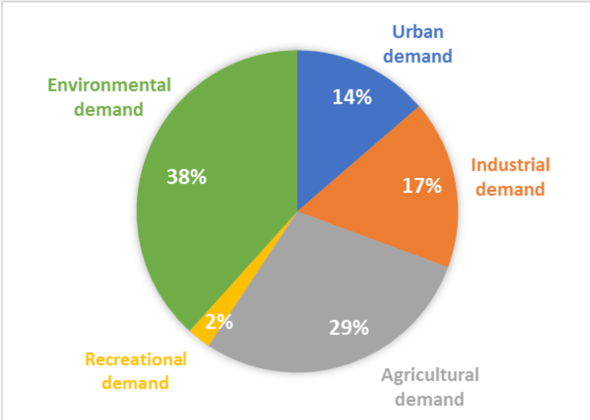

Figure 1. Reclaimed water demands estimated in Besòs-Tordera area [1].

In this basin there are a total of 30 wastewater treatment plants. Those managed by Consorci Besós-Tordera generate a total of 54 Mm^3/y which is the maximum available reclaimed water for the RWMP.

2.3 Aquifers characterization

The Besós-Tordera river basins are two small catchment areas of 1038 m^2 and 894 m^2 respectively, near Barcelona, that are highly populated and concentrate intensive industrial demand together with agricultural practices.

In this area 19 aquifers have been identified [2,3]. These can be classified in 4 main types:

- Alluvial aquifers. These are associated to main river courses and includes from 1 to 3 terraces.
- Detritic aquifers below alluvial aquifers. They are composed by different sedimentary materials resulting in a multilayered aquifer partially confined.
- Local aquifers in low permeability media. In those areas where predominate materials are of low permeability (mainly clays) it is possible to find isolated aquifers of sedimentary origin.
- Karstic aquifers.

There are several international studies that have developed methodologies to select the most suitable areas to implement MAR systems (4-8). As the source water in this case is reclaimed water additional parameters as location of water treatment plant and potential impacts have also been considered.

The parameters that have compiled for this study have been: Aquifer type, drainage system, slope, capacity of infiltration, land uses (including the location of existing wells), depth on unsaturated zone, aquifer thickness, transmissivity, travel time, quality of recharging water, groundwater dependent ecosystems, aquifer contamination and location of wastewater treatment plant.

2.3 MAR sites selection

As the final objective of the study is to propose areas where MAR with reclaimed water is potentially feasible in the context of the RWMP, the methodology have consisted in eliminating those areas where the values of these parameters do not recommend the groundwater recharge. The first task has consisted in identifying the most favorable aquifers based only in hydrogeological characteristics (permeability, depth of water, …). The values used for the selection have been [5-8]:

- Transmissivity > 50 m^2/d
- Infiltration > 1 m/d (in infiltration systems)
- Slope < 5% (in infiltration systems)

- Depth of non-saturated zone >5m (in infiltration systems) and >10 m (in injection systems)

To allocate the recharging areas in the selected aquifers, 3 aspects that have been considered:
- location of the water treatment plant at less than 2,5 km
- the land use has to be compatible with recharging system (preferably far out of urban or populated areas)
- a safe distance between recharging area and the existing downstream wells (this is a distance > than 1 km or travel time > 6 months).

3. Results

The most favorable aquifers based on hydrogeological characteristics have been selected using GIS tools (Figure 2). This selection includes the alluvial aquifers with enough available volume, the detritic aquifers with layers of course sediments at reasonable depths and the karstic aquifer.

To locate the recharging areas (MAR sites in Figure 2), GIS tools have been used to display the spatial distribution of wastewater treatment plants and to delineate a surrounding area of 2,5 km of radius. This zone has been overlapped with land uses to identify the less populated area and with wells distribution to ensure that the recharge will have minimum impacts over other groundwater uses.

As a result, 7 areas have been preselected for a more detailed analysis (Figure 2) taking into account the analysis of water demands. Considering the groundwater depth, the aquifer type and hydraulic properties, the most suitable MAR type have been identified for each site. Two of these preselected sites have been finally discard due to incompatibilities with other groundwater uses and the distance to wastewater treatment plants of the less populated zones.

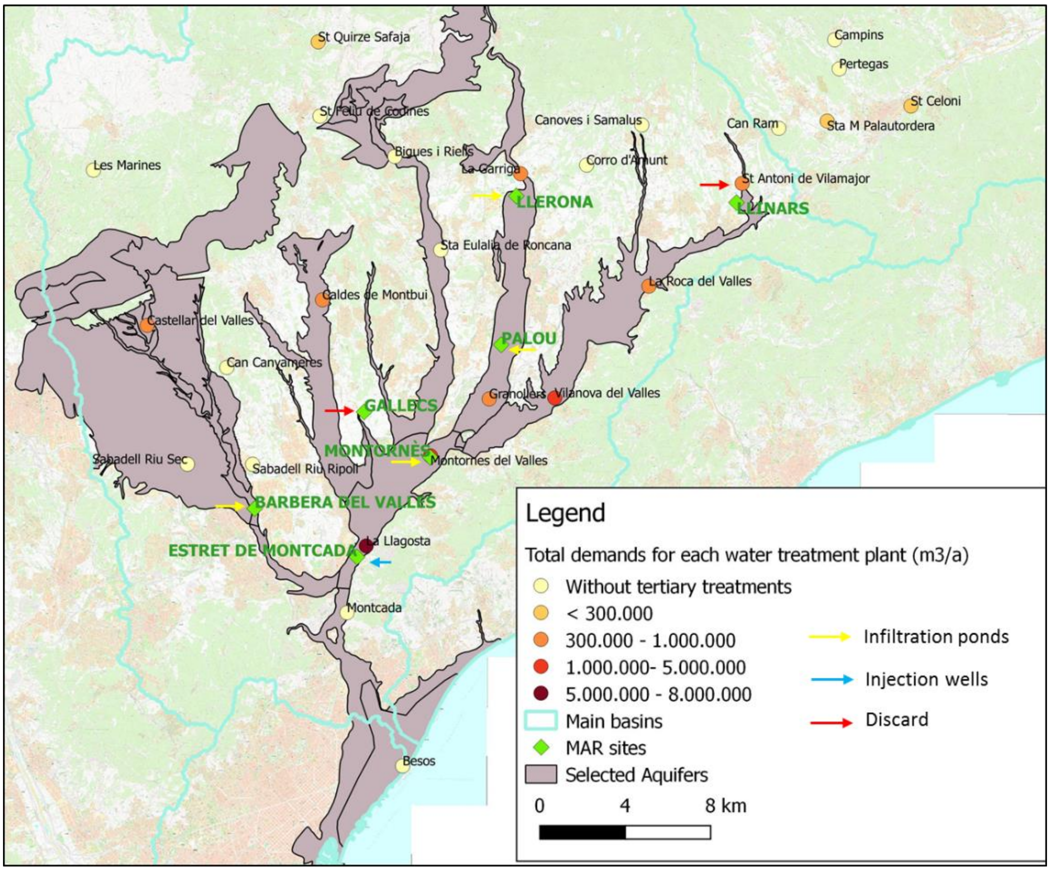

Figure 2. Location of selected aquifers and the most suitable areas for MAR systems.

The total volume to be recharged has been estimated based on the reclaimed water demands and the available water in the designed tertiary treatment obtaining a total of 8.2 MCM/y.

4. Discussion

Reclaimed water is an essential water resource that needs to be considered in areas with water scarcity and water quality problems. This water source requires an integrated management plan based in a site-specific decision-making tool and incorporating safety assessment considerations.

The results presented in the former section, have been integrated in the whole RWMP of the basin to define the tertiary water treatment systems. MAR with reclaimed water has been included as one of the environmental water demands together with industrial, urban, agricultural and recreative uses.

The selection of sites to implement MAR has been based in methodologies tested in international studies but adapted to local characteristics. More specifically, this analysis needs the consideration of hydrogeological characteristics but also it must combine multiple ratios of different nature -distance to water sources, to present groundwater uses and to the existing and planned infrastructure. To cope with local acceptance of these MAR systems it is not enough to carry out risk analysis and to ensure safe travel times. It is also important to consider the present land and groundwater uses which have been included in this analysis. Distribution of more populated areas, the existence of wells and groundwater dependent ecosystems have been considered in the analysis.

The implementation of MAR systems in the context of the whole RWMP becomes an additional strategy to increase water supply security in a planned and safe manner.

Abbreviations

The following abbreviations are used in this manuscript:
CBT: Consorci Besòs-Tordera
CWA: Catalan Water Agency
MAR: Managed Aquifer Recharge
RWMP: Reclaimed Water Master Plan.

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Paper for ISMAR10 symposium. **Topic No: 7 (064#)**

Enabling the reuse of industrial wastewater to meet freshwater demands of greenhouse agriculture by using aquifer storage and recovery (ASR)

Van Dooren, Teun C.G.W.[1*], Zuurbier, Koen G.[1,2], Raat, Klaasjan J.[1,2], Hartog, Niels[1,3] and Stuyfzand, Pieter J.[1,4]

[1] KWR Watercycle Research Institute, Nieuwegein, The Netherlands
[2] Allied Waters, Nieuwegein, The Netherlands
[3] Utrecht University, Utrecht, The Netherlands
[4] Delft University of Technology, The Netherlands
* Correspondence: teun.van.dooren@kwrwater.nl; Tel.: +31-30-606-9563

Abstract: Continuous availability of reliable and high-quality freshwater is a prerequisite for the greenhouse sector. This was not self-evident for Nieuw-Prinsenland, a modern greenhouse area of 260 ha developed in Dinteloord, the Netherlands. Local groundwater is brackish and inflow of fresh surface water is limited. Thus, the irrigation water demand is largely satisfied through collection of rainwater and storage in aboveground basins. However, serious water shortages arise during droughts. A neighboring sugar company produces large volumes of wastewater between September and January, which could form the required additional water source after treatment. Unfortunately, its availability is out-of-phase with the projected demand of the greenhouse sector (April-August). To bridge the gap between availability and demand, a large scale aquifer storage and recovery (ASR) system was realized. A careful path was followed to the realization of the water system, in which the ASR-facility is equipped with an automated control unit and connected to greenhouses, sugar factory, and neighboring food processing industries by a 5 km distribution loop. The system has the potential to supply an additional 300,000 m^3 of irrigation water every year, at an average price of 0.51 €/m^3. It exemplifies the feasibility of hybrid grey and green infrastructure, and demonstrates how managed aquifer recharge (MAR) can contribute to water reuse in the circular economy. The keys to success are thorough organization, gradual realization, automation, frequent evaluation, and transparent communication.

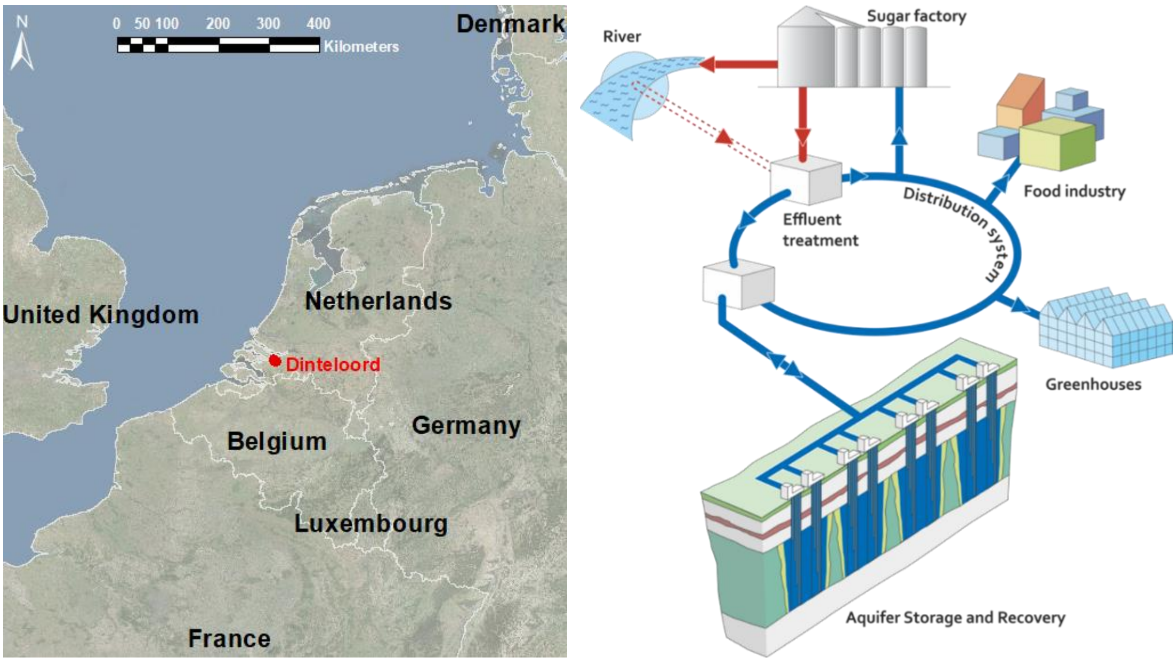
Keywords: MAR; ASR; wastewater; reuse; greenhouse; industry.

1. Introduction

Continuous availability of reliable freshwater is a precondition to meet domestic, industrial, and agricultural demands. Meeting these demands is challenging, especially in areas with a high economic importance, strict water quality requirements, and a limited availability of freshwater. In Dinteloord (Figure 1a), The Netherlands, the Tuinbouwontwikkelingsmaatschappij (TOM) realised the modern greenhouse area Nieuw-Prinsenland (260 ha). The region has a high economic importance for the Dutch greenhouse sector, but is located in a salinizing coastal area without a significant external freshwater supply. Consequently, availability of very high-quality (sodium <2.4 mg/l) water, which is required for greenhouse irrigation, is a major challenge. Rainwater collected at greenhouse roofs and stored in aboveground basins formed the basis for the irrigation water supply. However, these basins can not store sufficient water to overcome years with prolonged periods of drought. Use of groundwater and surface water was prohibited because these sources are threatened by salinization.

Wastewater reuse is recognized as a key solution to deal with water scarcity [1]. In Dinteloord, a sugar factory produces large volumes of wastewater between September and January, and provides a potential irrigation water source for the greenhouse sector. The wastewater can be treated and purified to high-quality irrigation water by using rapid sand filtration, ultra-filtration, and reverse osmosis. Besides treating the reuse water to the desired quality, management of its availability to meet its demand over time is vital for success. In Dinteloord, the availability of wastewater is out-of-phase with the projected irrigation water demand (April-August). The main question therefore was: 'How to transfer the available reuse water to the dynamic time of demand?'

Aquifer storage and recovery (ASR) can provide the crucial solution to the temporal mismatch between availability and demand, and can further safeguard water quality via aquifer passage [2]. In Dinteloord, a wastewater treatment facility is developed and connected to an ASR-system through a 5 km long distribution loop (Figure 1b). The ASR-facility is equipped with eight wells that store and recover treated wastewater between autumn and spring. Multiple partially penetrating wells (MPPW) were installed to counteract buoyancy induced recovery losses [3,4]. The ASR-system has been in full operation since 2018, and has the potential to provide the local greenhouse sector with 300,000 m^3 of irrigation water every year, with a maximum supply capacity of 200 m^3/ h [4,5].



(**a**) (**b**)

Figure 1. (a) Location of Dinteloord; (b) Final design of the Dinteloord water system.

The objective of this paper is to demonstrate the potential of hybrid grey and green infrastructure and to facilitate the development of wastewater reuse systems in combination with MAR in general and with ASR in specific. Therefore, the technical overview and the development of the complete system is explained, the organisational structure is described, the economic feasibility is elaborated upon, and the performance of the system in the first operational years is discussed.

2. Materials and Methods

The Dinteloord water system followed a careful path towards realisation [5]. The complete stepwise approach is listed in Figure 2 and is described in a guiding document [5]. It can be regarded as a guideline for evaluation and implementation of ASR in the scope of wastewater reuse. The most important results of this step-wise approach are further elaborated upon in the next chapter.

I. Desk-study: literature on regional hydrogeological conditions, sampling of existing monitoring wells

II. First assessment of potential recovery efficiency of conventional ASR and ASR with MPPW (tools and models)
First cost estimations

III. Exploratory drilling including sediment analysis and groundwater sampling to obtain reliable local data

IV. Second assessment of potential recovery efficiency
Hydrological effect study (groundwater levels, subsidence, archeology) and final site selection

V. Preliminary design and permitting

VI. Execution of first injection/storage/recovery test, pumping test

VII. Advanced water balance and groundwater modelling to define operational parameters and assess final performance

VIII. Final design and realisation of the ASR system

IX. Monitoring and evaluation of the first ASR-cycles

Figure 2. Stepwise approach followed to enable water reuse in Dinteloord [5].

3. Results

3.1. Hydrogeology

3.1.1. Characterization of the target aquifer

The subsurface is characterized in existing literature [5]. Its main characteristics are briefly presented in Table 1. The target aquifer is about 18 meters thick and consists of (medium) fine sand with a thin clay layer at medium depth. The target aquifer is confined by fine heterogeneous sediments with a total thickness of about 10 meters. A sandy clay forms the base of the target aquifer.

Table 1. Characterization of the target aquifer (m ASL is the abbreviation for meters above sea level).

Layer top [m ASL]	Layer bottom [m ASL]	Formation	Lithology	Layer type
0	-10	Naaldwijk	Clay, fine sand, peat	Aquitard
-10	-20	Waalre	Fine sand, clay layer at the base	Target aquifer
-20	-28	Waalre	Medium fine sand	Target aquifer
-28	-32	Waalre	Sandy clay	Aquitard

3.1.1. Characterization of the native groundwater

The transition from saline to fresh groundwater is situated within the project area [5] (Figure 3). The regional occurrence of saline groundwater results from flooding and consequent infiltration of seawater in the Holocene, until closure of the North Sea estuaries in the 1970's. Three monitoring wells were used to determine the actual distribution of fresh and saline groundwater. Chloride concentrations observed in the target aquifer in the north of the project area range from 1000 mg/L to 4500 mg/L, which is too high for an efficient implementation of ASR. Deeper aquifers are more saline and thus even less suitable. In contrast, chloride concentrations observed in the target aquifer in the south of the project area are remarkably lower and vary between 25 mg/L and 60 mg/L. Moreover, groundwater flow is virtually absent, making the southern part of the project area the most suitable location for realisation of the ASR-system (Figure 3).

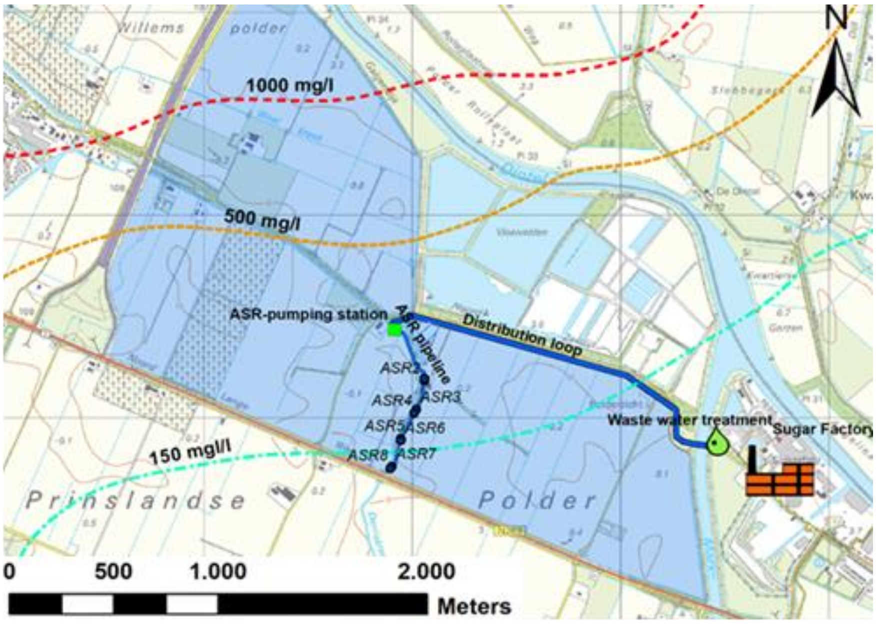


Figure 3. Overview of the project area. The red, orange, and blue contours represent estimated chloride concentrations of native groundwater [5].

3.2. ASR system

The first pilot ASR-well consists of four partially penetrating wells that can infiltrate or recover water independently (Figure 4). Recovering only with shallow partially penetrating wells allows counteracting buoyancy induced recovery losses resulting from the density difference between stored fresh water and brackish ambient groundwater [3]. Since buoyancy effects were not as significant as expected, the seven additional ASR-wells were later installed with only two well screens.

The ASR-system is equipped with an automated control unit to regulate infiltration and recovery automatically based on the irrigation water demand of the greenhouse owners and the availability of treated effluent [5]. It ensures a minimum infiltration rate of 60 m^3/h and a maximum recovery rate of 200 m^3/h. The unit records operational data and sends alarms upon disruptions. It can be operated on site with a touch-screen or remotely with a computer program, and thus allows for the manual regulation of rates, volumes, and settings whenever desired or required [5].

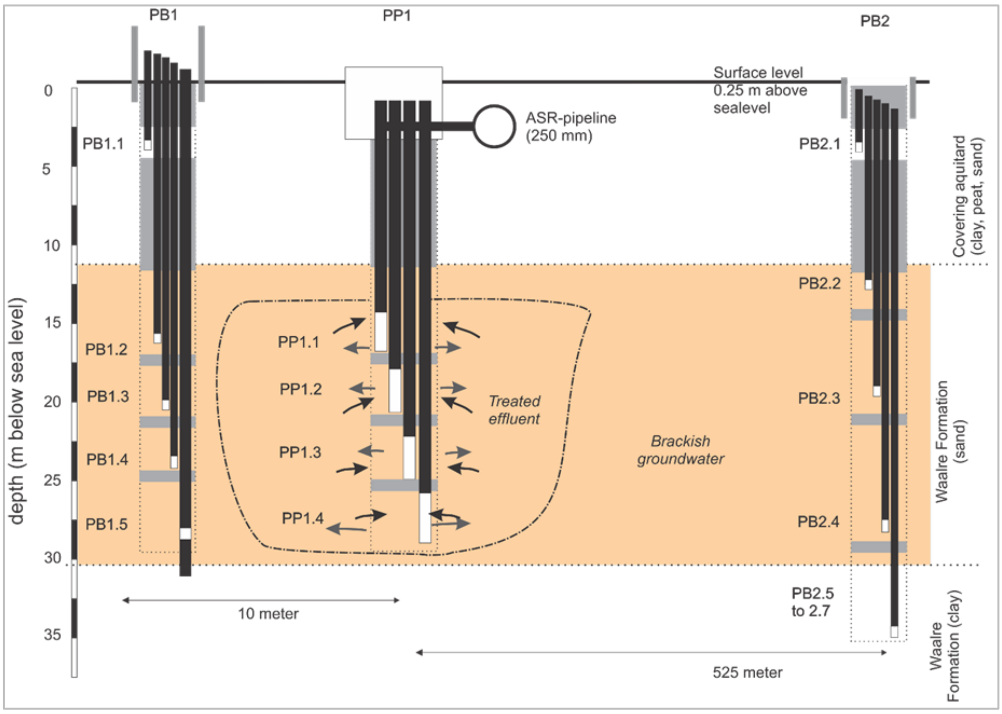


Figure 4. Well configuration of the pilot ASR-well (PP1) and two monitoring wells (PB1 and PB2) [5].

3.3. Water balance

3.3.1. Water balance model fundamentals

The water balance of the Dinteloord water system is composed of two main storage reservoirs:

1. The surface storage basins of greenhouse owners (*B*);
2. The subsurface as the storage reservoir for ASR (V_{ASR}), with a maximum capacity of 300,000 m^3.

The fluxes affecting both reservoirs are given in Figure 5 [5]. *B* is linked to V_{ASR} through the infiltration (ASR_{rw}) and recovery (ASR_{sup}) fluxes of the ASR-facility, having rates of 1,440 m^3/day and 4,800 m^3/day, respectively. Furthermore, *B* is fed by net precipitation intercepted by greenhouse roofs (I_{Roof}) and aboveground basins (I_{Basin}). Water stored in *B* is utilized by greenhouse owners for their water demand (*D*) and can leave the system by basin overflow (*BO*). The sugar factory refines sugar from April 1 to June 15, requiring 25,000 m^3 of water and producing 500,000 m^3 of wastewater. The sugar beet campaign runs from August 15 to September 1, requiring 5,000 m^3 of water and producing at least 1,500,000 m^3 of wastewater. The wastewater is treated and supplied at a maximum rate of 1,440 m^3/day (*IWD*). The treatment plant can operate on river water during calamities or when wastewater is unavailable. *SFU* represents water (re)used by the sugar factory.

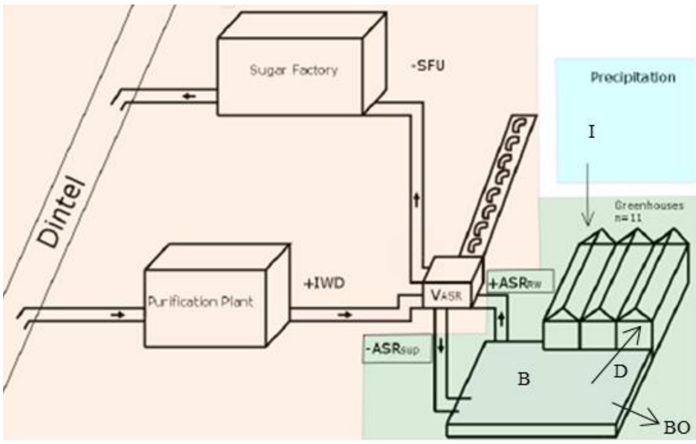


Figure 5. Schematic representation of the total water balance of Dinteloord [5].

3.3.3. Modelled results 2000-2016

The water balance was modelled with local weather data for 2000-2016 (Figure 6). The inclusion of ASR and water reuse keeps water shortages below 20,000 m³/year, with an average shortage of about 5,000 m³/year. This shortage is only 2.5% of the annual average volume supplied by ASR (203,056 m³), i.e. the shortage that would occur without ASR. Water shortages mainly occur during extended periods of drought, and are limited by the infiltration and recovery rates rather than the stored capacity. The stored volume only becomes limiting at low capacity, as mixing with ambient brackish groundwater is more significant. The model reflects a resilient cooperation between individual greenhouse owners and the ASR buffer, even during a prolonged drought in 2013. The only risk lies in consecutive dry years, possibly resulting in insufficient ASR replenishment and a consequential unavailability upon demand. Thus, annual supplementation of treated effluent to the subsurface is important, and supply of stored water to the greenhouse owners should occur betimes.

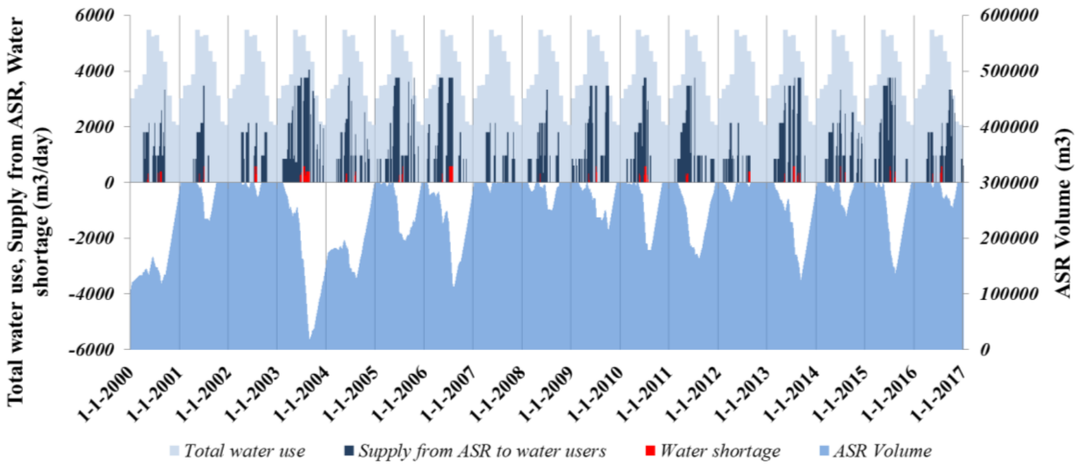


Figure 6. Water balance results modelled with weather data of 2000-2016. Water shortage is the water demand that can not be satisfied by precipitation stored in surface basins, by direct supply of treated effluent, or by water recovered from the subsurface via ASR.

3.4. Monitoring and evaluation of the ASR performance

3.4.1. Water quantity

The first ASR-well was realized in February 2016 for a pilot on a small controllable scale (Figure 7). During this ASR-pilot, 12,748 m³ of treated wastewater was infiltrated. After six months of storage, 1,470 m^3 was successfully recovered and met the strict water quality requirements for irrigation. Three additional ASR-wells are operating since June 1st of 2017. The last four wells were realized in 2018 and the ASR-system has been in full operation since March 6th of that year. In total, 271,889 m^3 has been infiltrated and 108,164 m^3 has been recovered and supplied upon demand. This amounts to a net infiltration of 163,726 m^3 and a recovery efficiency (RE) of 40% (Figure 7). This low RE is not entirely due to water quality restrictions or an insufficient recovery rate. The results do not include the recovery phase of 2019. In addition, when an ASR-well is taken in operation, a freshwater lens first has to develop in the subsurface for later use [6], i.e. the potential RE increases when net infiltration reaches the target storage volume of 300,000 m^3, as water quality limitations are less significant (see 3.3.3.). The actual RE can only be determined for full hydrological years after attaining the target storage volume. The most valuable results so far are obtained from ASR1 for the hydrological year 2016-2017. ASR1 recovered 80% of the infiltrated water with a suitable irrigation water quality (sodium <2.4 mg/L). Moreover, the ASR-facility supplied the already established greenhouse owners with sufficient reuse water during the dry summer of 2018, whereas greenhouse owners with conventional water supply systems already ran out of their supplies a month earlier.

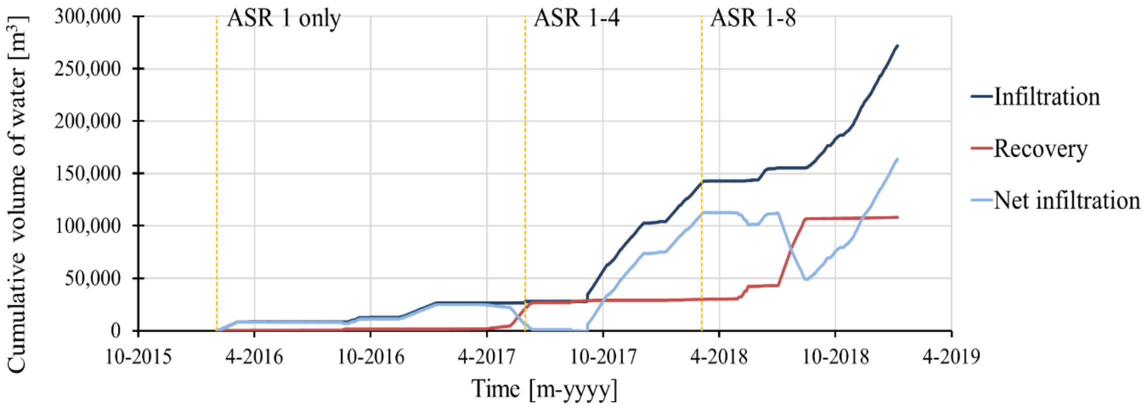


Figure 7. Performance of the ASR-system in the period 2016 – 2019.

3.4.2. Water quality

Sodium appeared to be the solute limiting the recovered water quality, with a maximum allowable concentration of 2.4 mg/L for irrigation. Moreover, exploratory drillings have revealed the presence of pyrite (FeS_2) and siderite ($FeCO_3$) in the subsurface. Oxidation of these minerals by continuous intrusion of oxygen via inadequate vent valves during infiltration and storage resulted in mobilization of iron. However, after aerating the recovered water in surface basins, mobilized iron settled out as iron oxides and operational problems were not observed. In addition, mobilised iron appeared to decrease over successive ASR-cycles, reducing the risks for irrigation. Mobilization of arsenic by oxidation of pyrite was neither observed to be a threat for the recovered water quality. The exploratory drillings have revealed a relatively high content of carbonates in the subsurface. Dissolution of these carbonates buffers the acid produced by oxidation of pyrite and siderite, thereby increasing the hardness of recovered water during recovery. This did not result in operational problems in Dinteloord, but might do so elsewhere.

3.5. Organizational structure

Using wastewater from one party for later use (after aquifer storage) by a second party involves clear agreements between the different parties involved. In Dinteloord, all parties were organised to properly operate and administrate the entire water system, and responsibilities have been distributed (Figure 8). The greenhouse cooperation, including its eight members, has a central role as owner and main end user of the water system. Veolia is operating the wastewater treatment system, while TOM and KWR operate the ASR-system. TOM is the developer of the greenhouse area, and Codema is the engineering company that constructed the ASR-system and is responsible for its maintenance. KWR was involved with the design and development of the ASR-system. KWR is also responsible for monitoring and evaluation of the ASR-system's performance, and is consulting partner for the TOM and the Water authority Brabantse Delta, manager of the local surface water system. Suiker Unie provides wastewater but is also end user of the treated water. The Province of Brabant was the permitting agent for the ASR system.

The maximum volume of fresh water that can be recovered by ASR and supplied to the users may vary every year. Each spring, KWR estimates the recoverable freshwater volume, upon which TOM distributes the water over the users. The recovery rate is limited to 200 m^3/h, i.e. 1 m^3/h per hectare of greenhouse area. The minimum guaranteed supply rate for each user is based on this rate and their greenhouse area. Users with a lower water demand can transfer their rights to users with a higher demand. These transfers must be communicated to TOM, which executes the billing. The costs are covered by a pay-per-use system through the price of a cubic meter of water (Figure 8).

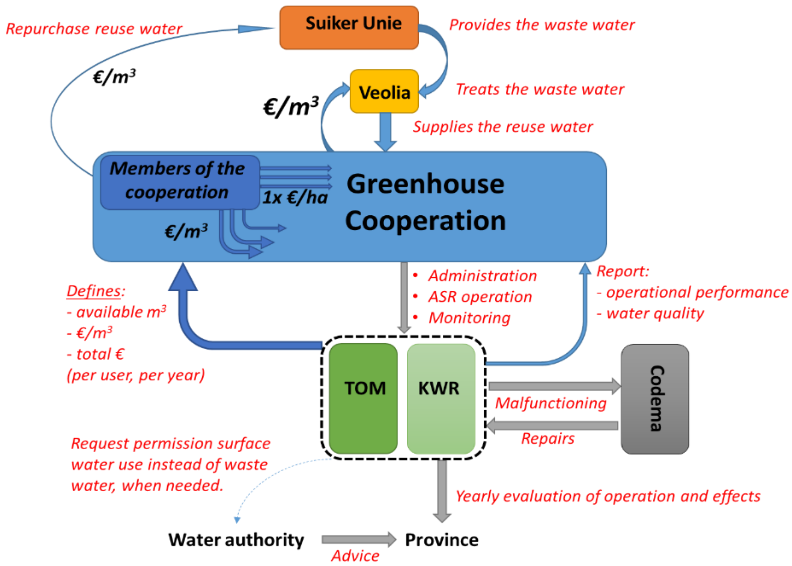


Figure 8. Organogram of the Dinteloord wastewater reuse system including ASR.

3.6. Economic analysis

The costs of the Dinteloord water system are twofold:

1. Investment costs or capital expenses (CAPEX): the total costs made to realize the installations, e.g. the wastewater treatment system, pipelines, pumping stations, and ASR-wells;
2. Variable costs or operational expenses (OPEX): costs made to operate the system. This includes costs for treatment, electricity, and monitoring. It also entails the costs for advice, maintenance, and evaluations. OPEX are calculated at the end of a year and may vary over the years, depending on the need for maintenance and the volume of water treated, stored, and supplied.

An economical model was made on the basis of CAPEX, OPEX, and relevant economical parameters, like financial depreciation and fiscal impact [7]. The main economical parameters are listed in Table 2. Based on these parameters, the price of a cubic meter of water supplied amounts to 0.51 €/m^3 [7]. This is competitive with local tap water, having a price of 0.43 €/m^3 for a normal connection and 0.90 €/m^3 for a temporary connection. However, local tap water requires additional treatment and thus costs, since its high sodium content does not allow for direct irrigation.

Subsurface water storage by ASR is especially cost-efficient compared to the alternative of aboveground storage, which has an estimated price of 1.06 – 3.09 €/m^3, depending on the basin's location and lifetime. These costs are dominated by the production loss related to aboveground space requirements and by more significant reinvestment costs due to a shorter life-time (15 years). CAPEX of ASR is lower compared to aboveground storage, whereas OPEX are slightly higher, due to the electricity needs for wastewater treatment and pumping to and from the subsurface [7].

Table 2. Economical input parameters [7].

Parameters	Value	Unit
Lifetime of the ASR-system	20	years
Initial investment costs	892 000	€
Reinvestment costs	112 900	€
Operational/variable costs	21 250	€/year
Average annual water injection	125 000	m^3/year
Average annual water recovery	125 000	m^3/year
Maximal annual water recovery	300 000	m^3/year
Required maximal volume to supply	300 000	m^3
Active surface area of water system	200	ha

4. Discussion and conclusions

The system in Dinteloord reveals that implementing ASR with treated wastewater is a viable and economic feasible strategy to automatically supply high-quality irrigation water to local greenhouse owners upon demand. Space requirements are negligible compared to aboveground storage, the subsurface acts as an additional treatment step for stored water, water shortages can be reduced by 97,5%, and average costs of supplied water are competitive with local tap water. Water supply by the ASR-facility in Dinteloord is limited by the infiltration and recovery rates rather than the stored capacity. Thus, annual supplementation of treated wastewater to the subsurface is important, and delivery of water stored in the subsurface should occur betimes. A resilient cooperation between individual greenhouse owners and the ASR buffer can exist, even during a prolonged drought. The only risk appears to lie in consecutive dry years. The most important lessons learned from implementing ASR for water reuse are [5]:

- Take it step-by-step: Various elements can fail when applying ASR with treated wastewater. A careful step-by-step approach with a critical but open perspective is required for realization. Perform a desk study, verify important assumptions with field measurements and models, and validate and demonstrate with a small-scale pilot. Technical feasibility, economic viability, and hydrological acceptability should constantly be assessed in an iterative process. Targeted end users, authorities, neighbors, and the wastewater supplier should be continuously informed.
- Demonstrate and communicate: Water reuse and ASR both involve complex technologies and processes. A clear demonstration and communication towards stakeholders, end users, and the public is vital. For Dinteloord, this was achieved by information panels, an informative movie, a public opening, and an article in a professional journal with details on the complete set-up [8]. End users were particularly informed by regular meetings with the cooperation. Participatory technology assessment sessions were organized to inform a broad range of stakeholders [9].
- Set up the organizational structure: Implementing water reuse and ASR with multiple end users requires a firm organizational structure with clear roles for every party. In

Dinteloord, the organization was set up by TOM, a stable, central party with a good overview of all processes. TOM was able to assess the technical and economic viability based on data provided by experts.

During the development and in the coming years, the water system in Dinteloord is intensively being controlled, monitored, and evaluated. This involves mainly to appropriately distribute infiltration and recovery over the various well screens, to examine water quality changes occurring during storage (KWR), to repair potential malfunctioning of the system (Codema), to record and report quantitative data, and to coordinate all aspects of the cooperation (TOM).

In short, the story of Dinteloord perfectly exemplifies how MAR and collaboration between multiple parties can bridge the seasonal gap between the availability of wastewater and the demand of irrigation water, and can contribute to the business case of water reuse in a circular economy.

Supplementary Materials: The following is available online at https://vimeo.com/256952109, Video S1: Water reuse and aquifer storage and recovery Dinteloord.

Acknowledgments: This project was executed by KWR Watercycle Research Institute and TOM. The majority of the project is financed from the allowance of 'Topconsortia voor Kennis en Innovatie' (TKIs) of the Dutch Ministry of Economic Affairs and from the EU Horizon 2020-project SUBSOL (grant agreement No. 642228). The technical realization of the ASR-system was executed by Codema B-E de Lier.

Author Contributions: T.C.G.W. van Dooren monitors and evaluates the ASR performance in terms of water quantity and quality, analyzed the data of the first operational years, and wrote this paper. K.G. Zuurbier was involved in the geohydrological research and the technical design, and monitored and evaluated the ASR system throughout the years. N. Hartog assisted in interpreting the geochemical results and their influence on the ASR performance. K.J. Raat is the project manager and P.J. Stuyfzand is the quality assurer of the project.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations:

The following abbreviations are used in this manuscript:

ASR: Aquifer storage and recovery
MAR: Managed aquifer recharge
TOM: 'Tuinbouwontwikkelingsmaatschappij' (Dutch)
MPPW: Multiple partially penetrating wells
RE: Recovery efficiency
CAPEX: Capital expenses
OPEX: Operational expenses

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Paper for ISMAR10 symposium. **Topic No:** 7 **(075#)**

Infiltration of reclaimed wastewater for drinking-water production: experience of Europe's first project of this kind

Van Houtte, Emmanuel[1]*, Lebbe, Luc[2], Samanta, Sayantan[3], Sheng, Zhuping[3], Munster, Clyde[3] and Verbauwhede, Johan[1]

[1] Intercommunale Waterleidingsmaatschappij van Veurne-Ambacht (IWVA), Koksijde, Belgium
[2] University of Ghent, Ghent, Belgium
[3] Texas A&M University, College Station, TX, USA
*Correspondence: emmanuel.van.houtte@iwva.be; Tel.: +32 58 533 837

Abstract: At WPC Torreele in Belgium, wastewater is treated to recharge the dune aquifer in order to sustain the potable water supply on the Belgian coast [1]. The treated water from the WPC Torreele is transported to two infiltration ponds where it is recharged into a 30m deep phreatic aquifer by the natural process of infiltration under gravity. One of the challenges of the MAR facility is the reduced infiltration rates during the winter season when pond water temperatures vary from 4 °C to 10 °C. Correlation statistics and linear regression analysis have been used to determine the sensitivity of infiltration rate to the aforementioned factors. Results showed that water temperature has the maximum impact on infiltration rate. Cyclic variations in water viscosity, occurring as a result of seasonal temperature changes, influence the saturated hydraulic conductivity of the pond bed. A lower infiltration rate through the pond bed is observed during the winter months due to increased viscosity, which results in a decline in saturated hydraulic conductivity of the sandy soil. Temporal changes in the vertical hydraulic gradient is another factor that could alter infiltration rate as the pumping rate around the pond causes fluctuations in the groundwater level [2].

Keywords: Infiltration, managed aquifer recharge, water reuse, drinking-water production.

1. Introduction

In July 2002 the Intermunicipal Water Company of the Veurne region (IWVA) started reusing wastewater effluent at WPC Torreele (Figure 1) for infiltration of an unconfined aquifer (Figure 3) in its dune water catchment St-André [1]. The treatment at WPC Torreele includes ultrafiltration and reverse osmosis, and the whole concept of reuse/infiltration is based on the multiple barrier approach, securing both the microbiological and chemical quality of the potable water. According to Lazarova and Asano [3], IWVA is one of the pioneers in water reuse for indirect drinking-water production and the first in Europe.

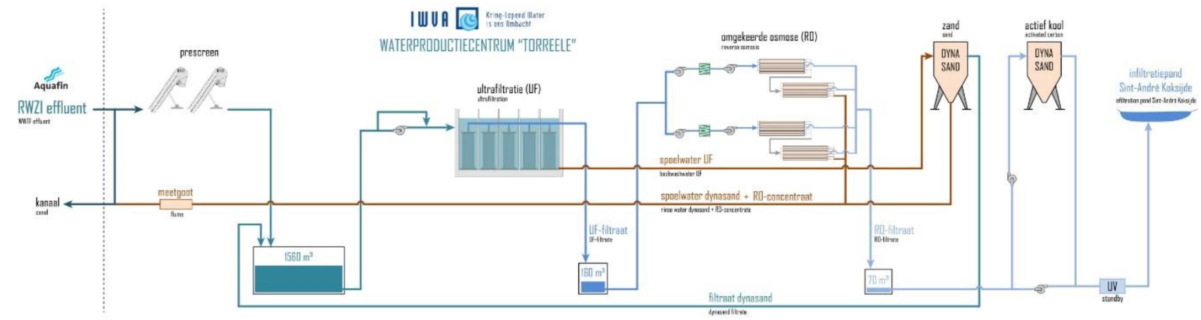

Figure 1. Process Scheme of WPC Torreele (Water Reuse Facility).

Two consecutive draughts in Western Europe (2017 and 2018) have shown that the combination of reuse and infiltration enabled the IWVA to maintain groundwater levels high enough to ensure drinking-water production and protect its quality. This is in contrast with numerous other areas in Western Europe suffering from water shortage due to declined river water discharge, increased salinity or depleted aquifers. In these circumstances IWVA's drinking-water production was less vulnerable (than in these other areas) and this experience proved that water reuse can help to mitigate the impact of climate change. Water recycling, if possible combined to aquifer recharge, will become more important to meet the growing global fresh water demand. According to the United Nations the (2017) world population of 7,6 billion is expected to reach 8,6 billion in 2030, 9,8 billion in 2050 and even 11,2 billion in 2100 [4].

Compared to the period prior to reuse/infiltration the current groundwater extraction is less than 50% resulting in higher groundwater levels and enhanced natural and ecological values. Typically, around the infiltration pond wet grasslands emerged and consequently typical plants like Orchids and Parnassia are back in the dunes. They disappeared over 50 years ago.

An evolution of infiltration capacity was observed since the start-up in 2002. In the first years the infiltration was better compared to the designed ratio between extraction and infiltration which was 1,4. Since 2009, on two exceptions, the yearly ratio exceeded 1,4 (Figure 2).

Infiltration rate (IR) is the most important parameter controlling recharge and a higher infiltration rate through the pond bed signifies better recharge capacity and in turn providing groundwater extraction potential. However, data collected from this facility indicates that the infiltration capacity is lower in the winter and higher in the summer. The loss of infiltration capacity was more obvious during the first 4 months of the year and thus mainly due to temperature. Colder water during winter results in a decrease of infiltration capacity which can be as high as 1.5–2 times with respect to summer infiltration [5]. As a result, water yields from the MAR system are lower during the winter.

In November 2014, IWVA introduced a novel infiltration technique in an area 60 m south of the existing wells. A well battery was present there until 2002. Infiltration boxes of the type that are used to store rain water, were placed at a depth of approximately 1,6 m under ground level and covered with 1 m of dune sand. A first experiment expanded 50 m length, the system being 4,8 m wide. It was called 'subterranean infiltration' and the feed water for the system was the infiltration water of WPC Torreele. The system offered several advantages compared to the existing infiltration system. There is no recontamination due to wildlife or leaf fall and temperatures remain constant compared to the infiltration water leaving WPC Torreele: no cooling down in winter and no heating up in summer. This meant that during the colder periods the infiltration capacity of 'subterranean infiltration' exceeds the conventional infiltration. Based on the positive results the system was expanded in February 2016 to 300 m length. This resulted in higher yearly infiltration capacity and better ratio (Figure 2).

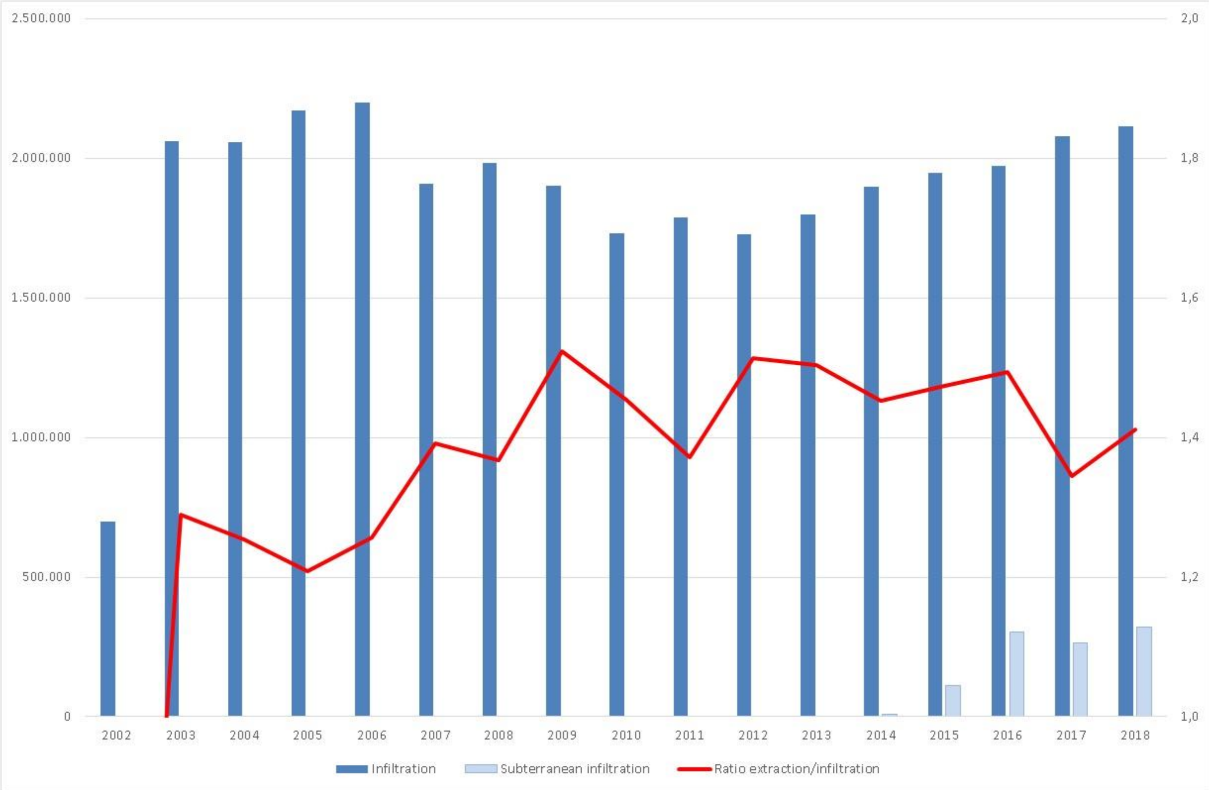

Figure 2. Yearly infiltration (m^3/year, left axis) compared to yearly ratio extraction/infiltration (right axis).

In December 2018 the western part of the infiltration pond was extended in length (100 m). This resulted in an increased infiltration and ratio of approximately 10% in January and February 2019.

Since the start-up of infiltration there have been no quality issues. The quality of the infiltration water is excellent as was demonstrated in different European projects [6, 7, 8]. From the start of infiltration, the ambient groundwater (700 µS/cm at 20°C) was replaced by infiltration water. During the soil passage the water takes up some minerals. The electrical conductivity of the water in every well is yearly checked. Of the 124 wells operational in 2018, the average conductivity was 327 µS/cm varying from 127 to 928 µS/cm. There is a relation between the salinity and the distance from the well to the infiltration pond and this distance varies from 33 to 153 m with an average of 59 m. The extracted water is bacteriologically safe and is treated with aeration and rapid sand filtration prior to distribution. However, compared to the quality of the drinking-water prior to the project the main advantage for the customer is that the hardness halved.

2. Materials and Methods

3.1. Study Area

In the western Flemish coastal plain, the dune ridge protects the inland from the sea and is situated in the northern part, with a width varying between 2 and 2,5 km and a ground level from +6 to +35mTAW (TAW is the reference level of the Geographic Institute in Belgium; 0 mTAW is 2.3 m below the mean sea level). The unconfined aquifer under the dune belt was formed by 25 to 35m thick Quaternary sandy deposits; in some dune areas thin layers of fine-grained sediments occur. South of the dunes, in the polder area, lower marsh basins (+2,5 to +4mTAW) occur with more elevated sandy creek ridges (+3,5 to +5mTAW) being the exception. Under the marsh basins fine grained sediments (clay, silt and peat) occur; under the creek ridges more sandy Quaternary sediments are present. The polder area is drained by canals that discharge large amounts of surface water to the sea, especially during winter [9].

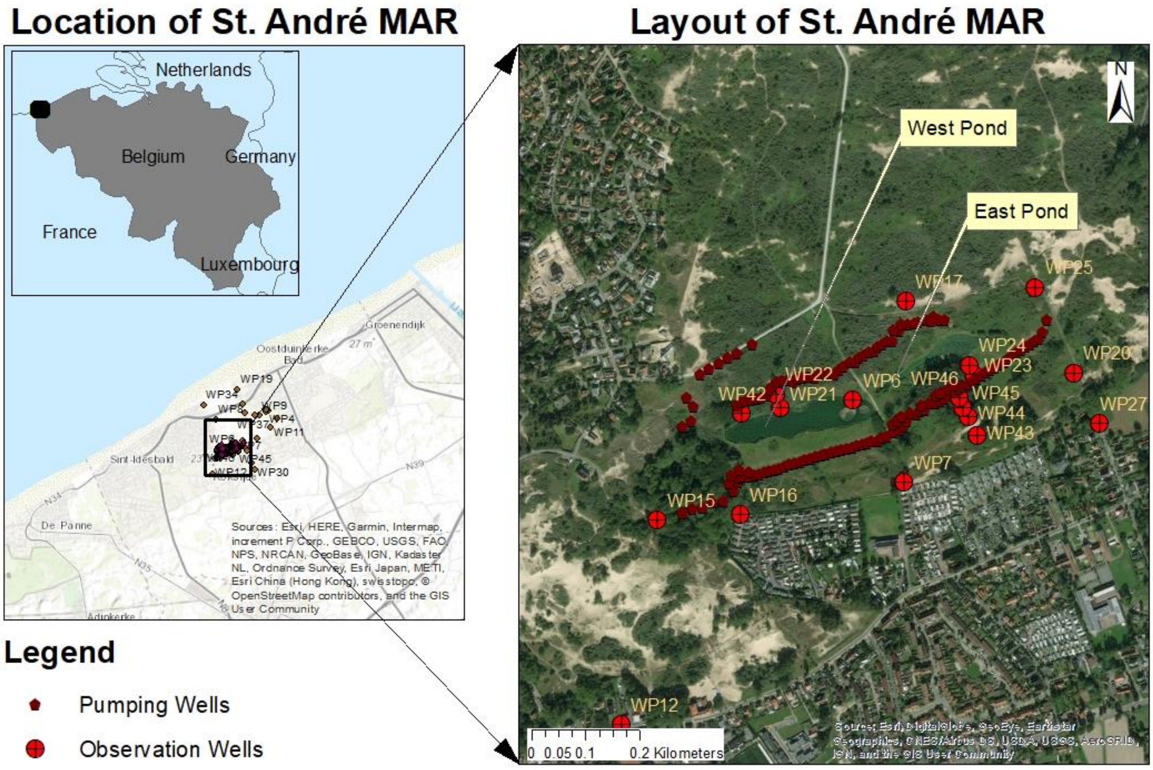

Figure 3. Managed Aquifer Recharge in water catchment of St-André.

Beneath the dunes there is a fresh water lense formed by infiltrating rainwater. North of the dunes salt water is present under the shore. In the polder area, fresh water filled the upper and relict salt water the lower part of the aquifer with a small transition zone of brackish water in between. Under the creek ridges more fresh water occurs [9].

In natural conditions, groundwater flows from the dunes towards the polder area and the shore, preventing ingress of saline water. As IWVA extracts groundwater from the dunes of De Panne (De Westhoek) and Koksijde (St-André) the fresh water outflow from the dune area diminished. The combination of reuse and infiltration at St-André was installed to prevent the inflow of salt water from the aquifer under the beach and polder areas [9].

At St-André (125 ha) the infiltration was installed in the south western part of the catchment where 3 existing well batteries were present. The central battery was replaced by 2 interconnected infiltration ponds (Figure 3). The yearly permitted volumes for this area amount 2,5 million cubic meters of infiltration water and an extra 1 million cubic meters of groundwater. Hence, as described before, the infiltration capacity decreased over time. The effects of temperature was studied based on measurements in the pond and in piezometers respectively north of the western (WP21 and WP22) and south of the eastern pond (WP23 and WP24).

3.2. Vertical hydraulic gradient

Vertical gradients are calculated using heads at elevations 3.55 mTAW (approximately 3 m below the surface), 0.55 mTAW (approx. 6 m below the surface) and -5 mTAW (approx. 11.5 m below the surface) at well series WP 21, 22, 23 and 24 surrounding the infiltration ponds using eq. 1. The average heads for the summer months (JJA) and the winter months (DJF) for 2015 and 2016 have been analysed for the variation of vertical gradients. WP 6 is assumed to reflect the conditions exactly underneath the ponds as it is located centrally between the two ponds. Vertical hydraulic gradient has been calculated between WP 6 and the pond bed to observe the variation of vertical gradient between summer and winter.

3.2. Infiltration rate and temperature

Infiltration rate was calculated from eq. 2 developed using water budget. Hargreaves method [10] was used to calculate the evaporation of water through the pond surface. Precipitation was observed from a weather station at Koksijde, Belgium. Temperature was monitored in the infiltration pond and in monitoring wells adjacent to the pond (figure 3). The wells are represented as WP, which is the abbreviation of Dutch words "Waarneming Putten", meaning observation wells. The convention used for numbering the wells is shown in figure 4. All monitoring wells have a series of 4 levels of well with screen openings at different depths. The level 1 wells have screens at -20 mTAW, which are the deepest wells and level 4 wells are the shallowest wells having screens at -3.55 mTAW. The ground elevation around the pond is 7.1 mTAW and the pond bed elevation is 6.2 mTAW.

Viscosity and density are two factors that are directly influenced by temperature. Viscosity of water is calculated using the International Association for the Properties of Water and Steam 1997 (IAPWS 97) (eq. 4) and density of water is calculated using eq. 5 [11]. Density and dynamic viscosity have been analyzed to check the maximum influence on infiltration rates. The idea is to formulate an understanding of the variation of infiltration rate with the seasonal temperature change, which might be caused by the influence of one or all of the aforementioned factors. Linear regression has been employed to check the sensitivity of infiltration rate to density and viscosity of water. It attempts to develop a relationship between two variables by fitting a linear equation to an observed parameter. A good coefficient of determination (R^2) between the observed and predicted parameter values indicates a better sensitivity.

Table 1. List of equations; *dh* is change of head (m), *dz (m)* is change in elevation, Q is the measured inflow to the pond ($m^3\ day^{-1}$), A is the surface area of the pond (m^2), H is the ponding depth (m), t is time (day), E is evapotranspiration ($m\ day^{-1}$) and P is precipitation ($m\ day^{-1}$), λ is Latent heat of vaporization of water ($MJ\ kg^{-1}$), E_{t0} is evapotranspiration ($mm\ day^{-1}$), R_A is extraterrestrial solar radiation ($MJ\ m^{-2}\ day^{-1}$), *TD* is the difference between maximum and minimum average monthly temperature (°C**)** and *T* is mean daily temperature (°C**).**

Parameter	**Eq. no.**	**Equations**
Hydraulic Gradient (i)	1	$i = \frac{dh}{dz}$
Infiltration Rate (q)	2	$q = \frac{Q}{A} + \frac{dH}{dt} - E + P$
Evapotranspiration from Hargreaves method (E_{t0})	3	$\lambda E_{t0} = 0.0023 \times R_A \times TD^{1/2} \times (T + 17.8)$
Dynamic Viscosity of water (η)	4	$\eta(T) = 2.414\ x\ 10^{-5} x\ 10^{\frac{247.8}{T+273.5-140}}$
Density of water (ρ)	5	$\rho(T) = 1000 \times \left(1 - \frac{T + 288.9414}{508929.2 \times (T + 68.12963)} \times (T - 3.9863)^2\right)$
Kinematic viscosity (v)	6	$v = \frac{\eta}{\rho}$

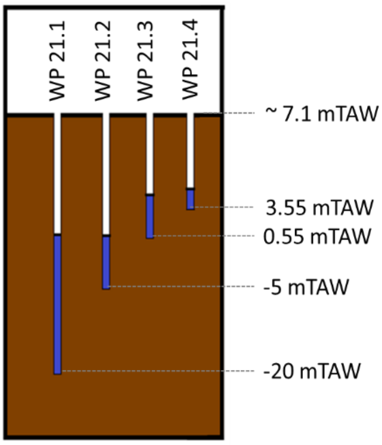

Figure 4. Schematic reference of well screen depths at St-André MAR.

3. Results

3.1. Variation of vertical hydraulic gradient

Between 3.55 mTAW and 0.55 mTAW elevation, the hydraulic gradient is higher in summer than in winter for WP 21, 23 and 24 (figure 5). However, at WP 22, the winter of 2016 showed a higher gradient than the summer gradients. This may be attributed to a less permeable soil lens present in the area. WP 21 shows very high hydraulic gradients in both summer and winter, suggesting the presence of a less permeable lens in the area between 3.55 and 0.55 mTAW in the northern side of the west pond. The occurrence of a shallow low-permeable layer under the western pond is also mentioned by Vandenbohede et al. [12]. However, the lateral extent of the layer is unknown.

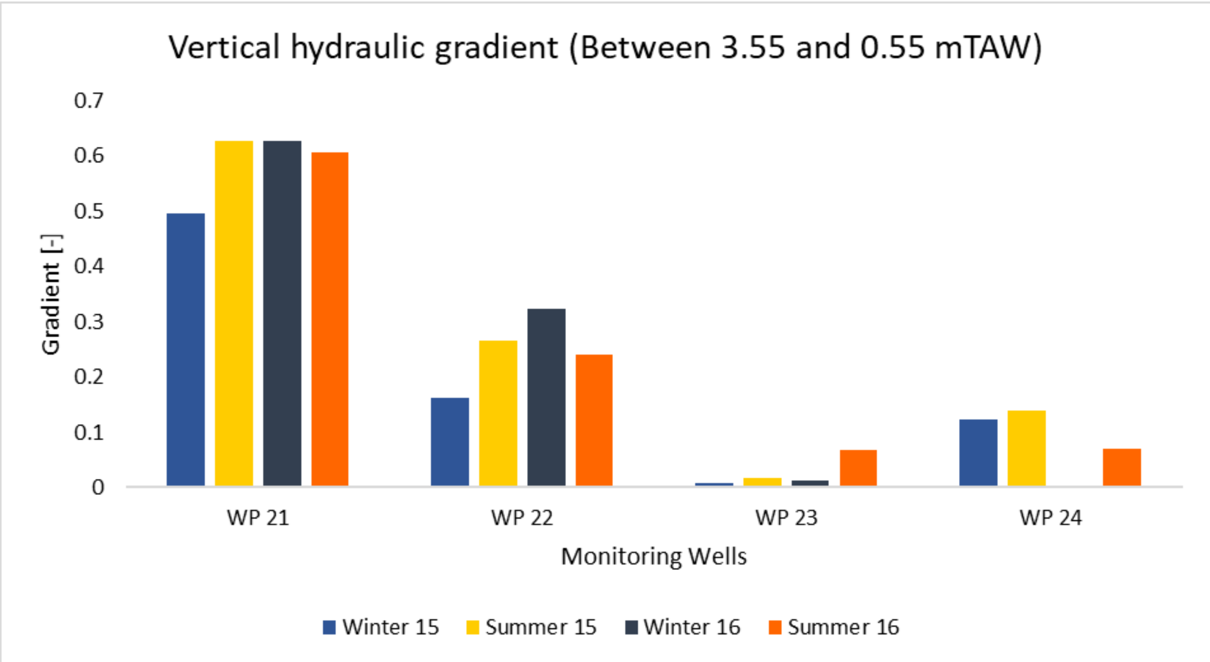

Figure 5: Vertical hydraulic gradient in Well series 21, 22, 23 and 24 for 2015-2016 period between Level 4 (3.55 mTAW) and Level 3 (0.55 mTAW) wells.

Between 0.55 mTAW and -5 mTAW elevation, there is not much variation in gradients (figure 6). The lower part of the aquifer has lower hydraulic conductivity [13]. From the regional groundwater model and the existing local groundwater model [5], it is inferred that the hydraulic conductivity is approximately 20 m/d at the top of the aquifer and 1 m/d at the bottom. In WP 23, the summer gradients are smaller than the winter gradients. This occurrence is probably due to the high anisotropy and heterogeneity in the region.

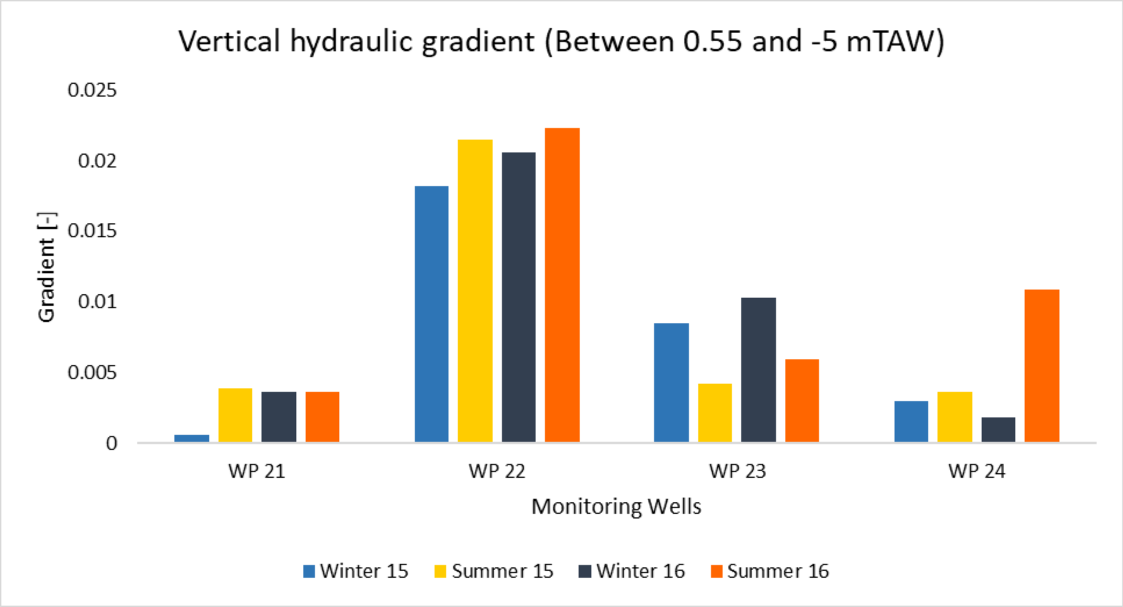

Figure 6. Vertical hydraulic gradient in Well series 21, 22, 23 and 24 for 2015-2016 period between Level 3 (0.55 mTAW) and Level 2 (-5 mTAW) wells.

Vertical hydraulic gradient has been calculated between WP 6.2 and the pond bed to observe the variation of vertical gradient between summer and winter. Figure 7 shows that the gradients are higher for summer of 2015 and 2016 in comparison to the winter of 2015 and 2016. This also suggests that the rate of infiltration through pond bed is higher in summer as compared to that in winter.

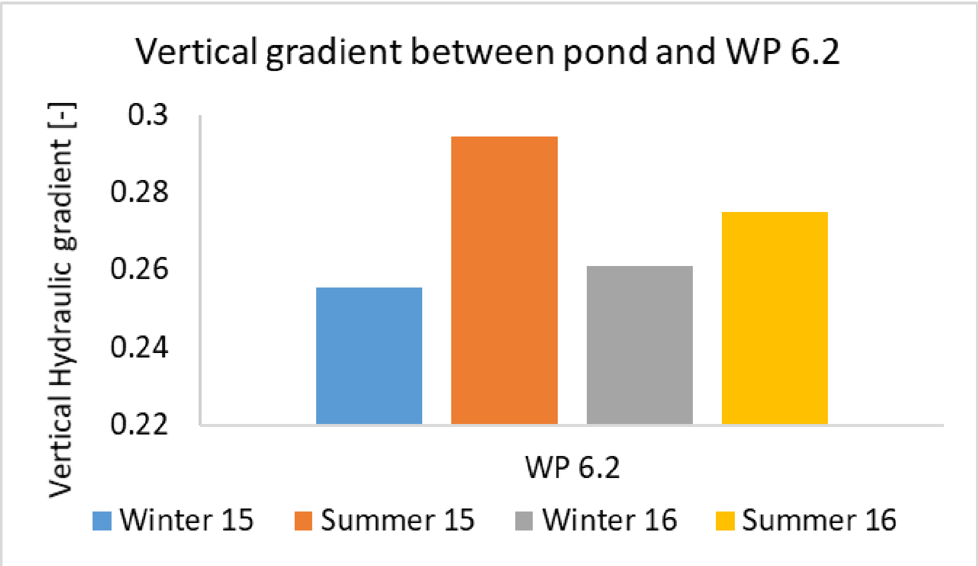

Figure 7. Vertical hydraulic gradient between WP 6.2 and pond bed.

3.2. Influence of temperature on infiltration capacity

Temperature follows a sinusoidal pattern [5] and infiltration rate is also seen to follow a cyclic pattern where the highest rates are observed in summer and lowest in winter (figure 8).

The coefficient of determination between temperature and infiltration rate is 0.53. Viscosity and density are the two derivate properties of temperature. Sensitivities of density and viscosity on infiltration rate are obtained using linear regression. It is necessary to know which property affects mostly the variation of the infiltration rate. From figures 9 and 10, it is seen that with an increase of both viscosity and density of pond water, the rate of infiltration through pond bed decreases. The variation of the infiltration rate is mostly affected by the dynamic viscosity. The applied dynamic viscosities vary between 0.0008 and 0.0018 Pa.s whereas the relative range of the applied densities is much smaller (applied densities between 996 and 1000 kg/m³).

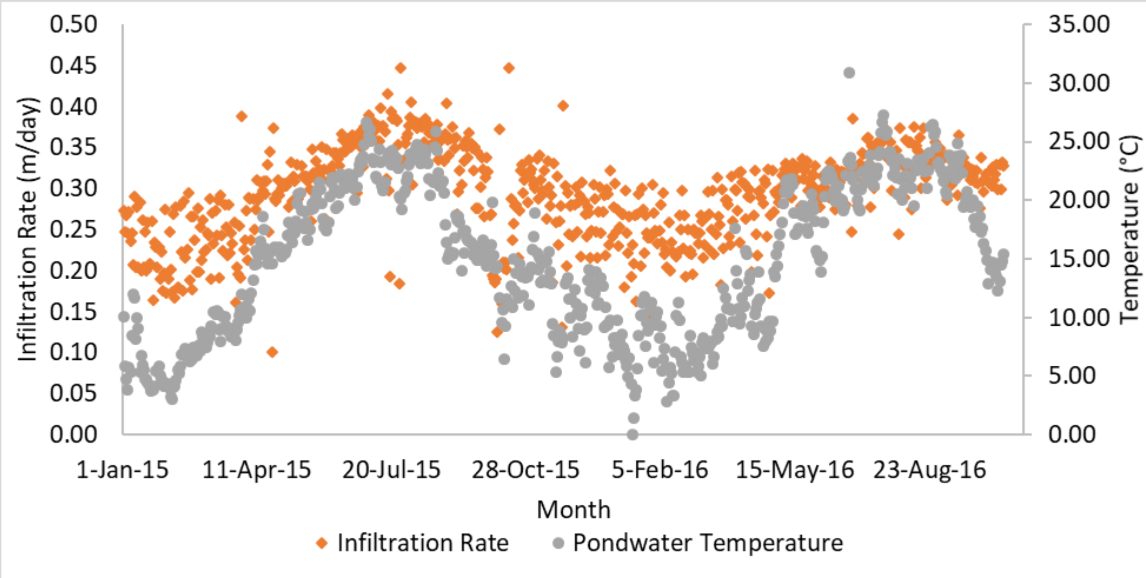

Figure 8. Comparison of mean daily pond water temperature and infiltration rate through pond bed.

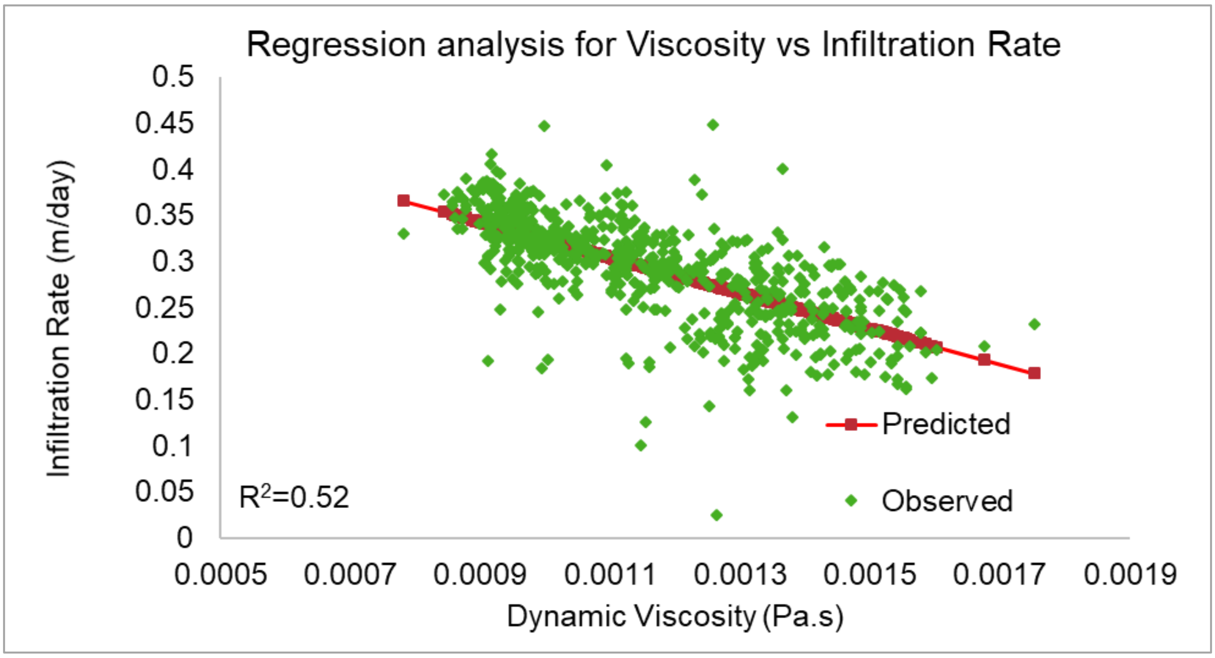

Figure 9. Regression analysis for viscosity of water vs infiltration rate through pond bed.

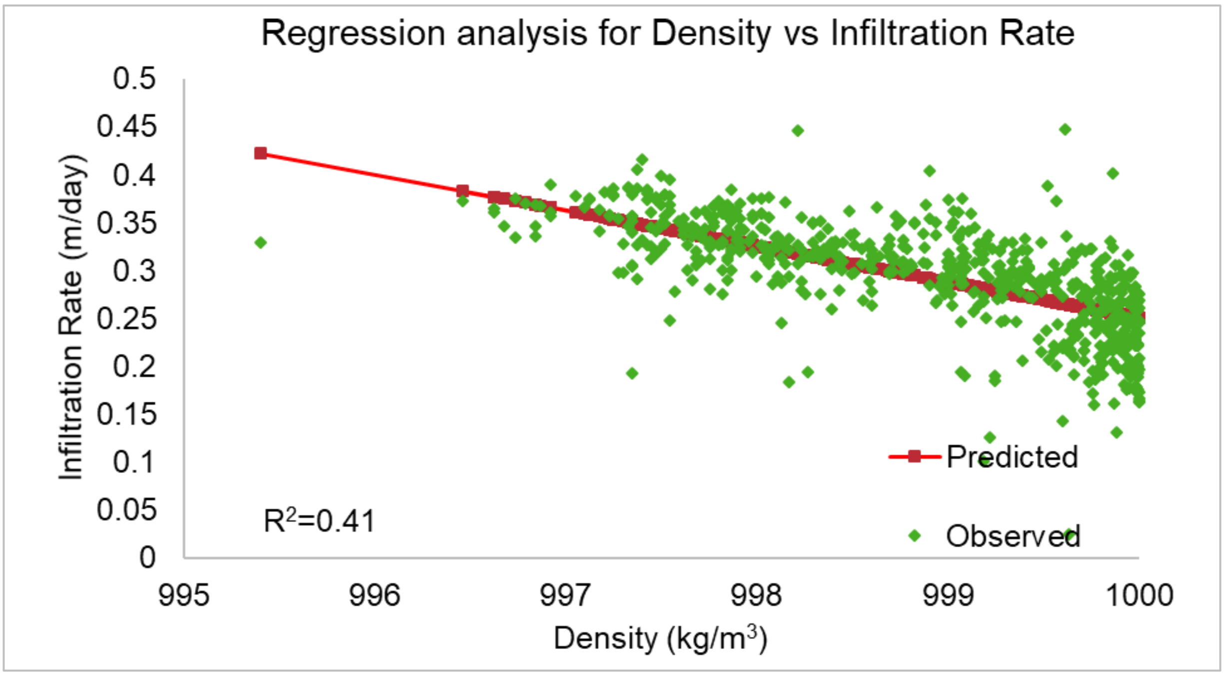

Figure 10. Regression analysis for density of water vs infiltration rate through pond bed.

4. Discussion

Assuming that hydraulic conductivity does not change over time, rate of vertical flow through the pond bed is directly proportional to the change in vertical hydraulic gradient. During the summer season, a lowering in hydraulic head is observed followed by an increase in vertical gradient. As a result, the vertical flow velocity is expected to be higher in summer. During the winter, the reverse phenomenon is observed. As the hydraulic head rises, the vertical gradient lowers and vertical flow velocity reduces. It is seen from the vertical hydraulic gradients at WP 6.2 that the hydraulic gradient reduces considerable in winter as compared to that in summer.

The average reduction in regional vertical hydraulic gradient in winter as compared to summer is 32 % from 3.55 to 0.55 mTAW depth and 4 % from 0.55 to -5 mTAW. However, Vandenbohede & Van Houtte [5] reports that colder water during winter results in a decrease of infiltration capacity which can be as high as 1.5–2 times with respect to summer infiltration. Thus, the variation in vertical hydraulic gradient alone does not contribute to the overall fluctuation of infiltration rates. Hence, the assumption that hydraulic conductivity is constant over time does not stand valid and it is essential to take into account the variability of hydraulic conductivity as well.

Taking into account the variability of saturated hydraulic conductivity, it was found that dynamic viscosity influenced infiltration rate more than density. This can be explained using Muskat's equation [14], which can be modified as eq. 7.

$$\boldsymbol{K = k \times g \times f(T)} \tag{7}$$

Where K is hydraulic conductivity (msec^{-1}), k is intrinsic permeability (m^2), g is acceleration due to gravity (m sec^{-2}), and f is fluidity of water (sec m^{-2}) which is the inverse of kinematic viscosity (eq. 6).

Intrinsic permeability is a physical property that is associated with a medium and is assumed not to vary drastically over time. It is safe to consider intrinsic permeability (k) and acceleration due to gravity (g) as constants. Hydraulic conductivity (K) is thus proportional to temperature. Hydraulic conductivity at any given temperature can be expressed as eq. 8.

$$\boldsymbol{K(T) = K_{ref} \times \frac{f(T)}{f(T_{ref})}} \tag{8}$$

The median temperature of infiltration water recorded from St. Andre MAR facility is 15 °C. The upper quartile (3rd quartile) of pond water temperature provides the reference for the average hydraulic conductivities in summer and the lower quartile (1st quartile) provides reference for the winter conductivities. The upper quartile of pond water temperature is at 21°C and the lower quartile is at 9.3 °C (figure 11). After fitting these values to equation 8, it is established that the hydraulic conductivity increases by 15 % in summer and decreases by 14.7 % in winter. In other words, there is a 34.8% increase in hydraulic conductivity of the pond bed in summer as compared to winter. The change in hydraulic conductivity is not constant through the entire soil profile since the temperature variation with depth is not uniform. According to Vandenbohede & Van Houtte [5], the temperature of water changes as it moves down, this is influenced by the existing groundwater residing in the aquifer. Temperature becomes constant after a depth of 25 m below the ground.

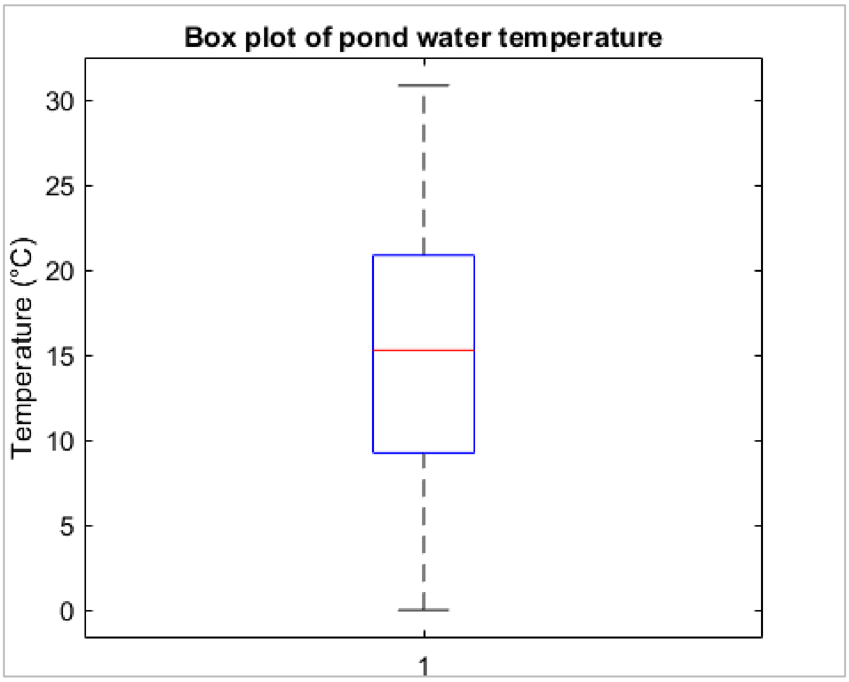

Figure 11. Box plot of pond water temperature.

5. Conclusions

More than 16 years of experience at IWVA's water reuse/infiltration project in the Flemish dunes have shown that reuse combined to infiltration or managed aquifer recharge is able to ensure drinking-water of good quality and produced in a sustainable way. This project shows that water reuse is one of the solutions to remedy increasing water scarcity, the negative impacts of climate change and to provide drinking-water for the growing population worldwide.

A seasonal variation of recharge rate from the infiltration ponds at MAR facility St-André in Belgium, especially in winter months, was observed and this has been studied for a period of 2 years. From 2010 until 2014 the infiltration capacity was 58 % higher in summer as compared to that in winter. Two major factors impacting this variation are variation in hydraulic gradient and hydraulic conductivity.

Observed heads at the monitoring wells are mostly found to be higher in winters and lower in summers, creating a higher gradient in summers. 32 % reduction in vertical hydraulic gradient have been observed in the top portion of the aquifer which directly influences the recharge rates. Regarding the variation of hydraulic conductivity, temperature has been identified as the dominant factor influencing this process. Results show that there is a strong correlation between temperature and infiltration rate on a daily scale. The temporal variation of temperature causes variation in kinematic viscosity, which plays an important role in the flow of water. With increase in viscosity of recharge water, higher resistance is imparted by the pond bed to the flow of water.

In addition, the temperature of water influences the hydraulic conductivity of the soil. With the data obtained, it is theoretically found that there is a 34.8 % increase in conductivity in summer as compared to winter. Lowering of temperature causes a reduction in hydraulic conductivity, thereby providing additional resistance to the flow of water through the pond bed. MODFLOW models have been used to simulate different conditions for summer and winter and it is found that with a lower leakance of the pond bed in the winter months, the recharge rate decreases by about 27 %. Combining the effects of both gradient and conductivity variation, it was found that the recharge rate in winter months reduced by about 72 % as compared to that in summer, which was consistent with the findings of Vandenbohede & Van Houtte [5].

Temperature of recharge water changes as it moves into the subsurface and it is highly influenced by the previously residing water. Temperature at different depths in the aquifer creates a definite response in the conductivity of the media. Lack of temperature data at multiple depths hindered the study of the impact of groundwater temperature on the soil properties. This can be a scope of future study and would greatly enhance the understanding of the flux in the area.

In order the achieve the permitted infiltration volume of 2.5 million cubic meters per year, in 2014 subterranean infiltration using infiltration boxes was introduced in the southeastern part of this infiltration area and in December 2018 the western part of the infiltration pond was extended.

Acknowledgments: A part of this work was made possible in part by the Water Seed Grant: Creation and Deployment of Water-Use Efficient Technology Platforms Program of Texas A&M AgriLife Research, the Texas A&M AgriLife Extension Service and the Texas A&M Engineering Experiment Station (TEES), US Department of Agriculture-National Institute of Food and Agriculture Hatch Project (TEX0-1-9448) via Texas A&M AgriLife Research.

Author Contributions: Dr. Luc Lebbe and Mr. Emmanuel Van Houtte conceived the project. Mr. Van Houtte managed the whole project from its beginning. Dr. Lebbe was always helped on questions and several of his students had worked on the project producing thesis reports. Mr. Van Houtte in collaboration with Dr. Lebbe, started monitoring temperature on-site to better understand the infiltration process. Mr. Sayantan Samanta, supervised by Dr. Clyde Munster and Dr. Zhuping Sheng, worked on the temperature data as part of a thesis. This collaboration began as Dr. Munster started an abroad learning course for Texas A&M University at K.U. Leuven and engaged his American students to visit the project. Ir. Johan Verbauwhede is the general manager of the IWVA and supervises all of the work.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper for ISMAR10 symposium. **Topic No: 7 (210#)**

Natural-Engineered System (NES) for the improvement of Conventional Soil Aquifer Treatment (cSAT) in Shafdan (Israel)

Avi Aharoni[1]; Haim Cikurel[2] and Hadas Raanan Kiperwas[1*]

[1] Mekorot Ltd, 9 Lincoln St., PO Box 20128, Tel-Aviv 61201, Israel
[2] Environmental Engineering Services, Tel Aviv, Israel
* Correspondence: o-hraanan@mekorot.co.il

Abstract: Three effluent treatment technologies were compared with respect to their chemical composition, indicator bacterial counts, and Trace Organic Compounds (TrOCs): 1) a natural process based technology currently applied at the Shafdan (cSAT); 2) improved ozonation (using 27% less ozone and 25% less H_2O_2 compared to previous studies) followed by a short SAT (sSAT) with residence time of 22 days combining natural and engineered technologies (O_3-sSAT); and 3) ozonation followed by an engineered processes (O_3-BAC-cUF). cSAT has been in operation at the Shafdan WWTP for many decades, and has been shown to produce water with DOC concentration lower that 1 mg/L, fecal and total Coliforms, and fecal Streptococcus counts typically below the detection limit, and CBZ concentration typically between 121 and 1650 ng/L. Water produced from the O_3-sSAT system had low DOC concentrations of 1.0-1.1 mg/L, Fecal and total Coliforms and fecal Streptococcus counts typically below the detection limit, and CBZ concentration typically lower than 300 ng/L during periods of continuous infiltration of ozonated water. Other TrOCs measured were under 100 ng/L. NDMA and Bromate concentrations were below 10 ng/L and 10 μg/L, respectively. The O_3-sSAT system successfully reached the specifications for most of the California IPR-quality water parameters. The exclusively engineered configuration (O_3-BAC-cUF) was not able to reached the specifications for IPR-quality water and requires further optimization.

Keywords: Soil Aquifer Treatment; Ozonation; Trace Organic Compounds; Potable Reuse.

1. Introduction

The Shafdan WWTP is located west of the city of Rishon Lezion in the south of the Dan Region, the most densely populated area in Israel, and provides services to more than 2.5 million equivalent inhabitants residing in Tel Aviv and the surrounding cities. The plant treats around 140 Million m^3 of wastewater annually to produce secondary effluents using an Activated Sludge process (with partial nitrification-denitrification). To complete the treatment train, 125-130 Mm^3 secondary effluents are infiltrated annually to the local aquifer through dedicated basins (conventional Soil Aquifer Treatment, cSAT). Later, these water are re-abstracted by recovery wells and supplied to farmers in the south of Israel as reclaimed water of excellent quality, suitable for unrestricted irrigation (1). To meet its 2040 development goal of providing a polishing treatment for 160 Mm^3 secondary effluents annually, the Shafdan must be able:

- to either increase the infiltration rate at the existing basins, or
- to provide an alternative, engineered post-treatment system for excess water that cannot be infiltrated by cSAT, that can produce water with SAT-equivalent quality without the need for using infiltration basins.

Table 1. IPR guidelines of the State of California and water quality typical of the AquaNES O_3-sSAT system.

Analysed parameter	California IPR regulations (2)	AquaNES reclaimed water quality (at R1)
pH	6.5 -8.5	6.9-7.4
Turbidity (NTU)	0.5	0.1-0.4
TOC (mg/l)	0.5*	1-1.1**
Total Nitrogen (mg/L)	10	15.6-18.3
Total coliform (MPN/100 mL)	<2	ND
Total fecal coliform (MPN/100 mL)	ND	ND
Srorage time (months)	>2	0.9
Crytosporidium oocyst	10 logs	ND
Giardia cyst	10 logs	ND
Enteroviruses	12 logs	ND

* TOC ≤ 0.5 mg/L divided by the fraction of recycled water contribution
** As DOC

The system tested here was gradually developed during two EU-funded projects: Demoware (FP7) (2) and AquaNES (H2020). The main treatment train consisted of PolyAluminum Cloride (PACl) enhanced flocculation, H_2O_2-enhanced BioFiltration, and Ozonation (Fig. 2). Post treatment included either infiltration at a short SAT (sSAT) facility located on site (with residence time of 22 days between the infiltration pond and the nearest observation well, or alternatively, filtration through a Biologically Activated Carbon (BAC) system followed by Ultrafiltration through a ceramic membrane (cUF, figure 2).

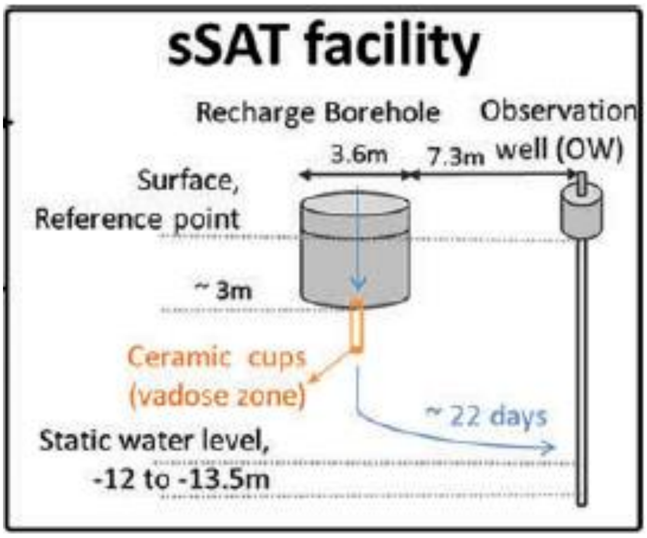

Figure 2. SAT facility which included a Dug well (i.e., recharge borehole) and an observation well marked as R1 below (3)

The tested systems had two main goals – test the effect of the short residence time at the sSAT facility on the quality of the reclaimed water (22 days at the sSAT compared to typically 6-12 months at the cSAT) and compare the effect of the engineered (BAC-cUF) and natural (sSAT) polishing treatments. An additional goal was to reduce the operational cost of the system, which was attempted primarily by lowering the concentration of the chemicals used in the process (PACl, H_2O_2), as well as by changing the HRT in the BioFilters (BioFs) and attempting to recirculate ozonated water for further treatment back through the BioF.

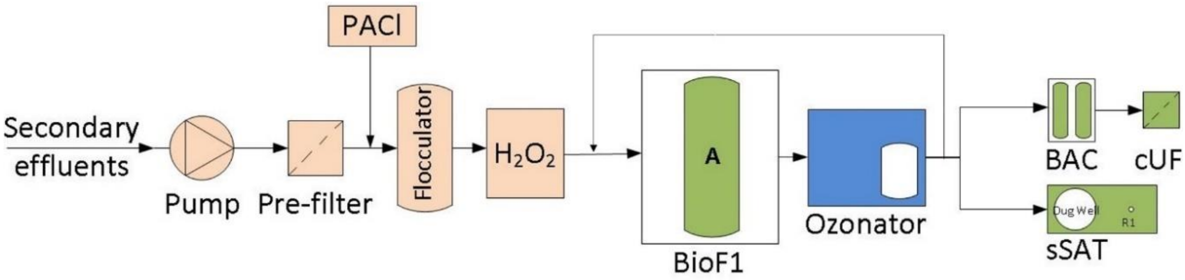

Figure 3. A schematic description of the systems applied at the Shafdan as part of the AquaNES and Demoware research projects

2. Materials and Methods

A description of the system can be found in reference (2). Ultrafiltration was carried using a Nanostone's ceramic UF membrane CM-121 with a membrane surface area of 3.2 m^2 and an average pore size of 30 nm. The BAC system was provided by Leopold, and consisted of two 8" PVC column filled with 25cm gravel, 35cm sand, and 90cm of spent GAC, each producing ca. 200 L/hr. BioF1 had the same features as the BioF mentioned before (2) except it was 2m high, and contained 20cm support basalt, 60 cm basalt and 120 cm of anthracite (Fig. 3). DOC and TkN were measured at Mekorot's Central Laboratory using standard methods. TrOCs were measured by the ISO17025 certified laboratory at the German Water Center in Karlsruhe. UVA samples were filtrated using 0.45µm syringe filters and measured using a RealTech REALUV254 monitor located on site. NH_4, NO_3, and NO_2 were measured either at Mekorot's Central Laboratory using standard methods, or on site on a HACH DR3900 using HACH cuvette test kits (for NO_3 – LCK339; for NO_2 – LCK341; for NH_4 – LCK304 and LCK303) calibrated against duplicates measured at Mekorot's Central Lab. Total Bacterial Count (TOTB) was carried using Standard Method 9215B (4). Total coliform, fecal coliform, and fecal streptococcus m-enterococcus counts were conducted using Standard Method 9221 (4). All bacterial measurements were carried at Mekorot's Central Laboratory.

3. Results

The system was operated under the conditions described in Table 2. The results were primarily evaluated to assess:

1) Water quality after a natural (as sSAT) vs an engineered (BAC-cUF) polishing treatment; and

2) Comparison of water quality after sSAT vs cSAT.

Table 2. BioF system operation conditions.

Parameter		Units	Value
BioF Diameter		m	1.2
BioF height		m	2.0
Media type			
		Grain diameter (mm)	Media height (cm)
	Anthracite	0.8-1.5	120
	Basalt # 0	0.16-0.5	60
	Basalt # 1	0.6 – 1.18	10
	Basalt # 2-3	2.36 -4.75	10
Porosity (avg)		---	0.45
BioF Flow velocity		m/hr	6.2
BioF HRT (avg)		min	8.7
O_3 dose		mg/L	7
H_2O_2 dose		mg/L	21
Recirculation rate		%	21

Water quality data is presented in Table 3. Specific UVA (SUVA) was calculated at each sampling point as the ratio of UVA to DOC. The ratio of ozone to DOC is taken as the amount of ozone applied by the ozonator divided by the amount of DOC in the secondary effluents. To account for the effect of recirculation, the amount of applied ozone is corrected as:

$$[ozone]_{corrected;\,recirc}(mg) = [ozone]_{applied}(mg) \times (1 + recirculation\ ratio)$$

Due to changes in the operation regime of the Shafdan WWTP, a significant difference in secondary effluents quality is evident when comparing the results of this study with those of its predecessor Demoware (2). During Demoware, NH_4-N in the secondary effluents ranged between 1.2-5.4 mg/L and NO_2-N between 0.2 -0.9 mg/L. During the current study NH_4-N concentrations were between 1.4-6.2 mg/L and NO_2-N ranged between 1.7-2.4 mg/L). These increased NH_4-N and NO_2-N concentrations serve as ozone scavengers, increase the potential for the formation of ozonation by-products (mainly NDMA) and had to be lowered prior to ozonation in order to allow the system to reach its intended performance. To address these challenges a modification was made to the system that introduced ozonated water back into the BioF). This change allowed for very efficient removal of both NH_4-N and NO_2-N before entering the ozonation, and enabled improved TrOCs and microorganism removal by using a lower O_3/DOC ratio (0.7-0.9) (Table 2) as compared to O_3/DOC ratio (1.0-1.2) applied during the Demoware project (2). The introduction of the recirculation line also allowed using 25% less H_2O_2 in the current study. The nitrogen balance shows the BioF was able to reach complete nitrification with minimal loss of TN, indicating no denitrification or anoxic regions existed along the BioF.

Table 3. General water quality of samples collected in the pilot (with and without recirculation. BioF operational parameters: Q bioF = 7 m^3/h, H_2O_2= 21 mg/L, PaCl = 4.3 mg/L.

Date	Sampling point	O_3 (mg/l)	Recyc. %	UVA (1/m)	DOC (mg/l)	O_3/DOC (gr/gr)	SUVA (l/mg-m)	NH_4-N (mg/l)	NO_2-N (mg/l)	NO_3-N (mg/l)	TkN (mg/l)	NT (mg/l)
12-Feb-19	Secondary effluents	0	0	19.7	10.60			3.93	1.70	5.55		11.17
	Filtration product tank			12.8	7.40			1.28	0.04	12.05		13.38
	Observation well 1			1.6	1.00			0.02	0.01	17.53		17.57
19-Feb-19	Secondary effluents	7	0	19.9	10.30	0.68	1.93	6.22	1.77	5.19	9.91	16.87
	Filtration product tank			13.0	7.40		1.76	4.82	0.02	10.16	6.39	16.57
	Infiltration tank			6.9	7.10		0.97	5.37	0.14	9.94	7.17	17.25
	After BAC 210			6.0	5.60		1.07	4.18	0.25	12.75		13.00
	After BAC 220			5.6	5.00		1.12	1.86	0.08	14.73		14.81
	After BAC tank			6.2	5.30		1.17	3.05	0.11	12.65		12.76
	After cUF membrane			5.7				3.68	0.12	12.43		12.55
	Observation well 1			2.4	1.00		2.40	0.02	0.01	18.29	0.03	18.30
	Ceramic Cups			5.0	4.00		1.25	<DL	<DL	16.07		16.07
25-Feb-19	Secondary effluents	6.8	31	21.5				1.35	0.06	12.63		12.69
	Filtration product tank			11.4				0.01	0.01	13.81		13.82
	Infiltration tank			6.2				0.01	0.01	14.07		14.08
	After BAC 210			5.4				0.01	0.01	13.99		14.00
	After BAC 220			5.2				1.77	0.04	11.57		11.61
26-Feb-19	Secondary effluents	7.2	21.7	19.6	10.20	0.86	1.92	5.16	1.79	5.57	5.40	12.76
	Filtration product tank			12.3	7.20		1.71	0.93	0.01	12.49	1.81	14.31
	Infiltration tank			6.6	7.00		0.94	1.74	0.06	12.63	1.84	14.53
	After BAC 210			5.6	5.10		1.10	0.01	0.01	13.81	0.62	14.44
	After BAC 220			5.3	4.60		1.15	0.01	0.01	14.07	0.56	14.64
	After BAC tank			5.4				0.01	0.01	13.99		14.00
27-Feb-19	Secondary effluents	7.4	21	20.1	10.40	0.86	1.93	4.18	2.18	5.19	6.26	13.63
	Filtration product tank			13.4	7.50		1.79	1.05	0.02	12.19	1.41	13.62
	Infiltration tank			7.8	7.50		1.04	1.33	0.04	11.74	1.78	13.56
	After BAC 210			6.1	5.40		1.13					
	After BAC 220			5.5	4.90		1.12					
	After BAC tank			5.4	4.70		1.15	1.35	0.06	12.63	0.68	13.37
	Observation well 1			2.6	1.10		2.36					
5-Mar-19	Secondary effluents	7.2	23	19.8	9.7	0.91	2.04	4.15	2.41	5.42	6.26	14.09
	Filtration product tank			11.0	6.3		1.75	0.44	0.02	12.65	1.20	13.87
	Infiltration tank			6.0	6.1		0.98	0.63	0.02	12.65	1.20	13.87
	After BAC 210			5.0	4.30		1.16					
	After BAC 220			4.9	4.10		1.20					
	After BAC tank			5.2	4.2		1.24	0.01	0.01	13.77	0.64	14.42
	After cUF membrane			5.1	4.40		1.16					
	Observation well 1			3.0	1.1		2.73	<DL	0.01	15.35	0.20	15.57
19-Mar-19	Secondary effluents	7	23	20.7	10.1	0.85	2.05	3.11	1.70	4.70		
	Filtration product tank			11.9	7.0		1.70	0.15	0.02	11.06	1.08	12.16
	Infiltration tank			6.6	6.7		0.99	0.19	0.01	11.52	0.94	12.47
	After BAC			5.5	4.5		1.22	0.02	0.01	12.19	0.58	12.78
	After cUF membrane			5.4	4.6		1.17					
	Observation well 1			2.7	1.0		2.70					

3.1. sSAT vs cSAT

Water was infiltrated using a sSAT facility which included a recharge borehole and an observation well. Approximately 40m3 of treated effluents were infiltrated daily and sampled periodically at observation well R1, representing residence time of 22 days (3). Three 15 cm long ceramic cups were installed at a depth of 1.5 m in the borehole to allow sampling of pore water from the vadose zone.

All samples collected at R1 had low DOC of 1.0-1.1 mg/L, similar to DOC levels typical of the cSAT (0.9 mg/L). CBZ concentrations measured at R1 on February 12th and 19th were lower than 100 ng/L and within the maximum recommended limit of 300 ng/L suggested in the recommendations of the German Environmental Agency (5). CBZ concentrations measured later at R1 were higher, and due to the 22 days residence time the water has before reaching R1 from the recharge borehole reflect un-ozonated water that were infiltrated at the sSAT during two weeks at the end of January. The decrease in CBZ at the R1 sample from the 19th of March (230 ng/L), again lower than the German recommendation of 300 ng/L, was to be expected and represents the resumption of infiltrating ozonated water in the beginning of February. The mid-February CBZ concentrations at R1 were higher than expected, since the water infiltrated at the recharge borehole did not contain detectable amounts of CBZ. The combination of two mechanisms is likely to explain this phenomenon. The first mechanism is related to the location of the sSAT facility, which is influenced by an upstream emergency storage pond for secondary effluents that contains water with CBZ concentrations typical of secondary effluents. The second mechanism is related to adsorption-desorption processes in the vadose zone, during which CBZ historically adsorbed in the vadose zone in the area of the sSAT facility, is slowly released back into the infiltrating water (6).

Table 4. TrOCs and Ozonation by products.

Date	Sampling point	IPDL ng/L	IHX ng/L	IPRM ng/L	Ibuprofen ng/L	Naproxen ng/L	BZF ng/L	CBZ ng/L	DCF ng/L	SMX ng/L	NDMA ng/L	BrO_3^- µg/L
	Detection Limit	10	10	10	10	10	10	10	10	10	1	1
12-Feb-19	Secondary effluents	18	36000	8000	150	560	120	460	870	120	5	<DL
	Filtration product tank	19	37000	9100	290	580	140	470	810	170	4	
	Observation well 1	11	<DL	11	<DL	<DL	<DL	99	<DL	31	<DL	11
19-Feb-19	Secondary effluents	42	41000	11000	220	630	120	550	900	150	5	<DL
	Filtration product tank	38	37000	8100	460	670	130	560	1000	170	2	
	Infiltration tank	26	16000	5200	110	<DL	26	<DL	<DL	<DL	62	10
	After BAC	21	17000	4200	<DL	<DL	26	27	11	20	22	8.4
	Observation well 1	18	<DL	11	<DL	<DL	<DL	100	<DL	53	<DL	10
26-Feb-19	Secondary effluents	30	26000	7500	160	510	94	730	1400	200		<DL
	Filtration product tank	32	36000	6600	160	440	57	640	1200	230		
	Infiltration tank	17	11000	4500	60	<DL	12	<DL	<DL	<DL		12
	After BAC 210	22	9400	4600	20	<DL	<DL	21	<DL	17		12
	After BAC 220	19	7400	2400	14	<DL	<DL	47	<DL	44		12
27-Feb-19	Secondary effluents	76	25000	9600	120	600	160	750	1300	210		<DL
	Filtration product tank	74	21000	7700	310	580	100	640	1100	220		
	Infiltration tank	42	15000	4800	90	<DL	30	11	23	<DL		4.7
	After BAC	18	12000	2800	<DL	<DL	<DL	26	<DL	23		15
	Observation well 1	13	<DL	<DL	<DL	<DL	<DL	360	<DL	140		3
5-Mar-19	Secondary effluents	71	31000	9400	220	590	450	750	1200	250	4	<DL
	Filtration product tank	51	21000	6900	270	490	230	620	1000	190	13	
	Infiltration tank	34	6600	5700	59	<DL	33	<DL	<DL	<DL	53	13
	After BAC	31	7800	3100	<DL	<DL	25	31	13	25	12	11
	Observation well 1	14	<DL	<DL	<DL	<DL	<DL	400	<DL	120	<DL	1.4
19-Mar-19	Secondary effluents	74	40000	12000	160	510	290	710	1100	200	5	<DL
	Filtration product tank	59	26000	8900	170	480	200	610	790	210	15	
	Infiltration tank	37	21000	5400	13	<DL	29	<DL	<DL	<DL	53	13
	After BAC	42	9400	3300	<DL	<DL	19	23	<DL	18	12	11
	Observation well 1	<DL	<DL	<DL	<DL	<DL	<DL	230	<DL	58	2	8.4

Therefore, the concentration of CBZ in R1 represents the degree of mixing between water infiltrated at the recharge borehole (not containing CBZ), background water – which contain much higher and changing CBZ concentration, and CBZ desorbed from the soil into the infiltrating water.

CBZ is measured periodically in wells producing reclaimed water from the aquifer. CBZ concentrations measured during 2017-2018 in 5 different wells producing water from the cSAT ranged between 121 and 1650 ng/L, with an average value of 702 ng/L and a mean value of 361 ng/L. These concentrations, measurer in wells with residence times ranging between 4.5 months to greater than two years, are similar to or higher than those measured at R1, with a residence time of only 22 days. These results join other observations (7) in indicating that residence time might not be the main factor controlling the concentration of CBZ produced from the SAT. Instead, we are suggesting that the quality of the infiltrated water and processes in the vadose zone are at least as important for controlling the quality of the water reclaimed from the aquifer.

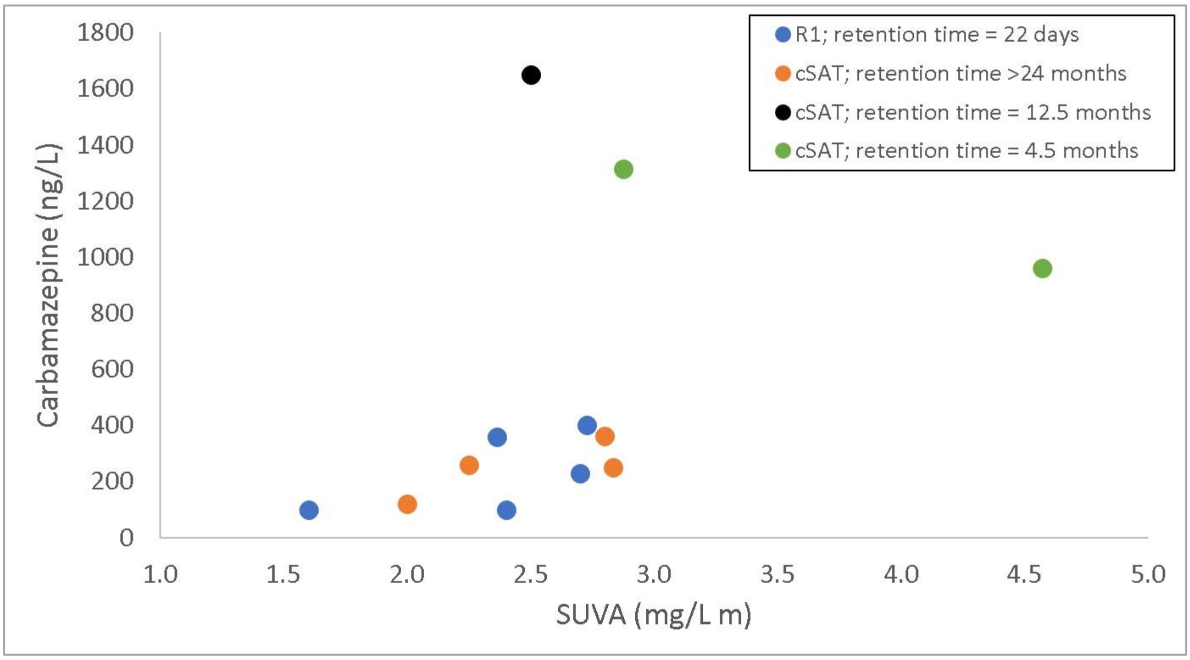

Figure 4. CBZ vs SUVA in R1 and in wells producing water from the Shafdan cSAT. cSAT samples were collected during 2017-2018

Bacterial counts in R1 were below the detection limit for total coliform, fecal coliform and fecal streptococcus m-enterococcus (Fig. 4). The counts for these three indicators for pathogenic bacteria are the same as those reported in the cSAT, pointing again to the fact that residence time in the aquifer is not the only mechanism controlling water quality of the reclaimed water, and other processes might play an equally essential role in maintaining the high water quality typical of water reclaimed at the Shafdan WWTP (7). TOTB counts at the sSAT for the reported period (360-750 MPN/100ml) were an order of magnitude higher than those previously reported (7) for the cSAT (0-220) for wells with residence times ranging between less than two months to greater than two years. Our assumption is that the high TOTB counts are due to an environmental effect are not directly related to the infiltrated effluents.

Table 5. Microbial removal after natural and engineered treatments

Date	Sampling pt.	Total Bacteria	Total Coliforms	Fecal Coliforms	Fecal Streptococcus
		cfu/1 mL	MPN/100mL	MPN/100mL	MPN/100mL
19-Feb-19	Secondary effluents	41,000	170,000	22,000	1,700
	Filtration product tank	2,900	2,400	110	ND
	Infiltration tank	87,000	540	350	5

	After BAC	8,300	49	ND	
	After cUF membrane	29,000	ND	ND	ND
	Observation well 1	480	ND	ND	ND
27-Feb-19	Secondary effluents	58,000	920,000	110,000	54,000
	Filtration product tank	9,800	3,500	490	2
	Infiltration tank	4,200	220	23	ND
	After BAC	54,000	130	11	ND
	Observation well 1	360	ND	ND	ND
5-Mar-19	Secondary effluents	88,000	35,000	16,000	2,400
	Filtration product tank	23,000	790	78	ND
	Infiltration tank	78,000	220	17	5
	After BAC	81,000	33	2	ND
	After cUF membrane	37,000	ND	ND	ND
	Observation well 1	530	ND	ND	ND
19-Mar-19	Secondary effluents	77,000	>1,600,000	>1,600,000	17,000
	Filtration product tank	6,600	1,700	33	ND
	Infiltration tank	70,000	79	5	ND
	After BAC	58,000	220	ND	ND
	After cUF membrane	500	13	ND	ND
	Observation well 1	750	ND	ND	ND

3.2. Natural vs. engineered post treatment

Alongside to infiltration in the natural process based sSAT facility, post ozonation water was also treated using an engineered BAC-cUF system installed on site. The purpose of this side-by-side demonstration was to compare the performance of the engineered BAC-cUF to that of the natural process based sSAT with respect to DOC, UVA, TrOCs and ozonation byproducts (NDMA and Bromate) concentrations and removal rates.

The engineered solution attempted here was not able to reach the same water quality observed after the sSAT. DOC concentrations in R1 (1-1.1 mg/L) were constantly lower than the concentrations measured after the BAC (average DOC of 4.63 mg/L). Average UVA values of 5.4 and 2.7 1/m measured after the BAC and at R1, respectively, also indicate that the BAC at its current configuration is not able to produce sSAT-quality water.

TrOCs removal shows several distinct trends. The concentrations of CBZ and SMX after the BAC, both with relatively high degradation rate when treated with ozone (k_{O3}), were higher than those received immediately after ozonation (up to 11 ng/L for CBZ and below the detection limit of 10 ng/L for SMX). Concentrations measured after the BAC were consistently very low and only slightly above the instrumental detection limit and reached a maximum of 31 and 25 ng/L for CBZ and SMX, respectively. These post-BAC concentrations are significantly lower than those measured at R1 for these compounds of up to 400 and 140 ng/L for CBZ and SMX, respectively, indicating the important contribution of both CBZ and SMX that comes from a long term secondary effluents SAT facility, where the infiltrated water were not directly treated for reducing TrOCs. All other measured TrOCs had a different trend: their concentration in the BAC was lower than the concentration immediately after ozonation, and their concentration at R1 was similar or lower than their concentration after the BAC. This trend is most profound for IHX and IPRM, iodine-based contrast media with very low k_{O3}, both with very high concentrations in the secondary effluents. IHX concentration after the BAC was only 52-75% less than the concentration measured at the secondary effluents, and IPRM removal ranged between 62-71%

compared to the concentration in the secondary effluents. The concentrations of both IHX and IPRM in R1 were very low and generally below the detection limit of 10 ng/L. This trend was also observed for NDMA, an ozonation by-product whose concentration significantly increases after ozonation but then decreases after the BAC and not detected at R1. This difference highlights the importance of removing compounds that are not degraded in the environment, such as CBZ and SMX, before secondary effluents are infiltrated to the aquifer.

Table 6. Class, chemical characteristics and rate constants at pH 7 of selected TrOCs. Reproduced from (8).

Name	Class	Rate constants		References
		k_{O3}	k_{OH}	
		($M^{-1}s^{-1}$)	($10^9 M^{-1}s^{-1}$)	
Iopromide (IPRM)	Contrast media	0.8	3.3	(Huber et al., 2003)
Iohexol (IHX)	Contrast media	1.4	3.3	
Iopamidol (IPDL)	Contrast media	1.4	2.8	
Bezafibrate (BZF)	Lipid regulator	590	7.4	
Carbamazepine (CBZ)	Anti-epileptic	$3*10^5$	8.8	
Diclofenac (DCF)	Anti-inflammatory	$1*10^6$	7.5	
Sulfamethoxazole (SMX)	Antibiotic	$2.5*10^6$	5.5	
Naproxen	Anti-inflammatory	$2*10^5$	9.6	
Ibuprofen	Anti-inflammatory	9.6	7.4	
NDMA	Organic carcinogenic chemical	0.052	0.45	(Lee et al., 2007)

Bacterial counts showed different trends for pathogenic bacteria and for TOTB (table 6). The three pathogenic bacteria counted were below the detection limit in all R1 and BAC-cUF samples. TOTB counts, however, were above the detection limit in all cases, with significantly lower values at R1 (360-750 cfu/ml) than after the BAC-cUF (500-81,000 cfu/ml). The source for this difference needs to be examined further as it is very likely due to a contamination of the permeate tank of the cUF, and not an indication of a lack of efficient in membrane performance.

4. Conclusions

Three effluent treatment technologies were compared for their compliance with IPR criteria with respect to their chamical composition, bacterial counts, and the presence of TrOCs:

1. a natural process based technology currently applied at the Shafdan (cSAT);
2. ozonation followed by a natural based technology with a short residence time of only 22 days (O_3-sSAT);
3. ozonation followed by an engineered process (O_3-BAC-cUF).

cSAT has been in operation at the Shafdan WWTP for many decades, and has been shown to be an extremely efficient technology for the removal of organic matter and all microbial parameters. TrOCs are also removed in great efficiency, except for CBZ whose concentrations in the cSAT do not decrease below 100 ng/L. This technology utilizes large infiltration ponds, and water resides in the aquifer from a few months up to several years before being abstracted. It suffers from being inhomogeneous, some areas experiencing exceptionally low infiltration rates, others experiencing anoxic conditions which lead to the release of dissolved Mn to the produced water, and down the line to the clogging of irrigation systems. cSAT generally complies with existing IPR criteria, with the exception of CBZ concentration that are higher than recommended by the German Environmental Agency.

The ozonation in the O_3-sSAT system is efficient for degrading hard to remove TrOCs, but is not sufficiently efficient in removing DOC, which is further removed with high efficiency by the sSAT. Results from this study show that water abstracted from the sSAT after 22 days in the aquifer are of better quality with respect to CBZ and of similar quality with respect to DOC, when compared to water abstracted from the cSAT after significantly longer residence times. This suggests that the residence time of infiltrated water in the aquifer might not be the only factor controlling the quality of the reclaimed water, and that other processes might play an equally important role. The O_3-sSAT system complies with existing IPR criteria with respect to bacterial, TrOCs, and DOC requirements (assuming the fraction of recycled water in the reclaimed water is ≤50%).

The main challenge of the O_3-BAC-cUF system was whether it can reach similar water quality as that obtained after the O_3-sSAT system. Our results indicate that this fully engineered solution still requires optimization before it can produce water of a similar quality to that produced from the O_3-sSAT system.

Adopting a new aquifer management scheme, which allows significantly shorter residence times, will allow increasing the amount of effluents reuse in a smaller footprint without having a negative effect on their quality. This approach, however, might only be applicable to new SAT basins, as it requires significant investment for creating reclaimed water production wells that correspond with shorter residence times than are currently available. The O_3-sSAT treatment train presented here was shown to be an effective chemical and biological treatment good enough to meet some of the most stringent IPR criteria currently available around the world (9). A thorough techno-economical comparison should be carried to complete the comparison between the cSAT and O_3-sSAT technologies.

Acknowledgments: This paper was the result of work carried in the Shafdan WWTP in the context of the AquaNES project supported by the European Union’s Horizon 2020 research and innovation programme, grant nb. No. 689450. We also thank Xylem Services GmbH and Xylem Analytics Germany GMBH who also participated in the project for their help in the ozonation, BAC and on-line analytics part of the project. We would like to thank Frank Sacher and the staff of the laboratory at the German Water Center in Karlsruhe for their very timely help in analyzing TrOCs. We would like to acknowledge the support provided by Riki Mor, the manager of the Shafdan and her staff, for enabling on-site support, Mekorot's Central Laboratory for their essential support of this research effort, and the continuous support provided by Mekorot's WaTECH division, which started at the early stages of writing the grant application and is still ongoing. And last but most definitely not least, we would like to recognize the extremely hard work of Mekorot's field technicians, Vadim Drobitzkiy and Michael Eliya, without whom this research work would not have been possible.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SAT	Soil Aquifer Treatment
BAC	Biologically Activated Carbon
BioF	BioFilter
BZF	Bezafibrate
CBZ	Carbamazepin
cSAT	conventional SAT
DCF	Diclofenac
DOC	Dissolved Organic Carbon

GAC	Granular Activated Carbon
H_2O_2	Hydrogen peroxide
IHX	Iohexol
IPDL	Iopamidol
IPRM	Iopromide
NDMA	N-Nitrosdimethylamine
PACl	PolyAluminum Chloride
SMX	Sulfamethaxazole
sSAT	short SAT
SUVA	Specific UVA
TOTB	Total Bacterial Count
TrOC	Trace Organic Compounds
UVA	Ultra Violet Adsorption

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Paper for ISMAR10 symposium. ***Topic No: 7 (218#)***

Reclaimed water quality improvement by means of MAR and nature-based solutions from local industrial reuse. The Alcazarén-Pedrajas, system, Valladolid (Spain)

Fernández Escalante[1], Enrique; San Sebastián Sauto, Jon[2] and Villanueva Lago, María[3]

[1] Tragsatec; jsss@tragsa.es
[2] Tragsa; efernan6@tragsa.es
[3] Tragsatec; mvillan2@tragsa.es
* Correspondence: jsss@tragsa.es. Tel.: +34-91 322-66-61

Abstract: Alcazarén is the Northernmost MAR site in Los Arenales Aquifer (Castilla y León, Spain). Three types of water sources are used for recharge: a transport pipe with surface water diverted from Pirón River dam through a River Bank Filtration System (RBF), run-off water from a canal collecting occasional drainage from Pedrajas Village streets and recycled water from Pedrajas WWTP. Surface water from the dam has been unavailable for the last years due to legal issues about water rights, so the percentage of recycled water has been higher than originally designed, and consequently, dilution rate of reclaimed water with freshwater has decreased. All available sources (river, WWTP and run-off) are mixed within a chamber, where different types of organic filters have been tested (post-treatment) previous to MAR occurs through three infiltration canals in an irrigation area. Selection of materials for filtering was based on low cost inversion and the availability in the area (pinewood industry). Tests have successfully validated the use of both, inorganic (siliceous and calcareous gravel, grit and sand) and reactive organic (pine bark and pine rachis into geotextile sacks) filters, removing certain pollutants from reclaimed water. 17 parameters were observed and 16 had a clear improvement. It is also worth mentioning that after several weeks of continuous post-treatment and recharge, the reactive layer was still active. Therefore, this technology is likely to be useful for longer-term applications, despite the small scale of the experiment and the short time of interaction. The project demonstrated that physical, chemical and biochemical post-processes associated with MAR plants represent a passive and affordable way to reduce the presence of certain contaminants, with economic and environmental benefits, complemented by further aquifer filtering after MAR. No negative effects have been observed in the infiltration rate as indicated by minimal variation in water levels in 6 piezometers.

Keywords: Managed Aquifer Recharge, reclaimed water, industrial wastes, water treatment plant, pine bark, Spain.

1. Introduction

Figure 1 presents the Alcazarén area sketch where these tests have been accomplished. The description of the aquifer and its hydrogeological conditions have already been extensively exposed in the literature associated to MARSOL project [MARSOL, 2015a, 6].

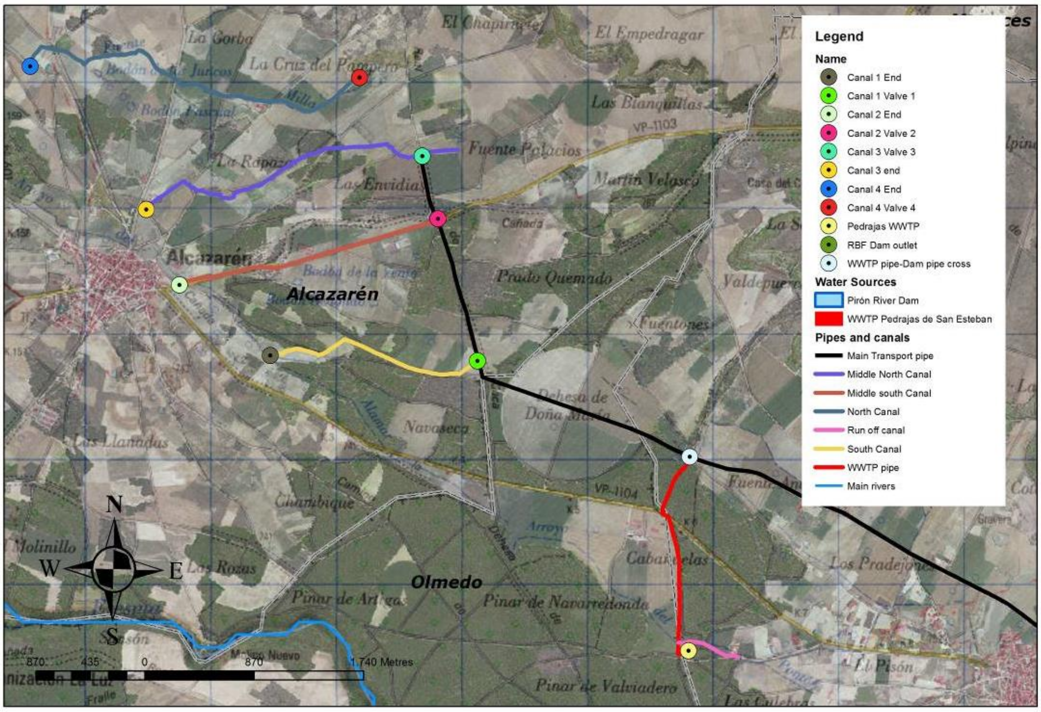

Figure 1. Alcazarén area. Cartographical mock-up for the MAR facilities in the area.

Water spill from the WWTP has been driven to the "connection point" where is eventually combined with water proceeding from Pirón River and from the Pedrajas Village runoff (figure 2). The connection point has a concrete chamber where different filters have been tried. There is a 2-km-long stretch between this point and the spillway used to test the in itinere treatment inside the same pipe (blue triangle in the accompanying figure). The final collecting samples point is the place where the disinfectants addition effect has been analysed and monitored in the valve 2. The figure 3 complements this scheme by means of six photographs that capture these singular points.

2. Materials and Methods

The design of filtering and interaction systems to improve the water quality for MAR is another important target within MARSOL project objectives. The most remarkable adhered objectives have been:

- Reclaimed water quality evolution after the interaction with filters made of gravel/grit/sand and geofabrics.
- Reclaimed water quality evolution after filtration across reactive layers (biofilm).
- Purification measures along the conductions after filtering, interaction with different disinfectants and with biofilms "in itinere".
- Reclaimed water quality evolution and response to chemical additives or Disinfection By Products (DBPs)
- Solar exposure´s effect on reclaimed water.

The planned activities consist on the filtering of the WWTP effluent by different materials (gravel, grit, sand, organic compounds) next to the WWTP (figure 2, red point). The point to drop the disinfectant liquid has been at the outlet of the WWTP. Sample collections spots have been the spillway (blue triangle) for the filtering results and valve 1, 2 and 3 for the three respective disinfectants.

Results have been tested in the grey points, collecting samples which were sent to laboratory.

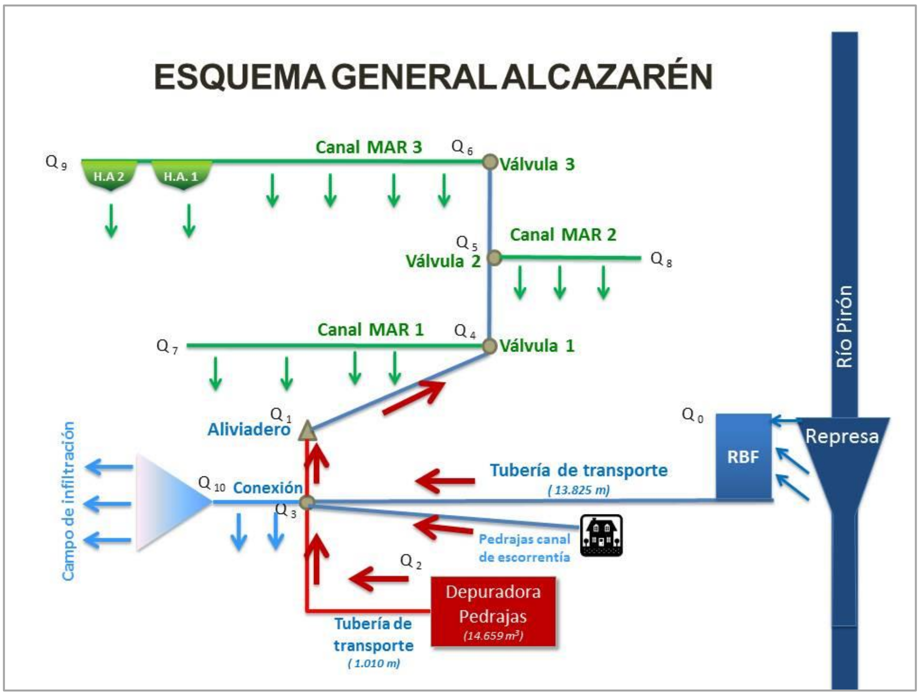

Figure 2: Alcazarén area general sketch where the conductions and piping tests have taken place. Topologic scheme.

Figures 3 a to f (from top to bottom and left to right): Alcazarén MAR system´s singular points: Pedrajas WWTP (a); connection point where converge water proceeding from the WWTP, runoff and Pirón river diversion pipe (b); runoff canal proceeding from Pedrajas village (c); spillway (d); valve 2 monitoring box (e) and final sandpit used as an infiltration pond (A.W. 2) (f).

3. Results

3.1 Additional constructions in the demo site (Alcazarén WWTP)

3.1.1 First stage:

At the beginning of 2016 February, some modifications were applied to the previous casket at the exit of the WWTP where samples were being collected. Gravel was inserted inside the casket to enhance the filtration process, closing the spillway to Pirón River and constructing a security mechanism to avoid over floods (figure 4).

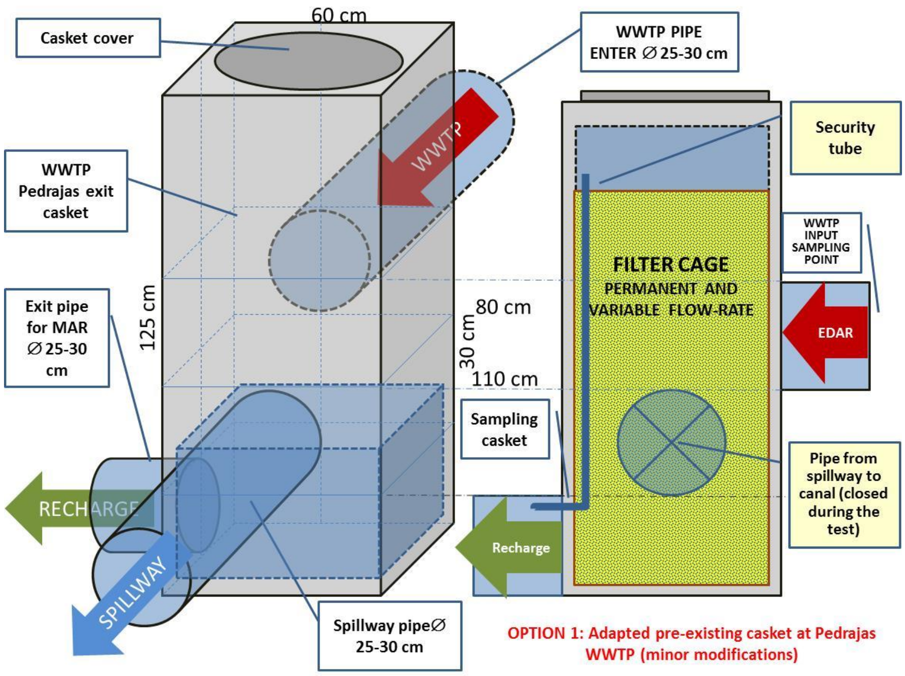

Figure 4: Initial filter casket with slight modifications.

Due to the fact that over friction by loss of load increased over expected forecasts, a new and specific construction 100 m down the pipeline was built (2nd stage).

3.1.2 Second stage:

From 2016 March to August some in-pipeline modifications at the convergence point of runoff, river and WWTP waters were conducted. This option required the construction of new elements such as lateral concrete walls to avoid flooding, a cage with embedded channel filter material, a lift gate and a tube to connect the runoff canal and the mixture chamber. Inorganic and organic filters were inserted into plastic boxes refilling completely the chamber capacity (figure 5).

The new structure has several advantages, e.g. the over flooding risk was minimized, installation of multiple modular filter cages adapted to the chamber in length and depth, large volume capacity to filter on continuous and its use was independent of the WWTP process.

Five types of different filters have been combined, three inorganic and two reactive materials, three DBPs tests using two different disinfectants (hypochlorite and hydrogen peroxide) and water samples have been collected in six consecutive campaigns in different points of the circuit.

The activity started in February 2016 when the already described constructions were finished.

- Siliceous Gravel: On March 10th it was inserted the first filter in the final location, composed by 12-20 mm Ø siliceous gravel. Samples for chemical analysis were collected on March 15th (1st campaign) in the spillway point and later displaced to the connection point. The parameters analysed in the laboratory were: Temperature in situ; O_2 (TDO); Conductivity; BDO_5; CDO; TDS; pH; SS; turbidity (NTU), DOC, nitrogen phases (total, Kjeldahl, nitrates, nitrites, ammonium); nematodes and E. coli.
- Calcareous Gravel: On April 6 and 7th the filter was replaced by 20-40 mm Ø calcareous gravel, proceeding with a new sampling campaign on April 20th (2nd campaign) in the

spillway point too. The parameters determined in the laboratory were the same than in the previous case, including faecal coliforms as well.

- Siliceous Grit And Sand And Hypochlorite: May 27th, after a rainy period, a new filter was set up composed by 6-12 mm Ø siliceous grit combined with sand inside geofabrics satchels. The first DBP took place dropping 50 l of hypochlorite during 36 h on June 8th. Samples were collected in valve 2 point on June 9th in with valves 1 and 3 closed (3rd campaign). Parameters analysed were the same than in the previous campaign including residual Chloride.

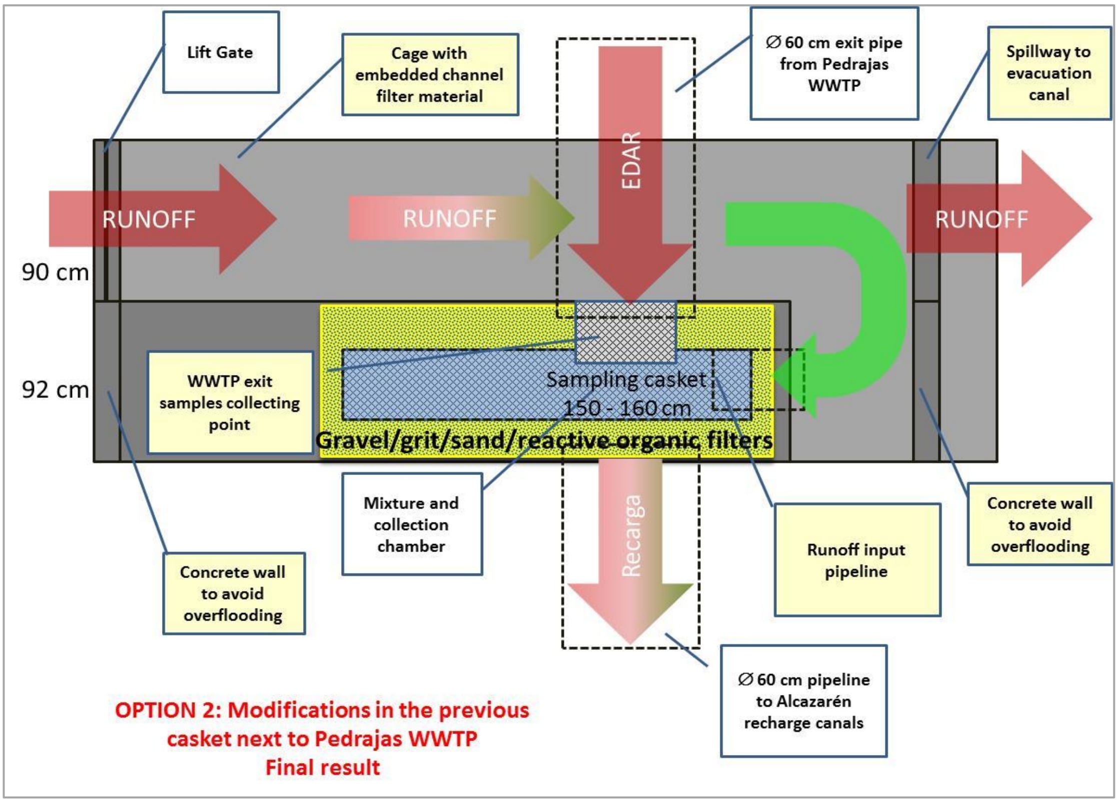

Figure 5: Specific system to perform the tests constructed in the point where two different water sources converge.

- Pine Bark: June 28th, the grit filter was replaced by an organic reactive one composed by 150 kg of pine bark (reactive layers employ materials cheap and abundant in the area) inserted into geofabrics sacks and compressed by gravel sacks located above in order to pressurize the filter. Samples were collected in valve 2 point on June 29th (4th campaign). Residual chloride was not analysed in this case.
- Pine Bark and Peroxide: July 13th, maintaining the organic filter, the second DBP took place, dropping 60 l of hydrogen peroxide 60% concentration (71,46 kg) during 36 h. Water samples were collected on July 14th in valve 2 (5th campaign; figures 3-54 and 3-55). Residual chloride was not analysed in this case.

The results of the chemical analyses of the different campaigns collected by Aqualia Company and analysed in their own laboratory must be consulted in the references.

During the whole testing period, precipitations data were measured in the Pedrajas village´s meteo station. The results are presented as figure 6.

Input and output water have been compared to achieve some practical advices regarding solar exposure. The effect of the sunlight on reclaimed water appears to be satisfactory and a good design criterion for improved designs.

Table 1: Campaigns and filters used to improve quality of WWTP outlet.

Nº campaign	Date	Filter
1	15-mar-2016	12-20 Ø siliceous gravel
2	20-abr-2016	20-40 Ø calcareous gravel
3	09-jun-2016	6-12 Ø siliceous grit/gravel
4	29-jun-2016	Pine bark + geofabrics + DBP 50 l Cl2
5	14-jul-2016	Pine bark + geofabrics + DBP 50 l H_2O_2

All contaminations with pathogens as well as organic and inorganic pollutants should be avoided to improve the reclaimed water quality as a safe source for irrigation and eventual indirect potable reuse purposes. Consequentely, understanding and achiving the degradative biogeochemical processes occurring within the post-treatment and during the aquifer infiltration are capital.

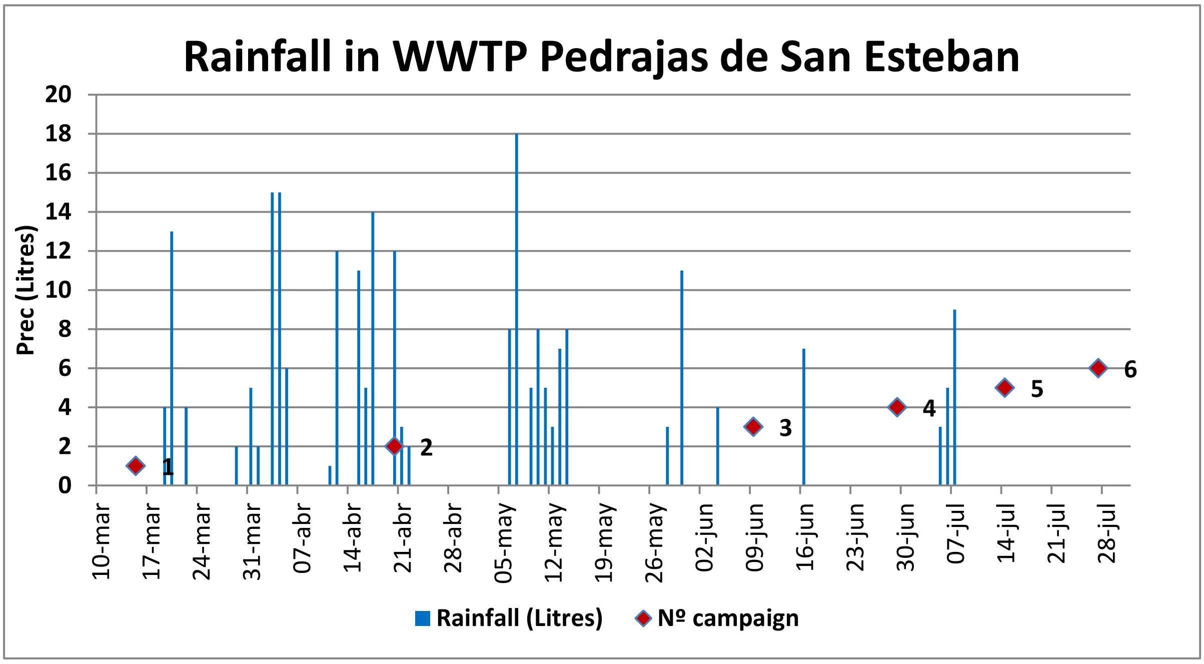

Figure 6 Precipitations measures along the tests slot. Water sample campaigns are included in the chart.

4. Discussion

4.1 Reclaimed water quality evolution after the interaction with filters made of gravel/grit/sand and geofabrics.

SAT-MAR is considered a series of techniques willing to enhance the attenuation of pollution using natural processes occurring through infiltration in the unsaturated zone.

The presence of inorganic filters has had the constraint of the scarce time of residence; water has crossed the filter in a matter of seconds, and the interaction processes have been very short in time.

There have not been observed important differences in the resulting chemical composition of the water using calcareous or siliceous gravel packs. A fact that, logically, has been adverted was the reduction in the total amount of suspended solids, especially with the gravel and grit filter.

The use of geo-fabrics has also retained a certain number of suspended solids, with a rather scarce or unappreciable influence on the reclaimed water composition.

Total Organic Carbon (TOC) has become the most important parameter to be controlled, due to the fact that a certain amount of TOC has been observed in an ascending trend at the closest piezometers. The reduction of this parameter is adverted with all the filters employed, and especially with those of organic composition.

4.2 Reclaimed water quality evolution after filtration across reactive layers (biofilm).

Permeable Reactive Barriers (PRBs) are installed in the flow path of the recharge circuit to improve the water quality in the MAR system. The contaminants in the plume react with the filter compounds within the barrier to either break the compound down into harmless products or to immobilize contaminants by precipitation or sorption.

The main objective of the action was the evaluation of the efficiency of the organic substrate layer installed along the circuit in terms of the evaluation of DOC and the variation of redox conditions by the reactivity of the organic layer. To characterize the studied system and to evaluate the effects above mentioned, several physical-chemical parameters were selected and analysed such as global indicators (pH, conductivity), nitrogen compounds, organic bacteria colonies and some inorganic combinations.

The organic filters to be installed in the demonstration site were selected due to their high availability in the zone and cheap prize. Both organic reactive filters, pine bark (figure 3-52b) and pine rachis, were mixed with natural soil. Moreover, a small fraction of clay (2% of the total volume) and iron oxides (1% of the total volume) were added to improve the ionic adsorption.

Both have had a clear interaction on TDS and DOC parameters improvement. These tests must be studied separately because some disinfectants were poured during the different stages of the experiments.

The geofabrics tested had rather a function of retaining the organic filter units than a filtering process. Gravel used as a weight to pressure the reactive layer sacks did not have any effect on the filtering process. The ultrafiltration process has not been achieved in these tests, characterized by the fast speed and the high porosity of the filters used.

4.3 Purification measures along the conductions after filtering, interaction with different disinfectants and with biofilms "in itinere".

The SAT-MAR tests applied have required a set of reagents to optimize the operation, such as: hypochlorite, sodium hydroxide, hydrochloric acid, anti-fouling to prevent precipitation of salts, bisulphite to prevent oxidation of membranes and biocides for periodic cleaning. This group of additives is usually used in the purification process.

Three of the experiences carried out had an addition of some disinfectant so a DBP post-treatment was performed. The chosen compounds were hypochlorite and hydrogen peroxide.

It is important to advance that the chloride doses dropped into the reclaimed water did not retain any amount of residual chloride in the observation points. This fact is attributable to the presence of organic matter in some stretches inside the pipeline, where, according to oral manifestations from the farmers, a certain amount of organic carbon is concentrated in zones with a very low slope and it is easily detected by its stench. The interaction between the additional chloride and the water along the course has caused purification in itinere, guaranteeing that zero residual chloride has been directly aggregated to groundwater.

The interaction between chloride and the reactive layer has been practically negligible; no modifications along the canal have been detected.

Regarding Hydrogen peroxide addition and its effect on TDO, several measures were taken along the circuit by means of a multiparameter sensor. As in the previous case, oxygen reacted with the TOC in the reclaimed water, reducing the organic vectors, but, no increase in the TDO parameter has been detected in the areas where recharge water arrives to MAR infiltration facilities. The observed effect has been positive in all the measured parameters except for turbidity, with a slight registered elevation.

After the post-treatment process and in the surroundings of the recharge canals, reducing conditions are mainly observed in unsaturated zone. Higher concentrations of nitrites and N-ammonia (compared to untreated recharge water) were found (campaign 3), exposing a significant decrease on nitrate concentration in the passage of the infiltration water towards the receiving medium, except in the 1st and 2nd campaigns, when total nitrogen content raised slightly.

4.4 Reclaimed water quality evolution and response to chemical additives (DBPs)

According to the water quality evolution charted for most of the analysed parameters (see graphs in annex 1); some of them have significantly changed and all of them deserve a separated treatment:

- Conductivity: The evolution of this parameter along the circuit (from the WWTP to the valves in the heading of the MAR canals) has not a clear trend, coming down in the tests where thick gravel was used as a filter for both, siliceous and calcareous (1^{st} and 2^{nd} campaigns). In the 5^{th} campaign, with addition of H_2O_2 for a DBP test, conductivity descended down along the in-pipe circuit, what is coherent with the expected "*in itinere*" purification.
- BDO5: The effect on BDO5 is clearly positive. There is a general descent along the pipeline except for the 2nd, using calcareous gravel as a sifter. The use of disinfectants products has conducted a progressive decline for this parameter.
- COD: The trend is parallel to the previous one, with a parallel behaviour, as it is expected.
- TDS: This parameter increased abruptly in the first campaign, using siliceous gravel as a filter. In the remaining campaigns TDS tends to come down slightly along the in-pipe circuit.
- TSS: Suspended solids and dissolved solids evolution do not keep a parallelism. The general trend is to decrease, except for the 2nd campaign, using calcareous gravel as a filter, when the tendency was opposite to the general behaviour.
- Turbidity (NTU): Oddly enough the line tends to rise, except for the 3^{rd} test, where the use of a finer filter constituted by grit and gravel caused the expected effect. Even the addition of Hydrogen Peroxide did not bring down the turbidity, thus, presumably, it has a high inorganic component.
- DOC: This is the sole parameter with a general bearish tendency. The biggest slope was caused by the finest filter. The addition of chloride has also caused a direct descent on DOC, being steeper with the addition of H_2O_2.
- Total nitrogen: The evolution is not very clear for most of the nitrogen phases, except for nitrates, with a crisp descent trend during the episodes when both disinfectants were dropped in the reclaimed water and reactive filter layers were employed.
- *E. coli.*: The trend has been notably descending during the spring. Once the summer time began, this sort of bacteria has appeared with a certain intensification along the circuit. Obviously, they were removed in itinere by the addition of chloride.

4.5 Solar exposure´s effect on reclaimed water.

In these facilities there is a unique area to test the effect of the solar exposure on reclaimed water, as the rest of the plant runs into a-pipe line.

There is a little pool between at the exit of the WWTP circuit where reclaimed water is submitted to solar exposure after the sludge digestion process. Due to the short distance between the output point and the connection point, the evolution of the parameters is insignificant, and it has not been tracked.

4. Conclusions

The results have demonstrated that all the filters had a certain effect on water quality, resulting obviously maximum for the finest ones. The organic layer has had a positive effect on water quality and especially for the Total Organic Carbon, with a direct reduction and a clear purification in itinere along the pipe-line circuit.

Neither TOC nor free chloride has arrived at the infiltration canals, terms that would be acceptable in no way. The treatment with both disinfectants, chloride and hydrogen peroxide, has been powerful, reducing the impact of recharge on the aquifer by progressive TOC accumulation.

The tests, therefore, have been useful as a demo activity to reaffirm its main objective: the incorporation of a reactive layer prior recharge of reclaimed water has a positive effect on the reduction of groundwater pollutants, enhancing their biological degradation and therefore, improving the general water quality for the final intended uses.

The tests have successfully validated the use of both, inorganic and reactive organic filters removing certain pollutants from reclaimed water to be used for recharge. It has been demonstrated that it is possible to improve natural decontamination processes and increase natural sorption capacity with the installation of reactive organic material in different additional points along the MAR course. It is worth also to mention that after several weeks of continuous post-treatment and recharge, the reactive layer was still active. Therefore, this technology is likely to be useful for longer-term applications, considering the little scale of the experiment and the short time of exposition too.

The project demonstrated that physical, chemical and biochemical processes associated with MAR plants represent a natural, passive and affordable way to reduce the presence of certain contaminants, with economic and environmental benefits. No negative effects have been observed in the infiltration rate due to the post-treatment processes, according to the scarce variations in the piezometers water table level.

Regarding energy savings, soft techniques should be used for sprinkle and drip irrigation. Greater improvements require hard treatments such as ultrafiltration membranes (UF) and reverse osmosis (RO) technologies, what require enormous power needs and an investment difficult to recover in the cost-benefit binomial. In these examples the use of available residues from nearby industries have shown again the recycled spirit of MAR, changing a rejected (pine bark or rachis) or affordable (gravel and sand) material in the area into a valuable filter.

These results have been transferred to the working group in charge of revision of the Water Framework Directive (2000/60/EC), where two MARSOL individuals take part, providing modifications for the future text of the major water Directive.

Acknowledgments: This paper has been edited by member of the TRAGSA Group team in the MARSOL European Project (Demostrating Managed Aquifer Recharge as a solution to water scarcity and drought) (WP5), with the support of the European Commission, Water Inno-demo summon (FP 7, Grant Agreement: GA nº 619.120. The information and views set out in this article/ are those of the authors and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

Authors want to express their gratituide for the colaboratuon and support of TRAGSA Group technical staff and IAH-MAR Commission.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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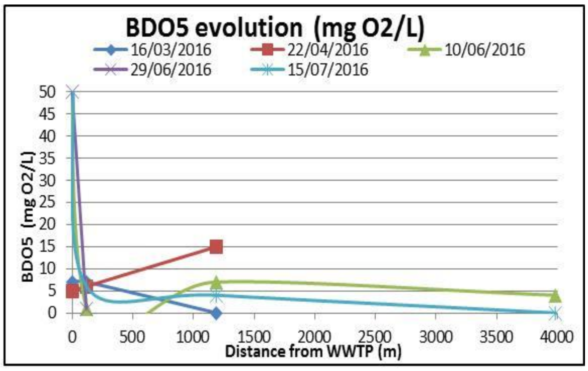
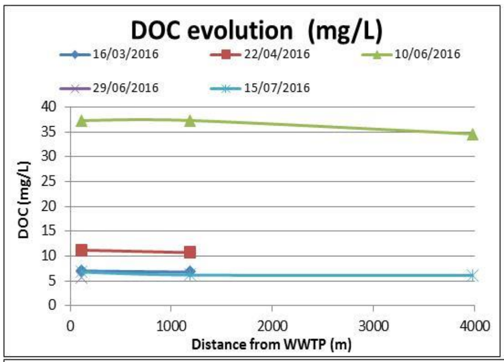
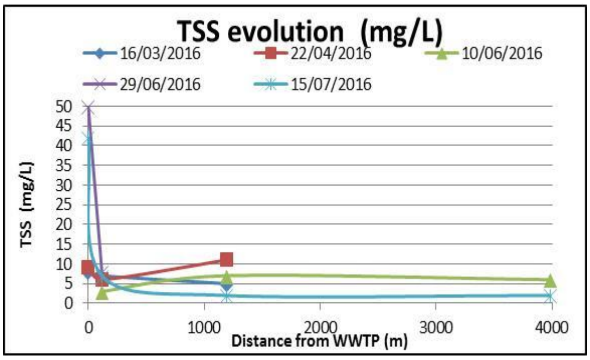
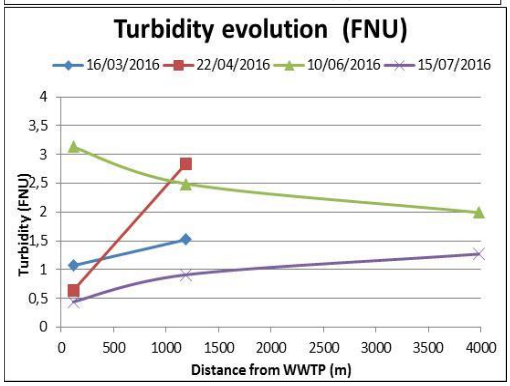
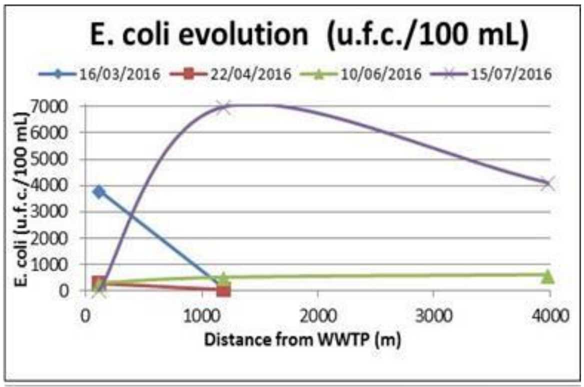
ANNEX A:

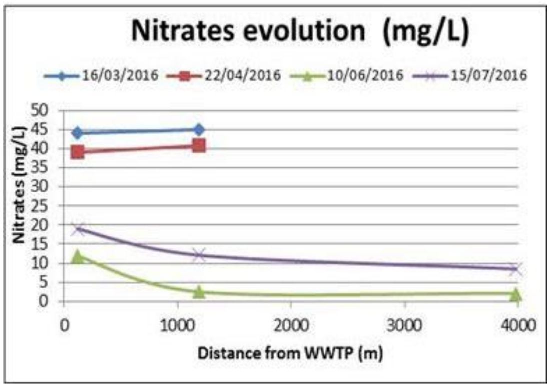












DBO5, DQO, TSS, TSD, COD, turbidity, E. coli, nitrogen/s, etc. Reduction for 16/17 analyzed parameters thanks to interactive filters.

Topic 8. SUSTAINABLE MAR TECHNICAL SOLUTIONS

Paper for ISMAR10 symposium. ***Topic No: 8 (025#)***

Dipolic MAR "Bubble" Inside Confined Brine Formation or Floating "Lens" on Top of Unconfined Saline Aquifer

Anvar Kacimov[1*], Yurii Obnosov[2] and Ali Al-Maktoumi[1]

1. Sultan Qaboos University, Oman; anvar@squ.edu.om, ali4530@squ.edu.om
2. Kazan Federal University Russia; yobnosov@kpfu.ru
*Correspondence: anvar@squ.edu.om; Tel.: (968) 99251302

Abstract: In arid desert environments, MAR sites are often characterized by high salinity of the ambient groundwater and intensive evaporation. We present mathematical modeling of two MAR scenarios: 1) injection-abstraction of fresh water through two horizontal wells with a quasi-vertical sharp interface/transition zone straddling between the caprock and bedrock of a confined aquifer; 2) infiltration from a surface pond into a floating fresh water lens with an interface pinned to two unknown frontal points. Analytical solutions for Darcian, steady, 2-D and axisymmetric flows utilize two types of mathematical dipoles: combination of a line sink and source and superposition of a distributed sink and source. For 2-D dipoles sandwiched between the caprock and bedrock, the theory of holomorphic functions is used (conformal mappings and Keldysh–Sedov's representations of characteristic functions via singular integrals). Numerically, MODFLOW-SEAWAT delineate isoconcentric lines of the MAR "bubble". For axisymmetric floating lenses, U-turn topology of fresh water circulation is modeled by the Dupuit-Forchheimer approximation, which is reduced to a boundary value problem for a nonlinear ordinary differential equation with respect to Strack's potential. The total volume of the lens is evaluated for evaporation rates, which are constant or exponentially decrease with the water table depth.

Keywords: Abstraction-injection wells; isoconcentric lines; sharp interface; density dependent flow; fresh water "bubble"; floating fresh water lens; evaporation from the water; analytical and numerical solutions.

1. Introduction

ASR in deserts of Central Asia, in particular, in Turkmenistan, has been traditionally practiced by local nomads who constructed the so-called "takyrs" (natural topographic depressions with dug wells) [1]. Runoff was collected in these infiltration basins during rainy seasons and infiltrated to an unconfined aquifer through a usually silt-clogged bed. Later on, old "takyrs" were amended by bulldozed excavations and systems of injection-abstraction wells [6,9], which currently supply water to towns, industries and large-scale irrigated agriculture in the desert. The created "perched" pore-water bodies in these ASR schemes belong to the class of terrestrial freshwater lenses [7], which are subtended by high-salinity "pristine" groundwater. A smart recovery of the stored rainwater from the "floating lens" is necessary to thwart overpumping-upconing. The "takyr" lenses have the following peculiarity: the phreatic surface is often shallow and the lens intensively evaporates and transpires (lash desert vegetation emerges on the ground surface over a MAR-generated lens) that causes dwindling-extermination of the lens if infiltration stops.

In this paper, we present analytical modeling of two MAR schemes:

In Section 2, we extend our idea of ASR by a dipole of horizontal wells [3]. In order to avoid evaporation and secondary salinization of the topsoil, a fresh pore-water "bubble" is confined by the caprock of a confined aquifer containing saline groundwater.

In Section 3, we investigate a "takyr" lens in an unconfined aquifer with saline water and nontrivial evapotranspiration from the water table.

2. MAR "bubble" generated by dipole sandwiched in confined aquifer

We consider a confined aquifer of a given thickness *b*, with a horizontal impervious caprock B_1B_2 and bedrock G_1G_2 (Fig.1a). The case of a half-plane i.e. deep bedrock ($b=\infty$) has been studied in [3].

Saline groundwater of density ρ_s is stagnant and, if no MAR, occupies the whole strip of Fig.1a. The dipole (a pair of injection-abstraction wells located a small distance $2j$ from each other) of intensity $2q$, is located at the depth $y=-h_1$ and creates a fresh water "bubble" (density of fresh water is ρ_f), which is laterally bounded by the interfaces E_2A_2 and E_1A_1. The piezometric head in saline water, h_{sa}, is counted from Nx. At a certain point B far away from the "bubble" in Fig.1a the pressure head in a hypothetical piezometer tapping saline water is p_B.

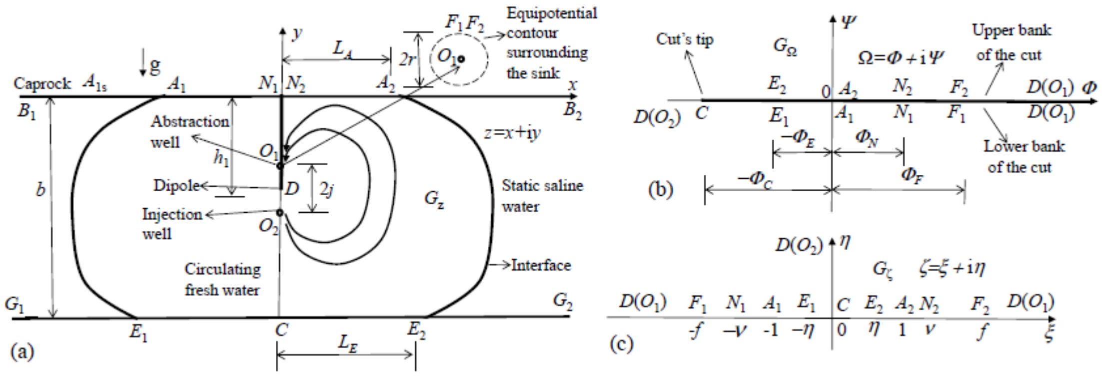


Figure 1. Vertical cross-section of the fresh-water lens generated by 2-D dipole in a confined aquifer (a), complex potential domain (b), reference plane (c).

We assume that the contours of the wells in the dipole are circles of a small radius *r* surrounding the sink and source. The pressure head at points F_1, F_2 (the apex of the abstraction well contour) is p_F (see a hypothetical piezometer zoomed in Fig.1a).We introduce a complex physical coordinate $z=x+\mathrm{i}\,y$, velocity potential $\Phi=-kh_f$ of the moving fresh water and the complex potential $\Omega=\Phi+\mathrm{i}\Psi$, where $h_f(x,y)$ is the hydraulic head in the fresh water, Ψ is a stream function and *k* is a given saturated fresh water conductivity. The specific discharge vector is $\vec{V}=\nabla\Phi$. The pressure and pressure head in fresh water are $P_f=\rho_f g p_f$ and $p_f(x,y)=-(\Phi/k+y+c_p)$, respectively. We select points A_2 and A_1 (Fig.1a) as fiducial i.e. $\Omega(A_1)=\Omega(A_2)=0$. Then $c_p=-\rho_s/\rho_f\,p_B$. The pressure and pressure head in saline water are

$P_s = \rho_s g p_s$, and $p_s(y) = p_B - y$. Along the two interfaces in Fig.1a the free boundary conditions are:

$$\Phi - cy = 0, \quad \Psi = 0, \tag{1}$$

where $c = (\rho_s / \rho_f - 1)k$ [10,12].

At points N_1 (N_2), F_1 (F_2), E_1(E_2), C the velocity potentials are Φ_N, Φ_F, Φ_E, and $-\Phi_C$, correspondingly. Point F_1 (F_2) is the apex of the abstraction well (a circular equipotential). The complex potential domain G_Ω is a plane with a horizontal cut (Fig.1b).

We map G_Ω onto the upper half-plane G_ς of an auxiliary reference complex variable $\varsigma = \xi + \mathrm{i}\eta$ (Fig.1c) by the function:

$$\begin{aligned} &\Omega = \Phi_C(\varsigma^2 - 1), \quad (0,1,\infty) \to (-\Phi_C, 0, \infty), \\ &\Phi_N = \Phi_C(\nu^2 - 1), \quad \Phi_F = \Phi_C(f^2 - 1), \quad \Phi_E = \Phi_C(1 - \eta^2). \end{aligned} \tag{2}$$

Taking into account eqn.(2), the holomorphic function $z(\varsigma)$ satisfies the following boundary conditions:

$$\begin{aligned} &x(\xi) = 0, \quad \xi \in (-\infty, -\nu) \cup (\nu, \infty), \\ &y(\xi) = 0, \quad \xi \in (-\nu, -1) \cup (1, \nu), \\ &y(\xi) = \Phi(\xi)/c = \Phi_C(\xi^2 - 1)/c, \quad \xi \in (-1, -\eta) \cup (\eta, 1), \\ &y(\xi) = -b, \quad \xi \in (-\eta, \eta). \end{aligned} \tag{3}$$

Solution to the mixed boundary-value problem (3) is bounded at infinity and at all transition points: $\pm\nu$, ± 1, $\pm\eta$. The last condition is satisfied if and only if $\Phi_C(1 - \eta^2) = cb$. The Keldysh-Sedov formula [2] gives, after simple transformations, the required solution to problem (3):

$$z(\varsigma) = \frac{2\varsigma\sqrt{\nu^2 - \varsigma^2}}{\pi}\left[\frac{\Phi_C}{c}\int_\eta^1 \frac{\tau^2 - 1}{\sqrt{\nu^2 - \tau^2}}\frac{\mathrm{d}\tau}{\tau^2 - \varsigma^2} + \int_0^\eta \frac{b}{\sqrt{\nu^2 - \tau^2}}\frac{\mathrm{d}\tau}{\tau^2 - \varsigma^2}\right]. \tag{4}$$

We introduce dimensionless quantities $(z_d, x_d, y_d, r_d, b_d,) = (z, x, y, r, b)/h_1$ $(\Phi_{Fd}, \Phi_{Cd}, \Phi_{Ed}, \Phi_{Ad}, \Omega_d) = (\Phi_F, \Phi_C, \Phi_E, \Phi_A, \Omega)/(kh_1)$, $\delta = \rho_s/\rho_f - 1$. If the parameters c, b, r, Φ_F are fixed, then from the condition of solvability and the corresponding relation (2) it follows:

$$\eta = \sqrt{1 - b\delta(f^2 - 1)/\Phi_F}, \tag{5}$$

that implies the inequality $b\delta(f^2 - 1) < \Phi_F$. From the condition: $z(\infty) = -\mathrm{i}$ (the dipole is placed at a given depth h_1 under the caprock) and $z(f) = -\mathrm{i}(1 - r)$ (the apex of the contour of the abstraction well, point $F_{1,2}$ is at an elevation r above the sink) we obtain

$$\nu = \sqrt{1 + \frac{4}{\pi^2}\left[\frac{\Phi_F}{3\delta(f^2 - 1)}\left(\eta^3 - 3\eta + 2\right) - b\eta\right]^2}, \tag{6}$$

$$1-r=\frac{2f\sqrt{f^2-\nu^2}}{\pi}\left[\frac{\Phi_F}{(f^2-1)\delta}\int_{\eta}^{1}\frac{\tau^2-1}{\sqrt{\nu^2-\tau^2}}\frac{d\tau}{\tau^2-f^2}+\int_{0}^{\eta}\frac{b}{\sqrt{\nu^2-\tau^2}}\frac{d\tau}{\tau^2-f^2}\right]. \quad (7)$$

The system of three nonlinear equations (5)-(7) with respect to η, f, ν is reduced to a single equation with respect to f. We solved this equation by the **FindRoot routine** [13]. Then, similarly to [3], we used eqns. (2) and (4) and computed the shapes of the bubble.

A finite difference variable-density, saturated groundwater flow and transport code, SEAWAT [8] has been also used to simulate the problem presented in Fig.2 which depicts a vertical cross section of a homogeneous isotropic aquifer having k= 10 m/day, porosity 0.25 and thickness b=10 m. The modeled domain is 30 m wide. It was gridded with 100 layers and 300 columns forming a total number of 30,000 active cells with the cell size dy=dx =0.1 m. The longitudinal dispersivity, αL, and the molecular diffusion coefficient, D_0 , were 10 m and 1×10^{-10} m^2/day, respectively. The initial concentration of solutes in groundwater across the aquifer is 35 g/L. The fluid density and solute concentration were linearly related to a factor of 0.7. At the time instance t= 0, the abstraction and injection wells started their operation by pumping at equal rates of 1600 m^3/day. Four sides of the rectangle in Fig. 2 are assumed impermeable to both flow and transport. Simulations continued with t until a steady state has been reached. The isoconcentric lines and the equipotential lines are presented in Fig.2.

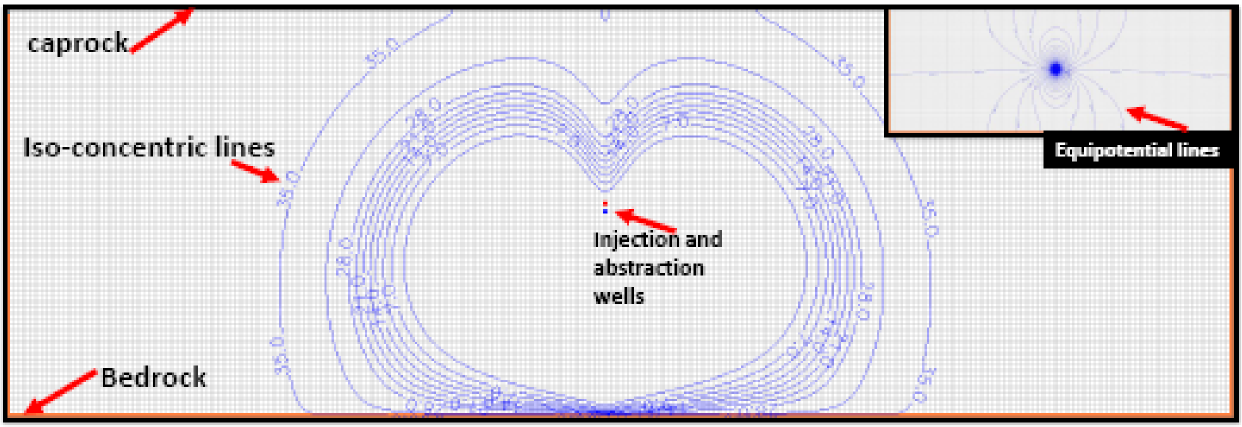


Figure 2.

Similarly to [3], the isoconcentric lines are downconing towards the upper abstraction well but the bedrock facilitates "bubble's" confinement.

3. Floating lens under infiltrating "takyr" in unconfined aquifer

A circular infiltration basin of a radius R_M^* has an average ponding depth H^* (Fig.3). The clogging layer (cake) has a thickness s and hydraulic conductivity k_c. A volume V_0 of runoff is collected and infiltrated in T^* days through the vadose zone into the lens beneath. A steady-state infiltration rate $N_0^* \approx Hk_c / s$ is not impeded by the mounding phreatic surface located well below the cake bottom. Prior to MAR, saline groundwater has a horizontal water table at the depth d_0^* under the desert surface.

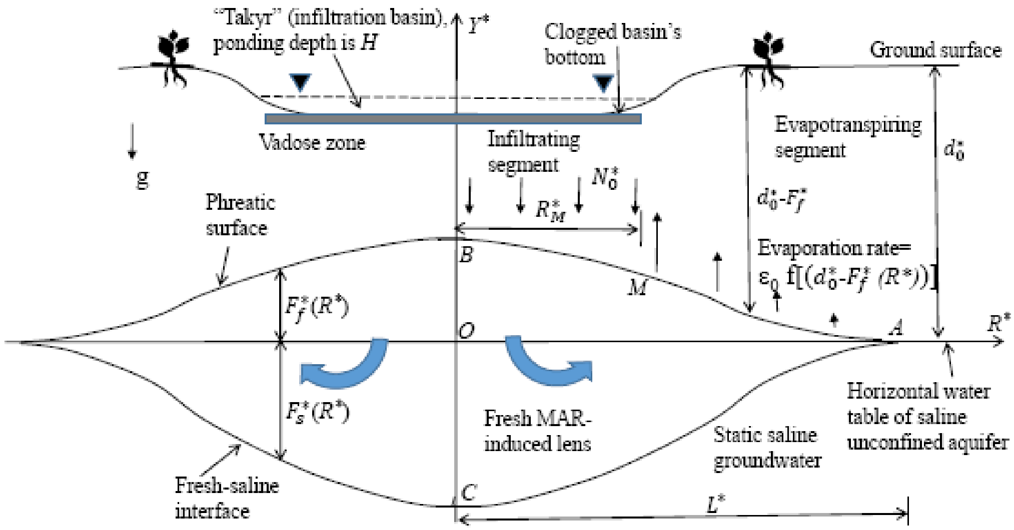


Figure 3.

Evapotranspiration (usually ignored in MAR models) is a key hydrological driver which maintains a stationary un-pumped desert lens subtended by saline static groundwater [4]. There is no abstraction (recovery) from the lens in Fig.3. Flow is axisymmetric and we consider one half of the axial cross section. A sharp interface *CA* in Fig.3 is a "magnified replica" of an *apriori* unknown phreatic surface *BMA*, along which the sink-source boundary conditions are similar to ones on the top of a Tothian "unit basin" [13], usually assumed to be a fixed rectangle or trapezium. In other words, unlike the flow domains in [13] ours is bounded by two free surfaces and none of the characteristic points (*B,M,* or *A*) are *apriori* known.

Along the segment *BM* of the phreatic surface the lens is recharged and along *MA* natural evapotranspiration discharges fresh water back into the vadose zone-atmosphere. The intensity of evaporation depends on the depth of *MA* under the ground surface according to the following relation:

$$\varepsilon=\varepsilon_0^* f(d_0^*-F_f^*[R^*]), \quad (8)$$

where ε_0^* is a given evaporation rate from a saturated ground surface (taken from, say, the FAO/Penman-Monteith formula) and *f* is a dimensionless function, which reflects experimentally measured decrease of evaporation from the water table with the increase of its depth. For simplicity of mathematical modeling, in [3] and [10] "trivial" regimes of a constant *f* and *f* linearly decreasing with the water table depth have been studied. Below, we adopt the model from [5], where experimental data for exponential relation in eqn.(8) have been reported.

The locus of point A (the tip of the lens) is a part of solution. The volume V_f^* of fresh water in the lens (a body of revolution) is a design parameter. We select cylindrical coordinates *(OR*Y*)*. The height of the water table above the reference plane Y^*=0 is $F_f^*(R^*)$.The depth of the interface is $F_s^*(R^*)$.

We use the Dupuit-Forchheimer model (see e.g. [10,12] for details) for flow inside the lens that yields an ODE

$$\frac{1}{R^*}\frac{\mathrm{d}}{\mathrm{d}R^*}\left(R^* k\,(F_f^*+F_s^*)\frac{\mathrm{d}F_f^*}{\mathrm{d}R^*}\right)=\begin{cases}-N_0^*, & 0\le R^*\le R_M^*,\\ \varepsilon_0^* f(d_0^*-F_f^*[R^*]), & R_M^*\le R^*\le L^*.\end{cases} \quad (9)$$

We select an evaporation function:

$$\varepsilon=\varepsilon_0^*\exp(-\alpha^*(d_0^*-F_f^{*2}[R^*])), \quad (10)$$

where α^* (1/m) is a given constant which quantifies the decay of evaporation with depth.

According to the Ghijben-Herzberg relation [10,12] the height of the water table and depth of the interface are related as:

$$F_s^* = F_f^* / \gamma, \quad \gamma = (\rho_s - \rho_f) / \rho_s. \tag{11}$$

We introduce dimensionless quantities:

$$(F_s, F_f, R, Y, R_M, L, d, d_0) = (F_s^*, F_f^*, R^*, Y^*, R^*_M, L^*, d^*, d^*_0) / V_0^{1/3},$$

$$\varepsilon_0 = \varepsilon_0^* / k, \ \ N_0 = N_0^* / k, V_f = V_f^* / V_0, T = T^* k / V_0^{1/3}, \alpha = \alpha^* V_0^{1/3}, \beta = 1 / \sqrt{T\pi}, R_M = \beta / \sqrt{N_0}$$

Then eqn.(9) reads:

$$\frac{\gamma}{1+\gamma} \frac{1}{R} \frac{\mathrm{d}}{\mathrm{d}R}\left[R\, F_f \frac{\mathrm{d}F_f}{\mathrm{d}R} \right] = \begin{cases} -N_0, & 0 \le R \le R_M, \\ \varepsilon_0 \exp(-\alpha(d_0 - F_f^2[R])), & R_M \le R \le L, \end{cases} \tag{12}$$

The following boundary conditions are:

$$F_f'(0) = 0, \quad F_f(L) = 0. \tag{13}$$

They reflect field observations of “takyr” lenses [6] which are indeed symmetric and taper towards point *A* in Fig.3.

By integrating eqn. (12) over the interval $(0, R_M)$ under the first condition (13), we obtain

$$F_f(R) = \sqrt{c - \frac{N_0(1+\gamma)}{2\gamma} R^2}, \tag{14}$$

where *c* is an unknown integration parameter (the apex of the MAR groundwater mound). A trivial “ellipsoidal cap” (14) appears due to linearity of eqn.(12) with respect to Strack’s comprehensive potential [11]. Along the interval (R_M, L), eqn.(12) is a nonlinear second-order ODE with two boundary conditions:

$$F_f(R_M) = \sqrt{c - 0.5N_0(1+1/\gamma)R_M^2}, \ F_f(L) = 0. \tag{15}$$

The boundary-value problem (12), (15) has to be solved in a domain of an unknown width $L - R_M$ and with a boundary condition at the left edge, which depends on c i.e. the elevation of point *B* (Fig.3), the apex of the “ellipsoidal “cap” of the lens. In this manner, the infiltrating centre of the lens is conjugated with its evapotranspiring “periphery”.

The value of *L* is found from conservation of mass:

$$N_0 R_M^2 = 2\varepsilon_0 \int_{R_M}^{L} \exp[-\alpha(d_0 - F_f^2(R))] R \mathrm{d}R. \tag{16}$$

Eqn.(16) states that all water which enters the lens through an infiltration disk (bounded by *BM* in the axial cross-section of Fig.3) makes a U-turn and exfiltrates/evapotranspires through the annular zone (bounded by *MA*), exactly as the Toth model [13] stipulates. The volume of fresh water in the lens is:

$$V_f = 2\pi(1+1/\gamma)\int_0^L r\, F_f(r) \mathrm{d}r.$$

We used *Mathematica* routines NDSolve and NIntegrate [14] to solve the boundary-value problem (12)-(16).

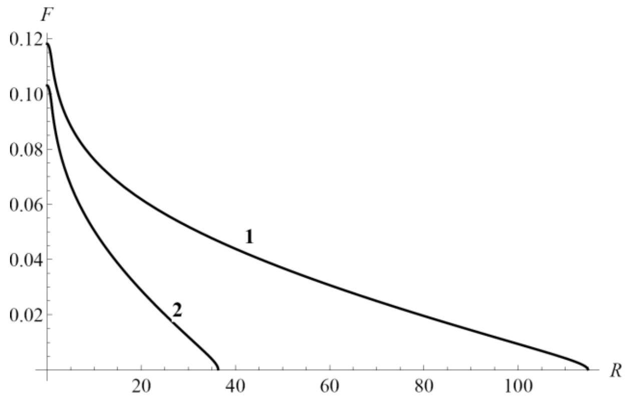


Figure 4

Figure 4 shows the computed water table for d_0=1, N_0 =0.1, $\alpha = 5$, β=0.316 (R_M =1), γ =0.03 and ε_0=0.001 and 0.01 (curves 1-2, correspondingly). The radii L of the "takyrs" in Fig.4 are 114.8 and 36.5, the fresh water volumes V_f are 32520 and 3256 i.e. significantly reduced by increased evaporation, although the apex B dropped less than 20%.

4. Discussion

In saline confined aquifers of arid deserts, a new technology of MAR by continuous injection-abstraction of fresh water into a confined (i.e. evaporation-protected) aquifer is proposed. Pore water circulates in a "bubble" vertically squeezed by a caprock and bedrock and laterally bounded by sharp interfaces demarcating a heavy and static groundwater. Mathematically, this problem is similar to another (traditional) MAR scheme: infiltration of fresh water from a surface basin into a fresh water lens which "floats" on saline groundwater [6]. We developed two conceptual models and obtained new analytical and numerical solutions for potential 2-D and axisymmetric Dupuit-Forchheimer flows and solute transport in the "bubble" and lens. In particular, we found the sizes of MAR-generated fresh water zones. Phreatic surfaces, sharp interfaces or transition zones between waters of contrasting density-salinity are delineated. It is noteworthy that steady state flow of fresh pore water is maintained by a continuous action of an intricately commingled hydrodynamic dyad (source and sink, either linear or distributed). Without a sink (abstraction well or evapotranspiration) a steady lens or "bubble" do not exist. Our solutions answer several pending questions [6,7] on mechanisms of MAR in desert oasis lenses, viz. how the sizes of the fresh water entities depend on the density contrast of the two waters, infiltration-evaporation or injection-abstraction rates and geometrical parameters of the corresponding dipole schemes. Analytical and numerical tools can be also used for optimization of characteristics of the "bubbles" and lenses, e.g. the lens storage V_f can be maximized by varying the basin sizes R_M and infiltration rate N (proportional to the depth of water in the "takyr").

Acknowledgments: This work was supported by SQU, grant IG/CAMS/SWAE/18/01. The cost to publish in open access is not covered by this grant.

Author Contributions: A.K. and Yu.O. developed analytical solutions; A.A-M. obtained numerical solutions; all three authors wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations:
The following abbreviations are used in this manuscript:
ASR: Aquifer storage and recovery
MAR: Managed aquifer recharge.

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Paper for ISMAR10 symposium. ***Topic No:*** *8* ***(028#)***

Conjunctive Use of Aquifer Storage Recovery Wells and Desalination to Mitigate Salt Water Intrusion and Achieve Water Supply Reliability

R. David G. Pyne

ASR Systems LLC, Gainesville, Florida, USA

*Correspondence e-mail: dpyne@asrsystems.ws

Abstract: Aquifer Storage Recovery (ASR) is increasingly utilized in conjunction with desalination and other advanced water treatment processes, particularly in coastal and other areas subject to salt water intrusion, subsidence, flooding and loss of power supplies. This reduces overall capital and operating costs while achieving water supply reliability during droughts and emergencies, plus meeting peak seasonal demands from aquifer storage. ASR is a subset of Managed Aquifer Recharge. Water of suitable quality is stored underground through wells during times when it is available and is recovered when needed to meet a broad variety of needs. To date, 30 different applications of ASR have been identified but the primary applications are for meeting seasonal and drought water demands and providing water supply reliability during emergencies. Interesting examples include two ASR programs at Hilton Head Island, South Carolina, which have now been operating for five or more years storing desalinated groundwater plus seasonally available treated surface water; plus three in Texas which are in development to store desalinated saline groundwater, fresh groundwater and surface water, and one in California, which is partially constructed and will store very highly treated wastewater. An interesting element for two of these ASR projects is the planned vertical stacking of ASR storage in two or more aquifers at the same location. One proposed project would utilize landfill methane gas to provide power supply for a desalination plant.

Key Words: aquifer storage recovery; desalination; subsidence control; salt water intrusion; methane gas for power supply.

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1. Introduction

The first applications of ASR at Wildwood, New Jersey; Gordons Corner, New Jersey; Goleta, California; Manatee County, Florida and many others were focused on meeting seasonal peak demands from aquifer storage, rather than from expanding water treatment plants to meet increasing peak demands. The potential for significant cost savings associated with this ASR approach, typically exceeding 50%, motivated all of these projects. As the years went by, other applications of ASR were recognized and implemented. To date 30 different applications of ASR to meet a variety of water management needs have been identified. These are shown in Table 1.

Table 1. ASR Applications.

1. Seasonal storage and recovery of water
2. Long-term storage, or "water banking"
3. Emergency storage, or "Strategic Water Reserve."
4. Diurnal storage
5. Disinfection byproduct reduction (TTHM and HAA5)
6. Restore groundwater levels
7. Reduce subsidence
8. Maintain distribution system pressure
9. Maintain distribution system flow
10. Improve water quality
11. Prevent salt water intrusion (salinity barrier)
12. Reduce environmental effects of streamflow diversions
13. Agricultural water supply
14. Nitrogen reduction
15. Phosphorus reduction
16. Total organic carbon reduction
17. Hydrogen sulfide reduction
18. Arsenic attenuation
19. Enhance wellfield production
20. Defer expansion of water treatment facilities
21. Compensate for surface salinity barrier seepage losses
22. Reclaimed water storage for reuse
23. Soil aquifer treatment
24. Stabilize aggressive water
25. Hydraulic control of contaminant plumes
26. Water temperature control, such as for fish hatcheries, industrial processing
27. Aquifer thermal energy storage (ATES)
28. Maintenance or restoration of aquatic ecosystems
29. Reducing distribution system water temperatures to control biological growth
30. Transferring water rights from one location to another

There are more than 500 ASR wells operating in the USA, at approximately 140 ASR wellfields in about 25 states, distributed nationwide. Many more ASR wells are operating or in development in many other countries. Well depths typically range from 50m to 1,000m and individual well yields range from about 2 Ml/D to 23 Ml/D. Hydrogeologic settings typically include semi-confined and confined aquifers, although a few ASR wells are in unconfined aquifers. Lithologic settings include sand and gravel aquifers, limestone, sandstone, basalts, glacial deposits and fractured crystalline rocks.

A logical first step in any proposed ASR program is to identify applications of potential interest at any proposed site, and then to rank those applications in order of importance. That exercise helps to ensure that ASR wells are located correctly and are constructed in the best aquifer(s) or storage interval(s).

The following recent examples illustrate a variety of ASR applications and associated lessons learned.

2. ASR Cases

2.1. Hilton Head Public Service District, Hilton Head, South Carolina

A presentation on this project was presented at ISMAR8 in Beijing in 2013, so a repeat of that presentation is not suggested. However, a recent development of interest is completion of a review of daily operating data for the first seven years of operation (2011 to 2018). The purpose of the review was to evaluate whether any changes in operating procedures would be appropriate.

Briefly, Hilton Head Island is a coastal residential/tourist community that obtains most of its water supply from local wells, supplemented during winter months with imported drinking water from the mainland, obtained originally from the Savannah River and treated to meet drinking water standards. The imported water is available during winter months at approximately half of the normal wholesale cost during peak summer months, providing a strong financial incentive for storing water in winter months and recovering it from storage during summer months. Originally local water supply wells were completed in a shallow (30m to 80m) fresh semi-confined limestone aquifer, however during the past few decades these wells have been steadily lost to salt water intrusion caused primarily by heavy groundwater production on the mainland. They have been replaced by a combination of new brackish water supply wells in a deeper semi-confined limestone aquifer (156m to 175m), water from which is treated with desalination. An ASR well was constructed during 2011 to 2013, storing seasonally available treated drinking water from the mainland, supplemented by any spare capacity from the desalination plant. A buffer zone was originally estimated at 900 Ml to separate the stored drinking water from the surrounding brackish groundwater. The Target Storage Volume (TSV) comprising the buffer zone volume plus the volume required each summer for recovery to meet peak demands was originally estimated at 1800 Ml. Well recharge and recovery flow rates are about 7.6 Ml.

Original well construction and testing indicated the following aquifer hydraulic and water quality characteristics: Transmissivity 418 m^2/D; Storativity 1 x 10^{-4}; Thickness 29 m; Static Water Level 8 m below ground surface; Chloride concentration 685 mg/l.

From analysis of seven years of operating data from the ASR well and two monitor wells, one in the storage aquifer at a distance of 100m and another that is close to the ASR well but in the overlying, salt-water intruded aquifer, the following conclusions were drawn:

- Recovery efficiency achieved 100% early during this period and has remained at 100% since then. Initial formation and maintenance of the buffer zone has been successful to ensure acceptable recovered water quality.
- Recovery water quality has been very similar to recharge water quality. Slight, consistent changes in pH and slowly increasing specific injectivity suggest some limestone dissolution.
- The original estimate of Target Storage Volume (TSV) and buffer zone volume (1,800 Ml and 900 Ml, respectively) were surprisingly close to the values evident from seven years of operations, which were 1,900 Ml and 950 Ml.
- Water is stored not only in the storage aquifer but also in the overlying semi-confining layer, displacing native brackish water vertically upward during recharge months and being displaced by water moving downward during recovery periods. The greatest pressure differential causing vertical water movement is adjacent to the ASR well. At the end of a typical summer ASR recovery period lasting about four months, the chloride concentration at the ASR well is slightly higher than the chloride concentration in the

storage zone monitor well, about 100m away. Recovery continues until the chloride concentration is less than 250 mg/l, the drinking water standards, or until the need for recovery to meet peak demands is over. Actual end of recovery chloride concentrations have ranged from 184 mg/l to 230 mg/l. At the beginning of recovery, the chloride concentration is about 45 mg/l. The storage aquifer baseline chloride concentration is 685 mg/l.

- Supporting the conclusion that some limestone dissolution is occurring in the storage aquifer is that the original wellhead pressure to achieve a recharge rate of 7.6 Ml/D was 19.3 psi. This has steadily declined to 10.5 psi in 2018.

Of particular interest is that during summer 2018 Hurricane Florence hit the east coast of the USA, causing major damage. Hilton Head Island lost its power supply, water supply and road access for several days. However, HHPSD was able to maintain its emergency water supply from the ASR well, which had been equipped with a standby generator and fuel supply. Emergency water supply and achieving water supply reliability are two of the more common ASR objectives identified to date, along with meeting seasonal peak demands. Twenty-seven other ASR objectives have been identified to date, as shown in Table 1.

A second ASR installation on Hilton Head Island has two ASR wells and has been operating since 2014 with great success. The owner is South Island Public Service District. The storage aquifer is the same as for Hilton Head PSD, however the water source for recharge is a combination of shallow aquifer freshwater wells that have not yet been lost due to salt water intrusion, plus desalinated water from a 3,700 ft deep Cretaceous aquifer well. One of the ASR wells is at ground elevation of 2m where the hurricane storm surge elevation is 4m. The wellhead facilities are on a platform elevated above the storm surge level and are enclosed in a wellhouse.

2.2. New Braunfels Utilities (NBU), Texas

Located near San Antonio, Texas, New Braunfels is one of the fastest growing cities in the USA. Water supplies are obtained partly from wells in the freshwater portion of the Edwards aquifer, which is a very productive, limestone aquifer that outcrops in the New Braunfels area. Groundwater withdrawals are restricted during droughts in order to maintain minimum flows in Comal Springs, a greatly-valued environmental feature in the region. Depending on drought severity, groundwater withdrawals may be reduced by up to 44%. Groundwater production is supplemented by withdrawals from the Guadalupe River, which is also fed by discharges from the freshwater portion of the Edwards aquifer. During droughts, diversions from the river may also be severely reduced. Achieving water supply reliability during droughts, while also meeting peak summer demands, is therefore an important element of long-range water supply planning for NBU.

Beginning with an ASR feasibility study completed in 2012 and followed by construction and testing of a monitor well and continuous wireline core hole in 2018, an ASR development program is underway. The selected site is adjacent to the New Braunfels Regional Airport, about 8 km from Comal Springs. The Edwards aquifer at this location is divided into an Upper Edwards and a Lower Edwards, separated by what is known as a “Regional Dense Member (RDM),” about 7 m thick, that appears to be continuous and provides good confinement. Both the Upper Edwards and the Lower Edwards are saline and are believed to be fully-confined, above and below. Total dissolved solids (TDS) concentration of the Upper Edwards, extending from 165m to 217m is 9,460 mg/l, as determined from samples pumped from the onsite monitor well in this interval. TDS concentration of the Lower Edwards, as obtained from a sample pumped from the monitor well during construction, is estimated at 10,000 mg/l and may be higher than that. The Lower Edwards extends from 226m to 290m.

Procurement is underway for construction of an ASR demonstration well and a Lower Edwards monitor well at this site, plus two additional monitor wells to be located 3.2 km toward Comal Springs, one in the Upper Edwards and one in the Lower Edwards. The purpose of these two monitor wells is to monitor any water level or water quality changes that may be caused by future ASR wellfield operations. No such impacts are expected. The ASR well will be constructed with a nominal 500mm open borehole from 180m to 216m. Inner casing will be either 610mm OD SDR-17 PVC Certa-Lok or 316L stainless steel, depending on the selection by the qualified well driller who provides the lowest bid. Stainless steel is far more expensive but can be grouted in a single procedure. PVC is less expensive, but requires grouting in several stages, typically a day apart, to avoid weakening and collapse of the casing. During future phases of construction, the wellfield would be expanded with additional ASR wells, tentatively spaced about 200m apart in a cluster, assuming that the demonstration well is deemed successful.

ASR storage of drinking water in brackish aquifers has been implemented successfully at many locations, including storage aquifers with TDS concentrations of 8,000 mg/l, 20,000 mg/l and 35,000 mg/l (sea water). Many ASR wells are storing water in aquifers with TDS concentrations in the range of 1,000 mg/l to 6,000 mg/l. In addition to salinity, key technical issues affecting ASR success include aquifer thickness and confinement; hydraulic conductivity of the materials in the storage aquifer; duration between end of storage and beginning of recovery, expected recovery duration and regional lateral velocity in the storage aquifer. For NBU, the expected recovery duration is up to nine months continuously during a hypothetical repeat of the Drought of Record, which lasted from 1947 to 1956. Expected recovery rate from a single ASR well is in the range of 4 to 8 Ml/D. A key issue that has yet to be confirmed is the effectiveness of the Regional Dense Member (RDM) to provide lower confinement. Geotechnical analysis of two core sections from this interval indicated essentially no vertical hydraulic conductivity, which is encouraging. However, the RDM is not very thick so it is possible that a fault or fracture may exist near the well, close enough to affect ASR plans. Aquifer performance testing at the ASR demonstration well will indicate whether upwelling of brackish water from the Lower Edwards, moving through the RDM, would occur during a nine-month period during which water stored in the Upper Edwards would be pumped out to meet service area water demands. To some extent, the pumping rate from the Upper Edwards can be adjusted to increase or reduce the head differential across the RDM and thereby manage any upconing.

Another interesting feature of this project is that the stored drinking water will be slightly less dense than the native groundwater, so it will tend to “float.” It will tend to “pancake” against the underside of the overlying confining layer and spread out away from the well. It will be replaced at the base of the Upper Edwards by more brackish water moving slowly toward the ASR well. This effect will likely be small since the density differential will be small. It is analogous to having a big storage tank with a small hole in the bottom. A typical solution is to cluster the wells closer together, create an adequate buffer zone around all of the wells, and if necessary to supply a trickle flow of recharge water during storage periods. Other options are available, such as recharge over the full thickness of the storage aquifer but recovery only from the upper producing intervals; or use of the Lower Edwards for ASR storage, in addition to the Upper Edwards. This is called “stacking.” Any water leaking through the RDM during ASR recovery would then be fresh, not brackish. This would reduce the number of ASR well sites required since two wells would be at each site, side by side.

There is a trade-off between individual ASR well yield, spacing between wells in an ASR well cluster, and minimizing the potential for upconing of brackish water from the Lower Edwards to the Upper Edwards during an extended ASR recovery period. Data from the ASR demonstration well will help to achieve an optimum configuration of wells and wellfield facilities, and operation of the wells.

2.3. Harris Galveston Subsidence District, Texas (HGSD)

Many areas around the world are experiencing subsidence due to heavy groundwater production. For coastal areas this can be a serious challenge compounded by climate change and sea level rise. For the Houston Texas area of Harris and Galveston counties this is a major issue, with areas along the Houston Ship Channel having subsided up to two meters. Regulations have been developed and implemented to limit groundwater production from local aquifers and to encourage water importation to the region. Local surface water supplies from the Brazos River are usually plentiful; however during a recent dry period it became apparent that actual availability during a more severe drought might be inadequate to meet local needs. Recently a study was conducted to evaluate whether “subsidence-neutral ASR” might be viable for storing water deep underground to help meet demands during a severe drought while not contributing to any further subsidence. The study was conducted by INTERA in association with ASR SYSTEMS and ARCADIS. The area is underlain by coastal plain sediments to depths exceeding 1,000 m.

Most of the study related to hydrogeology and groundwater modeling, focused on subsidence estimates associated with different assumed ASR operating scenarios. For the purpose of this paper, a particular element of the study was to develop the conceptual design for a 19 Ml/D ASR wellfield, stacking the water vertically in several confined aquifer intervals at depths up to about 700m. Sand bed thicknesses were typically in the range of 30m to 150m, separated by clay layers 6 to 15m thick. The wellfield area was compact, including 10 closely-spaced ASR wells storing water in 5 storage intervals. Shallower intervals were more productive, marginally fresh to brackish, with relatively greater historic subsidence but also a significant subsequent recovery of groundwater levels. The working assumption at the time was that so long as pumping water levels during ASR recovery did not lower water levels below historic water levels, little to no additional subsidence would occur. That working assumption was later found to be inaccurate. Deeper intervals were less productive and more brackish; however preconsolidation of these deeper coastal sediments, caused by the weight of the overlying sediments, would suggest that they were likely to be less vulnerable to subsidence than shallower sediments. Deeper intervals were also more likely to be geochemically sensitive. The operational concept that emerged was for the shallower storage aquifers to be utilized primarily for storage to meet normal seasonal peak demands while deeper storage aquifers would be utilized for longer-term storage to meet demands during extended droughts. Multiple ASR wellfields may then be developed across the area, meeting projected water needs with high reliability.

The concept of "subsidence-neutral" ASR remains to be developed further or to be implemented locally. Modeling and studies of subsidence at other locations such as Las Vegas, Nevada, USA; Shanghai, China, and Antelope Valley, California suggest that subsidence may continue for many years, decades or longer after depressurization of an aquifer has been reversed. It may be difficult to separate out any increment of future subsidence due to ASR operations from subsidence due to historic groundwater production.

A related remaining question still to be addressed is "subsidence neutral within what radius around an ASR well or wellfield?" Would 10m be acceptable, or 100m, or 1,000m? Most analyses and models to date indicate that subsidence potential is greatest very close to a well and rapidly diminishes with increasing radial distance. But these are model results, not validated with field surveys around operating ASR wells after a few years of operation.

A key finding of the study was that ASR, as compared to pumping without ASR, can result in less compaction while producing the same volume of groundwater. This introduced the concept of ASR Credits. The concept of an ASR Credit would expand the amount of groundwater a permit holder could pump. An ASR Credit would be associated with a specific project site condition and predictions of compaction. The ASR Credit would be dependent upon the project's unique operating requirements and the hydrogeology at the site.

For others around the world who are faced with similar subsidence issues, it would be worthwhile to monitor how this develops at HGSD over the next few years.

2.4. Barton Springs Edwards Aquifer Conservation District, Texas (BSEACD)

Located near Austin, Texas, BSEACD is a local regulatory agency that manages water resources for its 66,000 Hectare service area. A recently completed investigation is of considerable interest and potential transfer value globally. Adjacent to the service area is a very large landfill that processes municipal waste products from the entire Austin region. A large portion is recycled while the remainder goes to the landfill. It is one of the largest landfills in the USA. The landfill is underlain by an impermeable, thick clay layer that serves as an effective overlying confinement for the Edwards aquifer, which is brackish at this location. As at New Braunfels, the Edwards aquifer is divided into an Upper Edwards aquifer and a Lower Edwards aquifer, separated by the Regional Dense Member (RDM). The Upper Edwards has a TDS concentration of about 9,000 mg/l and the Lower Edwards has a TDS concentration of up to about 18,000 mg/l. Although some uncertainty remains, the saline portion of the Edwards aquifer in this area is believed to be quite productive.

The conceptual plan that was developed by Carollo Engineers, assisted by ASR Systems, was to produce saline water from the Lower Edwards; desalt the water to meet drinking water standards; and store it seasonally in the Upper Edwards at the same landfill site, but at a lateral distance of about 3 km. The energy required for desalination would be obtained by running an engine generator with landfill methane gas, a steady supply of which is expected for at least the next 40 years. Brine resulting from the desalination process would either be pumped into a much deeper aquifer at the site, if the TDS of that aquifer exceeds 10,000 mg/l TDS. If it does not, then the brine would need to be pumped several kilometers to a location more suitable for brine disposal by deep well injection.

The conceptual ASR plan included three saline water production wells; three ASR wells, and several monitor wells, plus associated wellhead facilities. A 1 m diameter potable water transmission pipeline owned by the City of Austin is adjacent to the site, providing an opportunity for integrating local ASR operations with regional water supply reliability goals. Much larger volumes could be stored and recovered at this site, supplementing production from the landfill desalination plant.

BSEACD is currently developing a regulatory framework to guide development of ASR operations within their service area. Further progress with development and implementation of the landfill ASR program will probably await the outcome of these regulations. This proposed project illustrates the potential for implementing desalination at locations far inland from the coast and utilizing methane gas from landfills as the energy source for desalination/ASR operations.

2.5. City of Oxnard, California

Situated in southern California where rainfall is negligible and water supply reliability is a continuing, significant challenge, the City of Oxnard has constructed an advanced wastewater treatment plant that produces excellent water quality consistently meeting all California drinking water standards. It has also constructed, but not yet equipped, an ASR well. Under current state regulations a final step in the treatment process is to store the water underground for at least three months. It may then be recovered and blended with other drinking water sources, disinfected and sent to customers. The next step in the Oxnard program is to equip the existing ASR well for recharge, storage, recovery, periodic back-flushing to waste, and trickle flow recharge during extended storage periods and then to begin cycle testing operations. Once ASR viability has been validated, the City can add ASR wells as needed.

This is not the first well to be recharged with advanced treated reclaimed wastewater, however it may be the first ASR well. Other locations producing high quality reclaimed water for aquifer recharge tend to use recharge wells or injection wells. The primary objective is to get the water into storage or to dispose of the water, without specific plans or goals for ultimate recovery. For Oxnard, the clear objective is to store the water for three months or more, and then to recover it from the same well for potable use. This is a textbook example of ASR. Unless recharging a cavernous aquifer system, most recharge wells or injection wells need to be designed just like ASR wells so that adequate facilities are provided for periodic back-flushing to waste to control well clogging, and for maintaining a disinfectant residual downhole during any extended storage periods. The appropriate wellhead facilities design is the same as for ASR but the operation is different. The well design for an ASR well, however, can be quite different compared to the well design for a recharge well or an injection well.

Many urban areas globally have significant water supply reliability challenges. The most reliable supply of water during droughts is often treated wastewater. The advanced wastewater treatment cost may be high, however the demonstrated viability of ASR as an additional step to protect public health helps to not only provide aquifer treatment due to natural physical, microbial and geochemical processes, but also to gain public support. Oxnard will soon join other communities as part of this demonstration.

3. Conclusion

Experience gained at other ASR locations can provide useful points of reference to guide development of future ASR wells and wellfields. Examples discussed in this paper provide a variety of ASR applications and lessons learned. There are many more ASR examples from which lessons can be learned.

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Paper for ISMAR10 symposium. ***Topic No: 8 (037#)***

Recharge Systems in Urban Area as a Method of Groundwater Storage Enhancing

Sunjoto Suny[1]

[1] Department of Civil & Environmental Engineering, Universitas Gadjah Mada; sunysunyoto@ugm.ac.id
* Correspondence: sunysunyoto@ugm.ac.id; Tel.: +62-811-259-694

Abstract: Drainage engineering is a technique which was implemented since ancient civilization with the aim to maintain some places from excess water. Usually the excess water comes from precipitation falls on the roofs and other impermeable pavements, then the runoff inundated with water the lower elevation of ground surface. The existing technique till now days is to allow water flows from inundation area to drainage canal then to river and finally to the sea, therefore the source of groundwater storage decreases. This technique is not in accordance with sustainable development due to less rain water can infiltrate to the ground and this technique and it is called Con-water mazhab (School of thought). Since the last twentieth century researchers from many countries had developed manual of storm water management which are compatible to the Pro-water mazhab for instance from USA, Australia, Japan, Malaysia and some formulas from Indonesia. Almost of all those formulas of this system in this case recharge well and recharge trench, all together base on the difference of volume of water stored in the certain duration minus infiltration rate. Sunjoto S. (1988), developed analytically an unsteady state flow condition formula of computation of recharge well dimension and for the recharge trench was developed in 2008. All of those formulas will be implemented to compute the dimension of recharge well and recharge trench for equal data and the results will be analyzed to get the most reliable formula. The result of this study shows that Sunjoto's and USBR formulas are the most reliable from point of view of mathematical logic.

Key words: Drainage, Con-water mazhab, Recharge system, Pro-water mazhab, Groundwater storage.

1. Introduction

Ratification of Sustainable Development Goals (SDG's) had been done by members of United Nation and according to Part Six that providing of water and sanitation must be reached in 2030. In the developing countries for instance in Indonesia almost two third of the people get domestic water from swallow well and unfortunately the storage of groundwater decreases as an impact of urbanization which create density of population and density of buildings increase and water infiltrate to the ground decreases (Fig.1). Beside of those impacts it is triggered by drainage engineering which was implemented until resent day. Drainage engineering is one technique to maintain some places from excess water. Usually the excess water comes from the precipitation, which inundates the low elevation of ground surface. The technique implemented nowadays is to allow water flow to the drainage canal then to the river and finally to the sea and this technique can be called Con-water mazhab. This technique is not in accordance with sustainable development and the impact is degradation of groundwater storage. New techniques of drainage engineering had been developed since a year 1980 and this concept is called Pro-water mazhab. The principle of Pro-water mazhab is that the surface runoff not directly allowed flowing to the sea and it have to be infiltrated to the ground using well or trench as a recharge system. According to Sunjoto (2011) this technique can solve not only flood control problem but it can solve all at once pollution control problem and groundwater control problem, but the climate chance problem can't be solved by drainage engineering (Fig. 1). Many formulas had been developed by some researchers but the results of computation were not yet convergence results. In this paper the divergence of those formulas will be analyzed to get a reliable equation for the design using the equal data and the results will be analyzed.

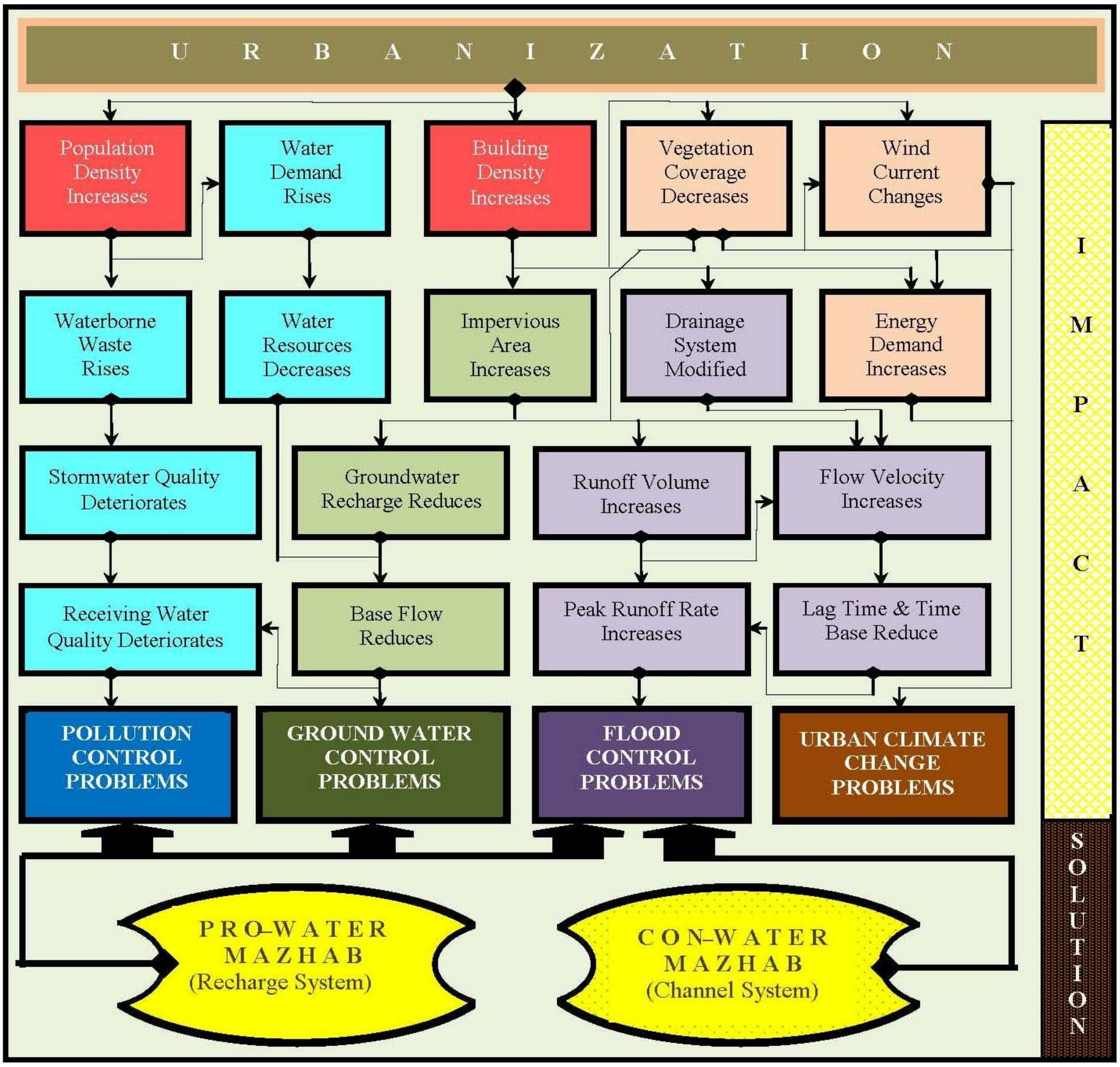

Figure 1. Flowchart of water resources degradation as an impact of urbanization and the solution alternative (Sunjoto, 2011).

2. Existing Formulas

Recharge system which the constructions are well and trench, is a technique of drainage engineering where runoff is not allowed flowing directly to the sea but it must be infiltrated to the ground. The dimension of recharge well and recharge trench can be computed by some equations which had been developed by many researchers. The dimension of the recharge system usually are the depth of water inside a well to determine height of well (*H*) and length of the trench (*L*). Parameters needed are hydrological data like intensity of precipitation, dominant duration of precipitation and geotechnical data like coefficient of permeability, soil layers and wall of well and trench condition. For the purpose to better understand of the comparison between each formula the parameters in this paper are changed to the generic legend without decreasing its substance, for example volume inflow is *V* instead of T_v (VSMM), depth of water is *H* instead of d_t (MSMA), etc, as on the original formula it differs each other. And for the dimension of the parameters are chosen SI (Standard International) instead of the others.

2.1. Recharge well formulas

Many researchers had developed formulas of computation to determine the dimension of recharge well and in this case is the depth of water on the well after certain time of flow as follows:

1. Sunjoto (1988)

Sunjoto in 1988 developed an equation to compute built up of recharging well on the unsteady state condition which was derived mathematically by integration solution, as:

$$H = \frac{Q}{FK}\left\{1 - exp\left(\frac{-FKT}{n\pi r_w^2}\right)\right\} \quad (1)$$

This equation (1) can compute the condition of permeable and impermeable wall of well using different value of shape factors and for unique soil layer and the equations are:

- Permeable wall

  Shape factor for partial penetration well on unconfined aquifer and permeable wall of well (Sunjoto, 2017):

$$F = \frac{2\pi(H + r_w ln2)}{ln\left\{\frac{H + 2r_w}{2r_w} + \sqrt{\left(\frac{H}{2r_w}\right)^2 + 1}\right\}} \quad (2)$$

- Impermeable wall

  Shape factor for partial penetration well on unconfined aquifer and impermeable wall of well (Sunjoto, 2002):

$$F = 2\pi r_w \quad (3)$$

2. DPW-GOI (1990)

In 1990, Department of Public Works Government of Indonesia (DPW-GOI) developed a formula that the depth of well is measured from difference volume of inflow water from the roof with outflow water on the well through only base of well (impermeable wall) or also through the wall of well (permeable wall) and in certain duration as:

- Permeable wall

$$H = \frac{AIT - \pi r_w^2 KT}{\pi r_w^2 + 2\pi r_w KT} \quad (4)$$

- Impermeable wall

$$H = \frac{AIT - \pi r_w^2 KT}{\pi r_w^2} \quad (5)$$

3. USBR (1990 in Massman 2004)

United Stated Bureau of Reclamation (USBR) developed a computation formula of dimension of well without casing it means that the wall of well is permeable can be computed by:

$$Q = \frac{2\pi K H^2}{ln\left[\frac{H}{r_w} + \sqrt{1 + \left(\frac{H}{r_w}\right)^2}\right] - \frac{\sqrt{1 + \left(\frac{H}{r_w}\right)^2}}{\frac{H}{r_w}} + \frac{1}{\frac{H}{r_w}}} \quad (6)$$

it can be rewritten as:

$$H = \sqrt{\frac{Q\left[ln\left\{\frac{H}{r_w} + \sqrt{1 + \left(\frac{H}{r_w}\right)^2}\right\} - \frac{\sqrt{1 + \left(\frac{H}{r_w}\right)^2}}{\frac{H}{r_w}} + \frac{1}{\frac{H}{r_w}}\right]}{2\pi K}} \quad (7)$$

4. Imbe & Musiake (1998)

Masahiro Imbe from Association for Rainwater Storage and Infiltration Technology (ARSIT), Japan and Katumi Musiake from Department of Administration & Social Science, Fukushima University, Japan developed the formulas in *A Simplified Estimation of Infiltration Capacity for Infiltration Facilities* as follows:

- Permeable wall for diameter 0,2 m ≤ ϕ ≤ 1 m:

$$H = \frac{Q - K(4.0374 r_w - 0{,}15228)}{\frac{\pi\, r_w^2}{T} + K\left((0{,}7695 r_w + 0{,}76545)H + (9.8334 r_w + 0{,}8181)\right)} \quad (8)$$

- Impermeable wall for diameter 0,3 m ≤ ϕ ≤ 1 m:

$$H = \frac{Q - K(3.6612 r_w^2 + 1.03356 r_w - 0{,}00891)}{\frac{\pi\, r_w^2}{T} + K(2.42514 r_w + 0{,}081)} \quad (9)$$

5. Rusli (2004)

Rusli (2004) on his thesis developed a formula for permeable wall in difference form as:

$$H = \frac{1}{2}\left(\frac{CIA}{\pi . r_w . K} - r_w\right) \quad (10)$$

Where:

Q; discharge inflow or rate of flow (L^3/T); *F*: shape factor of well (**L**); *K*: coefficient of permeability (L/T); *H*: depth of water on the well (L); *T*: duration of inflow; r_w: radius of well (L); and *Q*=*CIA*; *C*: runoff coefficient; *I*: intensity (L/T); *A*: area of roof or pavement (L^2)

2.2. Recharge trench formulas

When water level of groundwater is high enough, implementation of recharge well is not an appropriate technique due to the lower part of recharge well will be fulfilled by existing ground water. The solution is development a horizontal recharge structure and it is called recharge trench. Many researchers developed dimension of recharge trench, to compute the length of trench when depth of water on the trench and width of trench have been determined. In the region that gravels and boulders are available, many recharge trenches don't need wall and the hole of the trench will be fulfilled by those material and as a consequence diameter of trench will be bigger due to only porosity of filling materials as a space available and the existing formulas are:

1. Imbe & Musiake (1998)

Beside of the formula of recharge wells, Imbe and Musiake, (1998) developed formulas of trench for permeable and impermeable wall:

- For permeable wall:

$$H = \frac{Q - K(1.0854W + 0.54837)}{\frac{WL}{T} + 2.50533K} \quad (11)$$

it can be rewrite as:

$$L = \frac{T\{Q - K(1.0854W + 0.54837) - 2.50533KH\}}{WH} \quad (12)$$

- For impermeable wall:

$$H = \frac{Q - 1.04247K}{\frac{WL}{T} + 0.01134K} \quad (13)$$

it can be rewritten as:

$$L = \frac{T\{Q - 1.04247K - 0.01134KH\}}{WH} \quad (14)$$

2. SMMWA (2004)

Stormwater Management Manual for Western Australia (SMMWA) developed an equation to compute length of trench as follows.

$$L = \frac{V}{\left[nWH + KT\left(W + \frac{H}{2}\right)U\right]} \quad (15)$$

It can be rewritten:

$$H = \frac{\frac{V}{L} - 2KTWU}{nW + KTU} \quad (16)$$

3. Sunjoto (2008)

Sunjoto (2008) developed an equation to compute length of trench analytically by integration and got the unsteady state flow condition as:

$$L = \frac{-fKT}{nW\left\{ln\left(1 - \frac{fKH}{Q}\right)\right\}} \quad (17)$$

It can be rearranged as:

$$H = \frac{Q}{fK}\left\{1 - \exp\left(\frac{-fKT}{nWL}\right)\right\} \quad (18)$$

This equation can be implemented to compute dimension of trench for permeable and impermeable wall with different value of shape factor as:

- Permeable wall (Sunjoto 2008)

$$f = \frac{4H + 4\sqrt{WL}ln2}{ln\left\{\frac{H + 4\sqrt{WL}}{4\sqrt{WL}} + \sqrt{\left(\frac{H}{4\sqrt{WL}}\right)^2 + 1}\right\}} \quad (19)$$

- Impermeable wall (Sunjoto 2008)

$$f = 4\sqrt{WL} \quad (20)$$

4. MSMA (2012)

Government of Malaysia Department of Irrigation and Drainage 2012, Urban Stormwater Management Manual for Malaysia, MSMA Second Edition, Chapter 8. Infiltration Facilities developed an equation for permeable wall as follows:

$$WL = \frac{V}{nH + KT} \quad (21)$$

it can be rearranged as:

$$L = \frac{V}{W(nH + KT)} \quad (22)$$

5. VSMM (2017)

In 2017, Vermont Stormwater Management Manual (VSMM) Rule and Design Guidance developed an equation for permeable wall as:

$$WL = \frac{V}{nH + KT} \quad (23)$$

it can be rearranged as:

$$L = \frac{V}{W(nH + KT)} \quad (24)$$

Where:

L: length of trench (L); *W*: width of trench (L); *H*: depth of water on the trench (L); *Q*: discharge water inflow to the trench (L^3/T); *V*: volume water inflow to the trench (L^3); *K*: coefficient of permeability of soil (L/T); *T*: duration of inflow (T); *f*: shape factor of trench (L); *n*: porosity; *U*: soil moderation factor (sand = 0.50; sandy clay = 1.0; medium heavy clay = 2.0)

2.3. Method of analyse

For the analyses of those formulas, the equal data of real condition from Yogyakarta Special Region Indonesia as:

- Depth of water on well — is *H* m (computed)
- Length of trench — is *L* m (computed)
- Area of roof or pavements — A= 200 m^2
- Intensity of precipitation — I = 0.036 m/h
- Coefficient of permeability — K= 0.24 m/h
- Duration of flow — T= 2 h
- Radius of well — r_w= 0.50 m
- Depth of water on the trench — H= 1.50 m
- Width of trench — W= 1.00 m
- Porosity of gravel filling — n= 1 (assumption)
- Soil moderation factor — U = 1.5
- Coefficient of runoff — C
- Discharge inflow — $Q = CIA$ (m^3/h)
- Volume water inflow — V and $V = CIAT$ (m^3)

These parameters are real data of hydrology and hydrogeology from Yogyakarta, Indonesia which were collected from secondary and the almost of area is medium and fine sand.

3. Results of Computation

This section contains results of computation of each formula using those equal data and for the well is presented on the Table 1 and for the trench can be seen on the Table 2. On the above formulas, researchers define the value of runoff coefficient in different value, therefore it will be small influence to the equalization of results of computation. The results of computation in these tables will be analyzed using comparison method. Beside of above analyzable method, those equations will be computed using imaginary data in this case surface roof or pavement area is null (A = 0 m^2) to solve the logical and reliability of the equation. From this analyze method can be concluded the equation which has most probable to be implemented for the design.

Table 1. Results of computation of depth of water on the well using equal data

No	Formula; {Equation}	Depth H (m) when A=200m²	Depth H (m) when A=0m²	Coef. Of Runoff (C)	Wall condition
1	Sunjoto (1988); {(1) & (2}}	2.69	0	0.95	Permeable
2	DPW-GOI (1990); {(4)}	6.11	< 0	1.00	Permeable
3	USBR (1990); {(7)}	2.64	0	0.95	Permeable
4	Imbe & Musiake (1998); {(8)}	2.10	< 0	0.81	Permeable
5	Rusli (2008); {(10)}	7.91	< 0	0.855	Permeable
6	Sunjoto (1988); {(1) & (3)}	7.74	0	0.95	Impermeable
7	DPW-GOI (1990); {(5)}	17.85	< 0	1.00	Impermeable
8	Imbe & Musiake (1998); {(9)}	7.81	< 0	0.81	Impermeable

3.2. Recharge trench

Table 2. Results of computation of length of trench using equal data

No	**Formula;** {Equation}	Length of trench L(m)	Depth H (m) when A=0m²	Coef. Of Runoff (C)	Wall condition
1	Imbe & Musiake (1998); {(12)}	6.05	< 0	0.81	Permeable
2	SMWA (2004); {(15)}	7.24	< 0	0.765	Permeable
3	Sunjoto (2008); {(17) & (19)}	4.54	0	0.95	Permeable
4	Imbe & Musiake (1998); {(14)}	7.44	< 0	0.81	Impermeable
5	Sunjoto (2008); {(17) & (20)}	6.39	0	0.95	Impermeable
6	MSMA (2017); {(22)}	5.82	< 0	0.80	Impermeable
7	VSMM (2017); {(24)}	5.87	< 0	0.85	Impermeable

4. Discussion

Those above tables show that the results of the computation of every equation with equal data have different values and it will be analyzed using the comparison and input data method.

4.1. Results of computation

- Recharge well
  The results of all equations of recharge well computation have similar value, except equation (4) and (5) which are too big compared to the others.
- Recharge trench
  The results of all equation of recharge trench computation are that the equation (12) and {(17) & (19)} for permeable wall of well have smaller result compared to the equation (14) and {(17) & (20)} for impermeable wall of well, it means that those are logical equations. For the overall result are difficult to be concluded due to it have not certain pattern.

4.2. Input of imaginery data

- Recharge well
  Imaginary data analyze for instance when we don't develop a house it is meant that no roof anymore or A = 0 m², therefore we don't need a recharge system therefore the value of H should be null. But the computation results of value of depth of water on the well all of those above equations are negative or $H < 0$ for equations (4), (5), (8), (9) and (10) except for the equation (1) and (7).
- Recharge trench

This condition has not difference results to the recharge well, when $A = 0$ m² all of equation have negative value of depth of water on the trench or $H < 0$ for equations (12), (14), (15), (22) and (24) except equation (17).

5. Conclusions

- From point of view of the result of computation equation for recharge well shows that almost of equations have similar value except equation (4) and (5) and for recharge trench is difficult to be concluded due to it don't have certain pattern.
- From point of view of mathematical logic it can be concluded that equation (1) and (7) for the well and equation (17) for the trench are the most logic equations. Sunjoto's equations (1) and (7) are unsteady state flow condition and all together can compute for permeable and impermeable wall. The USBR's equation (17) is steady state flow condition and for permeable wall only.

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Paper for ISMAR10 symposium. ***Topic No: 8 (078#)***

Review of groundwater recharge experiences in Madrid tertiary detrital aquifer

Nogueras, Raúl[1*]. Donoso, Lucía[2]. Iglesias, José Antonio[3] and Martínez, Isabel[4]

[1*]: rnogueras@canaldeisabelsegunda.es *
[2]: ldonoso@canaldeisabelsegunda.es
[3]: jaiglesias@canaldeisabelsegunda.es
[4]: is.martinezgarcia@gmail.com

Abstract: Canal de Isabel II (CYII) is the main water and wastewater service provider in the Madrid Region. Water supply is accomplished through 14 dams which storage 946 Mm^3. In extended periods of drought and/or disruptions in the water supply system CYII is able to produce up to 70 Mm^3 per year from the Tertiary Detrital Aquifer of Madrid (TDAM). Groundwater level recovers between extraction periods. In 2004, a residual drawdown of 20 m on average was observed in the well network. In 2008, Tajo River Basin Authority (CHT) published "Schema of Important Issues" (ETIS, 2008), outlining aquifer recharge as a measure to reach a good quantity status of groundwater bodies.

During the last 10 years, CYII has been developing several projects about experimental water recharge. These projects include from the study and construction of several facilities in order to prove the feasibility in two different GWB to legal processing and administrative procedures.

Three different approach to Aquifer Storage and Recharge (ASR) experiences are shown, considering several perspectives: legal procedures, facilities design and monitoring. Suitable areas, where groundwater recharge has been proved according to experiences, will be a future expansion, adapting CYII's groundwater facilities to recharge units.

This document summarizes permitting, experimental recharge tests development, ASR design and feasibility to expand recharge, choosing optimal areas on existing well fields.

Keywords: Groundwater recharge, water management, artificial recharge, aquifer, Canal de Isabel II, Tertiary aquifer.

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1. Introduction

The groundwater volumes authorized to CYII in the TDAM (030.010 GWB Madrid: Manzanares-Jarama, 030.011 GWB Madrid: Guadarrama-Manzanares y 030.012 GWB Madrid: Aldea del Fresno-Guadarrama GWB) are considered as a strategic resource for periods of drought or water scarcity risks. Groundwater is pumped if water storage volume of the dam system drops until a given value (The Tajo River Basin Management Plan 2016-2021, Annexe No. 7). In addition, well fields are used in contingency operations in the Autonomous Community of Madrid supply system.

The TDAM is a detrital aquifer, composed mainly of clay and sand which fill the Tajo Basin. The total depth is near to 3.000 m and its extension is 2.600 km^2 in the Madrid Region. The thickness of the aquifer used for water supply is limited to 700 m because groundwater quality changes dramatically in high depths. Water conductivity in TDAM is about 300 µS/cm.

The Water Framework Directive (DMA, 2000 by its Spanish acronym) and CHT in diverse documents consider artificial recharge as a technique to maintain and improve quantitative and qualitative status of the GWB, achieving environmental objectives. CYII as the main user of groundwater in the Madrid Region took this challenge by implementing three experimental ASR facilities.

There were not previous ASR experiences in the TDAM, so CYII developed a plan made up of three stages to analyze the viability of the ASR through deep wells.

15. Feasibility analysis
16. ASR tests
17. Implementation of ASR wells in CYII's well network.

In this paper, only the first two stages are explained because the implementation of ASR wells has not been developed yet.

2. Methods

ASR tests through deep wells in the TDAM were conducted after a detailed planning. The main stages were: Granting recharge permits by CHT, optimizing ASR well design to the existing wells and choosing optimal areas to analyze recharge effects.

2.1. Feasibility and viability analysis

2.1.1. Preliminary studies

Artificial recharge could be approached using different techniques depending on how water is injected in the aquifer: surface, subsurface or induced recharge.

CYII well network is distributed through the entire water supply system of the Madrid Region. Wells pump water into unpressurized or pressurized pipelines between WTP (water treatment plants) and the supply network.

Well depths are in a range between 450 and 700 m and water table is lower than 100 m. Artificial recharge has to be done at 200 – 400 m which is the same aquifer layer used by the water supply wells. Then, the more suitable technique is ASR in deep wells.

Recharge water is diverted from pipelines close by CYII wells. Water quality, in these pipelines, meets water supply standards (Royal Decree R.D 140/2003).

Before the beginning of ASR experiences some aspects were analyzed:

- Mixing processes or interaction between recharge water, groundwater and the aquifer matrix. PHREEQC code was used to simulate chemical reactions of the mixing process in the aquifer. Also, possible effects of trihalomethanes (THMs) which are in the recharge water.
- Methods to avoid air clogging, controlling water release (see 2.1.3).
- Legal analysis focused on three main targets: recharge management, water rights and environmental assessment.

Recharge management is not considered specifically on the Spanish legislation and it is treated in the same way as any other water release to a river or a public watershed.

Water rights over the amount of water recharged is not granted for the individuals or companies which are making the effort of recharging. Groundwater Users Community was studied as a possibility to handle water rights, but it was not developed.

From environmental perspective, recharge projects have to be evaluated according to Annexe I or Annexe II of the law 21/2013 depending on the recharged volume.

- Groundwater flow was simulated based on piezometric heads and volumes extracted in CYII well network, including estimated pumping volumes of other users.

Groundwater models are suitable in the development and management of groundwater resources, and in predicting effects of management measures, this is the reason why a flow model was done with data until 2006, and then after ASR test simulations, was updated until 2018 for evaluating different management scenarios by analyzing responses of the TDAM and as an assessment tool for evaluating groundwater recharge.

The model extension is about 4.000 km2 and covers the three main GWB of the Madrid Region: Manzanares-Jarama, Guadarrama-Manzanares and Aldea del Fresno-Guadarrama, classified by the CHT as GWB 030.010, 030.011, 030.012 respectively. The conceptual model consists of 2 layers. The first one is 200 m deep and the second one which hosts CYII wells and is about 500 m deep. Different regions have been defined to assign different hydraulic parameters values. Once the flow model was calibrated the predictive model with three different scenarios was set to evaluate the impact that groundwater recharge will imply in the aquifer. The scenarios studied are intended to know the behavior of the aquifer in the GWB 030.010 towards different stress conditions and to know the best management scenario. The predictive scenarios called A, B and C are resumed in Table 1, the four periods consist in a combination of different pumped and recharged water volumes according to the authorization. Each period is 5 years length during 20 years.

Table 1. Pumped and recharged volumes (Mm^3) per period and scenario in Manzanares – Jarama GWB.

Period	Type of well	Secenario A	Scenario B	Scenario C
1	Pump	59,2	60	64,8
	Recharge	0	0	7,4
2	Pump	59,2	60	64,8
	Recharge	14	14	6,6
3		Same strategy as period 1		
4		Same strategy as period 2		

Inside each period a pumping schedule was fixed. In case of Scenario A, 59,4 Mm^3 were extracted for 18 months, without stops. Scenario B was less stressful for the aquifer, 60% of the volume was pumped during the first 12 months whereas the remaining 40% was pumped during the last 12 months. In both cases recharge was carried out just after pumping the 100% volume established per period. Pumping schedule in Scenario C is the harder one, besides pumped volume is higher than the others, recharged water is carried out along two periods instead of one.

Results in Scenario C showed that a residual withdrawal of 20 m is observed along the 20 years simulation, whereas a combination of scenarios A and B showed an increase of groundwater level in the aquifer of 3 m.

Simulations have tested that an optimal management of the aquifer is feasible, and it will be transferred as a quantitative improvement of groundwater levels.

2.1.2. The process to obtain permits

At the end of 2002 and the beginning of 2003, CYII requested water management permits for groundwater recharge which include environmental assessment. In 2003, 2004 and 2005, The Ministry of Environment exempted recharge projects of environmental evaluation. CHT granted permits for groundwater recharge in 2009 and 2010. These permits allow recharging water in the aquifer with water from the water supply system. Pointing that water contains trihalomethanes (always within the limits established in the regulation of water intended for human consumption).

During the ASR tests, groundwater quality control was done in accordance with the Ministerial Order of February 1988 (which establishes the methods and frequency of measuring, sampling and analysis of surface water used to produce drinking water) and RD 140/2003 (Table 2).

Table 2. Analytical quality control parameters established by CHT.

Group I	Group II	Group III	Others
pH	Fe	Fluorides	Acrylamides
Colour	Mn	B	Al
Suspended Solids	Cu	As	Sb
Conductivity	Zn	Cd	Benzene
Nitrates	SO_4	Cr	Bromate
Chlorides	Surfactants	Pb	Cyanotoxins
Phosphates	N. Kjeldahl	Se	Residual Chlorine
COD	Total Coliforms	Hg	Vinyl chloride
DBO_5	Faecal Coliforms	Ba	Cu
Ammonium		Cyanides	THM
		Hydrocarbons	TOC
		PAH	TRICLOROETHANE+TETRACLOROETHENE
		Pesticides	Turbidity
		Chloroform	
		Faecal Streptococci	
		Salmonella	

2.1.3 Experimental recharge facilities

CYII did ASR tests using three deep wells located in two GWB in the Madrid Region (Figure 1). Casilla Valverde bis and FE-1R facilities are in the north of the Manzanares-Jarama GWB (030.010) and La Cabaña Bis is in the north of Guadarrama-Manzanares GWB (030.011).

Each ASR facility has a groundwater level and quality measurement network which is composed of observation wells and piezometers in a distance around 20 to 1500 m. Piezometers are mainly in groups of three, with depths around 50, 150 and 300 m. Some are screened at the bottom or at several depths.

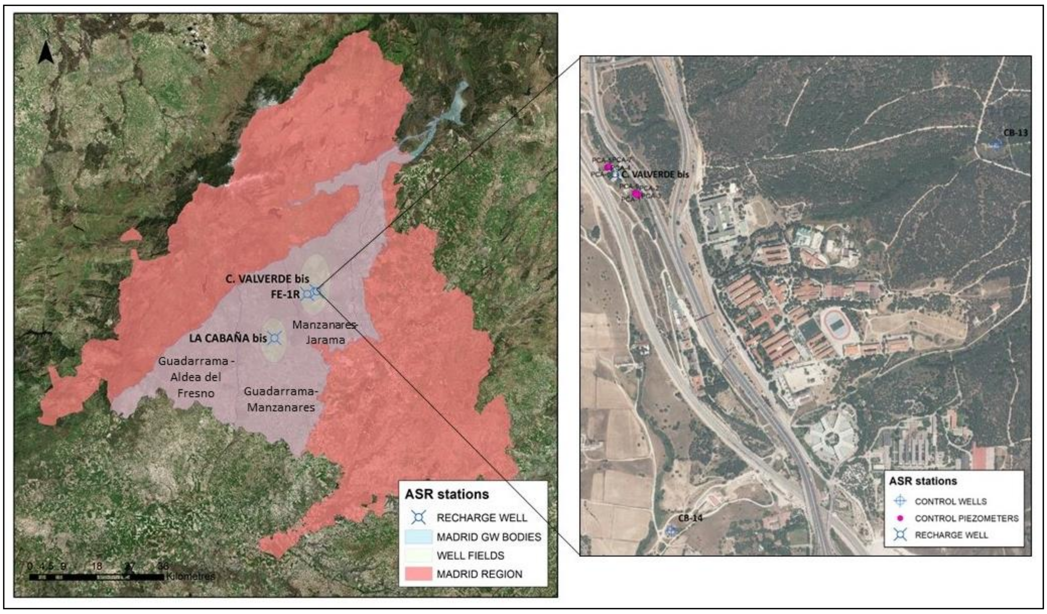

Figure 1. Location of the three ASR facilities and Casilla Valverde Bis control network.

Casilla Valverde bis and La Cabaña bis are dual purpose wells, enabling the recharge or pumping water depending on the needs of the water supply system. FE-1R well was the last one equipped which summarizes all the knowledge acquired through recharge experience. This well is used only for recharge purposes.

ASR wells are designed to release water under the static water level. Three independent and concentric pipes to the pumping pipe were designed with a reduced diameter of 60 - 80 mm. To avoid air clogging, recharge pipes are filled and emptied by a packer placed at the bottom of each recharge pipe. To locate all these pipes, bore casing diameter had to be around 600 mm until the recharge depth, and 450 mm the rest. Nevertheless, the stage of installing pumping equipment was complicated due to the difficulty to manipulate these recharge pipes, especially to automate the operation of them.

- ASR Facilities at Manzanares-Jarama GWB (030.010):

Casilla Valverde bis and FE-1R wells were placed in areas with different schemas. CYII is the main user of this GWB, having 25 pumping wells excluding ASR facilities. This condition makes easier the recovery of the water injected and stored. The main target is to understand the interaction between recharge water and existing groundwater using two types of facilities. There are two main areas in this GWB from CYII perspective. One of them is on both sides along M-607 road which is composed of 18 wells and the other is in Fuencarral area. In each of these areas an ASR facility was built to evaluate ASR tests.

Casilla Valverde Bis is a dual purpose well and it was chosen because of the geologic materials into which the well was drilled. In this case the well has a high sandy fraction which allows higher recharge water flow rates than nearby wells. The well casing of this well is 485 m deep (600 mm diameter from 0 to 200 m and 500 mm from 200 to 485 m) and the depth of the first screen section is at 102,5 m. Total screen length is 199,5 m and the type of screen is bridge slot screen. In the northern and southern parts of the facility there are two piezometer nests at around 200 m away from the ASR well. In addition, other wells of CYII were used to evaluate the extension of the water recharge.

FE-1R was chosen to evaluate exclusively for artificial recharge. This facility is located in the outer edge of the south of the Monte de El Pardo and inside of a well field with a high pumping capacity. It is composed of a recharge well (FE-1R) and a near pumping well named FE-1 bis which is employed during recovery operations after artificial recharge periods. Water is injected into de aquifer by the recharge well and FE-1 bis recovers recharged water. Besides, just like Casilla Valverde bis, there are two piezometer nests around to manage the recharged water. This well is 504,5 m deep and the casing diameter is 600 mm from 0 to 200 m and 500 mm from 200 to 504,5 m. The first screen section is at 95,5 m deep and the total screen length is 130,5 m with bridge slot screen.

Casilla Valverde bis and FE-1R take treated water from the main supply system. Injected water comes from Colmenar Water Treatment Plant (WTP), so any clogging due to the biological process is not expected.

- ASR Facilities at Guadarrama-Manzanares GWB (030.011):

CYII has 25 wells in Guadarrama-Manzanares GWB. In the north of this GWB there are 14 wells located in the municipality of Pozuelo de Alarcón or in other municipalities close to Boadilla del Monte. The rest of pumping wells are in the south of this GWB.

La Cabaña bis ASR facility is located in Pozuelo de Alarcón (Figure 1). It is a dual purpose well and it was chosen because this zone has a lot of users as well as CYII. Many suburbs and houses on this area have big plots and grass patches, so water consumption is higher than the average. Some of these users get ground water on summer months to irrigate and to fill swimming pools, observing important drops in the water levels measuring by CYII. This condition makes the area suitable for study the permanence of the recharge water in the aquifer. In addition, just like two other ASR facilities, there are two piezometers nests 15 and 200 m away.

La Cabaña bis is 703 m deep and the casing diameter is 600 mm from 0 to 200 m and 500 mm from 200 to 485 m. The depth of the first screen is at 63,5 m and total screen length is 78 m using bridge slot screen.

Injected water is diverted from Canal del Oeste conduit using a pump. This treated water comes from Colmenar and Majadahonda WTPs.

2.2. Test Development: Schedule and monitoring

A total of three ASR tests were developed, one per station (2.1.3), from October 2010 to June 2012. Each test consisted of a three-month recharge phase followed by one month of recovery before starting the subsequent recharge cycle. After ending the three recharge stages water was storage in the aquifer for over 12 months, then a recovery pumping was carried out during twelve months in order to extract all the injected water.

Quality and quantity controls were developed along water recharge tests. Water sampling was done in 7 piezometers in each station in which 78 parameters were determined. Moreover, 5 existing wells surrounding each station were controlled as well in order to check recharge extension area and other affections to other users.

3. Results

3.1. Recharge volumes

ASR test were done during 1364 days from October 2010 to July 2014. Specifically, artificial recharge was applied in the three recharge wells during 1054 days. The volume recharged in Casilla Valverde bis was 546.896 m^3 during 362 effective days of artificial recharge (Table 4). Then, 439.113 m^3 were injected in La Cabaña Bis for 343 effective days. Finally, in FE-1R 859.690 m^3 were recharged during 363 effective days. The three ASR tests are summarized in Table 3.

Table 3. ASR Casilla de Valverde bis, La Cabaña bis y FE-1 R: Volume, flow and schedule.

ASR Station	Period	Days	Volume Recharged (m^3)	Medium recharged flow (l/s)
Casilla Valverde bis	1º	128	187.885	18
	2º	114	176.388	18
	3º	120	182.623	18
La Cabaña bis	1º	109	137.023	15
	2º	111	165.181	17
	3º	123	136.909	13
FE-1 R	1º	119	137.023	15
	2º	111	165.181	17
	3º	123	136.909	13

Cleaning pumping was done in 12 effective days and the pumped volume was around 32.600 m^3, it represents only the 2% of the recharged volume. These pumping periods were carried out to regenerate recharge capacity.

3.2. Evolution of groundwater level

Changes in the water level in piezometers of 300 m deep were evident when artificial recharge was working. Rises of 8 to 10 m were observed although these variations disappear when artificial recharge ends.

Figure 2 shows how Casilla Valverde bis and piezometer PCA-3 located at 90 m distance follow the same trend. Water level rises in piezometers of 150 m deep were low or null and shallow piezometers of 50 m were not affected by the artificial recharge. Then, injected water was storage in depths higher than 200 m and lower depths were not affected due to the semiconfined nature of the aquifer. Subsequently, after the recharge and storage stages an improvement in the water levels between 2 and 4 m was observed in distant wells.

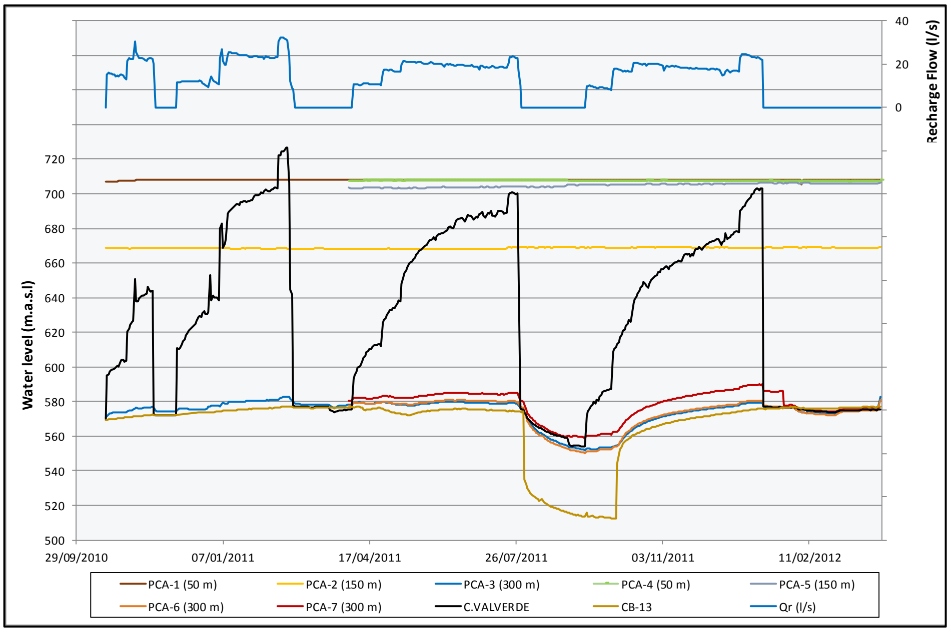

Figure 2. Evolution of groundwater level in Casilla Valverde bis ASR facility and levels in well CB-13 which is located 1.200 m away from the recharge well.

3.3. Water Quality after ASR

Measuring points were sampled after the 3 stages of artificial recharge, checking compounds referred on CHT authorization. Table 4 shows groups and average values which were higher than detection limit. In Group I 23-28 % of parameters were under the limit of detection, in Group II 70-80%, Group III 58 – 68 % and in others 70-73%.

Table 4. Average values (Avg) which were higher than detection limit during recharge periods.

Group I		Group II		Group III	
Parameter	**Avg**	**Parameter**	**Avg**	**Parameter**	**Avg**
Chlorides (mg/l)	20,7	Fe (µg/l)	33,9	Flururo (µg/l)	178,0
Conduct. (µS/cm)	297,6	Mn (µg/l)	20,9	As (µg/l)	7,5
DBO_5 (mg/l)	2,6	N.Kjeldahl (mg/l)	0,5	Cr (µg/l)	1,6
NH_4 (mg/l)	0,6	SO_4 (mg/l)	25,4	Se (µg/l)	1,4
Nitrates (mg/l)	8,5	Zn (µg/l)	33,1	Ba (µg/l)	4,6
Oxidability (mg/l)	0,6			Chlorof-extract mat.(mg/l)	2,4
pH	8,0			Dissolved hydroc. (mg/l)	0,01
SST (mg/l)	6,8				
Others					
Parameter	**Avg**	**Parameter**	**Avg**	**Parameter**	**Avg**
Al (µg/l)	30,6	COT (mg/l)	1,13	Ni (µg/l)	1,71
NO_2 (µg/l)	0,02	THM (µg/l)	9,50	Turbidity (U.N.F.)	10,36

Conductivity dropped due to the mixing process between recharge water and groundwater. This conductivity increased during recovery pumps, in the same way that occurs when pumping a well during droughts. There was an increase in the THMs because of recharge water from the water supply system. THMs were low during all the stages and they had similar values to recharge water. After recovery pumps, THMs disappeared and this indicated that recharge water had been recovered 100%. Table 5 shows a summary of some water quality parameters of the groundwater in different stages, before artificial recharge, one year after the recharge stages and at the end of recovery pumps.

The parameters N, Oxidability, TOC, NH_4, NO_3, NO_2 and DBO_5 were lower than the values established on R.D. 140/2003 during recovery pumps and they were without significant variations during artificial recharge.

Water quality at the end of the recovery pumps had similar values as the water analyzed before the ASR tests. Conductivity was higher than 300 μS/cm and arsenic, sulphates, chlorides or nitrates measurements were like those analyzed at the end of previous long pumping periods.

Table 5. The main water quality parameters during ASR stages.

Parameter	C. Valverde bis Well			FE-1 R Well		
	Before AR	Beginning of Recovery Pumps	At the end of Recovery Pumps	Before AR	Beginning of Recovery Pumps	At the end of Recovery Pumps
Conductivity (μS/cm)	219	149	317	260	220	431
pH	7,8	8,78	8,0	7,49	7,26	8,15
As (μg/l)	7,5	< 2,5	17	7,2	< 2,5	36,1
THMs (μg/l)	0,0	35,0	1,7	0,0	11,9	2,1
Nitrate(mg/l)	2,8	0,3	3,4	4,8	5,6	2,6

3.4. Level of recovery of the recharged water

In artificial recharge process is important to keep under control: the amount of water recovered after the recharge, the quality of this water and the distance affected.

During ASR test (see section 3.3), significant water quality variations were not observed. Recovery rate of recharged water was determined based on the evolution of THMs concentration during recovery pumps. There are no THMs on aquifer water and none reaction among aquifer matrix, aquifer water and recharge water has been detected. So THMs concentration on recharge water has been used as a tracer. Recovery pumps ended when the concentration of THMs was about 1 – 2 μg/l in the recharge well (Table 8). In addition, a mass balance was done with the injected and recovered THMs. This balance in Casilla Valverde Bis and FE-1R wells showed that more than 95% of the injected THMs were pumped. In the facility of La Cabaña Bis this amount was lower than 5%. Then the level of recovery of the recharged water was higher than 95% in Casilla Valverde Bis and FE-1R facilities. Whereas in La Cabaña Bis was lower than 5%.

Besides, the concentration of THMs was useful to determine the distance affected by the recharge after one year storaged in the aquifer and it allowed for evaluating the availability of the recharge water for the user who did the recharge and with which well the user could pump this water. Water recharged in Casilla Valverde Bis was detected for the first time in two wells located 1000 m distance from the recharge well at the end of the recovery pump stage. It was determined from THMs concentration which had values of 20 μg/l in those points.

4. Conclusions

ASR tests done by CYII have allowed for:

- Assessing the viability of the artificial recharge application using deep wells and injecting volumes of interest.

- Knowing that water levels around the recharge wells were hardly affected by the artificial recharge.
- Recharge water remained in the aquifer after one year in a radius of 1000-1200 m, in areas where there are not a large number of users (030.010 GWB). However, recharge water remained very little time in the aquifer when there are lots of users pumping water every year (030.011 GWB).
- Analyzing that the quality of pumping water after the recharge is valid for the water supply system (applying the same treatment system like water supply wells).
- Evaluating that the recharge volumes was about 40-50% of the volume allowed to pump in one well during one year of operation.
- Studying well equipment to apply ASR (removing auxiliary recharge pipes) and make pumping wells viable to dual purpose wells transformation (ASR).
- ASR needs legislative development in Spain, explain how recharged volumes reverts to the administrative authorization (concession granted by CHT), significance of the water quality control from the recharge stage until the recovery of the recharge volumes in order to make a comprehensive management of groundwater resources.

Abbreviations

The following abbreviations are used in this manuscript:

CYII: Canal de Isabel II
TDAM: Tertiary Detrital Aquifer of Madrid
CHT: Confederación Hidrográfica del Tajo (Tajo River Basin Authority)
ASR: Aquifer Storage and Recharge
AR: Artificial Recharge
GWB: Groundwater Body
RD: Royal Decree
WTP: Water Treatment Plant
THMs: Trihalomethanes.

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Paper for ISMAR10 symposium. ***Topic No: 8 (088#)***

Initial Results from Managed Aquifer Recharge Trials in the Hekeao/Hinds Plains, Canterbury, New Zealand

Houlbrooke, Clare[1]*; Bower, Bob[1] and Sinclair, Brett[1]

[1] Wallbridge Gilbert Aztec;
*Correspondence: choulbrooke@wganz.co.nz; Tel.: +64-27-6094618

Abstract: The Hekeao/Hinds Managed Aquifer Recharge Trial was established to explore the application of various MAR techniques to address both water quantity and quality issues. The techniques include surface infiltration and passive shallow injection, to accommodate the diverse hydrogeologic conditions of the Hekeao/Hinds Plains. The goal of this five-year trial is to provide a set of catchment-specific MAR tools that can be incorporated into the overall development of a community-led groundwater replenishment scheme. By Year 3, the trial programme consists of 18 test sites, including an infiltration basin (Lagmhor), 16 smaller-scale soakage sites and a floodplain recharge site adjacent to the headwaters of the Hekeao/Hinds River.

This paper presents an outline of the methods being applied across the Hinds Plains in consultation with the local community. It summarises the results from the trial to date, including observed groundwater level and water quality responses to site operations and upgrades at the main basin since its commissioning in 2016. The basin upgrades were pursued to overcome the effects of shallow aquitards, which limit overall infiltration rates. This paper also presents information on the design and results from the other methods being applied in this integrated water management MAR trial.

Keywords: Catchment-scale, Integrated water management, Water quality, Community collaboration.

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1. Introduction

The Hekeao/Hinds Plains are a subset of the Canterbury Plains, South Island, New Zealand. Groundwater quality in the Hinds/Hekeao Plains is degraded, with areas of elevated nitrate concentrations related to recent agricultural intensification. In addition, the area has been subject to long-term declining groundwater levels and decreasing coastal spring-fed drain baseflows. The reduced groundwater storage and spring base flows are attributed to a combination of irrigators moving to more efficient irrigation systems, progressive closure of unlined stockwater races, increased groundwater pumping and a changing climate.

Water management objectives for the Hinds/Hekeao Plains have been included in regional planning through collaboration and consultation. Implementation of Managed Aquifer Recharge (MAR) at the catchment-scale was incorporated into the community plan as a tool to help the community achieve agreed environmental and development objectives. Other planned changes adopted by the community to help achieve the objectives include; capping groundwater allocation, water metering and reductions in consented volumes, and reduction in on-farm nitrogen losses by up to 36% by 2035.

The objectives of the Hinds/Hekeao MAR programme are to help the community:

- Improve water quality in groundwater, streams and rivers,
- Enhance and protect groundwater-sourced drinking water supplies,
- Increase groundwater storage and thereby enhance water supply security, and
- Increase baseflows in the Hinds/Hekeao River and spring-fed streams.

The Hinds/Hekeao Managed Aquifer Recharge Trial involves several MAR techniques and sub-trials including:

- The Lagmhor infiltration basin (Lagmhor Trial),
- Sixteen soakage sites (distributed across the plains),
- A floodplain recharge site for a river restoration project (Hekeao/Hinds River Project).

This paper summarises the MAR techniques under trial on the Hinds/Hekeao Plains and provides some initial results from the various trials. It links to a paper by Bower et al. (2019) [1], which explores the processes in establishing a catchment-scale community-led groundwater replenishment scheme (GRS) and outlines the recently completed scheme business case.

2. Materials and Methods

3.1. Lagmhor Basin

The location for the Lagmhor Trial was chosen, among other reasons, because groundwater conditions in this area are characterised by degraded quality relative to environmental and drinking water values, and over-allocation of groundwater for abstraction. In addition, incidental recharge is declining due to improving irrigation efficiency, piping of irrigation water delivery systems and decommissioning of stockwater races. These factors have led to declining groundwater levels, baseflow reductions in spring-fed waterbodies and consequent negative effects on habitat and cultural values.

The key outcome sought for the five-year Lagmhor Trial is to provide 'proof of concept' that MAR can help the community achieve the catchment water quantity and quality outcomes **[2]**. To achieve this outcome, three primary objectives were defined for the five-year period of the Lagmhor Trial:

- Increase groundwater levels and overall groundwater storage near the Lagmhor Trial site.
- Decrease concentrations of nitrate-N in groundwater near the site.
- Increase baseflows and improve water quality in down-gradient coastal spring-fed waterbodies (drains).

Operation of the Lagmhor Trial started on 10 June 2016. Over the subsequent operational period of more than two years, the outcomes from the trial have been evaluated based on data derived from an extensive network of monitoring sites.

Source water for the site is derived from a catchment-wide irrigation water supply network, with an off-take from the Rangitata River **[3]**. Source water leaves a farm storage pond and enters the Lagmhor Trial site through a controlled flume. The source water then flows down a 900 m long open race into a forebay (Figure 1). A bypass gate allows water to be diverted to adjacent farm storage ponds during seasonal start-up periods if initial sediment loads would present a clogging risk to the infiltration basin (Figure 1). The forebay is designed primarily to facilitate the settling of suspended sediments prior to the source water spilling into the main infiltration basin

(Figure 1). Some infiltration also occurs through the base of the forebay, with the total infiltration area for the site being approximately 0.9 ha.

Figure 1. Lagmhor (Main) Basin site layout [3].

Dedicated monitoring bores have been installed at various distances from the infiltration basin and selected existing nearby bores are also used in the monitoring network. Eight of the sixteen current monitoring bores have automated water level transducers installed. Groundwater sampling for water quality analysis has been undertaken from approximately 16 monitoring bores, although monitoring site locations and sampling frequency have changed as the trial has progressed. Source water samples have been collected and analysed at monthly intervals. Samples collected from delivery flume have been analysed for *E. coli* and samples collected along the delivery race have been tested for ammonia, dissolved reactive phosphorus, nitrate-N, nitrite-N, total coliforms, total kjeldahl nitrogen and total nitrogen.

In addition, monitoring is being carried out in the coastal spring-fed streams and drains with a focus on water quality, ecology and flows. The clean MAR water plume is moving in the direction of these streams and drains. It is anticipated that the on-going monitoring programmes will assist in detecting and evaluating MAR water discharges into the coastal spring-fed streams/drains. A climate monitoring station has been installed close to the coastal drains area to support evaluation of the groundwater level and stream flow data.

Techniques were investigated to increase recharge rates at the Lagmhor Trial site. Geophysical surveys were carried out, including down-hole natural gamma surveys (Figure 2), and a deeper soakage system at the site was constructed to try to enhance recharge rates.

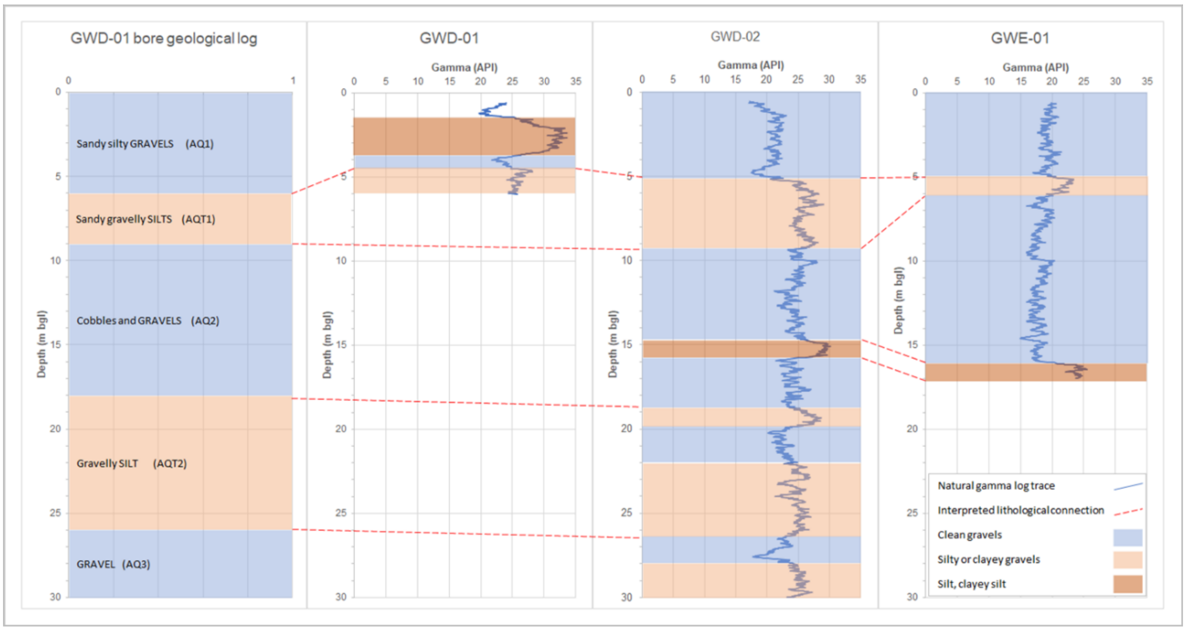

Figure 2. Interpretation of aquitard layers based on geophysical and lithological logs of nearby bores [3].

3.1. Soakage Systems

The Hinds MAR Governance Group has installed and is testing up to 16 new trial sites (depending on water availability) to determine recharge potential across the Hinds/Hekeao Plains. Each of these new sites is consented to recharge up to 50 litres per second whilst flow rates and water quality are carefully monitored. The sites were selected based on a number of factors including, access to source water and land, depth to water table, hydrogeological setting, proximity of drinking water supply and potential monitoring bores. Water is delivered to the test sites via irrigation scheme delivery systems. A standardised soakage system design and hydraulic testing programme is being used to enable comparison of the recharge performance between sites (Figure 3). Source water for each soakage system is diverted from either an open water race or an existing on-farm irrigation pond and delivered to a MAR site via a siphon that discharges directly to a soakage pit (Figure 4).

A series of hydraulic tests are being conducted on the new MAR test sites to characterise infiltration rates across the Hinds/Hekeao Plains. The key objectives of these initial hydraulic tests are to:

- Determine the infiltration rates achievable from a standard size test pit.
- Monitor and record infiltration flow data to enable a rating of the sites for further development.
- Determine if infiltration rates or in-pit water levels change over time during the test, indicative of clogging risk.
- Determine how the "bulb" of introduced water expands within the surrounding soil during the test.
- Monitor and record infiltration water quality to demonstrate that a standardised MAR site can be operated without putting the quality of the underlying groundwater at risk from microbiological contamination.

The outcomes of this testing programme will be used to support development of a catchment-wide GRS design and implementation of MAR concepts supported by a business case.

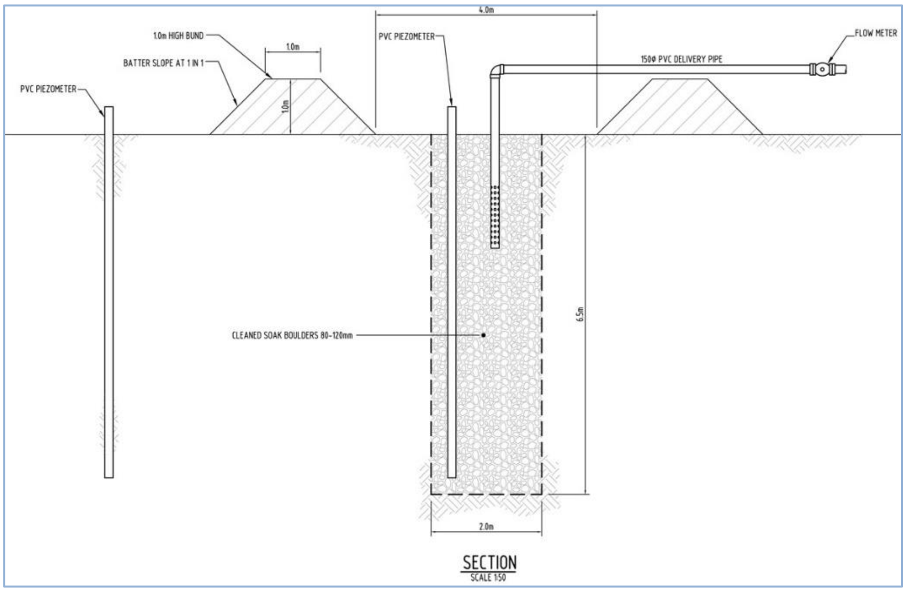

Figure 3. Cross-section of a standardize soakage pit [3].

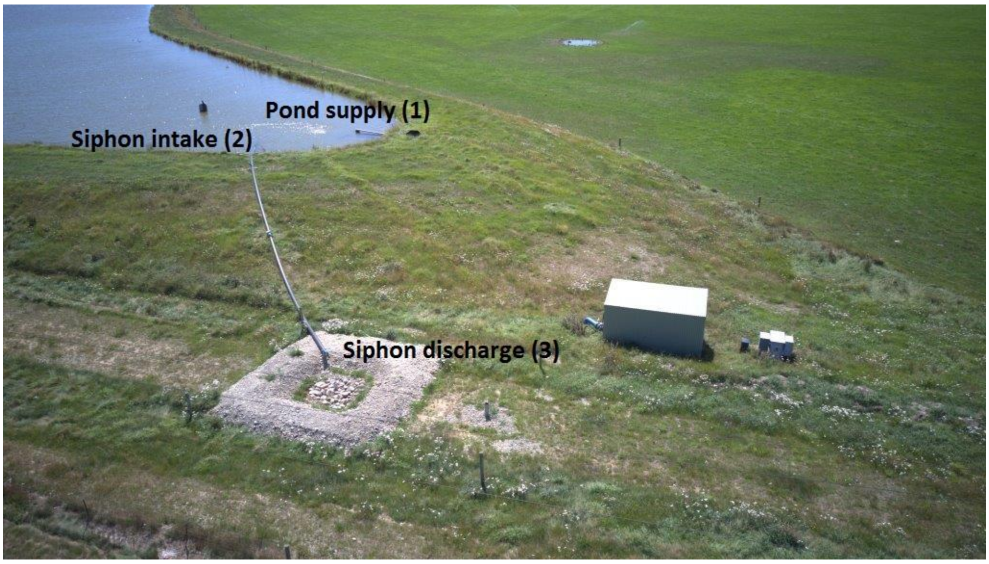

Figure 4. MAR Site #8 showing Valetta pipeline discharge (1), irrigation pond, siphon intake (2) and soakage pit discharge (3) [3].

3.3. River Restoration Project

A new recharge project located adjacent to the South Branch of the Hekeao/Hinds River has been designed and constructed in close consultation with local Maori leaders and community representatives. This project is focused on helping to restore the eel fishery in the river, along with a range of other beneficial outcomes. The project recharges up to 200 litres per second of water sourced from the Rangitata River through natural floodplain areas. This recharge will act to increase flows in the river and associated springs that support a wetland and eel habitat area (Figure 5). The project is to support re-establishment of native riparian vegetation on the floodplain, improve water quality in the river and recharge clean water into a groundwater system associated with community drinking water supplies (Figure 5).

The overall HHRP area includes two designated recharge (infiltration) areas located on the historic flood plain. Water is delivered via an open channel to recharge Area 1 (Figure 5). A delivery race diverts any water not recharged in Recharge Area 1 (approximately 20,000 m^2)

down-river, past a natural oxbow or wetland area, to Recharge Area 2 (approximately 60,000 m^2; Figure 5).

The HHRP monitoring programme incorporates both quality and quantity measurements for groundwater and surface water resources including; source water flow rates, Hinds River flow rates upstream and downstream of the site, groundwater quality (monitoring bores), surface water quality and aquatic ecology.

Figure 5. Hekeao/Hinds River Restoration Project site targeting a historic flood plain adjacent to the South Branch of the Hekeao/Hinds River [3].

3. Results

3.1. Lagmhor Basin

The Lagmhor Trial has operated successfully for a two consecutive 'recharge' years, from June 2016 to June 2018. During the two years a total of 4,296,000 cubic meters of water has been recharged.

The maximum observed infiltration rates were approximately 0.5 m per day (5,000 cubic meters per day per hectare of ponded area) at a peak rate of approximately 110 litres per second. Results from the groundwater quality monitoring programme show an expanding MAR clean water plume extending 7 km from the trial site toward the coast. Measured average nitrate-nitrogen concentrations in groundwater influenced by the Lagmhor Trial decreased from an average of 14 g/m^3 to less than 4 g/m^3, with the Hinds/Hekeao Plains community objective being an average of 6.9 g/m^3. Outside the clean water plume area, measured concentrations have been stable or rising. Although the source water in the main basin has contained *E. coli* at counts of up to 228 MPN/100mL, *E. coli* have not been detected in the MAR clean water plume during Year 2 of the trial.

There was significantly more rain during Year 2 than Year 1 of the trial, including three separate days of more than 80 mm rainfall. During Year 1, rainfall was less than half the monthly average rainfall for four of the twelve months. In contrast, rainfall during three of the Year 2 months was at least double the average. During Year 2, the July monthly rainfall recorded in Ashburton, the nearest town to the Lagmhor Trial, was the third highest since records commenced in 1909 [4]. This significant difference in rainfall between the first two years of site operation affected site operations in a couple of ways. Firstly, heavy rainfall events disrupted site operations due to mandatory shut downs linked to rainfall trigger criteria (>30 mm in 24 hours) on the MAR permit. Secondly, saturated shallow soil conditions and elevated regional groundwater levels reduced recharge rates at the site during Year 2. For the purposes of 'testing' MAR, the consecutive very dry and very wet operational periods provided a useful contrast for evaluation of outcomes.

Ongoing groundwater level monitoring combined with the geophysical assessment of ground conditions beneath the Lagmhor Trial site has identified two aquitard layers above the regional aquifer level. These aquitard layers work to separate the groundwater level responses into those observed in a perched upper aquifer and a deeper regional aquifer. Different degrees of response to the MAR trial and seasonal conditions were observed in each aquifer.

A real-time nitrate-nitrogen sensor has been in a monitoring bore approximately 1 km down-gradient from the Lagmhor Trial site place for two years. Results from monitoring at this location show groundwater rising by approximately 18 m (Figure 6), although this perceived change in the regional groundwater level is exaggerated by water flowing downward from the perched aquifer in disturbed ground around the drillhole. Nitrate-N concentrations correspondingly decreasing to approximately 2 g/m^3 (Figure 6). Increased rainfall and nutrient leaching from topsoils during Year 2 did not reduce the effectiveness of the Lagmhor Trial in improving groundwater quality.

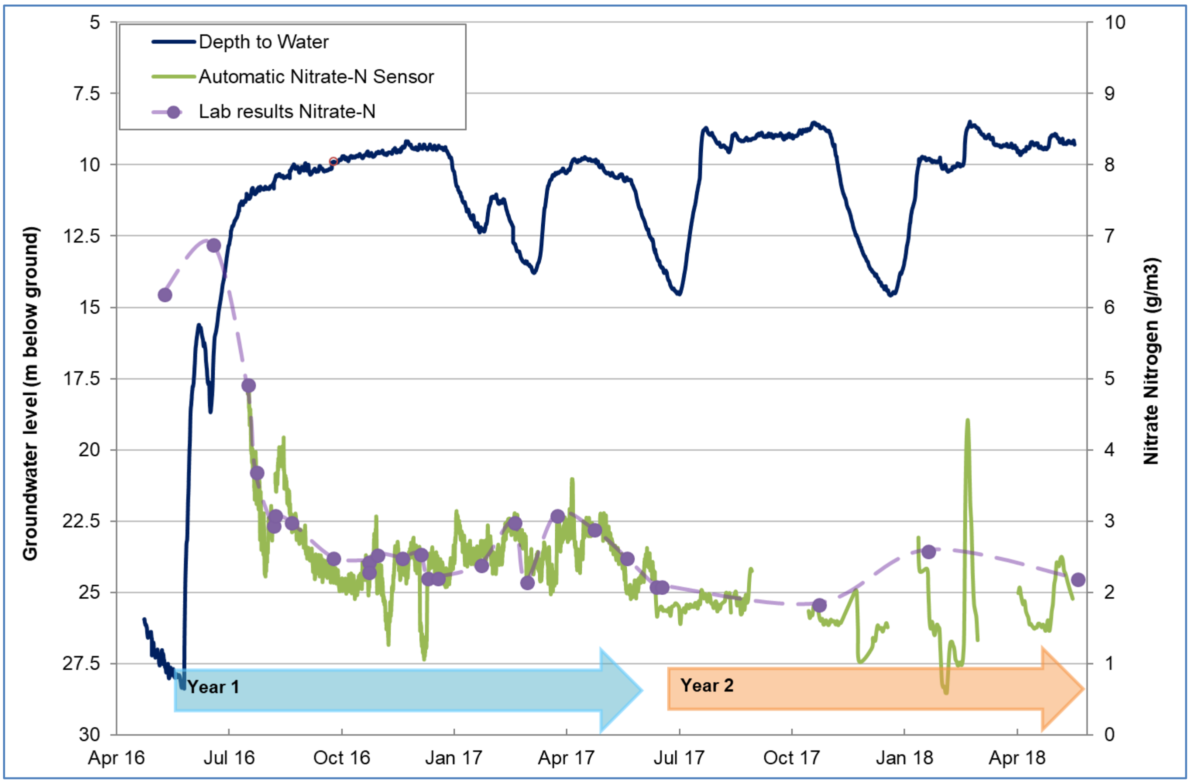

Figure 6. Lagmhor MAR combined results (Year 1 and 2) results showing increasing groundwater levels and decreasing nutrient (nitrate–N) concentrations [3].

3.1. Soakage Systems

Hydraulic testing began on the first new MAR site on 28 February 2018. Prior to and during the early testing period, major rainfall events occurred that contributed to an elevated groundwater level resulting in local and regional flooding. The elevated groundwater level reducing the potential maximum infiltration rates at some sites by reducing the available hydraulic head space.

The results of hydraulic testing showed that the new MAR test sites can typically receive long-term flow rates between 15 L/s and 30 L/s to pits that are approximately 1.5 m diameter. The testing of all sites is ongoing and an assessment of how representative these results are for the entire Hinds/Hekeao Plains will be undertaken once the testing programme has been completed. Given unusually high groundwater levels influenced the early tests, the results are considered to understate the normal infiltration performance at some sites. As groundwater levels recede, the maximum flow rate at these sites is expected to increase. Source water quality data collected showed source water *E. coli* values typically under 50 MPN/100 mL.

3.3. River Restoration Project

The Hekeao/Hinds River project has been constructed and the trial has started. Data from the trial are yet to be aggregated and results interpreted.

4. Discussion

4.1. Lagmhor Basin

There are benefits from a wetter year for groundwater levels and stream flows. However, very wet years also present challenges in terms of isolating the seasonal rainfall responses and then quantifying groundwater level responses to the Lagmhor Trial. Analysis of water level responses to the trial were made based on comparisons with background monitoring data and changes from groundwater levels measured at the start of the trial.

The plume of ‘clean’ infiltrated source water is considered to have continued to move parallel with flow directions derived from groundwater level data. However, the rate at which the plume expands is expected to change with variations in aquifer conditions. New monitoring bores have been established at the end of 2018 as it appears that the leading edge of the plume has moved past the existing lines of monitoring bores.

4.2. Soakage Systems

The soakage system testing provided learning opportunities related to hydraulic testing and the operation of multiple MAR site designs on the Hinds/Hekeao Plains. The results demonstrate that small MAR sites can be effective as a tool for regional groundwater recharge in the Canterbury groundwater environment. However, operating the smaller MAR sites also presents both individual and collective challenges. In summary:

- Source water protection - The open race sections of the irrigation scheme being used for source water delivery are relatively unprotected from external contamination, in comparison to pipeline delivery systems.
- Site design feedback – MAR sites supplied directly from an open race proved difficult to maintain at steady flow rates. This is caused by flow fluctuations in the supplying race that may change substantially over a week. In comparison, MAR sites that derive water from a pond typically receive steadier flow rates and are overall easier to manage. The irrigation ponds also

provide storage, which allows a MAR site to continue in operation despite transient water delivery restrictions (e.g., water restrictions due to low flows in the Rangitata River).

- Moving to automation – Flow rates at all new MAR test sites are operated manually through a butterfly valve on the siphon and recorded in the internal memory of the flow meter. The butterfly valves are typically highly sensitive. Automating the flow rates and telemetering the flow and groundwater level monitoring has the potential to maximise water delivery and reduce breaches to consent conditions.

5. Final comment

This River Restoration Project trial has been started but results are not yet available. Findings from operation of this site will be assessed following the completion of 12 months of operation.

Supplementary Materials: For more information about the Hinds/Hekeao MAR pilot project please visit: www.ecan.govt.nz/hinds-MAR.

Acknowledgments: This project has been carried out with support from New Zealand Ministry for Primary Industries and Environment Canterbury. The Hinds/Hekeao Managed Aquifer Recharge (MAR) Governance Group was appointed by the Ashburton Zone Committee to oversee a MAR testing and business case development programme. Membership in the group includes representatives from the community, local, regional and national government and local environmental and Iwi stakeholders. The Hinds/Hekeao MAR Governance Group's membership includes representatives from: Te Rūnanga o Arowhenua, Fish & Game, Ministry of Primary Industries, Environment Canterbury, Canterbury Water, Rangitata Diversion Race Management Ltd, Ashburton District Council, Ashburton Community, Mayfield Hinds Valetta Irrigation, MHV Water Ltd, Barrhill Chertsey Irrigation Ltd, Eiffelton Community Group Irrigation Scheme, Lincoln Agritech, Canterbury District Health Board, Tarbottons Contractors, Carrfields Irrigation Ltd, Boraman Consultants and Wallbridge Gilbert Aztec NZ Ltd.

Author Contributions: C.H., B.S. and R.B. analyzed the data; C.H. wrote the paper.

Conflicts of Interest: "The authors declare no conflict of interest."

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharge
GRS: Groundwater Replenishment Scheme.

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Paper for ISMAR10 symposium. ***Topic No:** 8 (135#)*

Laboratory and field experiments on the significance of the screen lengths for maximum well injection rates in an unconfined aquifer

José Pablo Bonilla Valverde[1,2,*]; Falk Händel[3]; Fritz Kalwa[3]; Amber Sharu[3] and Catalin Stefan[2]

[1] Instituto Costarricense de Acueductos y Alcantarillados, San José, Costa Rica
[2] Research Group INOWAS, Department of Hydrosciences, Technische Universität Dresden (TUD), Dresden, Germany; jana.sallwey@tu-dresden.de
[3] Department Monitoring and Exploration Technologies, Helmholtz-Centre for Environmental Research-UFZ, Leipzig, Germany; falk.haendel@ufz.de
* Correspondence: jpbonilla@aya.co.cr; Tel.: +506-2242-5331

Abstract: Direct injection methods, like aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) are viable techniques for the managed recharge of aquifers (MAR), especially in case of need of avoidance of open water areas or more complex hydrogeological conditions. For both ASR and ASTR, the injection efficiency depends on various parameters from screen clogging, well diameter and depth of injection to recharged water quality and rate. In this work, the efficiency of the well recharge system under different screen lengths has been tested in a laboratory scale and upscale to field experiments at the Pirna site (Germany). Both the laboratory and field results show that the screen length has a non-proportional effect on the infiltration rate, which is almost negligible for open screen length above 40% of the saturated aquifer thickness, but a high effect in the dynamic pressure level in the well. For field conditions, aquifer heterogeneities may play an important role the effect of the open screen length on the injection rate. Based on this results and literature findings, two recommendations are done for the dimensioning of the open screen length for injection wells: 1) ASR wells should be screened up to 40% of the total saturated aquifer thickness and 2) pure injection wells should be screened up to 80% of the total saturated aquifer thickness in unconfined aquifers. Furthermore, the heterogeneity effects should be further studied with the aid of numerical simulations. Both the experimental and field experiments have brought light into the dimensioning of injection wells.

Keywords: Managed aquifer recharge, ASR and ASTR well screen design, partial penetration.

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1. Introduction

Aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) are one of the most used techniques for the managed recharge of aquifers (MAR) around the world [1]. There is plenty of research on the construction and operational schemes for both ASR and ASTR [2–8], yet, there is no detailed research of the effect of the well open screen length on the injection rate, which is basically a partial penetration problem. A short description of partial penetrating wells is given in the following paragraph based on the review by [9]. Flow to a fully penetrating well and three partial penetration configurations wells in a confined aquifer are shown in Figure 1. To the best of the authors' knowledge, there is no design guideline for the configuration of the open screen length for an injection well; Bear [7] only states that the well hydraulics for an extraction or injection well are the same.

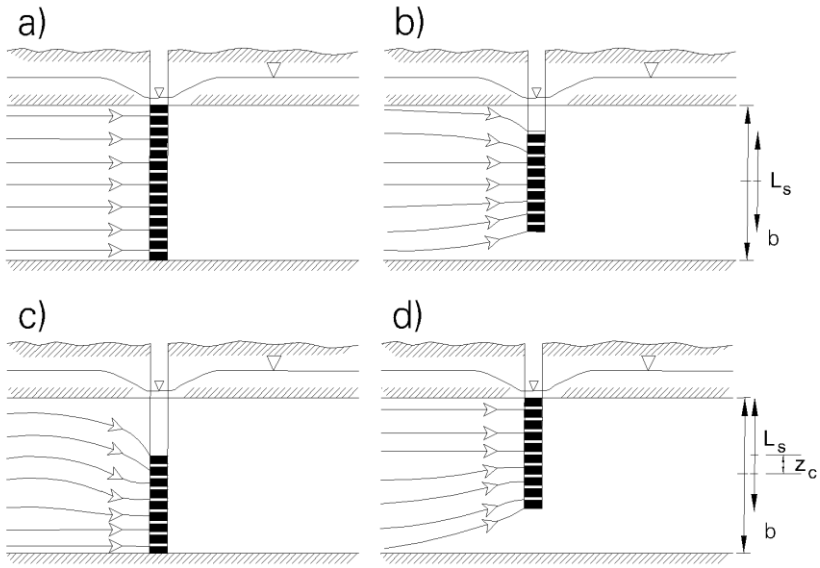

Figure 1. Flow lines for different well screen configurations in confined aquifers modified by Bonilla [9] from Houben [10] for: a) fully penetrating well, b) screen in the middle, c) screen at the bottom, and d) screen at the top.

A partial penetrating well is a well where the well screen length (Ls in Figure 1, also referred as open screen length) does not captures the whole saturated aquifer material (b in Figure 1). In a partial penetrating well the assumption that there are no vertical flow components towards the well are not met [7,11–13], as it is shown in Figure 1. Another assumption that is not met is that the aquifer is homogenous and isotropic, and most aquifers are not isotropic – the vertical saturated hydraulic conductivity is usually one order of magnitude lower than horizontal saturated hydraulic conductivity [6,7,11]. In a partial penetrating the flow lines approaching the well converge to the screen well, thus, having a vertical flow component and longer flow paths than a strictly horizontal flow path [7,10–12]. Longer paths and vertical flow lines (vertical Ks component) create a greater drawdown in a partially penetrating well than the drawdown expected for a fully penetrating one.

In an isotropic aquifer the effect of partial penetration in the drawdown becomes negligible at a distance of 1.5 to 2 times the saturated aquifer thickness [7]. In an anisotropic aquifer the effects of partial penetration in the drawdown becomes negligible at a distance that is function of the square root of the vertical and horizontal saturated hydraulic conductivities – $(Ksx / Ksy)^{1/2}$ [7]. Many authors developed analytical models for steady-state flow towards a partial penetration well, among them Kozeny (1933) [6,7,10], Huisman (1972) [10], Todd (1980) [10]), Barker and Herbert ([14]) and Parson (1994) [10]. A discussion on the well hydraulics, particularly on the effect of total head loss due to well configuration and well components, is given by Houben [10], including partial penetration using the analytical models by Huisman, Baker-Herbert and Parson.

Based on these analytical models, significant effects on the head loss start for partial penetration under 40% of the open screen length relative to the saturated aquifer thickness; and between 40-70% of the open screen length relative to the saturated aquifer thickness, the effect on the head loss are rather small [10]. For open screen length between 40-70% there is an almost linear relation with the percentage of penetration and the total head loss, i.e., the less open screen length (Ls) the higher the head loss [10], for open screen length under 40% the partial penetration effects starts being significant for and the relationship between them is no longer linear.

In order to define the optimal well open screen length on the injection rate, an experiment was setup at the laboratory facilities of the Institute of Waste Management and Circular Economy of the Technische Universität Dresden in Pirna, Germany by Bonilla [9], followed by an upscale setup in the field in the same facilities [15]. Both the laboratory and field results show that the screen length has a non-proportional effect on the injection rate. It is almost negligible for open screen length above 40% of the saturated aquifer thickness, but there is a large effect in the dynamic pressure level in the well.

Furthermore, three regions were recognized for the effect of the well open screen length on the injection rate: 1) a non-significant effect on the relative recharge for open screen length above 80% of the saturated thickness, 2) an effect on the relative recharge for 80-40% of the saturated thickness, and 3) a significant effect on the relative recharge for 40-15% of the saturated thickness. As expected, for field conditions, aquifer heterogeneities play an important role the effect of the open screen length on the injection rate.

2. Materials and Methods

The laboratory and field settings were implemented in the facilities of the Institute of Waste Management and Circular Economy of Technische Universität Dresden in Pirna, Germany. In the first section a description of the laboratory experiment is given and in the second section, a description the field experiments. The general description of the laboratory and field experiments is given in the third section.

2.1. Laboratory setup

A physical model of an aquifer-well system was built as a three-dimensional sand tank which is a 1.2-meter-high cylinder with a 0.5-meter internal radius built of fiber glass which aimed to reproduce an infinite aquifer, *i.e.*, the island aquifer conceptual model by Thiem [6,10]. One of the cylinder ends is closed and built-in monolithically to the walls while the other end is open to emulate an unconfined aquifer. The cylinder container is located on top of a 0.6-meter-high platform to gain access to the cylinder base, where nine piezometers were installed [9]. Piezometer accesses as well as outflow holes were drilled at the base of the cylinder into the walls [9].

The tank is equipped with a small-diameter well screen (inner diameter: 25.4 mm) of high-density polyethylene (HDPE) that fully penetrates the aquifer material located in the center of the sand tank. The HDPE well screen is perforated every 5 mm with 0.3 mm aperture – 6 % screen well open area. The aquifer material consists of medium/coarse sand (Ks = 6.2 x10-4 m/s). The particle sizes representing are: D60 = 0.87 mm and D10 = 0.24 mm, with a uniformity coefficient is 3.625. For more details on the building and configuration of the sand tank please refer to [11].

The injection and outflow systems control the flow in the sand tank. The first injected drinking water from a constant head tank to the sand tank via the well and the second control the sand tank outflow. The overflow of the injection´s constant head tank and outflow were connected to the water storage tank. The water is then recirculated to the constant head tank by a pump building a closed system. A schematic representation of injection and outflow systems of the sand tank is given in Figure 2. The injection pipe comprises a screen blockage reproduce different screen lengths. It consists of an inflatable rubber around a 12-mm rigid pipe which was also the largest injection diameter, the other two injection pipes were inserted into the 12-mm rigid pipe (diameter of 8 and 6 mm.

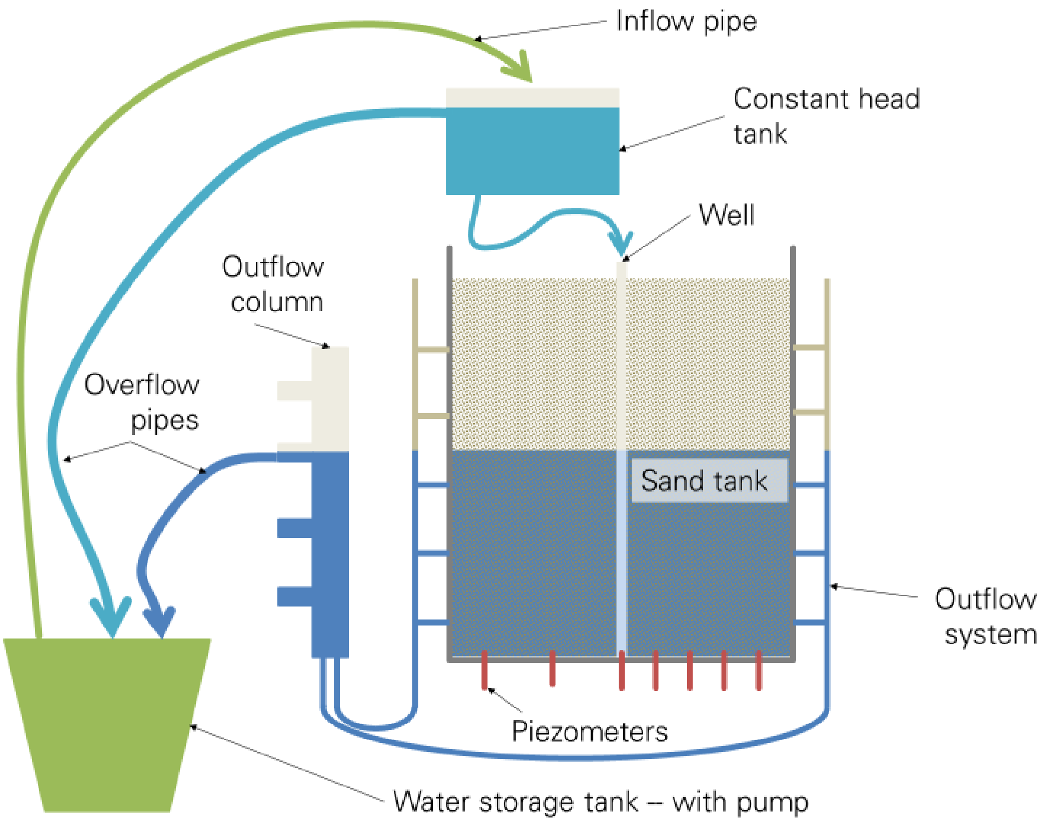

Figure 2. Laboratory injection experiments setup (sand tank) schematic injection and outflow systems from [9].

The outflow systems included five 0.05-meters side perforations at every 0.2 m from the bottom in two perpendicular axes (four sides in total) all connected to the outflow column. The outflow column allowed the same outflow head for all side perforations of the sand tank, as well as adjustable levels to simulate different water tables within the sand tank. A geotextile and coated polyvinyl chloride (PVC) wire were installed between the sand tank wall and the aquifer material as a drainage system to maximize radial flow. For more details on the injection, the outflow system and the measurement of the sand tank please refer to [11].

2.2. Field setup

The field site is located on the right margin of the Elbe River, one kilometer downstream of the city of Pirna and approximately 20 km southeast of the city of Dresden. The site is well characterize by [16,17], where the vertical hydraulic conductivity (*Ks*) was determined by sampling at nine locations at different depths [16], with variations between Ks = 1.9 x10-5 m/s and Ks = 9.0 x10-3 m/s. The aquifer is an unconfined coarse sand with an average depth of 15.3 meters and a saturated aquifer thickness of 7.5 meters [15]. Due to the relative short in time of the field experiments (<100 minutes) the saturated aquifer thickness is considered as constant. For long-term injection experiments the saturated aquifer thickness is likely to be affected by groundwater fluctuation because the location adjacent to the river Elbe and the dynamics interaction between the river and aquifer system [15].

The field injection experiment was carried out in the well G11, which is also a 1-inch (inner diameter of 25.4 mm) small-diameter well screen of HDPE that fully penetrates the aquifer material. Similar to the laboratory setup, the injection to the well was done from a one-cubic meter tank filled with drinking water, and the injection was done using a jet pump. An 8-cm long silicon packer was employed to block certain well screen section and stimulate the desire open screen length in the field well. Flow was measured using a flowmeter and pressure was measured using a pressure sensor inside the well. A schematic representation of field experiment setup is given in Figure 2, for more details on the experimental configuration of the field experiment please refer to [15].

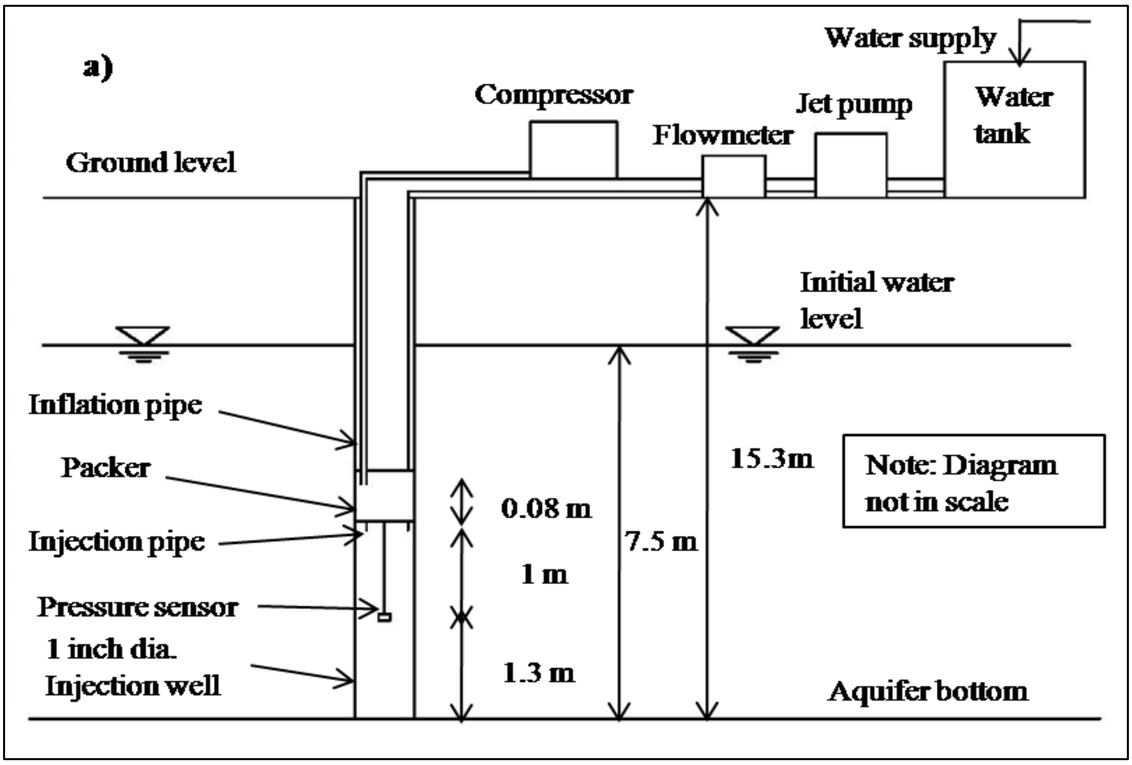

Figure 3. Field injection experiments setup schematic injection and outflow systems from [15].

2.3. Laboratory and field experiments

The dependent variable at consideration is the injection rate and the independent variable is the open injection screen well length for both the laboratory and field experimental setup. Both setups are configured to measure the injection inflow from the constant head tank by means of a flowmeter. The flowmeter resolution is 0.1 liters, where six times measurements (one every liter) were taken per open well screen length scenario. The injection rate is calculated by dividing one liter by the median time of the six measurements.

The injection experiment was performed at three different injection regimes controlled by the injection pipes in the laboratory setup and at two different injection regimes controlled by the valves setting in the field setup. The maximum injection capacity was obtained by the 12-mm injection pipe, followed by the 8 mm injection pipe and minimum injection capacity was obtained by the 6 mm injection pipe in the laboratory setup. The maximum injection capacity was obtained by the operating the valve fully open and the minimum injection rate was adjusted by the partial opening of the valve in the field setup.

Piezometers were installed at the bottom of the sand tank and a pressure sensor (Driver A5314, Co. Schlumberger Water Services) was equipped at the well to investigate the pressure change within the injection wells. Additional to the piezometer located at the center point of the sand tank to register the pressure head in the well, the sand tank had eight more piezometers. Six were distributed along the outflow axis and two at different angle from this axis. The sand tank piezometers were used to account for preferential flow within the sand tank. Additional wells are located at the Pirna field site, but due to the injection rates, distance between wells and high hydraulic conductivity no significant effect was measurable related to the injection experiment.

The laboratory setup included injection experiments at three different initial water levels – approximately 0.3, 0.5 and 0.7 meters of saturated aquifer thickness. Obviously, only one saturated aquifer thickness experiment was performed for the field setup. At each combination of saturated aquifer thickness and injection regime at least two injection batches were performed. An injection batch is a sequence of different open well screens that started and ended with the same open screen length [9]. One batch included increasing or decreasing the open screen length in 0.1 m steps. An injection batch started with an open well screen of 0.1 m and was move upwards the well in 0.1 m steps until the maximum open well screen length of 1.1 m was achieved and then was moved downwards the well in the same 0.1 m steps finalizing the batch for the laboratory setup. For the field experiments, injection hose along with the packer was placed in the well up to the desired open screen length, then the packer was inflated and the injection was carried out. The process was repeated till the open screen length reached the saturated aquifer thickness and for validation process a las injection was carried out a few meters above the saturated aquifer thickness.

3. Results

All the experiments, laboratory and field setup, show that there is an effect of the open screen length on the injection rate: it decreases as the open screen length is reduced – yet this relationship is not linear. In all cases there is a deviation from the maximum flow rates at open screen wells above the saturated aquifer thickness. The last is explained because for the injection above the saturated aquifer thickness there is no longer between two water surfaces – the water is freely flowing from the injection pipe to the aquifer, thus, a different flow regime happened in the injection pipe. As explained by Bonilla [9], because of the buildup in the well in the laboratory setup, the limit between these flow conditions in not at saturated aquifer thickness but after the injection pipe is above the buildup in the well. The particular results for each injection configuration are presented by Bonilla [9] for the laboratory setup and by Amber [15] for the field setup. In this communication all results are comprised in a graphic where both axes are standardized.

3.1. Standardized Graphic

In order to understand the effect of the open screen length in the injection rate, the injection rate was standardized with respect to the maximum flow rate (standardized injection rate); and open well screen length was standardized with the saturated aquifer thickness (relative open screen) for all arrangements in Figure 4. For the laboratory setup relative open screens up to three were achieved, but these results are not presented in Figure 4 as the main effects are under a relative open screen of 0.8. Three regions are recognized in figure 4 for both laboratory and field setup: 1) a region above 0.8 relative open screen, 2) a region between a relative open screen of 0.8 and 0.4, and 3) a region between 0.4 and 0.15 relative open screen. No injection arrangements were under a relative open well screen of 0.15 for the laboratory and 0.3 for the field setup, this is why no discussion can be made for this region [9,15].

For the first region (relative open screen >0.8) there is almost no variation in the standardized injection rate (between 0.95 and 1.0); any increment in the well open screen length above the saturated aquifer thickness (relative open screen higher than 1) has no effect on the injected rate according the laboratory and field experimental results. As stated by Bonilla [9], even if there is build up in the well, the flow in this area is not completely horizontal, but rather vertical. In the second region (relative open screen 0.8-0.4) the injection rate no longer reaches the maximum standardized injection rate – but there is also none beneath 0.9. Houben [10] based on [14] the partial penetration effects start to show themselves for open screen lengths between 0.1 and 0.9. In the third region (relative open well screen <0.4) a stronger shift from the maximum standardized injection is evident (no standardized injection rate above 0.95) in both setups. As stated by [9] even if this identified shift is stronger in the third region, in no case the relative injection rate is below 0.8 for the laboratory setup and 0.9 for the field setup. For a relative open screen above 0.15 observed injection rates are only 20% less than the maximum injection rate in the laboratory setup.

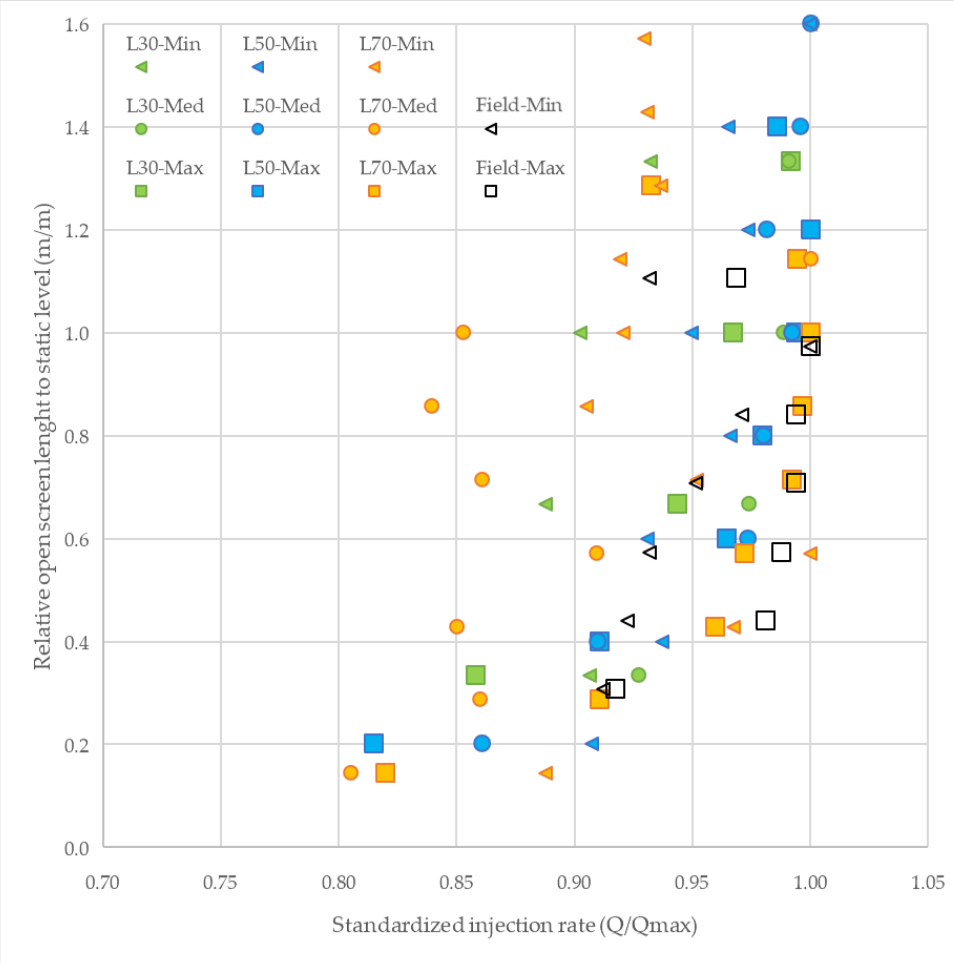

Figure 4. Standardized graphic for all the laboratory and field setups.

4. Discussion

The results from the laboratory and field experiments were congruent, the open screen length has an effect on the injection rate to an unconfined aquifer. For open well screen length above 80% of the saturated aquifer thickness, the achieved injection rate is over 95% of the maximum achievable injection rate – which occurs at open screen lengths equal to the total saturated aquifer thickness. With an open well screen length between 40% and 80% of the saturated aquifer thickness, the injection rate still can be maintained above 90% of the maximum achievable injection rate in an unconfined aquifer. For lower values of the open screen length (up to 15 %), the injection rate will still be above 80 % of the maximum achievable injection rate.

To the best of the authors' knowledge, there is no guideline regarding the dimensioning of the screen length of an ASR or an ASTR well in an unconfined aquifer. Based on the experimental results, it can be stated that the optimum well screen length is 40 % of the saturated aquifer thickness for both recharge and recovery. If the well will only be used as an injection well, then the well screen length should be 80 % of the total saturated thickness of the aquifer. Screening the whole aquifer thickness in an injection well will only render an additional 5 % of the maximum injection capacity. Screening the vadose zone (above the saturated aquifer thickness) renders no additional flow, based on the experimental results. To the best of the authors' knowledge, this work represents the first guideline based on scientific evidence regarding the dimensioning of the well screen length for ASR and injection wells in an ASTR setup for unconfined aquifers.

As discussed by [6], the drawdown in an extraction well in an unconfined aquifer should not exceed 67% of the aquifer thickness for economic reasons, *i.e.*, the open screen length of an extraction well in an unconfined aquifer should be less than 33% of the saturated aquifer thickness. Houben recommends that the open screen length of an extraction well in an unconfined aquifer should be 40% [10]. Based these criteria and the experimental results open screen length of an ASR well should be 40% of the saturated aquifer thickness in an unconfined aquifer – meeting both injection and extraction criteria. If the well is a pure injection well, as in an ASTR setup, the injection well could be screen up to 80% of the total saturated aquifer thickness in an unconfined aquifer and still achieved 95% of the maximum injection rate, *i.e.*, screening the whole saturated aquifer thickness. On the other hand, screening above the saturated aquifer thickness in an ASR well has no effect in the injection rate. Even if there is buildup in the well, it shows no effect in the injection rate in the experimental results.

The lower injection rate and the high-pressure development for the smaller open screen length for all laboratory and field experiments can be related to effect of partial penetration. In these cases, the flow leaving the well screen was not truly horizontal, but has some vertical component as presented in Figure 1. This leads to head loss and increase in pressure within the well to maintain the injection rate. For the field setup, the presence of low permeable layer at the bottom of the aquifer affects the result[16].

It is expected that the injection rate decreases at a high rate under relative open well screen area below 0.15, yet experiments have not yet been conducted to test this thesis. The laboratory setup can be easily modified to model other flow conditions, *e.g.*, extraction wells, confined aquifers, layered aquifers, among others. Other experiments could also bring insight into the injection process in an unconfined aquifer, like the injection process in partial penetrating well screened from the top of the saturated aquifer thickness, the effect on the injection rate if the well is screened only in the vadose zone and the effect of injection of a partially penetrating well in a confined aquifer. Furthermore, the laboratory setup could be modified to study distinct phenomena, such as: clogging in ASR or ASTR well and their solutions; the effect of developing a well on the injection/discharge rate; screen lengths in unconfined aquifers and their effect on the injection/discharge rate and piezometric levels; the effects of ASR in layered aquifers; and dual injection/discharge wells and their effect in the control of saline intrusion, among others.

4. Conclusions

The upscaling from the laboratory to the field experiments regarding the well open screen length effect on the injection rate show similar results, thus, validating the laboratory setup to simulate an infinite aquifer (Thiem's island aquifer conceptual model [6,10]) such as the one in the field at Pirna. Nevertheless, it was also observed that aquifer heterogeneities still play an important role in these experiments.

Both experiments brought light to the dimensioning of well length screen in an unconfined aquifer for both injection and ASR wells. To the best of the author's knowledge, this experimental setup and the research topic are the firsts of their kind. These results will aid technicians in dimensioning recharge wells in an unconfined aquifer.

Based on this results and literature findings, two recommendations are made for the dimensioning of the open screen length for injection wells: 1) ASR well should be screened up to 40% of the total saturated aquifer thickness and 2) pure injections well should be screened up to 80% of the total saturated aquifer thickness in unconfined aquifers. Furthermore, the heterogeneity effects should be further studied with the aid of numerical simulations.

Acknowledgments: This study was supported by the German Federal Ministry of Education and Research (BMBF), grant No. 01LN1311A (Junior Research Group "INOWAS"). We further acknowledge the support of the UNESCO and AyA who provided the funding for the conference participation.

Author Contributions: J.B. designed the overall study; J.B., A.S. and F.K. conducted the experiments, J.B., F.H and A.S. wrote the paper; C.S. contributed with discussion and advice.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations. The following abbreviations are used in this manuscript:

ASR – aquifer storage and recovery
ASTR – aquifer storage transfer and recovery
HDPE – high-density polyethylene
MAR – managed aquifer recharge
PVC – polyvinyl chloride.

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Paper for ISMAR10 symposium Ref. 202#. ***Topic No: 8 (202#)***

Managed Aquifer Recharge Solutions (MARSOL). Final statements

Fernández-Escalante, Enrique[1]; Sapiano, Manuel[2]; Lobo, Joao P.[3]; Guttman, Yossi[4]; Schütz[5], C.; Weffer-Roelh, A.[5]; San Sebastián, J.[1]; Kallioras, A.[6] & Dietrich, P.[7]

[1] Tragsa Group, Madrid, Spain
[2]. MEW-Energy & Water Agency, Malta
[3] LNEC, Lisbon, Portugal
[4] MEKOROT, Tel Aviv, Israel
[5] Technical University Darmstadt, Germany
[6] Technical University of Athens, Greece
[7] Technical University Leipzig, Germany
*Correspondence: efernan6@tragsa.es

Abstract: MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought) has taken place since 2014 to 2017 within EC FP7 call with GA 619120. In the final part of the project, first row members put together the conclusions from their personal point of view and after three years of intense research. All these statements have been put together in a seven minute video, where authors expose their final statements.
The first author collected and produced a video, concluding the following outcomes:

- MAR works, but needs experts to do it
- MAR is now a proven technology
- MAR is key solution to ecosystems depending on groundwater
- MAR is a sound, safe, and sustainable strategy that can be used with great confidence
- MARSOL has created a new generation of water managers that have an additional option now
- The awareness and the acceptance among stakeholders for MAR solutions is greatly increased

MAR as one of the best techniques to face frontally climate change adverse impacts.

Keywords: Managed Aquifer Recharge, technical solutions, water scarcity, drought, MARSOL.

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1. Introduction

Since the middle of the XX century, expansion of irrigation has led to decline in groundwater level at these points. After 10 years of operation MARSOL intends to provide technical solutions technology in order to improve the facilities efficiency and also nearing the MAR technique to agroindustry.

In the final part of the project, first row members put together the conclusions from their personal point of view and after three years of intense research. All these statements have been put together in a seven minute video, where authors expose their final statements.

2. Final statements

MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought) has taken place since 2014 to 2017 within EC FP7 call with GA 619120. The final statements from most of the first row members, gathered in a video and in this manuscript are:

Manuel Sapiano (EWA, MT):

The MARSOL project implemented a pilot initiative on managed aquifer recharge in Malta. That was the technical part of the project which yielded results on the protection of the coastal aquifer system from sea water intrusion, however the influx and connectivity with other partners in the project working on similar scenarios and using the same techniques provided the opportunity to look horizontally on managed aquifer recharge and also focus on tools, such as risk analysis and policy analysis, which help and will help to plan future initiatives on MAR not just in Malta but help to transpose these results on a wider dimension and therefore help in the wider water management in the European Union and particularly those regions of the union where water scarcity prevails.

Joao Paulo Lobo-Ferreira (LNEC, PT):

We were able to confirm that applied research and case studies demonstrated in the Southern part of Portugal Algarve, some different topics on the Managed Aquifer Recharge were achieved. We have demonstrated that we are able to use excessive water in wet years putting them in the ground and in basins to recharge well so that, later, in dry years we are able to collect them and then to supply agriculture, industry and human supply.

Yossi Guttman (MEKOROT, IS):

We gained a lot of experience at the many different MAR demo sites and therefore we think it is possible to bring it to other countries. A.R.O. concentrated on the unsaturated zone which cannot replace industrial pre-treatment. MEKOROT concentrated on the saturated zone and found that the models set up are very useful, and that good information was achieved on infiltration behaviour (e.g., relatively low amounts of water are no problem to infiltrate, but high amounts of water lead to a sharp decrease in infiltration rate after certain time).

Christoph Schüth (TUDA; GE):

During the MARSOL project there are many experiences of the operation of the MAR sites most effectively to infiltrate different water qualities. However there are certain basins that we have to look into for the future, one is related to water quality of, for example, infiltration of emergent pollutants as pharmaceuticals, not so easy to predict; and the second one related objection is the regulatory framework that has to be implemented to ensure MAR safe and sustainable.

Enrique Fernández Escalante (TRAGSA; SP):

After three years of MARSOL, I think we have truly increased the Managed Aquifer Recharge state-of-the-art, and there are three important conclusions:

First, we have realized that, nowadays, MAR is one of the most capable activities to face frontally some climate change adverse impacts.

Second, MAR is powerful alone, but its integration with other water resources management techniques, such as water transferences or the "never arriving" low cost desalination will permit achieving its full potential.

By last, thanks to MARSOL, I have the feeling that these messages are being disseminated around, and not only to scientists and practitioners, but to the whole population!

Annette Wefer-Roehl (TUDA; GE):

MAR is a sound, safe, and sustainable strategy for climate variability preparedness that can be used with great confidence, and through MARSOL and its demonstration sites the awareness and the acceptance among stakeholders for MAR solutions has been greatly increased.

Jon San Sebastián (TRAGSATEC, SP):

In the future the demand for water gained by MAR will be higher due to climate change, energy issues, increase of population etc. In general, economics is also an issue. Does MAR present a cost benefit? For the EU we have to present suggestions for the future. We have to link people and economy to MAR.

Andreas Kallioras (TUA, GR):

The possibilities of different techniques to apply in MAR were realized. What is still open is how to optimize and how to handle the big amount of data. A good level was already achieved for the data base but still needs further work. The black box turned into a grey box. More integration is needed between geo and water scientists and engineers. Products must be closer to the market.

Peter Dietrich (TUL, GE):

There is a lot of effort to clean the waste water and then it is discharged to the sea and then again there is a lot of effort to desalinate this sea water for drinking water purposes. Who is in charge of cleaning the water? MAR source water quality can be improved, what means, there is a need for improved waste water treatment facilities.

3. Outcomes in single sentences

- ✓ MAR works, but needs experts to do it
- ✓ MAR is now a proven technology
- ✓ MAR is key solution to ecosystems depending on groundwater
- ✓ MAR is a sound, safe, and sustainable strategy that can be used with great confidence
- ✓ MARSOL has created a new generation of water managers that have an additional option now
- ✓ The awareness and the acceptance among stakeholders for MAR solutions is greatly increased
- ✓ MAR as one of the best techniques to face frontally climate change adverse impacts.

4. Final suggestion

MAR is a sound, safe and sustainable strategy for climate variability preparedness that can be used with great confidence and through MARSOL and its demonstration sites, the awareness and the acceptance among stakeholders for MAR solutions has been greatly increased.

It is remarkable to include that apart from safe, sound and sustainable, MAR technique is also cheap.

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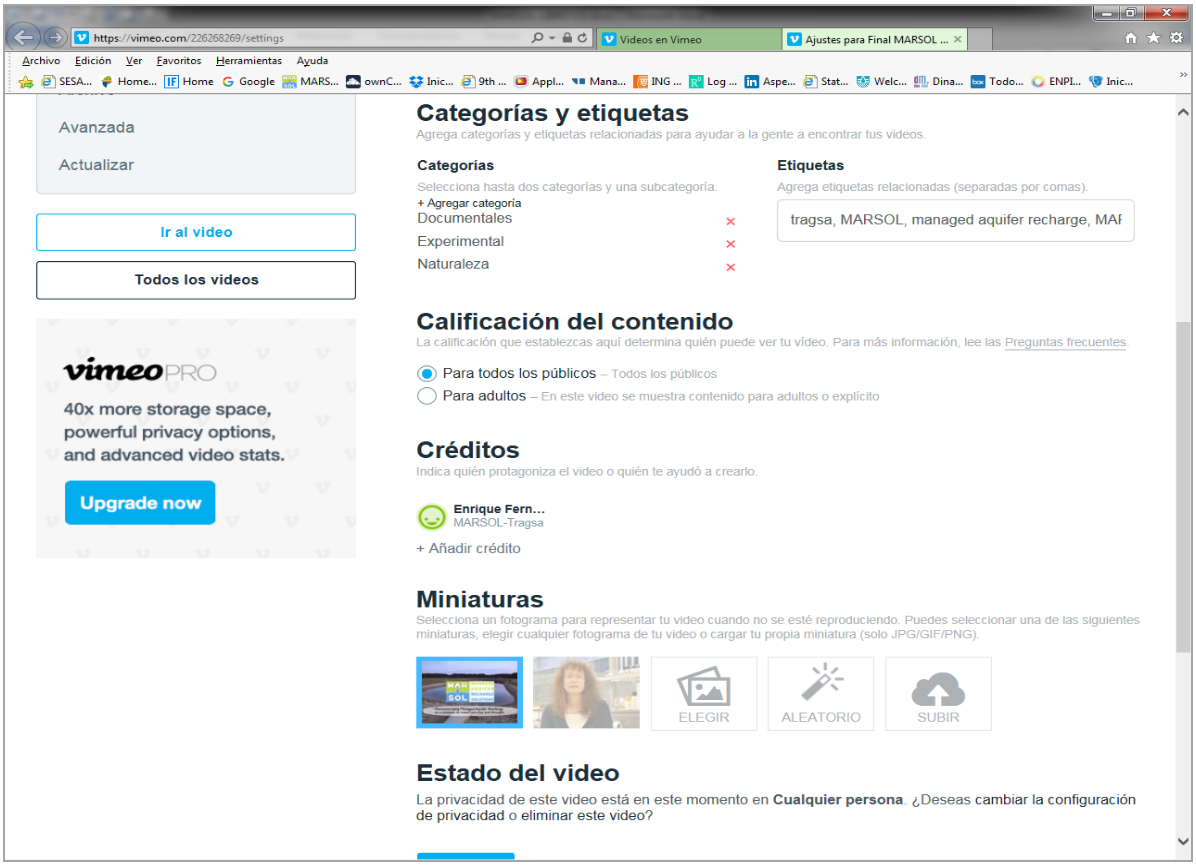
- ✓ Subtitled in Spanish: https://youtu.be/hBmzFy12cm8
- ✓ https://vimeo.com/227872076



Paper for ISMAR10 symposium **Topic No: 8 (215#)**

Ancient techniques of Managed Aquifer Recharge: Spanish Careos and Peruvian Amunas as an Adaptive Complex System. Breakdown, Anthropology and comparative analysis

[1]Fernández Escalante, Enrique; [1]García Asensio, José María; [2]Ayuga, Francisco; [3]Rojas Vega, Carola; [3]Guerrero Salazar, Pedro and [1]San Sebastián Sauto, Jon

[1]Tragsa Group, Madrid, Spain
[2]Technical University of Madrid (UPM), Spain
[3]Peruvian Water National Authority (ANA), Lima, Peru
*Correspondence: efernan6@tragsa.es

Abstract: Amongst the most ancient written references for MAR Recharge are the Careos, in the South of Spain, and the Peruvian Amunas. Both high mountain systems are complex and present extraordinary analogies and differences, despite being chronologically Pre-Columbian structures. From both there are written chronicles since the XII Century and both evolved in parallel, although disconnected, with amazing similarities.

After studying in detail 10 Careos and six Amunas sites from a construction techniques perspective, they have been broken-down in 24 different components. All these units have been compared, studying their analogies and differences according to the employed materials, hydraulic masonry, mortar types, carved stones, layout, profiles, relationships between the different elements, water origin and treatment and water recharge. Units' pathology and recovery measures have also been studied by means of polygonal, linear or punctual structures.

Some common environmental features are the low rainfall conditions, temporal water availability from snow melt and runoff, induced recharge by means of infiltration fields, canals, ditches and dolines, subsurface and deep groundwater transit and recovery from either springs or irrigation ponds. On the contrary, some of the differences are based on the form of carving the stone and masonry, maximum flowrate capacity from 200 L/s to 800 L/s, distance between consecutive canals along the mountain slope, time of transit (15 days to 7 months), recovery average flow rate (from 1 to 5 l/s) respectively for Amunas and Careos, etc.

Both MAR ancient structures work as a hydrogeological and socio-cultural complex system, with values, norms and traditions scarcely evolved during 8 centuries. Water management is accompanied by land and crops management too, to the extent that both can be considered a cultural met in the distance or "*cosmovision of water*", due to certain evidences of synchrony in their temporary development.

Both systems fit the definition for Adaptive Complex System (Murray, 2010) as an articulated group of subsystems with self-similarity, complexity, and self-organization, rather than a Multi-Agent System, defined as a composed one with multiple agents in permanent interaction (Wooldridge, 2002, for artificial intelligence).

Finally, the article recommends some improvement advices, based on their cross-comparison. It also studies the possibilities of replicability for other ridges of the world.

Keywords: Managed Aquifer Recharge, MAR, Amunas, Careos, canals, artificial recharge, ancestral water management techniques, climate change adaptation, resilience.

1. Introduction and definitions

It is surprising to study how our ancestors managed water through advanced methods that required a certain mastery of science and technique; and even more extraordinary, the strong parallelism between some management schemes, as is the case of the *careo* irrigation channels of Sierra Nevada (southern Spain) and the *amunas* of Peru, in the foothills of the Andes.

Both systems against water scarcity have very strong analogies, despite going back several centuries (dating at least from the 12th Century) and being separated by an ocean. According to references, both sites in both countries have been functioning for the past eight centuries (Apaza, 2006; Delaguie, 1995) without interruption, probably up to twelve for the Peruvian case (Apaza, 2006).

Amazingly these schemes have several elements in common, highlighting: they are management systems so valid that they have not disappeared over the centuries, both are exemplar examples of water harvesting and require communal management.

Analyzing their analogies and differences between careo Canals from La Alpujarra (Spain) and amunas from San Andrés de Tupicocha (integral son of water) and San Pedro de Casta, District of Lima (Peru), it is worth to mention the surprising similarity of both scenarios and of both constructions. After defining both systems, an anthropological (even pathological) study has been developed based on construction criteria, maintenance, use and social management.

1.1. Definitions:

1.1.1. Careo canal

This is a water management system based on irrigation and infiltration Canals implemented since the Arab-Berber era (8th Century) in the Southern Iberian Peninsula (Delaigue, 1995), southern slope of Sierra Nevada and La Alpujarra, Spain, which caused an intense transformation of the territory with the coexistence of cultivation terraces, pastures and humid ecosystems.

It is a water harvesting system from high mountain meltwater, which favours infiltration, reduces surface runoff and soil loss. The tracing of the careo canals follows the contour bunds either for the recharge of the surface aquifer (regolith) or deep aquifer (fractured metamorphic rock in the substrate) (Fernández et al, 2005 and 2006).

Each careos´ conceptual model varies according to the materials they run through, which condition their hydrogeological and hydrochemical functioning.

The intentional recovery of the infiltrated water is performed months later at sites either point shaped (springs) or linear (ditches crossing springs) or polygonal (spring areas) hydraulically connected to the recharge zones.

The system has a high resilience to meteorological variability.

Socially they are governed by well-organized water distribution rules and techniques, under advanced integrated Water Resources Management (IWRM) guidelines inherited from parents to children, with a rather scarce variation regarding internal organization in centuries (Apaza, 2006; Delaguie, 1995).

1.1.2. Amuna canal

It is an Andean water harvesting technology that forms a complex hydrogeological and socio-cultural system.

They capture water from rain, melting ice and runoff and lead it superficially or infiltrate it into volcanic rocks (in general) to distant springs located "downstream" (MINAGRI, 2016).

This technology entails water, land and crop management strategies, for final productive and domestic purposes. It also attaches some values, norms and traditions, e.g. rites, water parties, etc.

Consequently, these water harvesting systems present most of the elements common with any other artificial recharge structure.

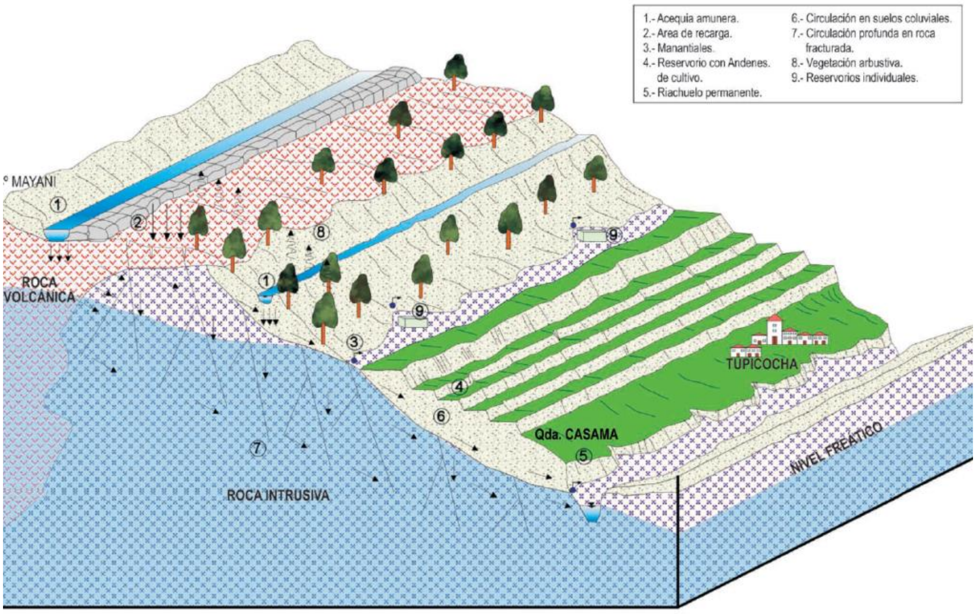


Figure 1. Block diagram for an amunas artificial recharge system. Hydrogeological scheme (Apaza, 2006)

1. Temporary or seasonal water availability from the rainy and/or thawing season.
2. Intentional recharge through point systems (dolines, fault crosses), linear systems (ditches, faults) or polygonal systems (infiltration fields) at different heights of the mountain slope.
3. Groundwater flows across two circuits, either subsurface (soil-regolith) or deep (through the network of interconnected fractures of the rock massif).
4. The capture and recharge canal is asymmetrical as it is adapted to the slope.
5. The recovery area encourages its immediate use from springs, wells and irrigation ponds, even fountains within an urban nucleus.

2. Materials and Methods

The methodology has been based on a first Google Earth recognition of the areas to be visited, and further on site studies for 10 careo canals and 6 amunas during more than 6 years, collecting data such as dimensions, materials, hydraulic masonry from a construction point of view so as to stablish further comparisons.

Some representative amunas and careos were further selected and scouted. In Granada (Spain), Mecina, Berchules and El Espino careos. In Huarochirí (Peru), San Pedro de Casta and San Andrés de Tupicocha amunas. After a detailed recognition, a breakdown was conducted for each, establish "construction units", singular elements which have allowed stablishing common features and differences.

Benchmarking was done using pathological techniques, by comparing equivalent divisions according to the materials employed and their function.

3. Results

The study of the 10 mentioned systems for both areas, from a constructive point of view, has allowed their decomposition into 24 components or work units. Some of the elements show great analogy while others display marked differences (elements identified by the numbers 1, 2, 7, 10, 22 and 23). These 24 differentiated constituents, exposed in the appendix 1, are:

1. *Diversion from the river runway*

Structures adapted to derive water from a stream or collect water from thaw and runoff along the slope. Intakes in the amunas are designed for greater geodynamism and terrain instability (what requires use of mortar and more frequent maintenance).

2. *Slab excavation for sides wall*

Both systems require excavating in the rock, with preference for regolithic zones because of their lower mechanical resistance and because of their aquiferous behaviour.

In the careos there is usually a levelling of the base by contour bunds at a single height; while for the amunas there are several parallel canals along the slope for greater catchment of runoff water.

3. *Construction channel: basal box on rock*

The floor rests on the bare bottom. The paved floors are usually due to the presence of metamorphic or Vulcan-sedimentary outcrops nearby, with abundance of crushed rocks.

4. *In soil channel excavation*

They are channels excavated in soils or areas of regolith. Their average width is 80 to 90 cm and their depth from 40 to 50 cm, either in trapezoidal or semi-circular section.

The areas where slope breaks have detention devices for speed control, such as staggered stones carved at the base and even in the walls of the conduction, so as to increase friction and dissipate part of the kinetic energy of the water.

5. *Water detention devices*

They are a set of additional elements to dissipate energy. It has been observed a greater abundance in careos than in amunas, whose layout is more faithful to the contour lines of the hillside in the studied cases.

6. *Specific channel above side construction*

The highest energy zone of the slope is the upper, which is the least modified. After the excavation and the construction of the retention profile by means of an elevated wall, the dynamism of the slope itself tends to recover its original shape, hence the importance of covering the high energy areas with stone and the use of the natural slope to direct the runoff water towards the channelling.

7. *Half-round profile channel excavation and hydraulic masonry*

In general, in low steep slopes or zones with difficulties to transport construction materials (rock and sandy) the excavation was dug with a semi-circular section. The bottom is more permeable and the infiltration rate is higher. They usually have hydraulic masonry on both edges.

8. *Sandy refills to raise the channel base*

In general at crossings with streams or ravines it is necessary to fill the terrain. For this were used rocks, slabs or remains from the excavation of sand and large fragments of rock.

9. *Stone refills to raise the channel base*

The bottom upholstery has a very careful design and execution in both studied zones. Each stone only overlaps the next one in areas with a high slope, while mosaics were built in the sectors with a lower slope.

10. *Both side walls elevated by hydraulic masonry*

The elevation above 40 cm of the edges is infrequent and appears in specific areas where it is necessary to save height. The layout is often accompanied by masonry walls. Artificial embedding is common in areas with the possibility of overflowing. The side of the valley has a more robust design, as it has to resist the natural trend to restore the previous relief.

11. *Protection of the canal with flagstones points*

There is a careful execution of hydraulic masonry in both cases. The rocks used in the careos are sliced (in general schists), which entails less carving effort. In the amunas are used blocks with a flat face, Vulcan-sedimentary rocks due to their greater flattening, or even came to carve the stone.

12. *Channel lower side habitation & path-way enabling*

The maintenance work became so necessary that both systems developed a service lane for the passage of the person in charge of the management of the floodgates and the maintenance of the hillside structures. This step is usually at the bottom of the slope, after the damming systems.

13. *Channel length extensions*

A technological solution in high-energy ditch areas was the modification of the layout. In modern times it has been common to use a crawler tractor for this purpose.

As a final result, there is a greater final length of amunas irrigation canals (undetermined length) and several parallel routes at various heights to capture the whole runoff from the slope, than in careo irrigation canals, whose total length, according to the inventory of Fernández et al, 2006, reaches 125 km (excluding irrigation ditches not designed for water harvesting).

14. *Widening of the channel at specific points*

Technological solution in line with the previous one based on widening the channel to slow down the speed of the water and energy dissipation. There are hardly any widening in the amunas, where the energy is more distributed due to their more faithful and detailed follow-up of the contour bunds, at least in zones willing to be excavated.

15. *Hydraulic masonry aqueducts construction*

The depressions are covered with filling or with the construction of aqueducts and siphons, simple technical solutions but sometimes very expensive. In modern times and in the case of amunas, simple technical solutions have been appreciated, such as hanging tubes laid from side to side of the valley to "bridge" the passage of water.

16. *Construction of walls of hydraulic masonry*

The retaining walls for slope stabilization generally lack mortar, which was reserved for high-energy areas in both systems.

17. *Construction of walls in dry masonry*

They were built as usual devices for slope stability, watercourses filling and curative measures to repair small landslides. In the interior of the canal they work as stopping devices to dissipate the energy of the water. They also reinforce areas with frequent falling of stones from higher elevations.

18. *Widening and raising of traditional bridges*

No traditional bridges have been observed in the amunas, whose crossings with roads were resolved by covering them with rock slabs, being uncovered in case of shallow depth (up to 25-30 cm).

19. *Splitters iron gates installation*

It is frequent the use of cutters in the careos for the distribution of the water. They also have complex "splitters" of water and "chasms", although this local term does not coincide with its more orthodox geological meaning. On the contrary, in the case of amunas, it is more common to find the use of stone boxes with different levels of overflow directed in different directions.

20. *Points, lines and/or polygons for water recharge*

The intentional water harvesting structures at the top of the circuit can be punctual, linear or polygonal.

Point: Requires a good knowledge of chasms and sinks by the local population.

Line: The most frequent are faults or ditches following the trace of the faults when the slope allows it. It is a system mentioned in some references to face climate change impacts (Ayala, 2000).

Polygon: The flood fields are a common structure in the careos, with derivations from the ditch in flat areas where the water is retained by its low slope. No flooding fields have been observed in the amunas, even in areas with slope breaks.

21. *Drains construction in the channel crosses*

At crossings with streams, spillways are often built in both structures. In general, more complex technological solutions have been inventoried in the careos. The amunas usually solve the spillways by means of a flat rock of exaggerated dimensions.

22. *Vegetal afforestation / restoration*

Plant restoration favours the cultivation of water, a belief assumed by the inhabitants of both systems. At present, there is an important afforestation activity, even more in amunas areas than in the careos zones.

23. *Water recovery points / natural springs*

The points of recharged water recovery are usually superficial springs. There is a popular belief that natural tracers were used (a hair colorant called *gena*) to improve the knowledge of hydraulic connections in addition to the "trial and error" technique. The person in charge of the system (acequieros) correlates certain points on the mountain with specific fountains in the village for careos, according to their verbal communications in Spain. Delaguie, 1995 also refers to tracers essays (in different terms) to study the faults interconnection in the rocky massif between the recharge and the discharge areas.

In the amunas it is usual to recover the water in wells or ponds, which in turn serve as a storage system. The water reaches the spillways designed at different levels as discharge points.

24. *Irrigation ponds*

The largest infiltration ponds have been inventoried in Huarochirí, while in Spain they are more dispersed and abundant, although they are smaller.

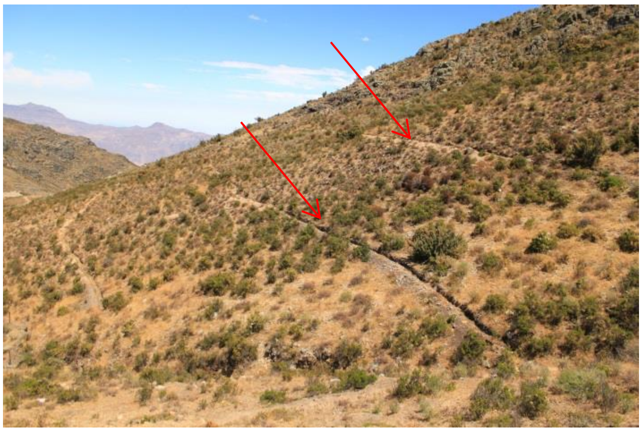


Figure 2. Conduction systems: parallel amunas canals for water harvesting.

a) Directs runoff water to recharge areas
b) Ditches lined in unstable sections
c) Technical solutions to overcome obstacles
d) Reception area of sufficient surface area
e) Search for fractures and geological faults
f) Reception of the water by means of centrifugal canals around a well, puquio or spring
g) Transit time between recharge zone and discharge zone: 6-7 months.

4. Discussion

The breakdown of amunas and careos according to "units of work" and the use of different scales of observation has allowed extending the knowledge of the analogies and differences between both. It is worth mentioning:

They are found in very high areas, above 3,000 m above sea level in general and with a steep slope (increasing concentration time in areas with very high runoff). The layout of the ditches (their trace allows both uses, direct irrigation and recharge) follows contour lines and is well known by its maintenance workers. Its most usual length is from one to four kilometres.

Direct recorded rainfall records are lower in amunas areas (around 400 mm/year as an average) than in careos (700 mm). This scarcity justifies the capture of the thaw from the mountains above.

In both study areas, the best favourable geologic materials for the artificial recharge of careos are the limestone and permeable detrital formations in careo canals. The topography is a strong condition of the design and layout of the canals.

Both have common function and objectives.

The geodynamism and the environmental conditions are linked to the slope and layout of the conduction and determine their height, width of the ditches, materials used, excavation and filling of the screed, complementary elements such as retaining walls, etc.

They have been developed in low inertia fissure type aquifers, with detritic layers or alteration regolith. Therefore, two groundwater flows can be distinguished through surface and deeper aquifers.

4.1. Analogies and differences according to their construction criteria

Geological materials have conditioned the construction habits: metamorphic rocks (careos) type micaceous schists (Mecina Bombarón) and graphitic micaceous schists (Trévelez and Bérchules) vs volcanic and intrusive rocks type basalt and andesite (amunas). The abundance of iron in these materials and in their waters is a common feature for both.

Stones used for construction is, perhaps, the biggest difference as they form natural slabs due to their schistosity (careos), whilst require stone carving or detailed selection due to their shape (amunas), case what requires a greater effort in stonework and adaptation.

Figures 3 a) and b). Metamorphic rocks: micaceous schists (careos) vs volcanic rocks andesite (amunas).

The construction of the stagnation box is asymmetrical in order to collect the runoff water and prevent it from overflowing over the edge of the irrigation canal. The profile allows the runoff water to be collected and dammed. The valley side presents the accumulation of the land as a dam and the transit zone for the *acequiero* or person in charge (figures 4).

The alteration of the natural profile of the mountain entails its natural tendency to rectify its inclination with time by means of landslides and "sores", a normal response for the recovery of the equilibrium profile.

Investigation of hydraulic interconnections by means of trial and error techniques, tracers (verbal mention) and observation of nature also facilitates an approximate knowledge of recharge rates and underground flow. The hard rocks aquifer in a "cracked" environment operates according to the "cubic law", which, in the case of volcanic rocks, constitutes an aquifer of certain importance due to its thickness, extension and degree of fracture. A detailed characterization of the rock massif has not yet been made according to modern geotectonic techniques (orientation and continuity of structural discontinuities, spacing, Joint Roughness Coefficient (JRC)...).

Figures 4 a) and b). Asymmetric profile common for careos and amunas Canals.

1- Edge of the riverbed: side of the summit
2- Ditch substrate
3- Dam and lane for the acequiero
4- Edge of the riverbed: (side of the valley).

Differences can be seen in the "derivation-capture" system, with common features for capturing melt water. While runoff is directed to natural drainage systems in the careo canals, capture systems collect and drain rainwater runoff along the slope in the amunas. The flow through the irrigation canals is, generally, less than 200 l/s, as a design parameter for possible replicas.

The morphology of the conduction-infiltration systems is analogous, with single-traced conductions on the slope (careos), or several, up to four in the study areas (amunas). Therefore, its main difference is its frequency.

The permeability range of the substrate varies according to the sources consulted, from 4-5 m/day (amunas); other sources indicate 10-14 m/day (Apaza, 2006). For careos this range is not clarified yet.

The flow between the recharge and recovery zone has a transit time through the subalveum of about 15 days (flow through the most superficial aquifer, soil and regolith) up to 5 to 7 months for the deepest (faults in the rocky massif) in the amuna zones.

The recovery flow rate is 1 to 5 l/s (Apaza, 2006). The recovery structures (springs, eyes of water…) generally have a flow-rate below 1 l/s. They are usually modified natural springs, whose flow is increased by man. In the case of amunas, they usually have associated storage structures or reservoirs (e.g. *aljibes* as a local Arabic name for semi-buried tanks).

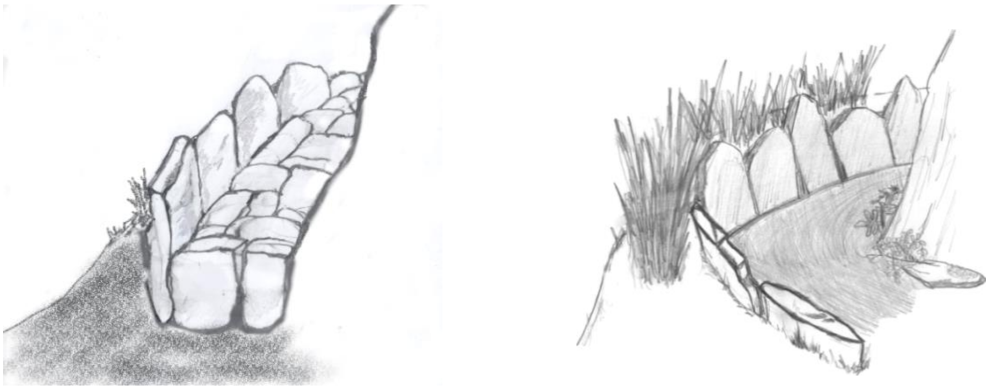
4.2. Maintenance and recovery

In general, the careos require an important maintenance. They are usually affected by diverse problems: hillside movements, fall of solids that cut or break the conduits, rill erosion, bad lands, etc. The most important recovery tasks that they carrying out are the following ones:

- Excavation of the bottom of the channel and rebuilt by buried stones and protection of the borders of the channel with flagstones (Figures 5).

- Enlarge of the channel in specific points and amplification of the longitude of the canal increasing this way the infiltration surface and construction of earth channel, by means of the opening of ditches, in order to improve the artificial recharge of the aquifer for direct infiltration in device type grave.

- Homogenisation of the slope to avoid damming in not wanted areas and construction of masonry aqueduct in the points where the canals cross ravines in those that lose great quantity of water.



Figures 5 a) and b). Drawings of hydraulic masonry (for courtesy of Cano M. and Tragsa Group in Granada province). A). Structure of the channel protected by stones mosaics buried in tracts of great slope and subject to a strong erosion B). Flagstones protecting the external border of the channel.

The maintenance of both systems is a communal activity, except for specific interventions, with greater requirements due to their greater geodynamism in the amunas, which have associated impacts of greater intensity, such as *huaycos* (local Peruvian name for large-scale landslides). Some of the preventive measures applied are the masonry correction of landslides and the new routes crossing *huaycos*´s deposits.

Figures 6 a) and b). Areas affected by landslides and huaycos and technological solutions: walls without or with mortar.

4.3. Social aspects

Water harvesting is carried out in high zones and by means of a communal action, organizational schemes and wise socio-technical management, what has made possible the occupation of inhospitable lands involving local population, to the extent of forming part of their idiosyncrasy. This is reflected in festivities such as "the feast of life" and other rites, becoming a "centre of the social and spiritual world" (Hendriks, 2018).

Careos have a joint administration with a person in charge called "*acequiero*" who is responsible for the floodgates and knows the exact recharge points and interrelations. Occupation inherited by kinship, which has transmitted their knowledge from parents to children for generations.

In general, the Communities of Users, main protectors of the system of canals, have scarce resources for their maintenance, so a part of the conservation expense is supported by the National Park for careos´ case.

Figures 7 a) and b). Channels maintenance in Mecina Bombarón, 1963 and Huarochirí, both as a social obligation.

In light of all these observations, both constructions fit the "Complex Adaptive System" or CAS definition (Murray, 2010) as an articulated set of subsystems or ancestral technology agents (CAS: self-similarity, complexity, emergence and self-organization). It differs from an SMA or Multi-Agent System, which is defined simply as a system composed of multiple interacting components) http://sistemasadaptativoscomplejos.blogspot.com.es/2010/06/premio-nobel-murray-gell-mann.html

Figures 8 a) and b). Whilst careo Canals are unique in the slope of the mountains (a), amunas have several parallel multi-teared pathways (b).

5. Conclusions

Both systems have the usual components of an artificial recharge surface system, with peculiarities motivated by adaptation to the environmental circumstances. Each element studied has been decomposed into work units, differentiating 24 elements differentiated by construction criteria. In this set, six out of 24 show significant differences between the careos of southern Spain and the amunas of Peru:

1- Diversion from the river runway: More robust systems in amunas than in careos.

7- Slab excavation for sides wall: following the foliation of the rock or with stonework techniques for solid rock.

10- Half-round profile channel excavation and hydraulic masonry: carved or worked stones in amunas and stone slabs in careos.

11- Both side walls elevation by hydraulic masonry. Stronger and thicker edges in amunas, except for areas with slab stones.

22-Vegetal afforestation / restoration. At present there is a more palpable effort around the amunas than in careos.

23- Water recovery points / natural springs. In amunas they are usually polygonal zones of recovery, and punctual for careos systems.

The technical solutions applied are aligned with environmental conditions (metamorphic rocks with schistosity and greater ease of carving for careos vs. volcanic rocks for amunas).

Hydraulic masonry is well-suited to certain construction sites, providing great durability and greater ease of subsequent maintenance than other methods such as traditional excavation.

Both constructions meet the definition of "Complex Adaptive System" or CAS (Murray, 2010) as an articulated set of subsystems or ancestral technology agents.

They are systems with replicability possibilities in other parts of the world with similar environmental characteristics.

It is a short term system with difficulties in achieving medium and long term storage and regulation.

It is also a cultural meeting in the distance (Cosmo vision of water), so, how can they not look alike? The common features are typical of the evolution of engineering itself.

Possibilities for improvement rely on more modern techniques (longer-lasting tracers, characterisation of rock massifs, modern tectonics, etc.).

There have been detected abundant signs of synchrony in their temporal development (open line of study). Even regarding terminology, *Amunar* and *carear* (as verbs) are common terminological words related to "open and close the water"). These verbs are used by the inhabitants of Spain and Peru in similar terms in spite of their geographical disconnection.

Although carving is key to facilitating construction, it is precisely in the amunas where more stonework is required. Even so, there are more kilometres of canals and were built at various heights along the hillside, with a greater focus on the capture of runoff. Careos canals construction is more focused on the conduction of water from the thaw of the mountain range to end-users emplacements.

It would be important to preserve and to maintain these systems, given their high historical and environmental value.

Conflicts of Interest: The authors declare no conflict of interest.

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6.1. Videos and web accesses

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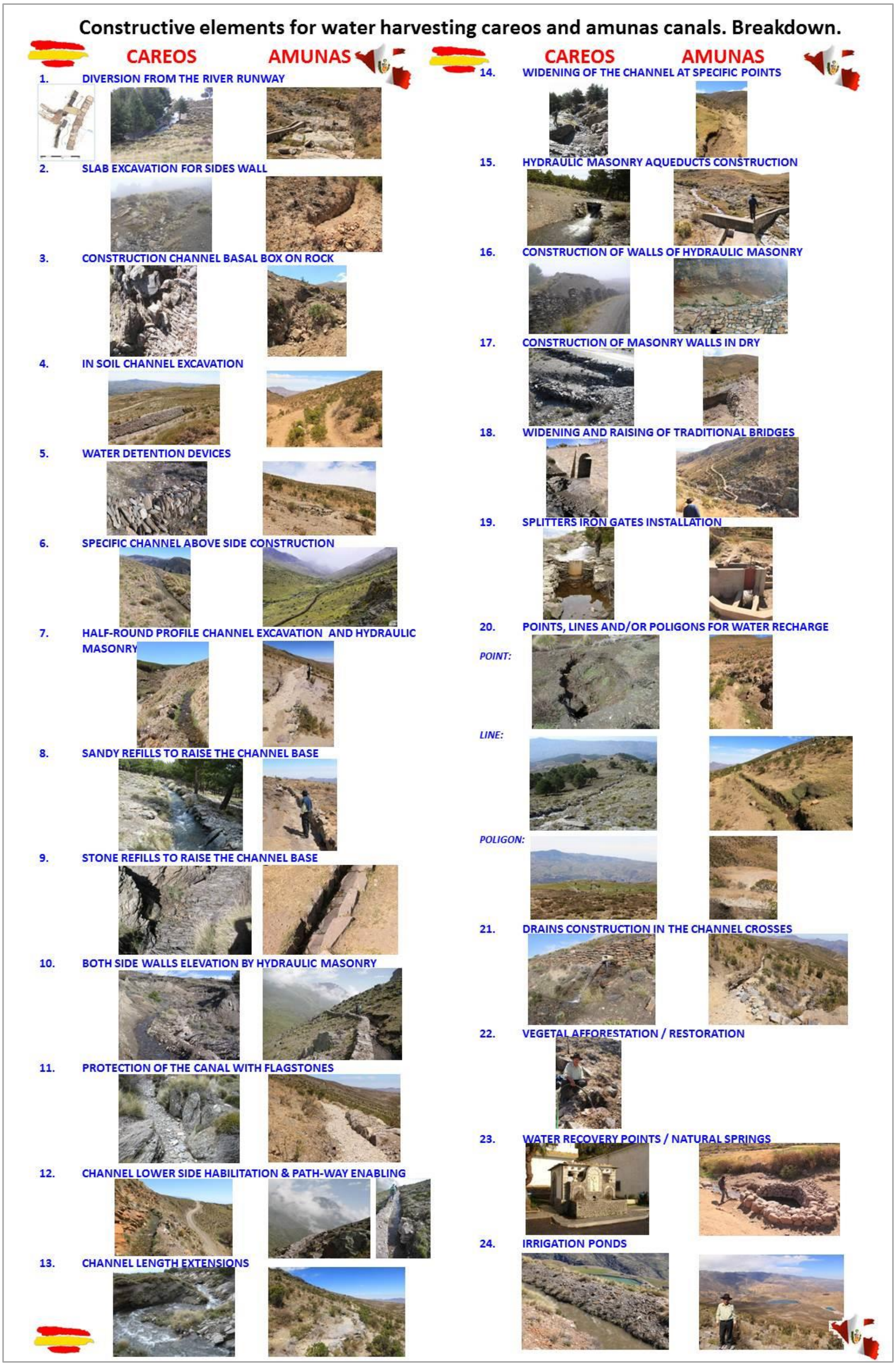
APPENDIX 1. SPANISH CAREOS VS PERUVIAN AMUNAS: PATHOLOGICAL COMPARISON BY CONSTRUCTION UNITS. PHOTOGRAPHIES:


Constructive elements for water harvesting careos and amunas canals. Breakdown.
CAREOS
AMUNAS
1. DIVERSION FROM THE RIVER RUNWAY
2. SLAB EXCAVATION FOR SIDES WALL
3. CONSTRUCTION CHANNEL BASAL BOX ON ROCK
4. IN SOIL CHANNEL EXCAVATION
5. WATER DETENTION DEVICES
6. SPECIFIC CHANNEL ABOVE SIDE CONSTRUCTION
7. HALF-ROUND PROFILE CHANNEL EXCAVATION AND HYDRAULIC MASONRY
8. SANDY REFILLS TO RAISE THE CHANNEL BASE
9. STONE REFILLS TO RAISE THE CHANNEL BASE
10. BOTH SIDE WALLS ELEVATION BY HYDRAULIC MASONRY
11. PROTECTION OF THE CANAL WITH FLAGSTONES
12. CHANNEL LOWER SIDE HABILITATION & PATH-WAY ENABLING
13. CHANNEL LENGTH EXTENSIONS
CAREOS
AMUNAS
14. WIDENING OF THE CHANNEL AT SPECIFIC POINTS
15. HYDRAULIC MASONRY AQUEDUCTS CONSTRUCTION
16. CONSTRUCTION OF WALLS OF HYDRAULIC MASONRY
17. CONSTRUCTION OF MASONRY WALLS IN DRY
18. WIDENING AND RAISING OF TRADITIONAL BRIDGES
19. SPLITTERS IRON GATES INSTALLATION
20. POINTS, LINES AND/OR POLIGONS FOR WATER RECHARGE
POINT:
LINE:
POLIGON:
21. DRAINS CONSTRUCTION IN THE CHANNEL CROSSES
22. VEGETAL AFFORESTATION / RESTORATION
23. WATER RECOVERY POINTS / NATURAL SPRINGS
24. IRRIGATION PONDS

Paper for ISMAR10 symposium. **Topic No: 8 (229#)**

ASTR facility design in a deep aquifer destined to supply the Community of Madrid

Sánchez, Esther and Gutiérrez, Elisa

Canal de Isabel II S.A. Madrid, Spain.
*esanchez@canaldeisabelsegunda.es, egutierrez@canaldeisabelsegunda.es, elenagarcido@gmail.com

Abstract: The main aquifer of the Community of Madrid and the system of supply as a whole, have ideal characteristics for the improvement of the supply guarantee through the application of recharge techniques. The recurrent droughts have given the detrital tertiary aquifer of Madrid (ATDM) a regulatory role in the hydrological variability and as a guarantor of the availability of resources in these scenarios. In these situations, the artificial recharge contributes to the improvement of the quantitative status of the aquifer, in addition to allowing the immediate availability of the water stored in the key areas of the supply system. In this work is exposed the constructive design of an experimental installation of ASTR constructed in the year 2010 by Canal de Isabel II, which is the company that manages the integral water cycle in the Community of Madrid, with more than six million inhabitants. The objectives of this installation was the realization of some tests that allowed to evaluate the suitability of the application of the technique of deep recharge in the aquifer of Madrid and to advance in its knowledge. The main conclusion obtained from this complex experimental installation is, precisely, its extreme complexity that gives it difficulty in the operation. This conclusion opens the door to assessing a design that can be generalized in the entire field of operation of the ARDM and that is more efficient in its execution and management.

Keywords: Madrid, Canal de Isabel II, Detritic tertiary aquifer of Madrid, aquit, aquifer storage transit & recove (ASTR), deep recharge, constructive desing.

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1. Introduction

Canal de Isabel II is a public company with more than 165 years of history, dedicated to the management and operation of the supply and sanitation services in the Community of Madrid (CAM). It currently serves the water needs of more than 6 million inhabitants, taking advantage of surface and underground resources. The average annual supply is around 500 million cubic meters, in a context of high variability in the availability of the natural resource. Thus, in the last 30 years, there have been minimum annual contributions of 324 million m^3 (yH 2004- 2005) and maximum contribution values of the order of 910 million m^3 (Hy 1995- 1996), requiring operations adapted to each circumstance.

Among the multiple conmitments of this company is that of maintaining, replace and planning infrastructures and services, adapting them to the expectatins of society, as well as minimising environmental impact and favouring the efficient use of available resources. Within this framework, groundwater and the infrastructures that allow its use in periods of water scarcity, when other resources are scarce, or in the event of contingencies in the supply system, are of special importance. For this reason, the application of techniques for artificial recharge of aquifers and the facilities that allow it, deserve special attention to take advantage of the structural characteristics of the supply system and the great potential of the main aquifer as a buffering element, also making it possible to take advantage of the existing hydrological variability.

Currently, Canal de Isabel II groundwater system has more than 80 facilities dedicated to this resource operations. These facilities are wells with depths greater than 400 meters, which operate groundwater as a strategic resource to cope with scenarios of scarcity and contingencies.

This article describes the design and main characteristics of a specific underground storage system with transfer and recovery (ASRT) design. It was built by Canal de Isabel II as a pilot facility to assess the suitability of the application of managed aquifer recharge (MAR) methods by deep injection into the region's main detritic aquifer. It has been called "**ASRT FE-1 Facility**" It consists, essentially, of one deep recharge well, one extraction well and a set of piezometers for the control and monitoring of the operation. In this case, the water to be recharged is of superficial origin and comes from the occasional and seasonal surpluses of drinking water which final destination wasthe population supply. The system makes possible to take advantage of scenius of abundance of the resource and the additional treatment capacity.

2. Geographical and hydrological framework of the Community of Madrid and the ASRT FE-1

Spain is a medium-sized country (505,990 km²) located between Europe and Africa continental masses and between the Atlantic Ocean and the Mediterranean Sea. It is a country with a great variety of climates. Although a large part of its surface is temperate, the area covered by this article has semi-arid climate characteristics (Figure 1).

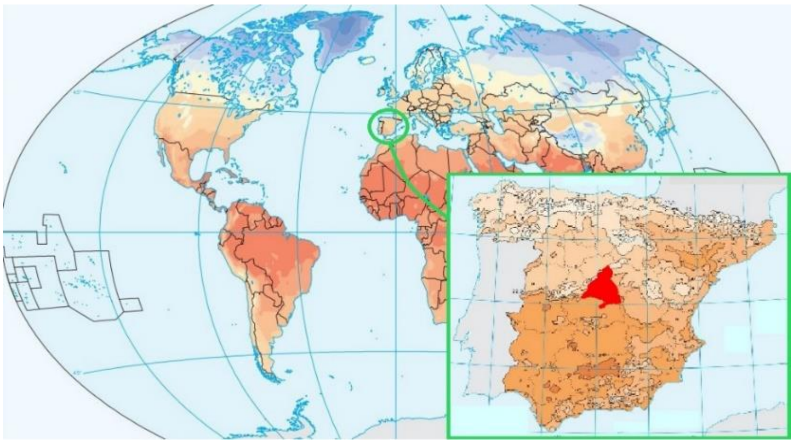

Figure 1. Location of Spain and the Autonomous Community of Madrid. *Source: NASA and Environmental Diagnosis 2017 of the Community of Madrid.*

Currently, in the Spanish zone of the Iberian Peninsula there are 15 main hydrographic basins that support water management and policy. In this context, the entire geographical area of the CAM is integrated into the scope of the Tagus Basing Agency (Confederación Hidrográfica del Tajo).

Madrid region has ten groundwater bodies of different characteristics, extension and location (Spanish part of the Tajo Hydrographic Demarcation, Basin Hydrological Plan, 2015), of which Canal de Isabel II has has the rignt of using four of them: Torrelaguna (030.004), Jarama-Manzanares (030.010), Manzanares-Guadarrama (030.011) and Guadarrama-Aldea del Fresno (030.012) (Figure 2).

2.1. Hydrogeological framework of the ASRT FE-1 facility

The groundwater management and operation carried out by Canal de Isabel II is structured by well fields distributed in the main aquifers of the region, following well defined exploitation criteria. 90% of the wells are in the central strip, which is the competent surface for the detritic tertiary aquifer of Madrid (ATDM). In this context, the ASRT FE-1 facility is in the Fuencarral well field, located in the center of the CAM wich constitutes one of the main well fields exploiting the ATDM (Figure 2).

Figure 2 represents the hydrogeological situation of the Canal de Isabel II wells, highlighting the Fuencarral well field and the location of the ASTR FE-1 installation.

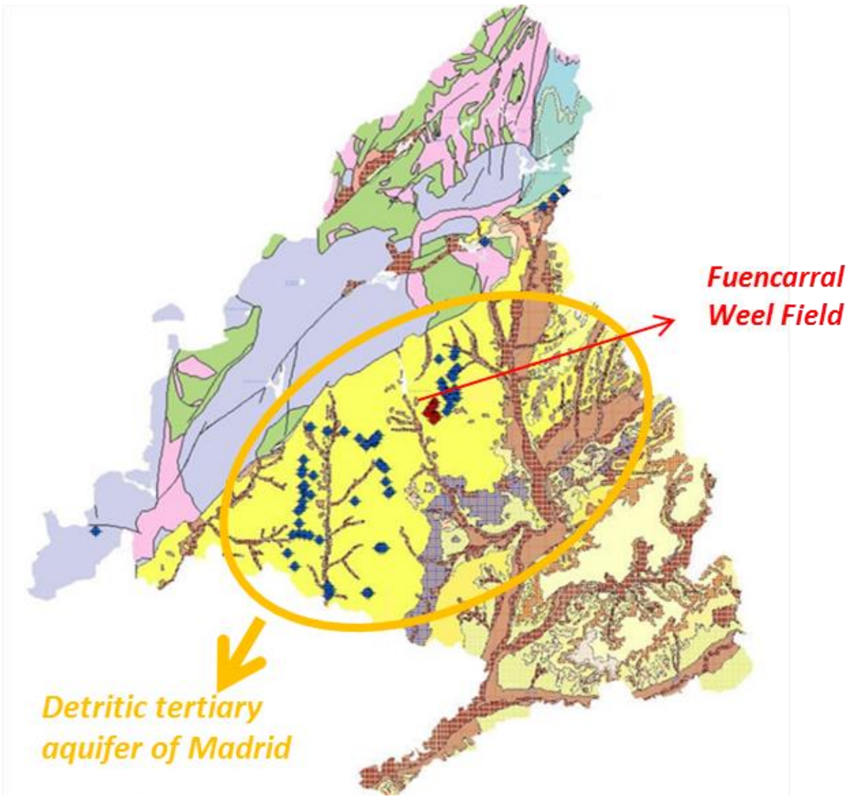

Figure 2. Locations of Canal de Isabel II wells.

ATDM is a multi-layer aquifer that constitutes an important strategic reserve, as it has adequate structural, hydrogeological and hydrochemical characteristics. Its great extension and thickness make it a great potential as a warehouse and as an element of hydraulic buffer, due to its large storage capacity, slow flow speeds, low vulnerability to variations in rainfall and pollution is more reliable than surface aquifers.

However, its hydrogeological parameters may be low (for example: average total porosity of around 50%, typical of clayey materials, and average vertical permeability between 0.03 and 0.15 m/day). It is an aquitard and not an aquifer itself, so the sustainability of its exploitation is a fundamental factor (Sánchez, E. 2018).

Its characteristics may vary greatly depending on the area and depth. Thus, in a very general way, according to CyPS-UCM-Group of Catalysis and Separation Processes (UCM, 2007), can show:

- Transmissivity (T): 1 - 852 (m^2/day)
- Vertical conductivity (KV): 0,089 - 0,31 (m/day)
- Horizontal conductivity (KH): 10-5 - 0,9 (m/day)
- Storage Coficient (S): 10^{-5} - 10^{-1}
- Porosity (m): 1 - 20%

The following are some *technical challenges* that hinder the efficient application of recharge in this aquifer:

- It is a very deep aquifer. The wells that are part of the extraction system have depths greater than 400 meters.

- Its hydrogeological parameters give these depths the condition of confined or semi-confined aquitard, making it difficult for water to enter the formation. However, this feature may help to keep the recharged water within a radius of less than 1000 meters from the injection point, being this aspect very interesting for later use.

- It is its configuration as a deep aquitard that influences, among other more operational considerations, the design of the artificial recharge facilities, forcing the injection to be carried out at high depths and preventing air from entering the system, in such a way that could be occluded, hindering the process of water admission into the aquifer and opening up possibilities of generating significant problems in the installation.

- These characteristics require to provoke narrow cones of pumping and with important descents, obtaining specific flows normally lower than to 0,5 l/s.m, wich do not facilitate the application of MAR techniques.

Figure 3 shows a lithological correlation profile of the Fuencarral well field, which includes the wells of the ASRT FE-1 facility. There is a predominance of fine particle size materials and, consequently, reduced permeability of the whole. The drilling depths are represented, as well as the position of the electro-pump units installed in the wells. The exploitation zone of the wells is defined between the two discontinuous lines that mark the maximum static level of the aquifer and the maximum dynamic level reached with the exploitations that occurred to date.

The water quality of the ATDM progresses with depth, from bicarbonated calcium facies to bicarbonated sodium facies. Figure 4 shows the Piper diagram of the wells and piezometers controlling the recharge zone. The extraction of water, increasingly deep as the extractive activity occurs, increases its sodium concentration and reduces the calcium concentration (there is an exchange of calcium from the water retained in the clays for sodium from the aquifer matrix) (IGME-CYII, 1997). Regardins conductivity, the average value of aquifer water is normally greater than 300 μS/cm, while the conductivity of the recharged water is 90-100 μS/cm.

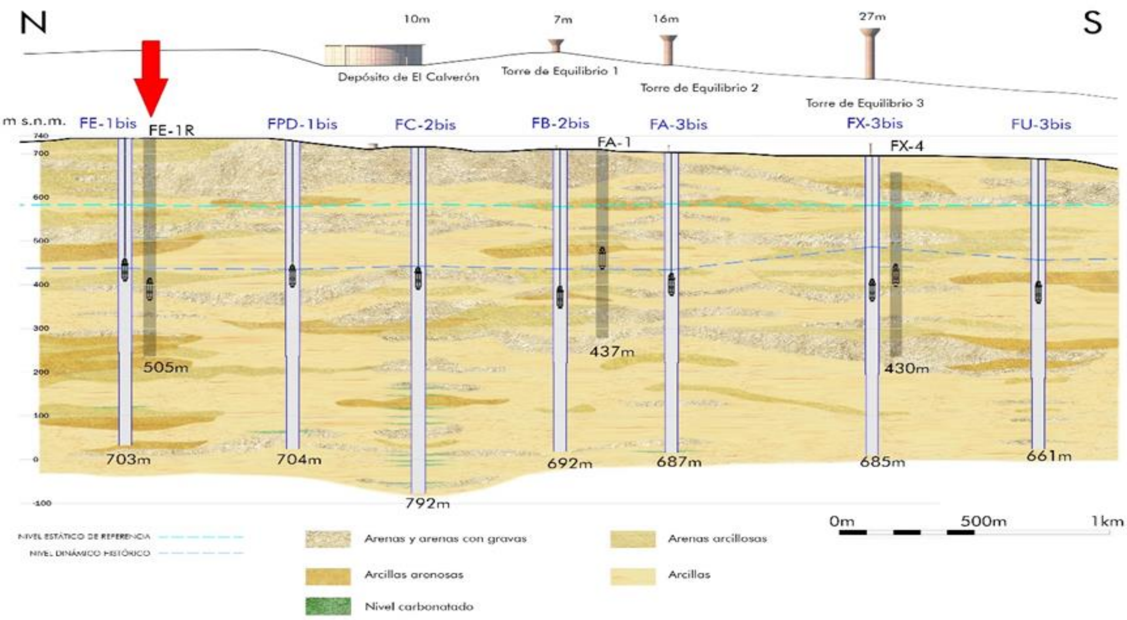

Figure 3. Lithological columns correlation for the Well Field.

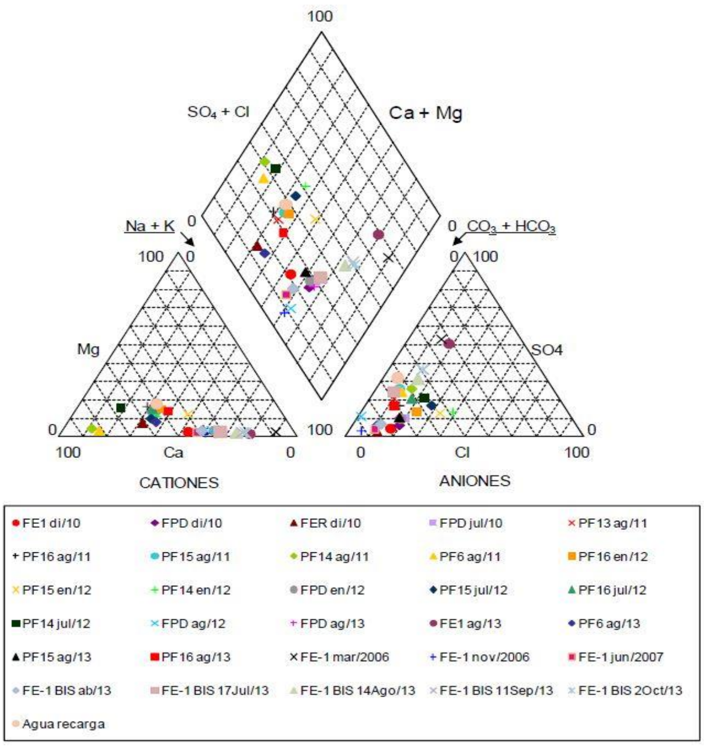

Figure 4. Piper diagram of the set of water samples from wells and piezometers around the ASRT FE-1 facility.

The quality of the water extracted must meet the requirements established in the Spanish standard of drinking water RD 140/2003, of February 7, *which will establish the sanitary criteria of the quality of water for human consumption.* Special attention is given to the arsenic parameter since the Fuencarral well field tends to give incidents related to this parameter. In the study area, this parameter remains close to 9 µg/l (in the recharge well, which is less deep, the concentration of As is lower than 3.8 µg /l). During exploitation, arsenic levels may increase and therefore dilution is required. A disinfection is also carried out before the water is incorporated into the supply system.

Further data related to the chemical quality of the aquifer water in the area are (table 1):

Table 1. Chemical physical parameters of the water extracted by the FE-1 Bis well (1996).

Conductivity	659 µS
pH	8,06
Temperature	28,3 ºC

The Basin Agency required that the water destined for recharge also comply with the Spanish standard of quality of water for human consumption (RD 140/2003). For this reason, the water used in the recharging activity comes treated and is suitable recide to suplly of distribution network of Canal de Isabel I.

3. Results

3.1. ASRT FE-1 facility synthesis

This ASRT facility is located in a common recharge and extraction emplacement, as well as operation control and system monitoring; all of them on 3.600 m^2 of surface. The zone is fenced off conveniently, preventing unauthorized persons from entering and without the presence of potentially polluting activities in the environment, thus reducing the possibilities of specific or zonal pollution (figure 5).

Water is injected into the aquifer by a drilling (FE-1R well) and is recovered from another well (FE-1 Bis) with a distance at 60 meters. This fact allows increasing transport time and benefitting from the aquifer treatment capacity (UNESCO PHI 2005). The installation has a complete monitoring and control system, with 7 different depths piezometers located closer than 80 meters from the recharge and extraction wells.

Moreover there are several buildings where control and operation elements are located in low voltage, as well as communication installations that enable comunicate signs with Canal de Isabel II Data headquaters to facilitate operation monitoring, a complete cathodic protection system and a transformation building.

Recharge average flow in experimental test cycles has been 27 l/s (67% of well exploitation flow) and the maximum 40 l/s. However, in the last cycle of the tests there is a reduction is about 20% in both cases.

Canal de Isabel II extraction activity is based on taking advantage of water at depths greater than 150-200 meters. Therefore, it is expected that if exploitation effects are focused on a strip between 150-250 meters, recharged water will also intervene in that area.

Figure 6 shows system operation scheme linked to the piezometry. It is manifested the connection between piezometric levels and recharge activity, as well as extractive activity, reflected on the seven piezometers set and the two wells. It is shown the connection between deepest piezometers and wells and also the disconnection with the most shallow ones.

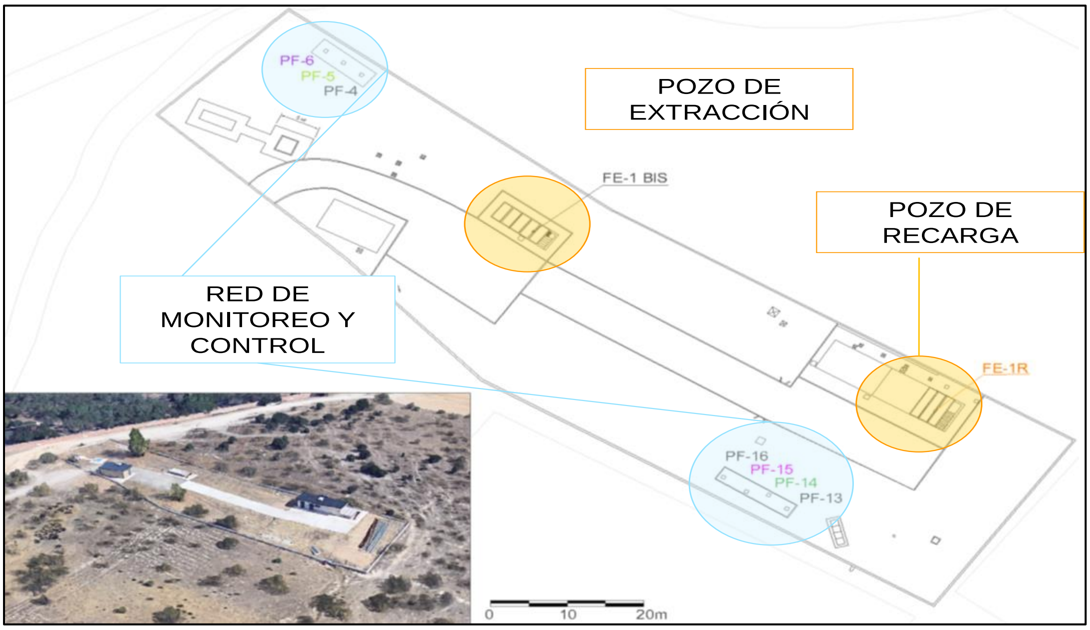

Figure 5. ASRT outdoor and floor ASRT facilities.

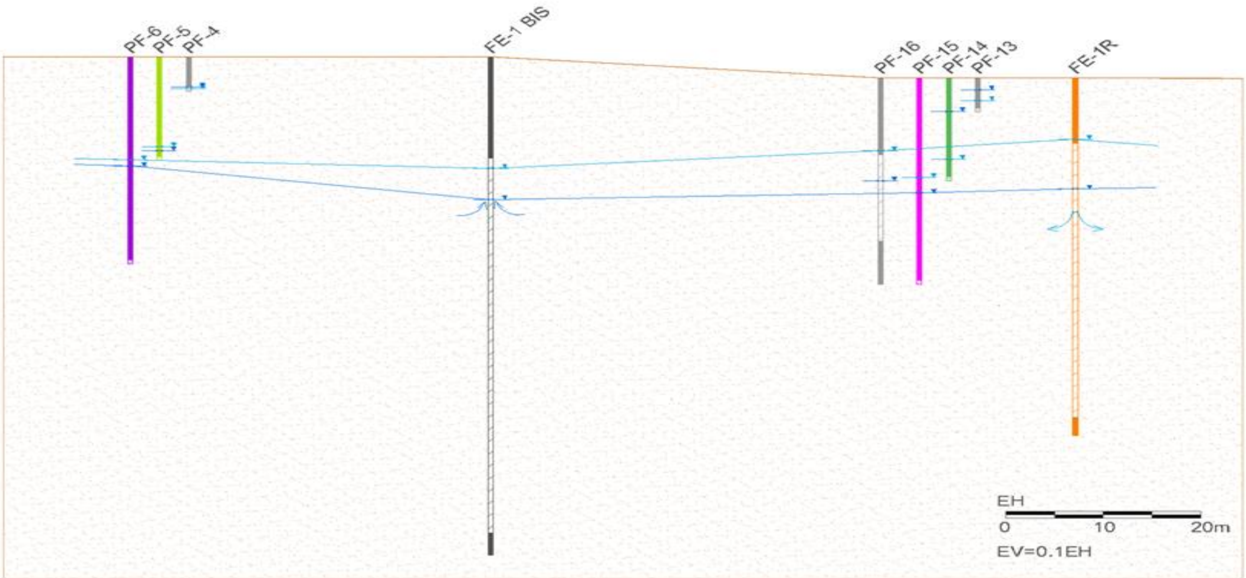

Figure 6. Recharge operation scheme.

3.1.1. FE-1 Bis well characteristics (extraction well)

Extraction well was drilled in 1996 and it is 722 m deep. It is located 60 m from the recharge well (FE-1R well). Submersible water pump is located at 285 m deep and its electric motor has 670 kW installed capacity to extract a flow rate up to 120 l/s. Initial specific capacity was 1.86 l/s/m.

Attached table shows pumping test results carried out after well construction, as well as some essential construction characteristics (table 2).

Table 2. FE-1 Bis well construction and operational characteristics table.

Drilling depth	722 m
Constriction depth	464,2 m
Drilling diameters	900/750/444 mm
Casing material	Carbon steel
Casing thickness	10/8 mm
Casing diameters	800/510/265
Cementation	First 20 meters
Screens	1,5 mm bridge slot
% Screening pipe	19%
First screen depth	147,5 m
Gravel type	Siliceous
Gravel diameter	2-6 mm
First static level (April 1996)	-172,5 m
Dinamic level (118 l/s flow)	-235,98 m
Final estatic level (89 h pumping test and recuperation)	-181,62 m

3.1.2. FE-1R well characteristics (recharge well)

FE-1R well is designed exclusively for recharge activities. It has a drilling depth of 519 m and its equipment was completed in 2010. Submersible water pump necessary for cleaning cycles is located at 250 m depth and has 355 kW installed power. Next table shows pumping test results carried out after well construction and its main construction characteristics (table 3).

Table 3. FE-1R well construction and operational characteristics table.

Drilling depth	519 m
Constriction depth	208 m
Drilling diameters	1200/850/750 mm
Casing material	Carbon steel
Casing thickness	10 mm
Casing diameters	900/600/500
Cementation	First 30 meters
Screens	1,5 mm bridge slot
% Screening pipe	26%
First screen depth	95,5 m
Gravel type	Siliceous
Gravel diameter	2-6 mm
First static level (April 2005)	-189,97 m
Dinamic level (100 l/s Flow)	-350,4 m
Final estatic level (89 h pumping test and recuperation)	-239,9 m

Static groundwater level is located at 150 meters depth, this factor conditions the water input into the deep aquifer. This recharge is got by three pipes with independent drive, 80 mm diameter. Each one of them is equipped with a packer located at 195 m depth that allows to close the pipe as a previous and necessary step for aquifer water input process.

Recharge cycles are followed by cleaning pumping cycles to ensure operation.

3.1.3. Control and monitoring system facilities

Control and monitoring, besides recharge and extraction facilities, is carried out by two nests constructed expressly to observe extraction and recharge operations and analyse them. Monitoring piezometric evolution and aquifer quality at different depths during operational phases is the purpose of these facilities.

Each nest is composed by three small diameter boreholes at different depths (50-100-300 m) and, in general, first 20 or 30 meters, are cemented. Filter zone is at the pipe's end (6 meters of total amount), while the rest is blind pipe (table 4). In addition, there is a multi-slot piezometer which allows to control the depth where the recharge is produced.

Table 4. Control nest constructive characteristics table.

Piezometers	Drillind depth (m)	Drilling diameter (mm)	Casing depth (m)	% Screened pipe
PF-6	300	250/152	300	2
PF-5	150	250/152	150	4
PF-4	50	250/152	50	12
PF-16	300	300/250	300	20
PF-15	300	300/250	300	2
PF-14	150	300/250	150	4
PF-13	50	300/250	50	12

3.2. Recharge and cleaning pipelines description

Recharge wells can be designed exclusively for this operation or be dual, allowing pumping and recharging phases at the same well. However, basic installation can be similar in both cases, as deep recharging operations require submersible water pumps and pipelines that allow cleaning pumping to be carried out and maintain the recharge capacity.

FE-1R well is designed to recharging operations only and pumping that has been carried out at the end of each recharge cycle is aimed to increase water admitted into the well. Therefore, it has two independent pipelines with different characteristics:

- Pipeline destined to recharge operation when there are water surpluses periods.
- Water extraction pipeline to allow filters cleaning that could be affected by clogging during recharging.

In this case, recharge water comes from a Canal de Isabel II water treatment plant (WTP) located at the north of the CAM, 14,5 km from the ASRT facility. Water is transported through an adduction channel that is part of the main supply system. To get this resource, it was constructed a pipeline 450 m away from the recharge well, with a ductile cast iron pipe and 200 mm nominal diameter, which is prepared to receive pressurized water at 2.5 kg/cm^2 (Figure 7).

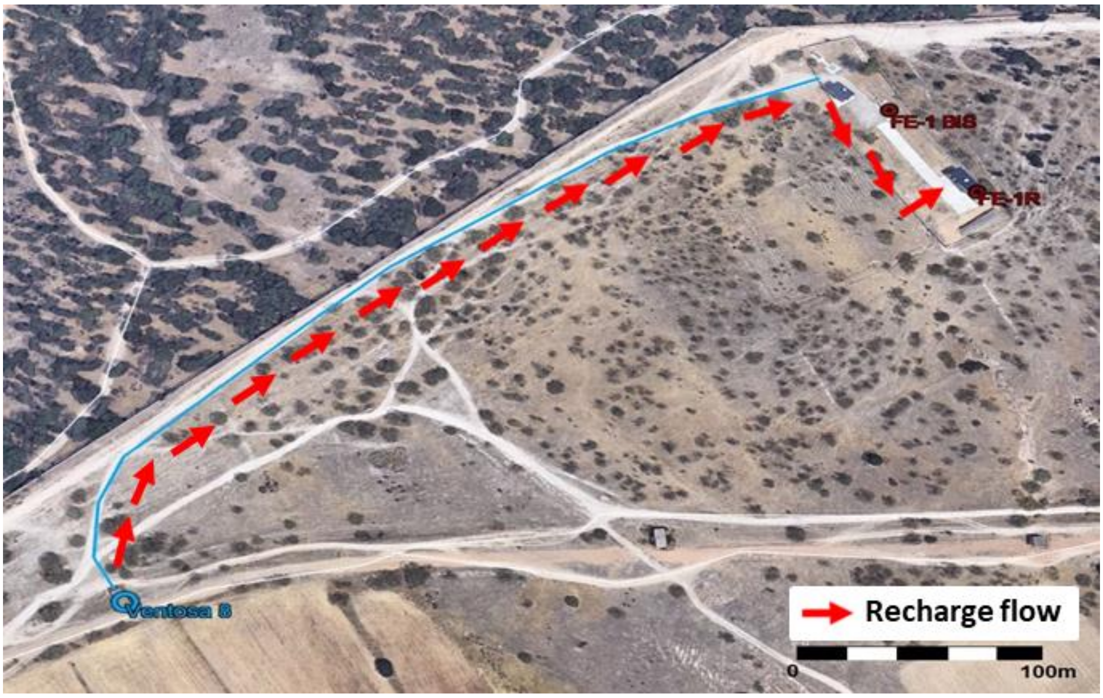

Figure 7. Location of the recharged water source origin.

Figure 8 shows different devices on two pipelines installed inside FE-1R recharge and pumping building. The main elements besides pumping and recharge pipes are: compressor, pneumatic tank, multi-hole valve, booster, three recharge pipelines, release valves and pressure and flow control systems.

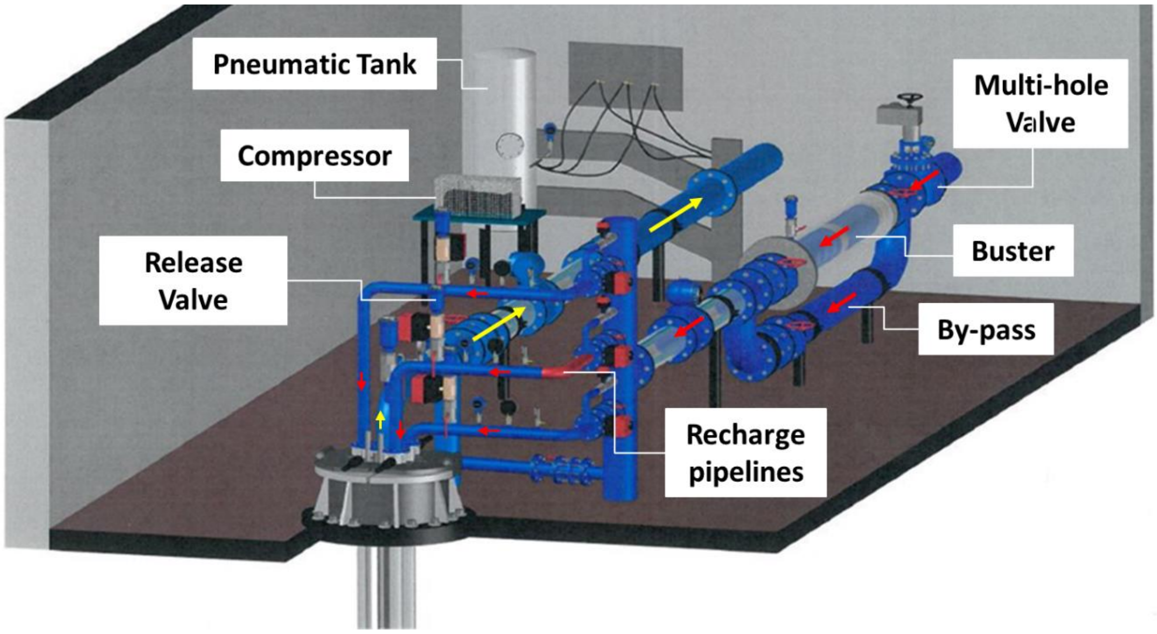

Figure 8. Facilities and devices inside the recharge and pumping building.

The first element embedded in the recharge pipeline is multi-hole valve. Its design allows to strain water flow to laminar regime and, in addition, causes cavitation inside, in this way cavitation is not generated due to booster aspiration.

System was set up with a booster that allows enought pressure to be injected on recharge operation. Furthermore, a bypass is also available as an alternative in the way (figure 9 a)). Therefore, recharge pipeline design allows water to follow two modes: passing through the booster where recharge pressure is increased, or circulating through by-pass recharging water by gravity without additional pressure. All cases include electromagnetic flowmeter that count flow and recharged volume (figure 9b)).

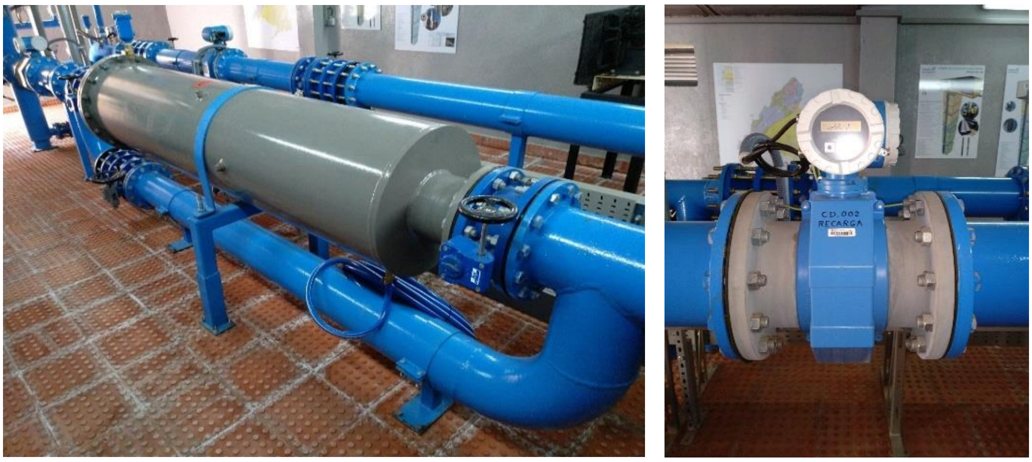

Figure 9. a) Recharge booster and bypass. b) Recharge electromagnetic flowmeter.

Three recharge lines (L1, L2 and L3) with same technical characteristics are shunted from general recharge pipe: approximately 195 m deep, 80 mm diameter and PN-16 (figure 10 a)). At the end, these pipes are grooved to allow recharge water input (figure 10 b) and c)).

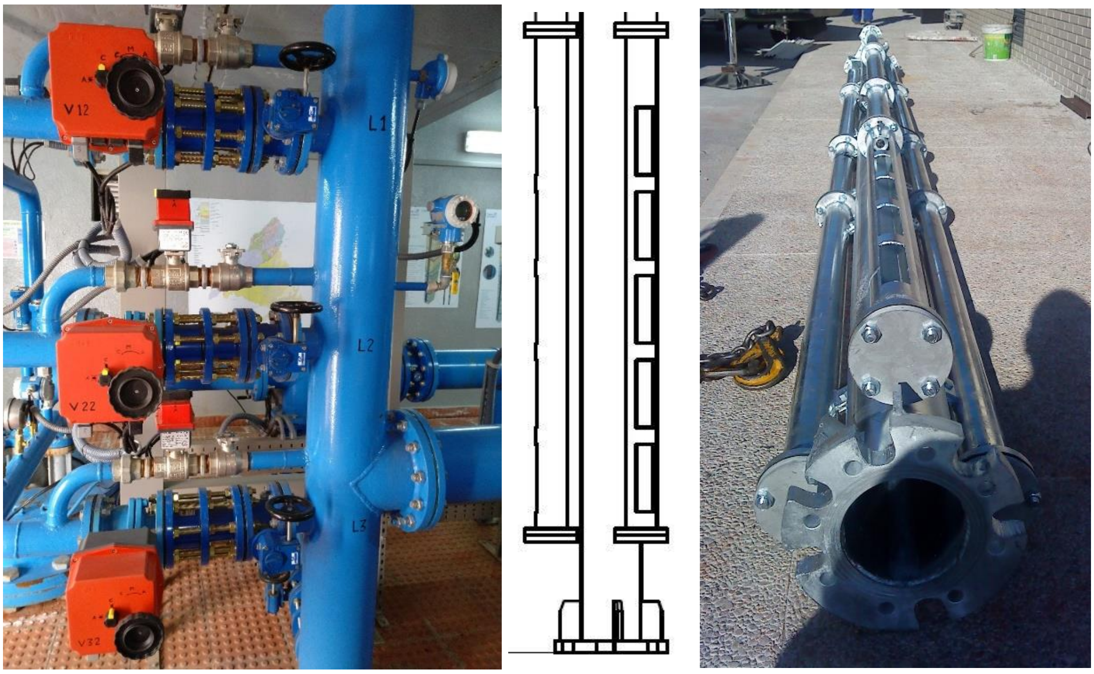

Figure 10. a) Recharge motorized valves and auxiliary lines. b) and c) Recharge pipes diagram and parts before assembling.

System is closed by packers located above screened pipes where water is injected into the aquifer from each recharge lines. Packers are part of pneumatic system, this facility also includes a compressor and a pneumatic tank of 120 liters capacity and 40 bar pressure, an automatism control and pneumatic control panel and valves whose mission is to close recharge flow in case of supply voltage failure.

Pneumatic tank, connected to compressor, is used to provide a resource in case inflation system demands more air than compressor can provide without backings. The aim of this system (whose fluid is air) is to contain water column until recharge pipes were completely filled.

To ensure that air is not injected from recharge lines and controlling injection pressure, essential elements are available in this equipment: motorized release valves, manometers and pressure gauges, all of them located on the surface (figure 11).

Figure 11. FE-1R recharge pipes and clamp.

There are also check valves and other motorized valves that support pressure of up to 35 Kg/cm^2, working as safety elements and control recharge water flow.

Pumping pipe (cleaning line) is 150 mm diameter and is assembled 6 in 6 meters. Joint between pumping pipe and recharge pipes has been designed by special triangular reduced flanges, with slots to electrical wires and piezometric pipes (figure 12). In addition, there are reinforcing bevels designed to hold maximum tensile stress that can be transmitted to them. Joints between pipe sections are elastic bands firmed up with 3 mm thick metallic fabric. Flanges are designed to withstand maximum water hammer, working at maximum pressure.

Submersible water pump necessary for carrying out cleaning pumpings is 250 meters deep and can supply a flow rate of 70 l/s at a 65 m.c.a. (total manometric height between 250-300 m.c.a.) with a yield capacity greater than 81%.

Figure 12. Details of the specifically designed flanges.

Two piezometric pipes were installed up extraction pumping depth controlling piezometric level. One of them hold in a pizorresistive level sensor, while the other remains empty, reserving it for manual checks.

In order to be able to count volume and flow extracted in the cleaning process, an electromagnetic flowmeter was installed. The pipe sections upstream and downstream of the flowmeter consist of 4 orthogonal fins, two by two, which are intended to laminate the flow of water as it passes through the flowmeter. In this way, by avoiding turbulent flow, the measurements of the appliances are more precise.

Pumping flow increases until well operating flow is reached in cleaning pumps, depending on draggings detected in the turbidimeter (figure 13) and piezometric level stabilization. This device is installed before flowmeter on cleaning line.

Figure 13 a) From right to left, following extraction line flow direction, sampling valve, temperature sensor, pressure gauge, manometer and turbidimeter. b) Turbidity measurement system.

3.3. Automatism and programming set

This facility requires a complete automatism that performs process in cleaning and recharging phases and monitors alarms that can be generated, guaranteeing to stop activity in safety conditions. Pressure and temperature control, among others, are fundamental aspects.

Injection process starts when static level is above recharge level (195 meters). With closed valves and once it has been verified that all system elements are ready, recharging operation begin.

Before filling recharge pipes, packer is inflated and release valves of the lines to be used are opened, which depends on maximum flow that will be recharged. In this way, recharge lines can be operated independently or all together.

Recharge water inputs to multi-hole valve before booster or bypass. Then, and after go through flowmeter, water is holded back in general recharge pipe until pressures are equalized. General recharge line must always be kept full, so that when recharge lines demand water, no air will be introduced into well or pressure differences can be generated.

Pipes filling time indicates packers correct operation, holding back water column inside pipes so that system remains pressurized.

When pipes are pressurized, packers are opened and recharge activity begins, increasing flow rate until reaching long-term flow rate. To ensure recharging non-turbulent flow, packers are preceded by stabilizer sections with fins inside that laminate the fluid.

Recharge water input is below well static level to avoid introducing air into it. Recharged water level is also controlled so that it never reaches the clamp.

3.4. Associated Costs

Installation cost has allowed an important learning for future designs and knowing recharge operation in a deep aquifer of these characteristics.

Investment has been carried out over 10 years and has meant approximately 1.8 € million, where more than half represent recharge well and its equipment. Figure 14 reflects main stages and elements percentage distribution that make up the system.

Operating costs (extraction and recharge) are less than 20.000 €/year. Specific energy consumption is around 0.8 - 1.1 kWh/m^3.

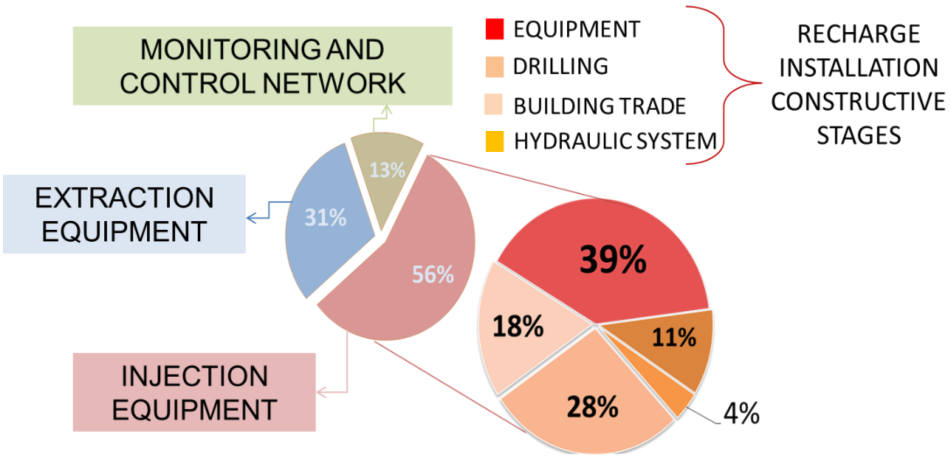

Figure 14. ASRT FE-1R facility cost percentage distribution.

3. Discussion

Successful tests have been carried out during 2011-2012 (table 5). A flow reduction of up to 20% was detected in the last tests cycles.

Table 5. Test results between 2011 and 2012.

Recharged volume	859.690 m3	Recharge period	363 days	Recharge phases	120 days x 3
Q max	40 l/s	Q med	27 l/s	Qr/Qb	50-60%

During tests, piezometric level increased 2 meters at control points after 60 days (for those that have more than 200 m depth). Figure 15 shows piezometric evolution 2011-2014 in ASRT FE-1 system recharge, cleaning and recovery phases, there is a clear connection between FE-1R recharge well and FE-1 Bis extraction well.

Recharged water is kept on less than 1000 m radius from recharge well, allowing it to be extracted. The exploitation effects are concentrated in a layer between 150-250 meters, which favors recharged water use.

Installation Tests carried out determined that, due to construction characteristics, the use of booster was not advisable since this pump demands more flow than can be provided.

Recharged water is kept on less than 1000 m radius from recharge well, allowing it to be extracted. The exploitation effects are concentrated in a layer between 150-250 meters, which favors recharged water use.

Installation Tests carried out determined that, due to construction characteristics, the use of booster was not advisable since this pump demands more flow than can be provided.

5. Conclusions

Experimental installation ASRT FE-1 confirms method feasibility despite its extreme operational and constructive complexity.

It's necessary to reduce/eliminate blockage processes that cause flow reduction.

ASRT technique is more efficient and sustainable when facilities already built are used. Canal de Isabel II has a suitable groundwater operation system for this use.

In order to prevent breaks, anomalies and clogging, ASRT technique is more appropriate than ASR for strategic supply infrastructures use.

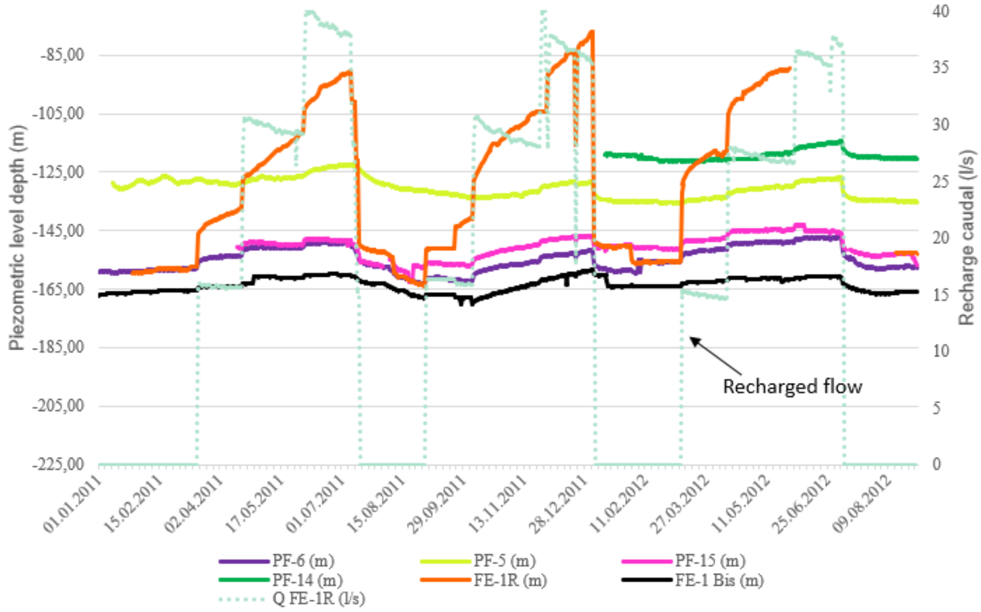

Figure 15. Recharging, cleaning and system recovery hydrogram (2011-2014).

This pilot could be complemented in whole ATDM looking for more execution and operation cost efficiency.

Whatever, since eventual prolonged exploitation temporarily affects aquifer quantitative state, artificial recharge contributes to the recovery of the good quantitative status and ensures the recovery of the stored water in key areas of the supplying system.

Abbreviations

The following abbreviations are used in this manuscript:
CYII: Canal de Isabel II
CAM: Comunidad Autónoma de Madrid
ATDM: Acuífero Terciario Detrítico de Madrid
ASRT: Aquifer Storage Transfer and Recovery
MAR: Managed Aquifer Recharge.

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Topic 9. MAR AND MANAGEMENT OF CLOGGING

Paper for ISMAR10 symposium. **Topic No: 9 (020#)**

Alluvial Aquifer Filtration as a Pre-treatment Option for ASR

Jason Keller[1,*], Robert Rice[1], Walter Burt[2] and Jason Melady[2]

[1] GeoSystems Analysis, Inc.
[2] GSI Water Solutions, Inc.
* Correspondence: jason@gsanalysis.com; Tel.: +01-541-716-4167

Abstract: Surface water diversions from Fifteenmile Creek to support agriculture in rural north-central Oregon, USA have adversely affected native fish species due to low flow and high-water temperature conditions during late summer periods. The use of Aquifer Storage and Recovery (ASR) to recharge a deep and confined basalt aquifer with surface water flows during the winter and spring months and then recover in the summer time in-lieu of surface water diversions is being evaluated to reduce impacts on the threatened fish populations. Because water treatment costs in this area would be high due to lack of existing infrastructure, a primary question for the proposed ASR program is whether the shallow alluvial aquifer can be used to filter captured surface water prior to ASR recharge. A program to characterize the near-surface sediments and shallow alluvial aquifer was performed to determine near-surface and aquifer properties and potential water quality improvement from aquifer filtration. Results indicate there is insufficient alluvial aquifer capacity to meet target filtration rates using vertical or horizontal wells, however, constructed surface recharge basins with horizontal well collection systems may be a viable alternative. No fatal flaws were identified in regards to surface water quality and potential shallow aquifer filtration.

Keywords: aquifer filtration; ASR; water treatment; water quality; conjunctive water management; agricultural water supply, endangered species.

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1. Introduction

Water treatment is typically necessary prior to recharge for Aquifer Storage and Recovery (ASR) wells to meet regulatory water quality requirements and/or reduce the potential of ASR well clogging. ASR water treatment can be a significant component of the overall cost of an ASR project and can limit the use of ASR in non-municipal areas where existing water treatment infrastructure is not present.

The Fifteenmile Creek in rural north-central Oregon, USA is home to threatened steelhead populations that are exposed to low flow and high-water temperature conditions during late summer periods. To increase summer flows and alleviate high temperature conditions, the Fifteenmile Watershed Council is evaluating the feasibility of ASR to support agricultural irrigation demands in lieu of Fifteenmile Creek summer time surface water diversions, or as flow replacement for agricultural diversions. Under the proposed ASR program, Fifteenmile Creek surface water would be injected into the deep basalt aquifer (approximately 245 – 300 m below ground surface) during the winter and early spring when surface water flows are more abundant. The injected ASR water would supplement agricultural demand pumping in the late summer to reduce surface water diversion, or would be used to replace agricultural diversions with cooler stored water. A primary question for the proposed ASR program is whether the alluvial aquifer can be used to filter captured surface water to allow direct ASR well recharge. Alluvial aquifer, or riverbank, filtration is used in many areas to cost effectively reduce suspended solids, biodegradable material, microorganisms, nitrate, and heavy metals from the water.

Three alternatives for collecting alluvial aquifer/riverbank filtered water were evaluated (Figure 1): 1) vertical wells, or; 2) horizontal collector-type wells placed in the alluvial aquifer adjacent to the creek, and; 3) engineered surface water diversions with passive infiltration and collection systems. Alternatives 1 and 2 rely on groundwater pumping to increase groundwater recharge via induced seepage from Fifteenmile Creek. Alternative 3 uses surface water diversions to constructed surface recharge basins with collection of infiltrated water via horizontal collector-type wells.

A program to characterize the near-surface sediments and shallow alluvial aquifer along a 9 km reach of Fifteenmile Creek was performed to determine near-surface and aquifer properties and potential water quality improvement from aquifer filtration. Using the field investigation data, an analytical model was applied to evaluate drawdown resulting from pumping wells near the creek and to determine well design criteria.

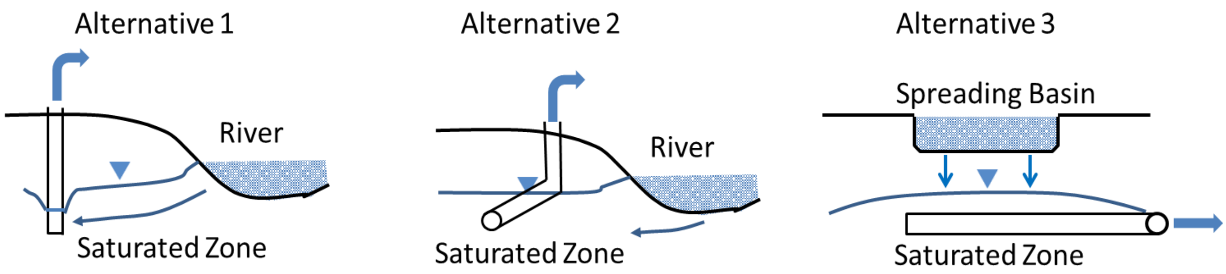

Figure 1. Alluvial aquifer/riverbank filtration groundwater collection scenarios.

2. Materials and Methods

2.1. Characterization Program

2.1.1. Test Pits and Geologic Logging

Near-surface and alluvial aquifer soil physical property evaluations were conducted adjacent to Fifteenmile Creek in February 2018 using test pits to characterize the near surface and alluvial aquifer material texture, depth to groundwater, and alluvial aquifer saturated thickness. Twenty five test pits were excavated with a track hoe at the locations shown in Figure 2. The location of an alluvial aquifer vertical or horizontal well would be restricted to approximately 15 m from the creek in order to remain outside of land being farmed, thus test pits were located outside of protected riparian areas but within 15 m of the creek. Test pits were excavated to the depth of track hoe refusal.

Lithologic layers encountered were texturally logged and classified using visual-manual methods following [1]. Representative grab samples were collected and stored in labeled and sealed plastic bags for further laboratory analysis. Additionally, 15-cm long by 5-cm diameter drive core samples were collected for laboratory analyses of bulk density.

2.1.2. Test Well Installation and In-Situ Testing

In April 2018, three alluvial aquifer test wells were installed at locations shown in Figure 2. The wells were sited to be approximately equidistant over the project area. Boreholes were drilled to the top of the basalt or cemented sand layer using a hollow stem auger (CME-75HT truckmounted rig). Boreholes were located adjacent to test pits; subsequently, the borehole material was not geologically logged as the subsurface material was assumed to be similar to the adjacent pit.

Test wells were installed in the boreholes to the top of the basalt or cemented sand layer. The wells were constructed of 10-cm diameter schedule 40 PVC with a 1.5-m long screen length and 0.05 cm slot width. A 6/9 silica sand filter pack that extended from the bottom of the well to a minimum of 30 cm above the well screen was placed, followed by a 30 to 60-cm thick hydrated bentonite seal. Each test well was instrumented with a submersible pump and a Level TROLL 400 data logger (In-Situ, Fort Collins, CO) to measure water level and temperature.

All three test wells desaturated at the submersible pump minimum pumping rate of 11 liters per minute (lpm), thus an aquifer test could not be performed. Instead, the Bouwer and Rice [2] slug test method was used to measure in-situ saturated hydraulic conductivity (K_{sat}) of the alluvial aquifer material. Slug tests provide an intermediate scale measurement of K_{sat} by quickly withdrawing or adding water from the well and measuring the subsequent rate of change in water elevations over time. Instantaneous lowering of the water level in the well was achieved by pumping until the well went dry and then turning off the pump and monitoring the rebound of the groundwater elevation.

Because of the low sustainable pumping rate, a sample of alluvial groundwater could only be obtained from one of the three test wells for water quality analysis. Two co-located surface water samples and a basalt groundwater sample from a nearby basalt aquifer well also were collected and analyzed for water quality parameters (e.g. turbidity, conductivity, temperature, common ions, metals, nutrients). One surface water sample also was analyzed for synthetic organic compounds (SOCs).

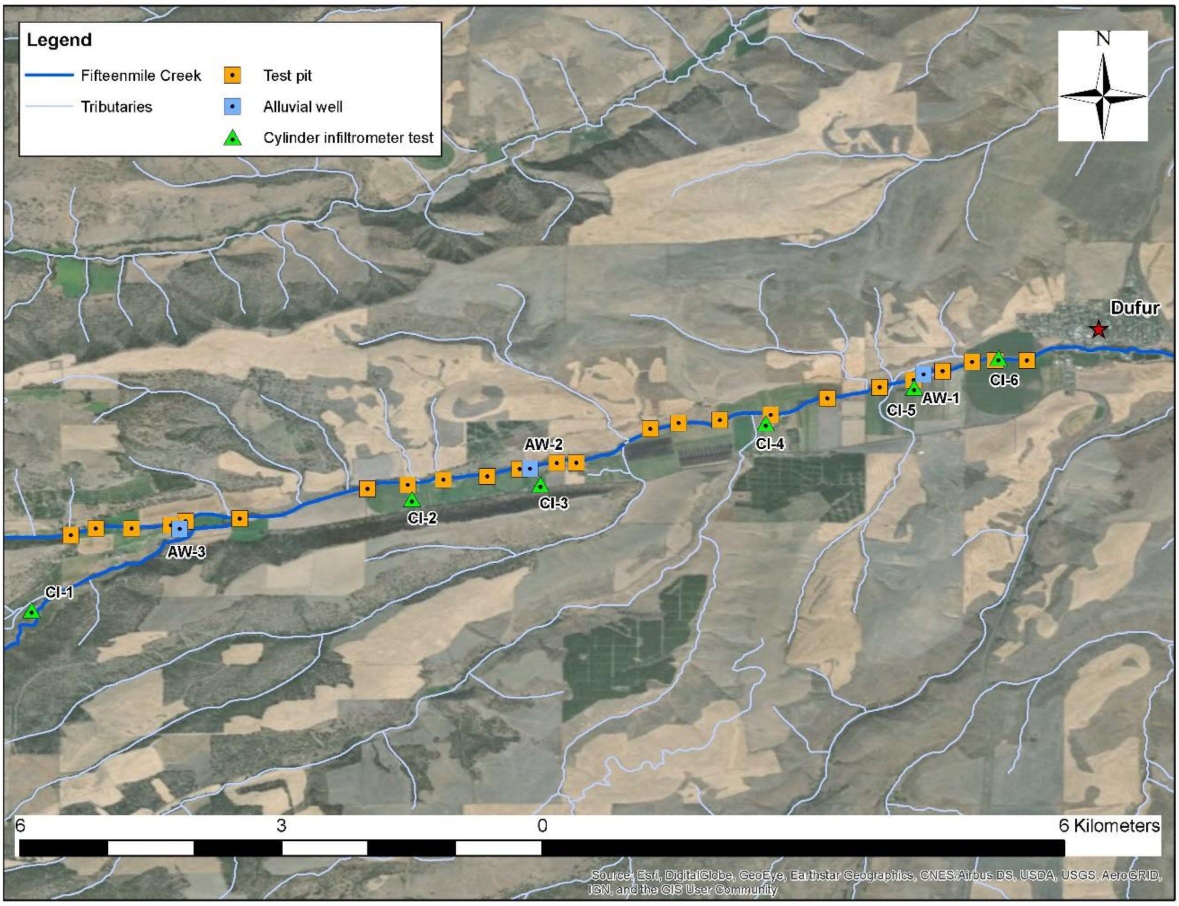

Figure 2. Test pit, alluvial aquifer test well, and cylinder infiltrometer test locations.

2.1.3. Near-Surface Cylinder Infiltrometer Testing

Single-ring cylinder infiltrometer (CI) tests with lateral divergence correction [3] were conducted at the soil surface to assess the effective in-situ K_{sat}. The CI tests are an intermediate scale test which represents the rate at which water infiltrates into the soil under field conditions. CI tests were performed at the locations shown in Figure 2. A total of six CI measurements were conducted on soils representing the predominant lithologic types observed in the project area.

2.1.4. Laboratory Physical and Hydraulic Property Testing

Eight samples representing the range of observed field textures were selected and analyzed for particle size distribution (PSD) and particle density to allow for laboratory calibration of the field texture estimates. Five grab samples were selected for K_{sat} testing based on the distribution of field texture estimates. Laboratory K_{sat} tests were performed in a 10-cm long by 5-cm diameter repacked column. Three core samples were selected for bulk density and water content measurements, which were used to guide packing bulk density for K_{sat} tests.

2.2. Alluvial Aquifer Groundwater Collection Rate Modeling

2.2.1. Vertical and Horizontal Wells

The maximum water collection rate for a vertical well completed in the alluvial aquifer was estimated using the two-dimensional analytical drawdown solution for a pumping well near a connected stream [4], described as:

$$s_{tot} = \frac{Q}{4\pi T} Ei\left(\frac{-S\left((L-x)^2+y^2\right)}{4Tt}\right) - \frac{Q}{4\pi T} Ei\left(\frac{-S\left((L+|x|)^2+y^2\right)}{4Tt}\right) \quad (1)$$

Where s_{tot} is the total aquifer drawdown (m), Q is the well pumping rate (m^3/min), T is aquifer transmissivity (m^2/min), S is aquifer specific yield (-), L is the distance from a pumping well to the center of the stream (m), x is the X coordinate measured from the stream center towards a pumping well (m), y is the Y coordinate measured from the stream center perpendicular to x (m).

The analysis assumes the alluvial aquifer is infinite in extent, streambed conductance is greater than the alluvial aquifer K_{sat}, and there is no interference from other pumping wells.

The maximum predicted pumping rate (Q) that can be achieved without alluvial aquifer drawdown (s_{tot}) exceeding the aquifer saturated thickness was calculated for a vertical well placed 6 m from the center of the creek (x = 6 m). A 6 m minimum well distance was established due to riparian protection programs likely to restrict placement of wells closer to the creek. A target total alluvial aquifer groundwater collection rate for all wells of 14,525 lpm was defined based on an evaluation of regulatory and physical surface water availability.

The maximum predicted pumping rate for horizontal wells completed in the alluvial aquifer is calculated using Equation 1 and the principle of superposition by solving for changes in groundwater levels resulting from pumping of a linear system of vertical wells. That is, Equation 1 was solved for multiple Y coordinates (y) and summed to identify the total maximum predicted Q that can be achieved without s_{tot} exceeding the aquifer saturated thickness. The calculation assumes the horizontal well is located near the bottom of the alluvial aquifer and 6 m from the center of the creek. A target total alluvial aquifer groundwater collection rate was again defined to be 14,525 lpm.

2.2.2. Surface Recharge Basins

The water collection rate for a surface recharge basin will in part be controlled by soil K_{sat} and the surface area of the basin. It is assumed the basin(s) will be located far enough off-stream to avoid return flow of infiltrated water back to the stream. The surface recharge basin area required for a defined water collection rate was calculated for a range of measured near surface K_{sat} values assuming 80% of recharge basin infiltrated water can be captured by a subsurface perforated pipe system that is located in the alluvial aquifer beneath the basin(s). An 80% drain pipe water capture has been measured for similar engineered surface recharge basins containing a subsurface water collection system (e.g. [5]). The drain pipe capture percentage will ultimately be guided by perforated pipe system design (e.g. pipe diameter, spacing, and depth).

3. Results

3.1. Characterization Program

Field geologic logging estimates of percent gravel, sand, silt and clay were adjusted using the results from the laboratory "wet sieve" PSD testing. Regression equations were determined for percent fines (silt and clay) and clay from the laboratory PSD testing versus manual field estimations to obtain lab to field correction parameters. These parameters were then applied to all field log estimates of soil texture.

Test pit observations were consistent throughout the study area. Silt loam and sandy loam soils were observed from approximately 0 to 1-m below ground surface (bgs), with increasing sand and gravel with depth (Figure 3). The water table was encountered at depths ranging from 1.5 to 3.7 m bgs which coincided with the surface elevation of Fifteenmile Creek, indicating the alluvial aquifer is hydraulically connected to the creek. The alluvial aquifer consists of sandy gravel with large cobbles (Figure 3). Track hoe refusal was encountered in all test pits due to a basalt or cemented sandstone (Figure 3) at approximately 1.5 to 4.9 m bgs. Both units are low permeable material that underly the shallow alluvial aquifer. Groundwater was encountered coincident with the top of the alluvial aquifer, and alluvial aquifer saturated thicknesses ranged from 1.2 to 1.5 m.

Observed test well saturated thicknesses were similar to test pit observations, ranging from 1.2 to 2.1 m thick. Table 1 provides slug test measured alluvial aquifer K_{sat} at the test wells. A geometric mean horizontal K_{sat} of 1.5×10^{-4} cm/s was calculated from the three slug tests.

CI measured effective surface soil K_{sat} values are summarized in table 2. Geometric mean effective K_{sat} was 1.2×10^{-2} cm/s for Tygh fine sandy loam soils, 4.6×10^{-3} cm/s for Endersby loam soils, and 7.1×10^{-4} cm/s for the single Pedigo silt loam soil measurement. Effective K_{sat} values were less for finer textured surface soils. The geometric mean effective K_{sat} for all tests was 5.5×10^{-2} cm/s.

Laboratory measured K_{sat} values are shown in table 3. Geometric mean laboratory measured K_{sat} was 3.8×10^{-4} cm/s for repacked samples from above the alluvial aquifer and 1.0×10^{-3} cm/s for samples from the alluvial aquifer. The laboratory K_{sat} values for samples from the alluvial aquifer were approximately one order of magnitude greater than the mean slug test K_{sat} value, and likely represents an upper end value for alluvial aquifer K_{sat}. The laboratory K_{sat} values for samples above the alluvial aquifer were approximately one to two orders of magnitude lower than the CI measurements. Laboratory K_{sat} values for samples above the alluvial aquifer are similar to Natural Resources Conservation Service (NRCS) reported range of K_{sat} for the near surface soils (Soil Survey Staff, 2017). Consequently, it is believed the laboratory measured K_{sat} value for soils above the alluvial aquifer is more accurate.

Figure 3. Examples of observed (A) soil profile; (B) silt loam/sandy loam soil; (C) alluvial aquifer material; (D) cemented sandstone.

Table 1. Slug test measured saturated hydraulic conductivity.

Test Well	Lithologic Classification	Saturated Hydraulic Conductivity (cm/sec)
AW-1	Gravely sandy loam	8.4E-05
AW-2	Gravely sandy loam	3.2E-04
AW-3	Gravely sandy loam	1.3E-04
Geometric Mean		1.5E-04

Table 2. Cylinder infiltrometer measured effective saturated hydraulic conductivity.

Test ID	USDA Soil Type	Effective Saturated Hydraulic Conductivity cm/sec
CI-1	Tygh fine sandy loam	1.4E-02
CI-2	Tygh fine sandy loam	2.2E-02
CI-3	Endersby loam	1.3E-02
CI-4	Pedigo silt loam	7.1E-04
CI-5	Tygh fine sandy loam	5.8E-03
CI-6	Endersby loam	1.6E-03
Geometric Mean	Tygh fine sandy loam	1.2E-02
	Endersby loam	4.6E-03
	All	5.5E-03

Table 3. Laboratory measured saturated hydraulic conductivity.

Sample	Location	Bulk Density (g/cm³)	Porosity (cm³/cm³)	Saturated Hydraulic Conductivity (cm/s)
TP-2 (2-6)	Above alluvial aquifer	1.45	0.472	$3.2E^{-04}$
TP-12 (1-3)		1.30	0.517	$1.8E^{-04}$
TP-18 (3-7)		1.55	0.434	$9.0E^{-04}$
	Geometric Mean			$3.8E^{-04}$
TP-6 (5-7)	In alluvial aquifer	1.59	0.421	$1.5E^{-03}$
TP-11 (6-11)		1.50	0.450	$7.0E^{-04}$
	Geometric Mean			$1.0E^{-03}$

3.2. Estimated Alluvial Aquifer Groundwater Collection Rates

3.2.1. Vertical and Horizontal Wells

The maximum predicted pumping rate that can be achieved from a single vertical well in the alluvial aquifer without exceeding 1.5 m of drawdown was calculated using Equation 1. A 1.5 m drawdown limit was defined since the observed saturated thickness of the alluvial aquifer was approximately 1.5 m. The calculation assumed the lab measured geometric mean K_{sat} value for the alluvium aquifer material (1.0×10^{-3} cm/s, Table 3). The lab measured alluvial aquifer material K_{sat} was approximately 7X higher than the slug-test measured K_{sat} and thus represents a "best case" scenario for alluvial aquifer groundwater pumping. The assigned K_{sat} and 1.5 m saturated thickness translates to an alluvial aquifer transmissivity of 1.3 m²/day. A specific yield for a gravelly sand of 0.25 % [6] was assumed.

Table 4 summarizes vertical well (Alternative 1) model results. The maximum pumping rate for a single vertical well is predicted to be 2.7 lpm, requiring approximately 5,400 wells to achieve the target alluvial aquifer groundwater collection rate of 14,525 lpm.

Table 5 summarizes horizontal well (Alternative 2) model results. The same model parameters applied in the vertical well model were applied in the horizontal well model. The maximum pumping rate for a horizontal well in the alluvial aquifer is predicted to be 1.2 lpm per linear meter of well, requiring over 12,100 linear meters of pipe to achieve the target alluvial aquifer groundwater collection rate.

Table 4. Maximum estimated alluvial aquifer pumping rate for a single vertical well and quantify of vertical wells to achieve the target collection rate.

Target Collection Rate (lpm)	Single Well Pumping Rate (lpm)	Number of Wells Needed for Target Recharge
14,525	2.7	5,400

Table 5. Estimated horizontal well maximum pumping rate and linear meter of horizontal wells to achieve the target alluvial groundwater collection rate.

Target Collection Rate (lpm)	Linear Foot Pumping Rate (lpm)	Linear Meter of Horizontal Well for Target Recharge
14,525	1.2	12,100

3.2.2. Surface Recharge Basin

Table 6 summarizes the estimated total recharge basin (Alternative 3) area required to capture the target collection rate of 14,525 lpm assuming the laboratory measured near surface K_{sat} and CI measured effective K_{sat} for the three NRCS soil textures tested. The needed total recharge basin area is greatest for the laboratory measured K_{sat} (7.7 hectares), whereas the CI measured effective K_{sat} indicated a total needed recharge basin area of 4.1 hectares for Pedigo silt loam, 0.6 hectares for Endersby loam, and 0.2 hectares for Tygh fine sandy loam. The surface recharge basin area is sensitive to soil material K_{sat} and specific soil K_{sat} measurements are necessary to improve predicted basin size requirements in any target area. Nonetheless, the calculated total basin area based on the laboratory measured K_{sat} represents the best estimate based on current data because the K_{sat} is believed to be most representative of near surface soils, based on NRCS reported K_{sat} values, and it is similar to the K_{sat} of the alluvial aquifer in which the subsurface collection system is assumed to be installed.

In general, the areas shown in green within Figure 4 are anticipated to have higher surface permeability and would likely need less area for an infiltration basin. Near surface loamy soils may be excavated in order to access underlying coarser textured soils that are more permeable. Additionally, multiple basins of smaller size may be constructed within the project area, as opposed to a single large basin.

Table 6. Total recharge basin surface area to achieve the target alluvial aquifer groundwater collection rate.

Measurement	Soil Type	Near Surface Saturated Hydraulic Conductivity (cm/sec)	Total Spreading Basin Surface Area (Hectare)
Lab	NA	3.8E-04	7.7
CI	Pedigo silt loam	7.1E-04	4.1
CI	Endersby loam	4.6E-03	0.6
CI	Tygh fine sandy loam	1.2E-02	0.2

3.3. Water Quality Assessment

Concentrations of all surface water analytes, except turbidity, phosphorus, aluminum, barium, iron and coliform bacteria were less than corresponding analyte concentrations in the deeper basalt aquifer groundwater. The differences between concentrations of aluminum, barium and iron reflect the different geochemical characteristics of the two waters, but do not appear to be a fatal flaw with regard to regulatory compliance, particularly if treatment through infiltration basins reduce constituent concentrations. Filtration of surface water from the creek prior to recharge is likely to sufficiently remove turbidity and bacteriological constituents (5, 7). The treatment step also is anticipated to remove iron and particulate-bound contaminants. Small scale pilot testing may be needed to determine treatment efficiencies and the optimal distance between the filtration media and collection piping for removal of suspended solids, phosphorus, bacteriological and other constituents.

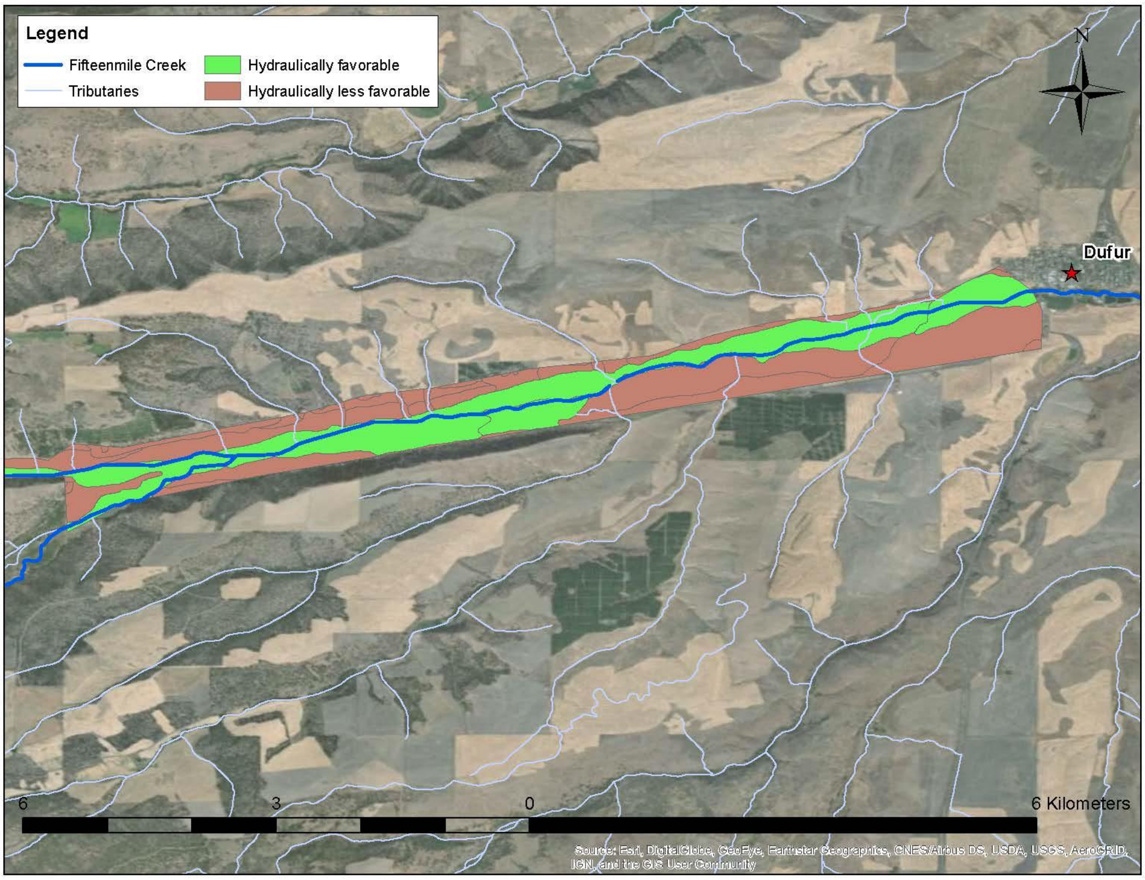

Figure 4. Predicted more and less favorable areas for infiltration basins.

4. Discussion

Based on measured hydrogeologic data for the alluvial aquifer there is insufficient alluvial aquifer capacity to meet target groundwater collection rates using vertical or horizontal wells. Approximately 5,400 vertical wells or 12,100 linear meters of horizontal wells are estimated to be necessary for achieving the target alluvial aquifer groundwater collection rate of 14,525 lpm.

Constructed surface recharge basins with a horizontal well may be a viable alternative; however, there remains large uncertainty in near surface K_{sat} values which dictate the necessary total basin surface area as well as uncertainty in the characteristics (e.g. depth, K_{sat}) of the shallow aquifer at potential off-stream basin locations. Near surface loamy soils may be excavated in order to access underlying coarser textured soils that are more permeable. Additionally, multiple basins of smaller size may be constructed within the project area, as opposed to a single large basin.

An evaluation of potential recharge basin sites based on a preliminary review of estimated K_{sat}, conveyance costs, probable land acquisition/leasing and right of way costs, and compatibility of land use and ownership is recommended. High priority sites identified from this analysis are recommended to undergo a characterization program to better define infiltration rates and assess aquifer filtration effectiveness.

Sampling of Fifteenmile Creek to assess recharge source water quality standards did not identify fatal flaws for using the creek as a source of water for ASR. As anticipated, some treatment will be necessary to remove suspended solids (turbidity) and microbiological constituents (e.g., coliform bacteria). A time-series surface water quality sampling and small-scale pilot testing of a surface infiltration treatment facility during the winter/spring recharge season is needed to verify treatment needs and methods prior to full-scale implementation.

Acknowledgments: This work was funded by the Wasco Soil and Water Conservation District, a grant from the Oregon Watershed Enhancement Board (OWEB), and a Water Storage, Reuse and Conservation feasibility study grant awarded by the state of Oregon.

Author Contributions: All authors conceived and designed the field characterization program. Mr. Rice performed the field characterization; Mr. Keller, Mr. Burt, and Mr. Melady analyzed the data; Mr. Keller wrote the paper.

Conflicts of Interest: Wasco County Soil and Water Conservation District performed the cylinder infiltrometer measurements.

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Extended abstract for ISMAR10 symposium. ***Topic No: 9 (036#)***

Effects of ionic strength on the formation of bio-clogging in MAR

Ruijuan Cui[1,2], Xueyan Ye[1,2], Xinqiang Du[1,2] and Ying Lu[1,2]

[1] College of New Energy and Environment, Jilin University, Changchun 130021, China
[2] Key Laboratory of Groundwater Resources and Environment (Jilin University), Ministry of Education, Changchun 130021, China
*Correspondence: cuirj17@mails.jlu.edu.cn

EXTENDED ABSTRACT

Clogging of porous media has become a limited factor in the implementation of managed aquifer recharge (MAR)which is becoming increasingly important water management strategy, alongside demand management, to maintain, enhance and secure stressed groundwater systems and to protect and improve water quality. Bio-clogging is the second most important type of injection well clogging. Which was caused by a combination of microbial cells and their associated metabolic products, e.g., extracellular polymeric substances (EPS) and generated gas.

Compared with physical clogging, the mechanisms of bio-clogging is more complex and permeability of media is more difficult to recover once bio-clogging occurred. In addition, bacteria secrete a large number of metabolites in the process of growth. These viscous polymers are easily to adsorb suspended substances of the water, and work together with physical clogging to speed up the clogging of porous media and reduce the operating efficiency of the recharge system. Therefore, study on mechanisms of bio-clogging in-depth which plays an active role in recovering hydraulic conductivity and extending the operation life of recharge facilities, reducing the cost of equipment maintenance and improving the efficiency of recharge. At the same time, it has important scientific significance for promoting MAR technology.

Exploring the impacts of various environmental factors on EPS production would improve the study for bio-clogging prediction and control as EPS were considered to be one of the major factors in bio-clogging process. Numerous environmental factors have been proved to influence EPS such as pH, temperature, heavy metals, nutrient, carbon, nitrogen, phosphorus sources, and C/N ratio of recharge water and so on. IS is a significant factor in bio-clogging but been discussed absolutely.

A series of laboratory experiments which focus on the influence of IS on the formation of bio-clogging were carried out. Pseudomonas aeruginosa was adopted as the mode bacteria and NaCl was used to adjust IS. Hydraulic conductivity of column was analyzed by Darcy's law, Water quality was detected by Hash Water Quality Analyzer and biomass of outlet was detected by Pierce™ BCA Protein Assay Kit (Thermo Co., Ltd, USA), the ions likes Mg^{2+}, Ca^{2+} were tested by Atomic absorption spectrophotometer (Shimadzu AA-6000CF, Japan), Al^{3+} was tested by Heavy Metal Aluminum Detection Kit (Lohand Biotechnolgy Co. Ltd, China), Si^{2+} was tested using the method of 1,2,4-trichlorobenzene amino phenol sulfonic acid reduction-silicon molybdenum blue.

The results show that IS could promote or inhibit the growth of the bacteria and the production of EPS which result in the different types of bio-clogging, moderate IS lead to surficial clogging,

whereas the higher or lower IS may lead to a mix of surficial and inner clogging. The mechanism of IS on bio-clogging mainly in: 1) Bacteria cells as bio-colloid have an isoelectric point ranging from 2 to 4, which means they have a negative surface charge at the pH of most natural water (6-8 in pH), thus IS would weaken the negative surface charge of bacteria, and the movement and migration of bacteria were also affected. Na^{+} of NaCl which have positive charge that neutralized the negative charge on the surface of bacteria and quartz sand, which enhanced the absorption of bacteria on the surface of quartz sand by compression of double layer and reduction of repulsive potential barrier. 2) SiO_2, Al_2O_3, CaO, and MgO of sand (sand consists of quartz (89%), followed by a small amount of alkali feldspar (6%) and plagioclase (5%)) dissolved as a result of alkaline substance that produced by bacteria, which result in the increase or the stable period before the reduction of hydraulic conductivity occurred. 3) Al^{3+}, Mg^{2+}, Ca^{2+} dissolved of sand also enhanced the absorption and production of EPS by stimulated the bacteria. In turn, the greater amount of biomass accelerated the Si, Ca, Mg, and Al dissolution and re-precipitation. 4) Al^{3+}, Mg^{2+}, Ca^{2+}, Si^{2+} re-precipitation results in more serious clogging and the corresponding hydraulic conductivity decreased faster by more than ~99%.

Keywords: Ionic strength; Bio-clogging; managed aquifer recharge; Weathering; Biochemical reaction.

Extended abstract for ISMAR10 symposium. ***Topic No: 9 (040#)***

The Effect of Soil Tillage Equipment on the Recharge Capacity of Infiltration Ponds

Ido Negev[1]*, Tamir Shechter[1], Lilach Shtrasler[1], Hadar Rozenbach[2] and Avri Livne[2]

[1] Mekorot, National Water Company, Tel Aviv, Israel;
[2] Plagey Maim, Megido, Israel
* Correspondence: nido@mekorot.co.il; Tel.: +972-3-6230653

EXTENDED ABSTRACT
The Dan Region Reclamation Project (Shafdan) reclaims ~125 MCM/year of treated wastewater from the Tel Aviv Metropolitan area. Following secondary treatment, the effluent is recharged into a sandy aquifer for Soil Aquifer Treatment (SAT). Over the past 3 years, a decrease in recharge capacity was noticed. Several operational causes were considered, including reservations regarding recharge ponds tillage procedure.
Tillage of the recharge ponds facilitates aeration, breaking surface crusts and the removal of vegetation. The procedure includes deep (40-60 cm) plowing, and shallow (10-20 cm) sweep-knives (SK) cultivator or discus. In this research, the existing tillage equipment was compared to new equipment, which includes deep subsoiler and a chisel-knives (CK) cultivator (Figure 1). The effects of each tool on the infiltration rate (IR), recharge capacity and soil compaction were examined.

(**a**) (**b**)

(**c**) (**d**)

Figure 1. Tillage tools used during the experiment: (**a**) Sweep-knives (SK) Cultivator; (**b**) Chisel-knives (CK) cultivator; (**c**) Plow and (**d**) Subsoiler (paraplow type).

The results suggest a significant improvement in the recharge capacity, up to 95% and 15% on average following subsoiler and CK cultivator treatments, respectively, with respect to the existing plowing treatment (Figure 2). In addition, the depth of the compacted soil layer increased from ~30 to ~55 cm after subsoiler treatment. Essential understanding on other operational factors such as drying periods, preparation of the field and soil micro-topography, was also achieved.

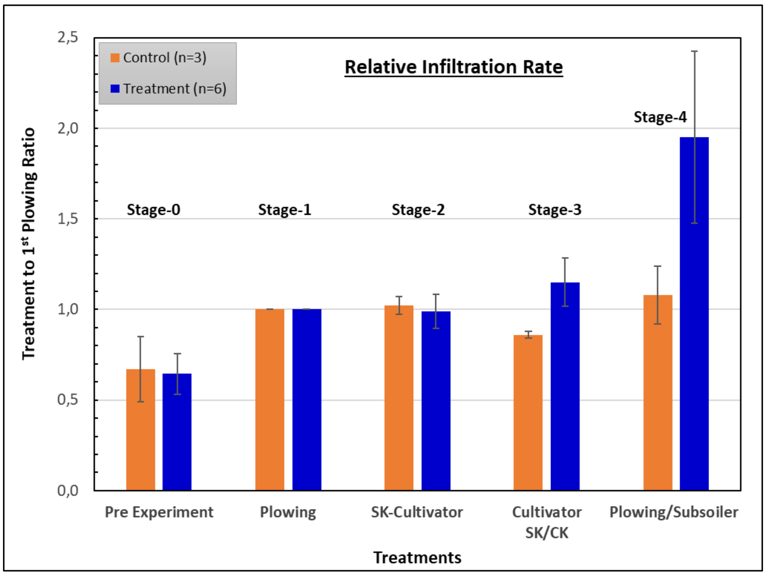

Figure 2. Relative Infiltration Rates calculated for each stage and treatment, relative to the average IR measured during Stage 1 (first plowing).

This study takes a classic approach, which advocates a return to the fundamentals of recharge field maintenance. With no apparent innovations, and during a recharge crisis, it dramatically, immediately, and with almost no additional costs, increased the recharge capacity of the Shafdan plant. The reduction of the recharge capacity, and on the other hand, its restoration, are not solely related to the tillage equipment, but also to other parameters that are required for correct maintenance procedures. These include: Complete drying (not draining!) of the soil before tillage operations; Employing tillage equipment with the maximum possible width, to minimize the number of passes on the pond; Employing tillage equipment that keeps the soil surface even, with minimum ridges and micro-topography effects; Strict adherence to the correct recharge regime, and especially to the drying stage before flooding

This study also showed that long-range clogging processes which results from incorrect operation and maintenance are reversible and can be overcome by reverting to correct operation principles. Further study is planned to examine the effect of the new tillage equipment (and regime) on recharge capacity during the winter, and to develop alternative approaches for vegetation treatment.

Keywords: SAT; Tillage; Infiltration pond, Infiltration rate, Soil compaction.

Acknowledgments: Mekorot, the Israel National water Co, funded and supported this study. We wish to express our thanks to Dani Cohen and Roi Elkayam who developed and enabled the automated measurement and analyzed system (SATix system), and to David Weisental, Efrat Cohen, and to the Shafdan Unit, for their help and support during this research. Special thanks for Zvika Bitan for the great help, advice and initiative in selecting the equipment and carrying out the soil tillage operations.

Paper for ISMAR10 symposium. ***Topic No: 9 (059#)***

Laboratory Research on the Laws of Fe(III) Clogging during Urban Storm-water Groundwater Recharge

Hexuan Zhang[1], Xinqiang Du[2] and Xueyan Ye[2*]

[1] Affiliation 1;zhanghx17@mails.jul.edu.cn
[2] Affiliation 2;Duxq@jlu.edu.cn
* Correspondence: Yexy@jlu.edu.cn; Tel.: +86-130-291-32162

Abstract: Groundwater artificial recharge (GAR) technology has become one of the important means to deal with water shortage and corresponding environmental geological problems. In the process of GAR using rainwater, the infiltration medium is obviously clogged with increase of recharge time, which leads to decrease of the efficiency of the recharge facilities and even the service lifetime. Therefore, solving the problem of clogging has become a key in use of rainwater for GAR.In this research, based on the results of urban rainwater and water quality survey, the laws of iron ion clogging in urban rainwater AR is studied.The result shows, (1) Fe (III) mostly remained near the surface of porous medium, and its retention rate, retention quantity, (2) the occurrence time and the depth and the degree of Fe (III) clogging are all affected by the particle size of porous medium, the infiltration Fe (III) concentration and the infiltration velocity,(3) the main mechanism of iron clogging can be concluded as filtration andalso has part of adsorption.

Keywords: Iron clogging; laboratory research; groundwater artificial recharge.

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1. Introduction

With the growth of population and economy, the demand for the environment, the change of precipitation, the pollution of water sources, the over-exploitation of groundwater, there will be a continuous shortage of water resources on the earth [1]. Groundwater artificial recharge (GAR) technology has become one of the important means to deal with water shortage and corresponding environmental geological problems. When using urban storm-water for the artificial recharge of groundwater, clogging usually occurs in aquifers and infection wells. The process is also very complex, usually related to the quality of the recharge water, the composition of the infiltration medium and the particle size [2][3]. Iron oxides, hydroxides and calcium carbonate are the main forms of geochemical clogging, but not widely recognized as the main mechanism of clogging, because they are often consistent with other forms of clogging or need a long time to develop. The presence of oxygen or nitrate in the recharge water can stimulate bacteria, such as Gallionella, produces iron or manganese oxides and hydroxide precipitates that cause clogging [4]. The deep well recharge in the Netherlands using the Rhine water has been blocked after 728 days. The main component of the blockage is iron (hydrogen) oxide ($Fe(OH)_3$) or iron hydrogen phosphate ($Fe_n(HPO_4)_m(OH)_{3n-2m}$), it may be caused by the reduction reaction of oxygen-containing water mixed with surrounding anoxic water [5]. Iron clogging is a serious and common type of groundwater artificial recharge.

In this paper, the phenomenon of iron clogging and its mechanism in the process of AR using urban rainwater are studied through vertical laboratory columns.

2. Materials and Methods

Figure 1 shows a schematic representation of the columns used in the experiment. The system comprised four parts connected with poly-fuoroalcoxy tubing, including water supply, seepage column, water pressure transducers, and water sample collector. The columns were made from clear plexiglass (16 cm long and 2.0 cm internal diameter) [6].The columns were packed with pure fine quartz sand, and the density of sand in all columns is about 1.6g/cm3. The water pumped into the column was a solution of pure $FeCl_3{\cdot}6H_2O$ (>99%) and ultrapure water, with Fe(III) concentration = 3.0 mg/L, and pH = 7, adjusted using with 25% ammonia water ($NH_3{\cdot}H_2O$)[6]. The experimental contents are shown in table1. Where D_{50} id the particle size in the infiltration medium.At the experiment conclusion, sand in the columns was sampled at 1 cm intervals. The sand samples were immersed in concentrated hydrochloric acid and shaken vigorously to dissolve Fe(III) clogging material into the 12.27 mol/L acid, and the Fe(III) ion concentration derived[6].

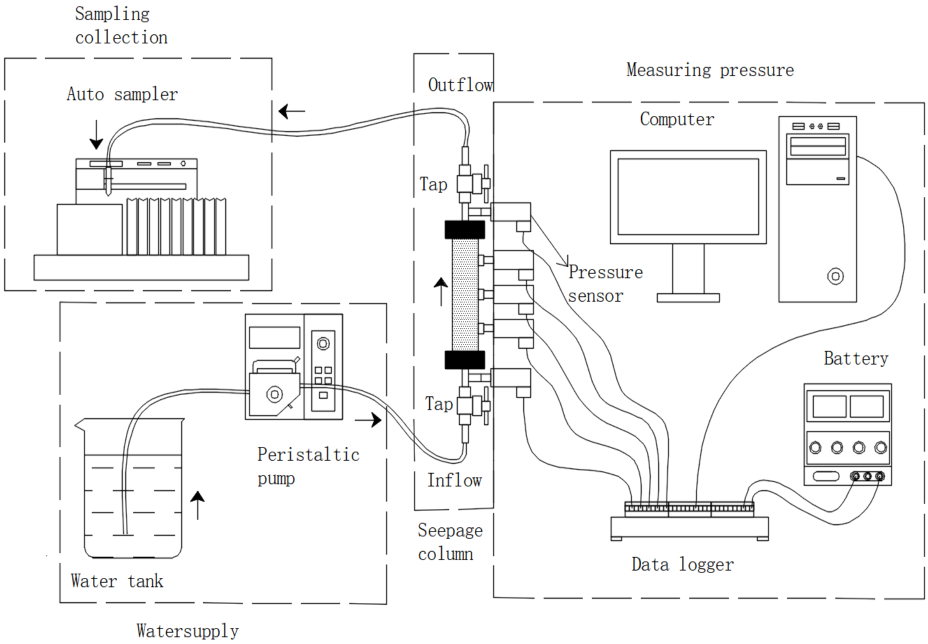


Figure 1. Experimental column set up

Table 1. Experiment under different conditions

No.	D_{50} (mm)	Infiltationvelocity (m/d)	Fe(III) concentration (mg/L)
E1	0.70	1.62	3.00
E2	0.38	1.62	3.00
E3	0.16	1.62	3.00
E4	0.16	1.62	1.00
E5	0.16	1.62	0.30
E6	0.16	0.46	3.00
E7	0.16	4.55	3.00

3. Results

The time dependent hydraulic conductivity in different locations of sand columns can be expressed as (Darcy's law):

$$K = \frac{Q \cdot \Delta x}{\pi r^2 \cdot \Delta dh}, \quad (1)$$

where Q (m³/day) is the flow rate, Δx (m) is the column length between any two pressure transducers, Δh (m) is the difference in hydraulic head between the two points along the column, and r (m) is the inner diameter of the column. K was defined for different locations in the sand columns (0-3cm,0-16cm).

The mass deposit distribution was also obtained by dismantling the column at the end of the experiment, and expressed as the mass ratio

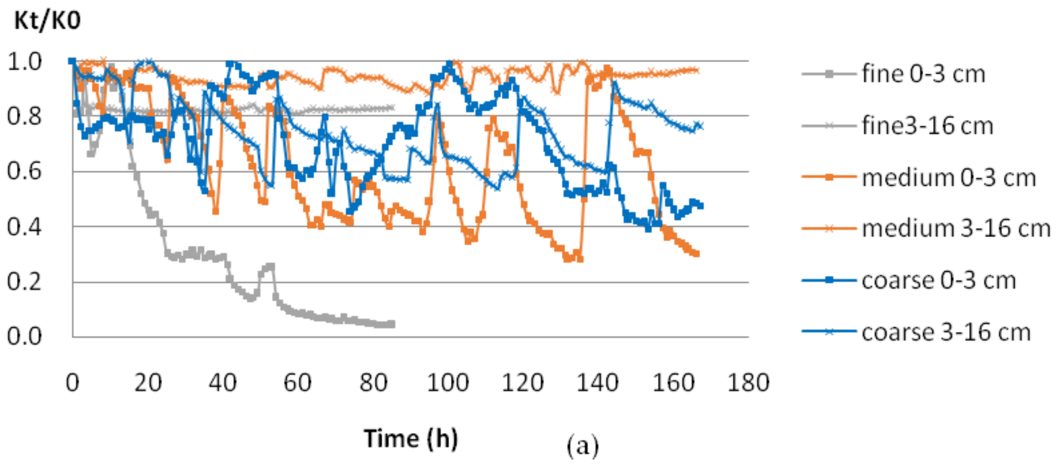
$$V_M = \frac{M_{Si}}{M_T} \quad (2)$$

where M_T is the total Fe(III) mass in the column at the end of the experiment, and $M_{Si}$is the Fe(III) mass in section Si.

3.1. Hydraulic conductivity changes

Hydraulic conductivity changes were calculated as the permeability ratio (Kt/K0), where Kt is the instantaneous hydraulic conductivity (m/d). Figure 2 shows the column permeability ratio decline for the three different conditions.

When the pH of the recharge water is between 7 and 8, the clogging substance is a hydroxide of iron, and the clogging mainly occurs at 0-3cm from the water injection port. The higher flow velocity, iron concentration and the smaller median particle size of the infiltration medium, the earlier the clogging occurs, and clogging degree more heave. The flow velocity has the greatest influence on the clogging, when infiltration flow rate is 4.55m/d, the sand was blocked by 90%, 38 hours after the start of the experiment. The coarse sand and medium sand have less influence on the blockage, and the clogging process is relatively close, but the fluctuation of the internal blockage of the coarse sand is more obvious.



(a)

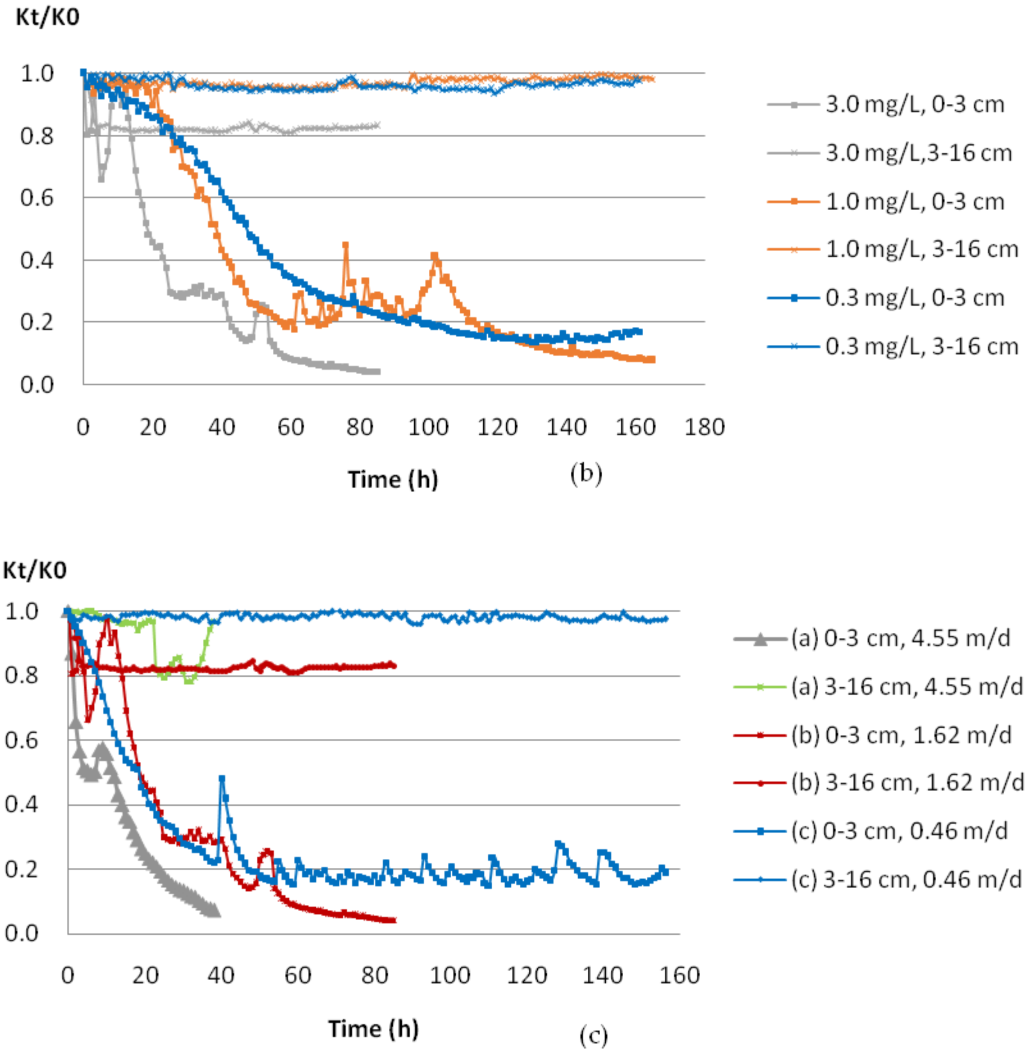


Figure 2. Permeability for different conditions. (a) Permeability at different locations for infiltration medium; (b) Permeability at different locations forFe(III) concentration; (c) Permeability at different locations for flow velocity.

3.2.Mass deposition

Most Fe(III) was deposited within 0–1cm, i.e., the inlet section. As Figure3 shows, the father from the water injection port, the smaller the deposit concentration effect. E3 has the most deposition at the water injection port, and with 95% Fe(III) retention. E5 has the least deposition, only with 46% Fe(III) retention. As Figure 4 shows, the mass deposition rate, dM/dt, stabilized at 0.48, 0.15, 0.05, and 0.018 mg/h for E7, E2 E3 and E1, E4 and E6, E5.

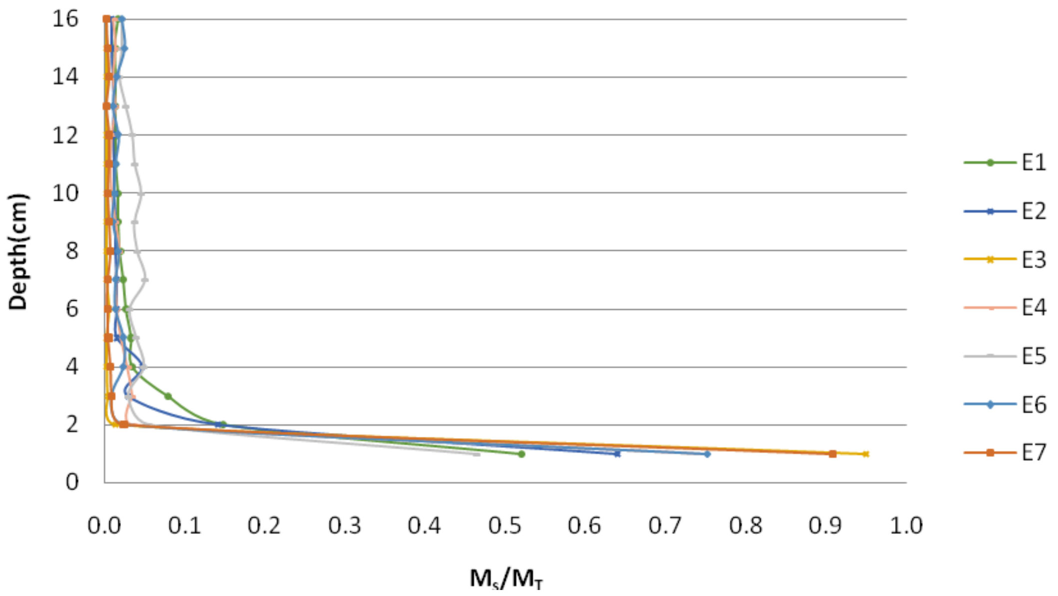


Figure 3. Deposition distribution along the column.

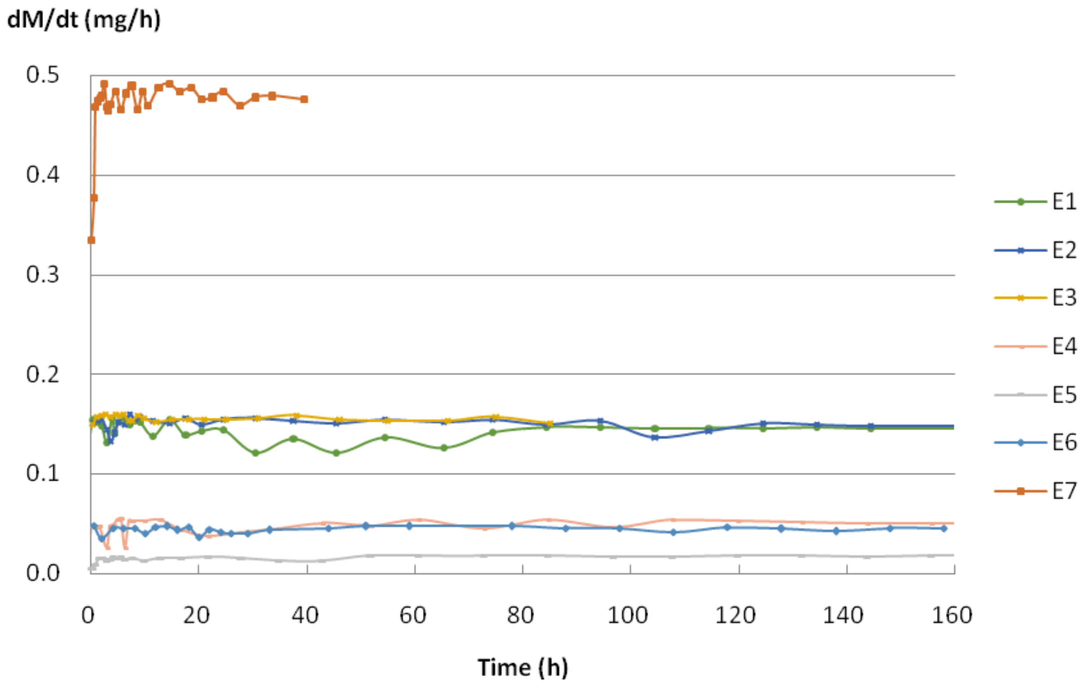


Figure 4. Mass deposition rate.

3.3. Fe(III) clogging mechanism

The experiments were conducted with recharge water of pH 7 and Eh = 0.4 V, as Figure 5 shown that Fe(III) is as precipitated as $Fe(OH)_3$when pH=7 and Eh>0[6][7]. As Figure 6 shown, Fe(III) was intercepted between 0-0.5 cm from the column inlet, with >75 % Fe(III) deposition within 0–1 cm.

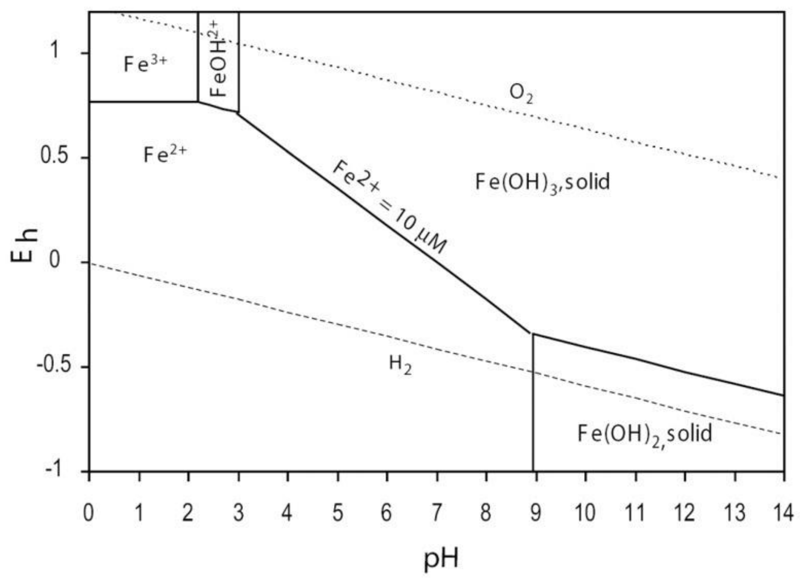


Figure 5. Pourbaix diagram for Fe(II), Fe(III), O_2 and H_2 calculated with Fe^{2+} concentration =10 μM.

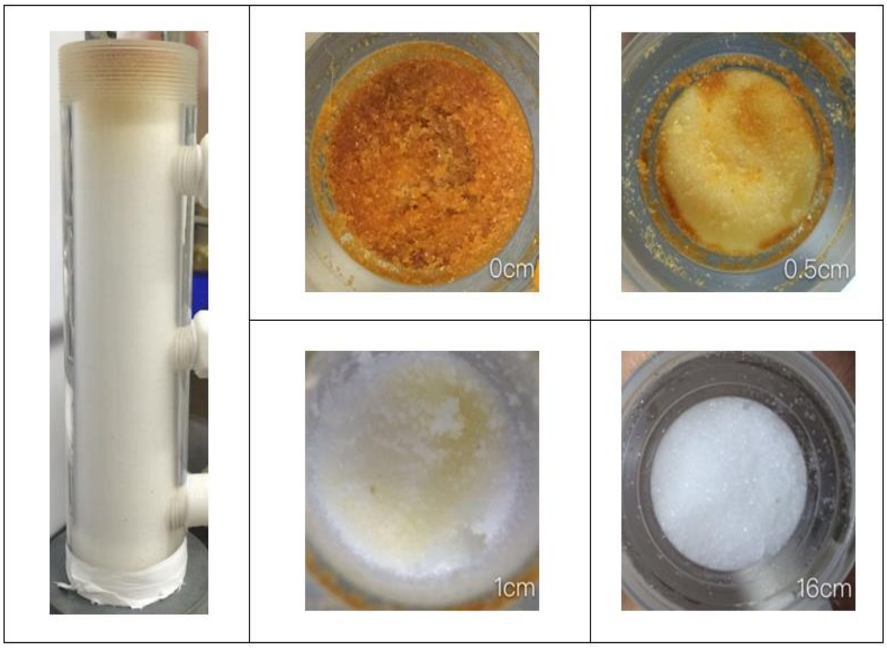


Figure 6. Pourbaixmatrix iron oxide particles interception for different sections.

Through the static adsorption experiment of quartz sand-iron hydroxide, the amount of $Fe(OH)_3$ adsorbed by quartz sand accords with quasi-second kinetic adsorption (R2=0.999) and Freundlich isotherm adsorption (R2 =0.996). The larger specific surface area of the adsorbent, the higher concentration of $Fe(OH)_3$ is , the larger the adsorption amount is , but the maximum adsorption amount is only 0.076 mg/g, and the constant of the Freundlich equation is 0.36, which is less than 2, means the adsorption process if difficult to occur. Therefore, as Figure 7 shown, the main mechanism causing clogging is surface interception filtration and a small part of adsorption.

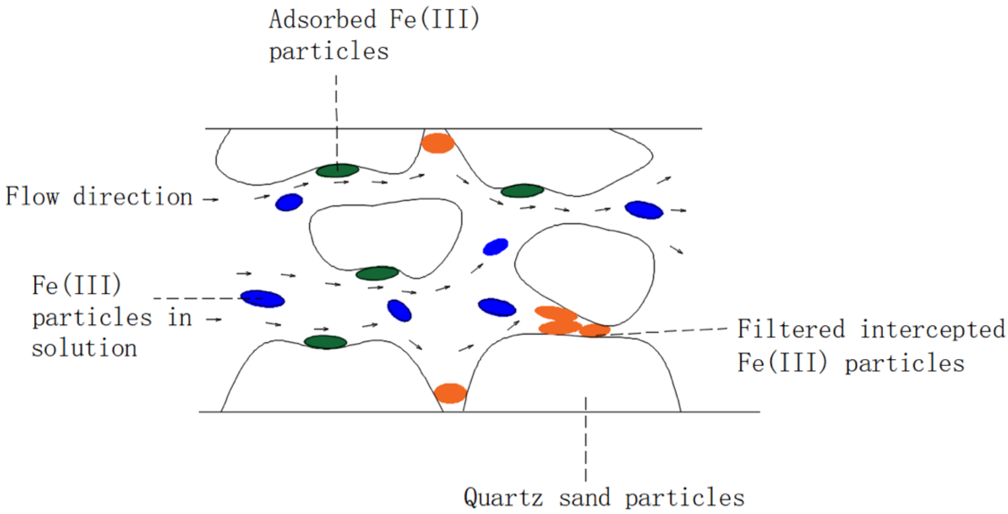


Figure 7. Clogging mechanism diagram.

4. Discussion

$Fe(OH)_3$ is mainly concentrated at 0-0.5 cm of the water injection port, which is also the main reason for the decrease of the permeability coefficient of the early injection port. Due to flocculation, the $Fe(OH)_3$ particles form large particles of ferric hydroxide colloid on the surface layer of the infiltrated medium, and are subjected to surface layer interception filtration. The median particle size of the infiltration medium is large, and the smaller the specific surface area, the easier the $Fe(OH)_3$ enters into the sand column through interception. In the coarse sand experiment column, the $Fe(OH)_3$colloidal particles easily enter the interior through the surface layer to form a clogging. Since the quartz sand is difficult to adsorb a large amount of $Fe(OH)_3$colloidal particles , temporary pore throat blockage was occurred inside, which cause the internal permeability coefficient of the sand column to fluctuate greatly.

5. Conclusions

This paper presents experimental work investigating Fe(III) clogging processes for different conditions, and the effect on hydraulic conductivity. The study also highlighted the interaction of experiment conditions effects on deposition and clogging dynamics. Some important conclusions are as follows:

(1) Fe(III) mostly remained near the surface of porous medium, and its retention rate and retention quantity were affected by the particle size of porous medium, theinfiltration Fe (III) concentration and the infiltration velocity.The particle size smaller, the Fe(III) more concentrate on the surface layer, the retention quantity bigger, the retention rate faster, the concentration of Fe(III) smaller, the stabilitytime of the effluent concentration later. The infiltration concentration of Fe(III) is high, the retention quantity is bigger, the retention rate is faster, outflow Fe(III)concentration is higher. Infiltration flow velocity is high, more quickly into the sand column in unit time, the remained Fe(III) quantity is larger, the occurrence time ofstable concentration is earlier, and the surface retention rate is larger.

(2) The occurrence time, the depth and the degree of Fe(III) clogging are allaffected by the particle size of infiltration medium, the infiltration concentration and the infiltration velocity. The bigger the medium particle size and the lower the infiltration Fe(III) concentration, the later the occurrence time of clogging and thelighter the degree of clogging, but the greater the depth and influence of clogging. The smaller the infiltration flow rate, the clogging occurs later and lighter, the more concentrated in the surface.

(3) The main mechanism of iron clogging can be concluded as filtration. Ironions will become iron hydroxide precipitate at a pH value greater than 1.87, theaggregation of hydroxide precipitate in porous medium leads to clogging.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (Grant No. 41472213, 41602077).

Author Contributions: Zhang Hexuan and Du Xinqiangconceived and designed the experiments; Zhang Hexuanperformed the experiment and analyzed the data; Du Xinqiangand Ye Xueyancontributed reagents/materials/analysis tools; Zhang Hexuanwrote the paper and revised by Ye Xueyan and Du Xinqiang.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MDPI: Multidisciplinary Digital Publishing Institute
DOAJ: Directory of open access journals
TLA: Three letter acronym
LD: linear dichroism

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Extended abstract for ISMAR10 symposium. ***Topic No: 9 (090#)***

Underground Transfer of Floods for Irrigation (UTFI): Global to field scale assessments

Alam, Mohammad Faiz[1]; Pavelic, Paul[2]; Sikka, Alok[1] and Sharma, Navneet[1]

[1]International Water Management Institute (IWMI), Delhi, India
[2]International Water Management Institute (IWMI), Vientiane, Lao PDR
*Correspondence: m.alam@cgiar.org

Key Words: Recharge, Flood, Drought, Site Suitability, Economics.

EXTENDED ABSTRACT

Dealing with inherent challenges associated with intra- and inter- year water resource variability, which are expected to intensify under climate change and manifested as extreme flood and drought events, are amongst the most critical water management challenges globally. Most river basins around the world routinely face difficulty in balancing between water availability and water demand across time and/or space. Water storage infrastructure plays an important role in balancing gaps between water supply and demand. Groundwater storage, with its high storage, buffering capacity, reliability and accessibility provides a potentially attractive water storage option.

One way of utilising groundwater storage to balance water variability is through an approach known as “Underground Transfer of Floods for Irrigation” (UTFI) [1]. UTFI provides a nature-based approach to co-manage floods and droughts at the river basin scale [1, 2]. It involves targeted groundwater recharge of seasonal excess surface water flows that potentially pose a flood risk to mitigate downstream flooding and increase groundwater storage. Here, we provide a multi-scalar assessment of UTFI suitability feasibility at the global scale, economic feasibility at river basin scale and performance assessment of a pilot trial at the village scale.

Biophysical suitability assessment is a critical first step in UTFI planning to identify potential regions and basins where UTFI could be potentially implemented. A UTFI suitability assessment was conducted on a grid scale resolution of 30 arcminutes (i.e. approximately 55 × 55 km at the equator) to give an understanding of the wider applicability and potential of UTFI across the globe. Analysis was done using a multi-criteria spatial suitability approach [3]. Multiple datasets covering flood, drought and hydrogeology related variables were grouped into three categories that cover water supply, water demand and aquifer storage. The results of the analysis showed that regions of high UTFI suitability are distributed across with world with South Asia, East Asia, South East Asia and Sub-Saharan Africa having the highest UTFI potential. About 622 million hectares of crop land, with 3.8 billion people residing in these areas is classified as areas of high UTFI suitability. Aggregation of UTFI suitability levels at the river basin scale reveals high suitability across 16 of the 100 largest basins of world, with some of the major basins in Asia (Ganges, Chao Phraya, Mekong), Sub-Saharan Africa (Volta, Awash, Tana, Niger), Latin America (Sao Francisco, Magdalena, San Juan) and North America (Sacramento, Brazos) classified as high suitability for UTFI.

Assessing whether the overall benefits of UTFI outweigh the costs associated with UTFI implementation is an important indicator to support decision making. Economic analysis was performed for three basins showing high UTFI suitability in different sub-regions: Awash basin in Ethiopia, Ramganga basin (part of Ganges basin) in India and Chao Phraya basin in Thailand [3]. A generalized and replicable economic framework was developed and applied in each basin. In the analysis, total costs of UTFI were divided into infrastructure cost, land use cost, and recovery cost. Total benefits were divided into two parts: flood damage reduction and increased water availability for irrigation used for increasing crop production. The results were summarised in terms of 3 economic indicators: Benefit Cost Ratio (BCR), Internal Return Ratio (IRR) and Net Present Value (NPV). Economic analysis shows high economic feasibility if investments into UTFI are directed towards geographic areas of high suitability with IRR values ranging from 20 to 122%. However, major benefits vary driven by contrasting regional contexts with additional crop production being the predominant benefit in the Awash and Ramganga basins, whilst for the Chao Phraya basin flood mitigation is the major benefit. At the same time, results show that significant costs would be required to set up UTFI infrastructure (US$ 336 – 1,041 million) over the vast scales of the river basins. The high cost associated with UTFI could be minimized by incremental staging of projects in sub-catchments, with lessons learnt from earlier phases taken into account in later phases.

UTFI was piloted at Jiwai Jadid village in the Ramganga basin, India [4]. Piloting was done to analyse the performance of UTFI in the field and generate the knowledge required to support upscaling UTFI in similar setting of intensively irrigated, high yielding alluvial aquifer settings. As land availability is a serious constraint due to high population density and intensive year-round cultivation in the region, UTFI pilot made use of unused pond in the village to install UTFI infrastructure consisting of 10 gravity-fed recharge wells. Detailed operation and monitoring protocol was prepared to guide the monitoring of the physical performance of the pilot system. Result shows that pilot recharged on average of 45,000 m^3 of water of over recharge season of ~ 70 days from 2016-18 [5]. However, there is high inter-year variation in recharge rates observed with highest recharge of around 62,000 m^3 taking place in 2017 (at average recharge rate of 775 m^3 day^{-1}) and lowest recharge of around 26,000 m^3 in 2018 (at average recharge rate of 283 m^3 day^{-1}). The inter-year variation in recharge rate is a function of number of factors including the magnitude and intensity of rainfall, hydraulic gradient available, quality of recharge water and frequency/extent of de-clogging operations. The recharged water from pilot system is sufficient to irrigate between 7.5 and 17.7 ha of crop land (*rabi* wheat with an irrigation requirement of ~ 350 mm). Recharge from UTFI on average represents ~ 3% village total recharge, reflecting the limitation of one pilot structure in the high storage/transmissivity setting. Groundwater table response to recharge was confounded number of factors including rainfall, intensive pumping, canal and river flows. Distinct mounding from UTFI was only visible in 2017 and was limited to 0.8 metres or less and was most clearly evidenced at the beginning of the season when recharge rates were highest. Based on the performance of pilot, the number of structures required to recharge 10-50 % of excess monsoonal flow in the Ramganga basin range from 13,014 – 65,068 with corresponding land requirement of 3,416 - 17,080 hectares.

The information and knowledge from the studies carried out at multiple scales are useful in early identification of the likely prospects for UTFI and provide the basis and framework for more detailed implementation and research at the country, basin and village scales.

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Paper for ISMAR10 symposium. ***Topic No: 9 (107#)***

The characteristics of clogging issues at the riverbank filtration site with long-distance infiltration pathway to the Lalin River, NE, China

Bin Hu[1]*; Weishi Wang[2] and Yanguo Teng[1]

[1] College of Water Sciences, Beijing Normal University, Beijing 100875, China; e-mail: bnu_hb@163.com
[2] Institute of Earth and Environmental Science, University of Potsdam, Potsdam 14476, Germany; e-mail: wewang@uni-potsdam.de
*Correspondence: bnu_hb@163.com

Abstract: Although the riverbank filtration (RBF) has applied in northern China with its advantages of contaminants removal by natural purification along with infiltration process, the inevitable clogging during continuous RBF operation was not given enough attention. Thus, we selected an RBF site which features the long-distance infiltration pathway from the Lalin River nearby, in northeastern of China, as the study area to estimate characteristics of clogging issues. Both laboratory column experiments and field research were adopted. According to the materials of the hydrogeological survey in the study area, the infiltration system can be divided into two regions: (1) infiltration dominated zone (0-560m), and (2) in-situ groundwater-dominated zone (2000-3000m). Physical clogging was a dominating factor in both areas. Whereas, according to the laboratory experiments results, the influence of chemical clogging in the in-situ groundwater-dominated zone was more significant than in the infiltration dominated zone. For the long-distance RBF site, the clogging issues were caused by both suspended particles of the groundwater and precipitation of redox reaction, resulting in the filter pipe clogging.

Keywords: riverbank filtration; clogging; long-distance infiltration pathway; column experiments.

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1. Introduction

During the continuous operation of RBF, clogging issues in the infiltration areas are inevitable [1-2]. Infiltrated RW which contains suspended particles, chemicals, and microbial components will lead to clogging at the riverbed/aquifer interface and infiltration zone [3]. After mechanical sorption, chemical reaction (e.g., redox reaction, ion exchange), and microbial process (e.g., microbial activity, degradation, biofilm growth), the grain size of particles will increase, resulting in the decrease of pore size. The hydrodynamic conditions in the hyporheic zone and infiltration areas will be changed, such as the decline of RW infiltration rate and permeability in the hyporheic zone [4-5].

For China, the first RBF facility is in the northeast region in the 1930s, and nowadays, there are more than 50 riverside source fields constructed along the Yellow River, 15 RBF sites in Hai River and Luan River basins [6]. However, clogging issues during RBF are rarely studied in China. [7]

(p. 111-114) demonstrated that clogging of a riverbed in Yangzi River at Baisha County had affected RBF operation. [8] (p.178-183) have reviewed the clogging types and relevant alleviating mitigating approaches. The study of clogging characteristics in China is still not being noticed.

Thus, in this paper, we studied the characteristics of clogging issues at an RBF site with long-distance infiltration pathway from the Lalin River, NE, China, by both field hydrogeological survey and laboratory column experiments. Prior information of the hydrogeological characteristics was adopted from a hydrogeological report of the study area. Aiming at the evaluation of the clogging extent, the permeability of the mediums was monitored by a digital decline pressure sensor. Besides, the hydrogeochemical parameters, including turbidity, COD, NH4+, Mn2+, total Fe, Fe2+ and the soluble Fe, were analyzed to reveal the relationship among purification effect, the permeability of mediums, and clogging types. As a first local study of the clogging related problem in this RBF waterworks. It would fill the knowledge gap on this vital point for sustainable management and attract the attention of the managers on possible future influence, further improve the management of the riverside source field in the study area.

2. Materials and Methods

The study area is located in an RBF waterworks near the Lalin River, NE, China. According to the materials of the hydrogeological survey in the study area, the infiltration system can be divided into two regions: (1) infiltration dominated zone (0-560m), and (2) in-situ groundwater-dominated zone (2000-3000m).

The laboratory column experiments were conducted to investigate the clogging-related happening on this waterworks. Four columns with 20 cm depth were built to simulate the infiltration process (Fig. 1). The quartz sands (grain size is 0.3mm) after biocidal treatment (by $HgCl_2$) were selected as mediums filled in the columns. The infiltrated water was taken from the in-situ Lalin River and pumping into the columns by a peristaltic pump with 50rpm (5.4L/h). The sampling sites located in the 10cm, 30cm, 50cm and 80cm respectively.

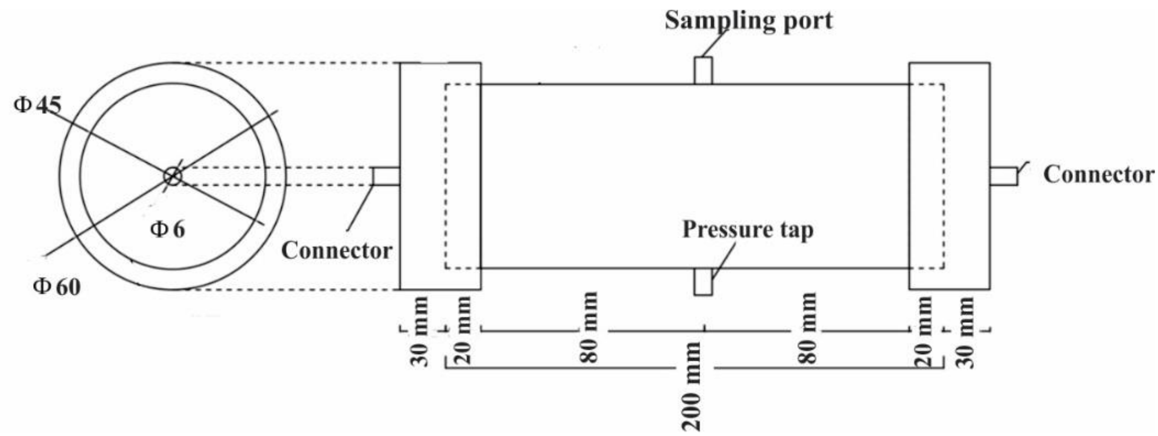

Figure 1. The structure of the column in the experiment.

The hydrogeochemical parameters, including turbidity, COD, NO3-, NH4+, Mn2+, total Fe, Fe2+ and other soluble Fe, were analyzed with spectrophotometry in China, respectively and the hydraulic head was monitored by a digital decline pressure sensor (CY201).

The water sampling for hydrochemical analysis was once per 24 hours, and the for the hydraulic head was once per minute.

3. Results

3.1. Permeability

The permeability of the mediums in the column experiment continuously decreased and reached steady state after 120h (Fig. 2). The maximum decrease of relative hydraulic conductivity (K/K_0, K is the real-time monitoring data, K_0 is the initial hydraulic conductivity of the medium) was 88.29% at the 80cm sampling port, while the highest decreasing speed happened in the first 24 hours. The overall decreasing speed of the hydraulic conductivity got smaller along with the time, in all the four depths. For the depth of 50cm and 80 cm, the changing curves almost overlapped with each other, which denoted that hydraulic change between these sections is smaller than upper layer.

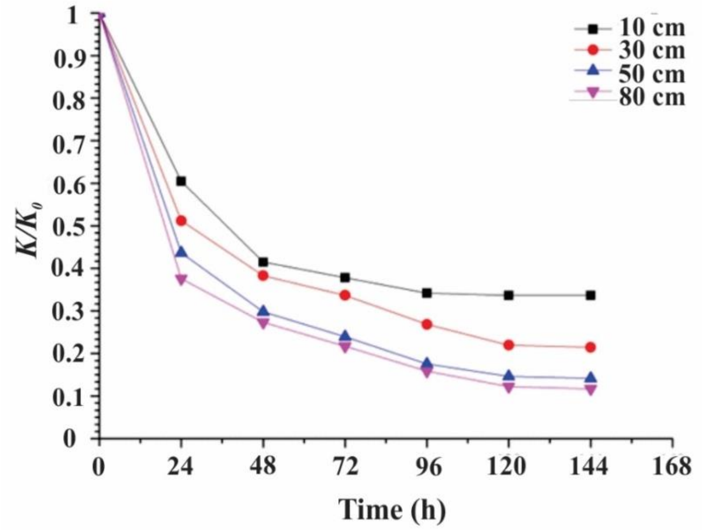

Figure 2. The variation of relative hydraulic conductivity. K denotes to measured hydraulic conductivity (m/s); K_0 denotes to initial hydraulic conductivity (m/s).

3.2. Turbidity

The curve of the turbidity ratio kept decreasing from 0 to 96h and the maximum of the turbidity decline was 51.94% after 96h (Fig. 3). The decline of turbidity ratio rose with the infiltration distance. However, the turbidity ratio continuously increased after 96h in the infiltration path of 10-30cm and kept almost constant in the after 120h infiltration path of 50-80cm (Fig. 3).

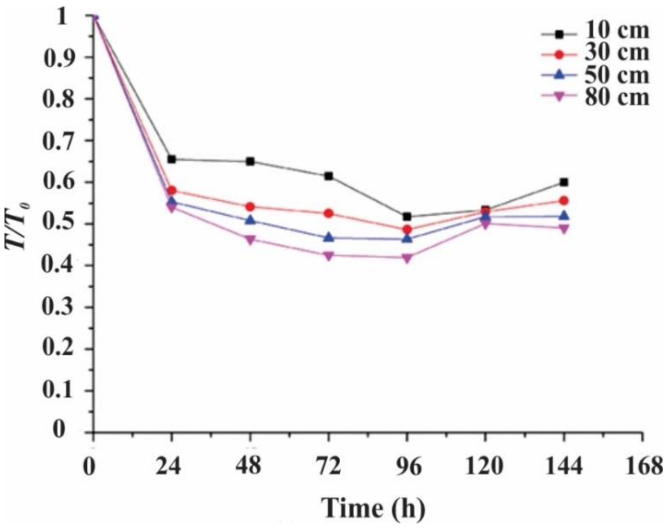

Figure. 3 The variation of relative turbidity. T denotes to measured turbidty (NTU) from samples; T_0 denotes to initial turbidity in the river water (NTU).

3.3. COD and NH_4^+

The concentration variation of COD and NH_4^+ was similar (Fig. 4). The concentration of COD and NH_4^+ kept decreasing in the time-period of 0-120h. During the concentration decline process, it suddenly became significant in the 72-96h. Besides, in the infiltration path of 10-30cm, the COD and NH_4^+ concentration rose in 120-144h. For the infiltration path of 50-80cm, the COD and NH_4^+ concentration were still decreasing in 120-144h.

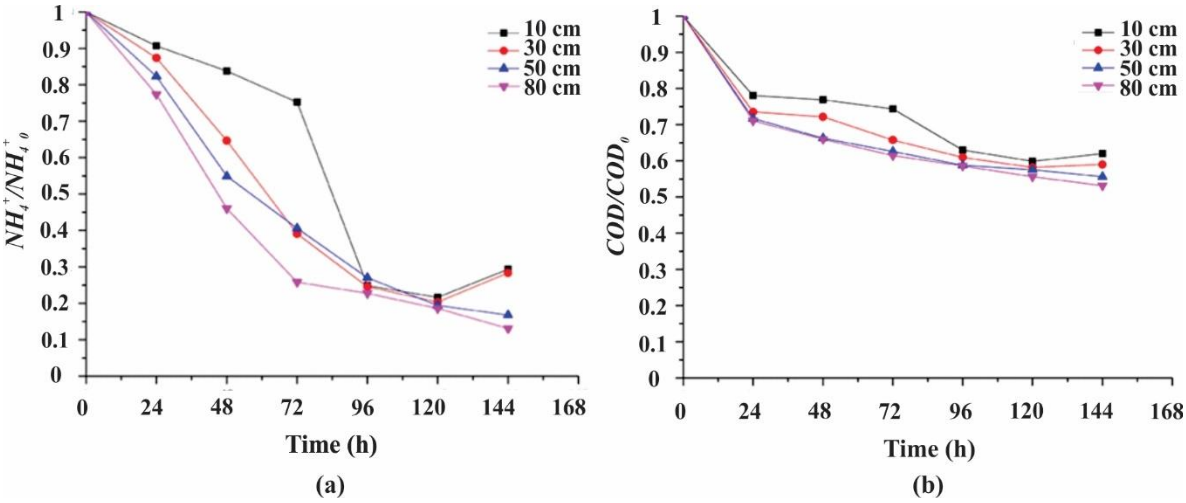

Figure 4. The variation of relative concentration of COD and NH_4^+. (a) is the variation of relative concentration of NH_4^+: *NH_4^+* denotes to measured NH_4^+ concentration from the samples (mg/L); *$NH_4^+{}_0$* denotes to initial NH_4^+ concentration in the river water (mg/L). (b) is the variation of relative concentration of COD: *COD* denotes to measured COD concentration from the samples (mg/L); *COD_0* denotes to initial COD concentration in the river water (mg/L).

3.4 Total Fe, Fe^{2+} and other soluble Fe

The concentration variation of total Fe, Fe^{2+} and other soluble Fe were different in the experiment (Fig. 5). First, the concentration of these parameters continuously decreased in 0-120h. And then, the concentration total Fe and other soluble Fe were recovered in 120-144h at 10-30cm infiltration path. However, the concentration of total Fe and other soluble Fe at 50-80cm were still decreasing in the same time-period. For Fe^{2+}, it decreased at the same distance in 120-144h.

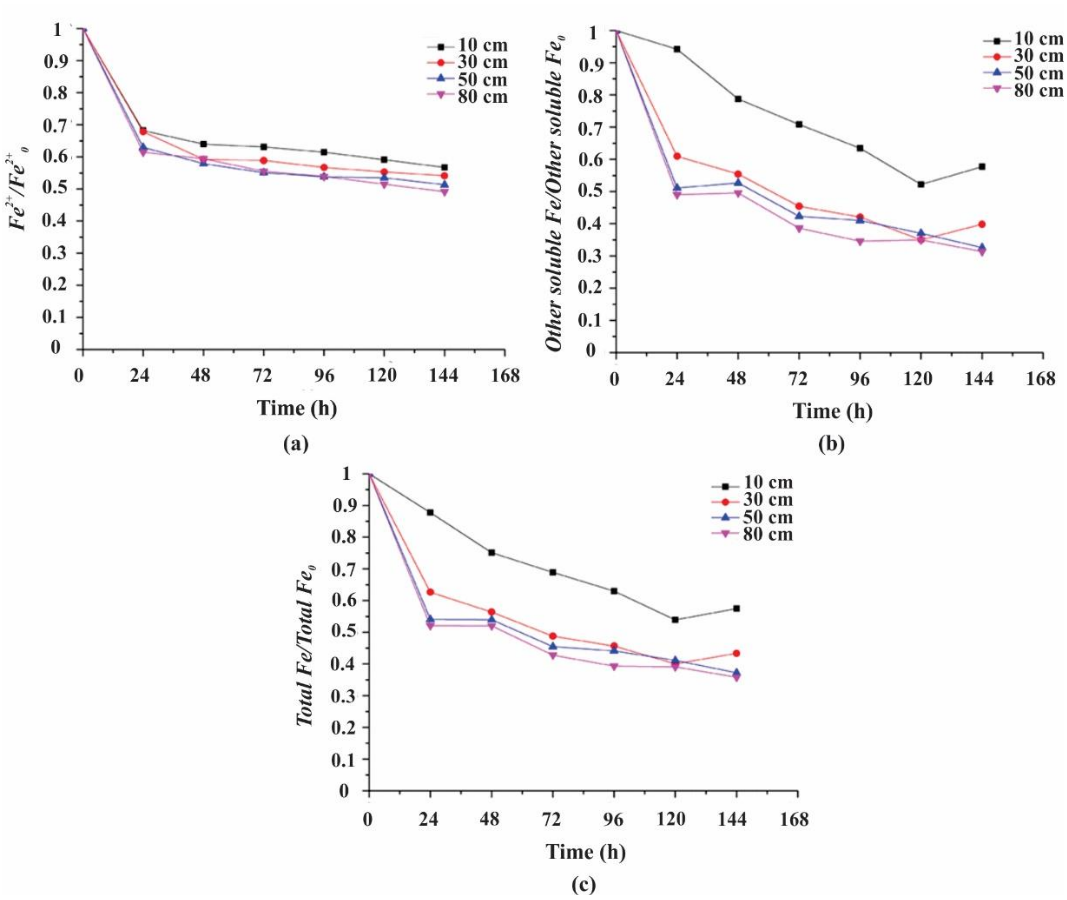

Figure 5. The variation of relative concentration of total Fe, Fe^{2+} and other soluble Fe. (a) is the variation of relative concentration of Fe^{2+}: *Fe^{2+}* denotes to measured Fe^{2+} concentration from the samples (mg/L); *Fe^{2+}_0* denotes to initial Fe^{2+}_0 concentration in the river water (mg/L). (b) is the variation of relative concentration of other soluble Fe: *other soluble Fe* denotes to measured other soluble Fe concentration from the samples (mg/L); *other soluble Fe_0* denotes to initial other soluble Fe concentration in the river water (mg/L). (c) is the variation of relative concentration of total Fe: *total Fe* denotes to measured total Fe concentration from the samples (mg/L); *total Fe_0* denotes to initial total Fe concentration in the river water (mg/L).

3.5. Mn^{2+}

The decrease of Mn^{2+}ratio was 33.34% during the experiment, which was not remarkable as other parameters (Fig. 6). It decreased in 0-120h, and then rose in 120-144h. During the concentration decline process, the decline range was more significant in the 96-120h than other time-periods.

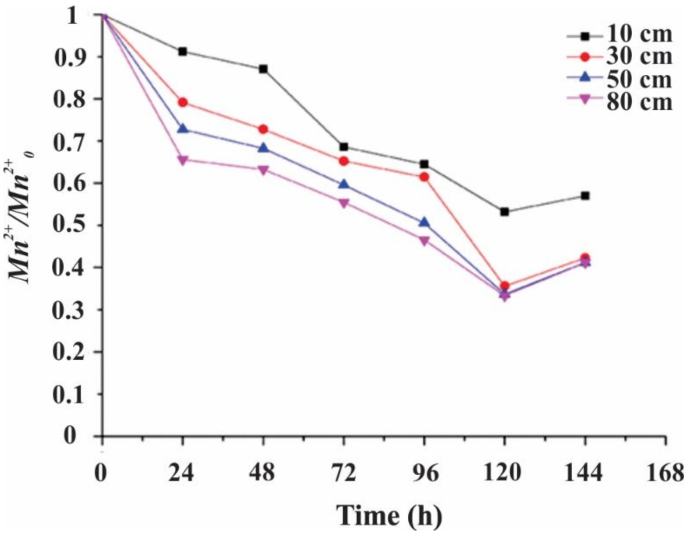

Figure 6. The variation of relative concentration of Mn^{2+}. *Mn^{2+}* denotes to measured Mn^{2+} concentration from the samples (mg/L); *Mn^{2+}_0* denotes to initial Mn^{2+}_0 concentration in the river water (mg/L).

4. Discussion

Due to the long-distance pathway effect, the infiltration rate of surface water is low, which is beneficial to increasing residence time of infiltrated water, and resulting in the increase of physical adsorption, chemical adsorption and redox reaction.

The variation of relative concentration of the parameters demonstrated the changes of physical clogging and chemical clogging in the system. The continuous decreases of turbidity, COD, NO_3^-, NH_4^+, Mn^{2+}, Fe^{2+}, total Fe and other soluble Fe have proved the advantages of water improvement by RBF system. Meanwhile, the recovery of the curves of these specific parameters also illustrated the variation of clogging (Table 1).

Table 1. The interpretation for the changes of the parameters in the experiment.

Parameters	Special changes	Interpretation for variation	Influenced clogging
Turbidity	Reach steady state in the columns after 96h.	The physical clogging becomes dominating after 96h.	Physical clogging
COD and NH_4^+	Significant decrease in 72-96h.	Chemical reactions are most intense in this time-period.	Chemical clogging
Fe^{2+}, total Fe and other soluble Fe	i. Total Fe and other soluble Fe continuously decrease in 0-120h, and increase in 120-144h at 10-30cm; ii. Total Fe and other soluble Fe continuously decrease in 0-144h at 50-80cm; iii. Fe^{2+} kept continuously decreasing in 0-144h	i. The chemical reactions of total Fe and other soluble Fe reach equilibrium in 120h at 10-30cm; ii. The chemical reactions of total Fe and other soluble Fe do not reach equilibrium in 144h at 50-80cm. iii. The redox reaction of Fe^{2+} does not reach equilibrium and may proceed.	Chemical clogging
Mn^{2+}	Decrease in 0-120h, and then increase in 120-144h	The chemical reaction of Mn^{2+} has been reached equilibrium in 120h.	Chemical clogging

According to the time and infiltration distance for the variation of these hydrochemical parameters, it demonstrated the physical clogging is dominating in 96-144h at 10-30cm, 12.5%-37.5% of the infiltration pathway. The chemical clogging is dominating in 120-144h at 50-80cm, 62.5%-100% of the infiltration pathway. Based on the characteristics of infiltration system in the study area we can know that, the physical clogging is significant in the infiltration dominated zone (0-560m) ; and chemical clogging is significant in in-situ groundwater dominated zone (2000-3000m). Besides, the physical clogging is faster than chemical clogging in the study area. The duration of physical clogging is longer.

5. Conclusions

According to the laboratory column experiment results, the characteristics of clogging issues at the RBF waterworks with long-distance infiltration pathway to the Lalin River have been studied. The physical clogging and chemical clogging both existed in the local RBF system. The physical clogging is dominating at 12.5%-37.5% of the infiltration pathway; the chemical clogging is dominating at 62.5%-100% of the infiltration pathway. For the infiltration system in the study area, physical clogging is significant in the infiltration dominated zone; and chemical clogging is significant in in-situ groundwater dominated zone. Besides, the physical clogging is faster, and duration of it is longer than the chemical clogging in the study area. Due to the biocidal treatment, the microbial clogging is not included in the study. The effect of microbial clogging in the waterworks, near the Lalin River, needs further study in the future.

Acknowledgments: This study was supported by the National Key Scientific and Technological Project of China (No. 2014ZX07201-010).

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Paper for ISMAR10 symposium. ***Topic No 9 (257#)***

Clogging map for Santiuste basin MAR site, Los Arenales Aquifer, Spain. Multivariable analysis to correlate types of clogging and groundwater quality

Fernández Escalante, E.[1] and San Sebastián Sauto, J.[2]

[1]Department of R&D Integrated water management, Tragsa, Maldonado 58, Madrid, Spain
[2]Department of Water engineering, Tragsatec, Julián Camarillo 6, Madrid, Spain
*Correspondence: efernan6@tragsa.es; Tel.: +34-91-3226106

Abstract: Clogging is considered one of the major negative environmental impacts caused and affecting the 'artificial recharge' devices. Consequently, several experiments aimed at the study of clogging have been accomplished in managed aquifer recharge (formerly known as artificial recharge) facilities within the framework of the EU founded DINA-MAR and MARSOL R&D Projects. Since 2010 research is specially being conducted on the detection and distribution of physical, chemical and biological clogging processes and their combinations by means of sampling in 34 stations, visual inspection using magnifier and/or microscope, reaction to acid tests, biochemical analyses, radiometric images, photographs in the field and physical parameters determinations.
These activities have led to a classification of these complex clogging processes, by binocular microscope, serial radiometric images taken at the infiltration ponds and canals of the main site used as an experimental laboratory where the project is developed: Santiuste basin, Los Arenales aquifer (Segovia, Spain), locations before studied and well known through other methods, such as chemical analysis, interaction models, sequential gauging tests, infiltration tests, etc.

The article aims a new characterization of clogging processes in the area, developing distribution cartographies for the different clogging processes and combinations. Later correlations with groundwater quality are performed by means of multivariable geostatistical analyses and comparisons with groundwater quality isoline cartographies. Finally, the different clogging processes are mapped and related to the distribution of the major components of groundwater.

The findings propose a methodological approach to correlate clogging-groundwater quality and the specific geological conditions for each area. It is especially remarkable the bi-directional influence of MAR water in the groundwater and the opposite, thus, groundwater has a direct action on clogging processes generated on the surface, at least for the environmental conditions of this aquifer.

Keywords: Managed Aquifer Recharge, MAR, artificial recharge, clogging, groundwater quality, multivariable geo-statistical analyses, Los Arenales.

1. Introduction

Within the framework of the MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought) FP7, www.marsol.eu, have been studied and characterized the different clogging processes generated in the MAR facilities of Santiuste Basin (a sector of Los Arenales aquifer, the biggest area for Managed Aquifer Recharge or simply "MAR" in Spain). The devices studied have been canals, ponds and isolated wells, paying a special attention to the possible relations between the clogging genesis and the groundwater quality of the beneath located aquifer.

On the one hand, clogging presents different and complicated processes in the area, in special in Santiuste basin. On the other hand, there is a groundwater quality monitoring network since 2002, designed by the former Ministry of Agriculture of the Spanish government (MAPA) with 48 points of water used to check the potential groundwater quality variations caused by MAR activity.

This article presents a brief exposition of the interacting elements, the main clogging types detected and their distribution and the relations between groundwater quality, soil, aquifer and clogging processes, looking for coherence in their spatial distribution by means of iso-contents cartographies and multivariable statistical analyses.

1.1. Objectives

The article aims:

- To perform a new characterization of clogging processes in Los Arenales aquifer, in concrete at Santiuste basin, where MAR activities are performed since 2002 and where the process has become very complex after 14 years of activity. Elaboration of a specific map attending the physical, chemical and biological vectors of the clogging there generated, plus their multiple combinations.

- To suggests a methodological proposal to correlate clogging and groundwater quality, based on two different methods: the comparison between the clogging distribution and the groundwater quality cartographies (made from monitoring campaigns datasets collected in the area´s network); and also the study of correlations by means of multivariable geostatistical analyses and calculations.

- To convert the findings into practical conclusions in order to provide some specific guidelines to face the clogging impact in this aquifer and in analogous scenarios, with special dedication to pursue practical interventions ad hoc in order to reduce the clogging genesis, including air entrainment, to increase the effectiveness of the facilities, and provide recommendations for cleaning and maintenance operations.

1.2. Background

The demo-site has become a living-lab for MARSOL project where new activities are permanently tested. Regarding this article´s objectives, Santiuste basin has been considered the most suitable area in Los Arenales, due to the broad scope of clogging processes detected along the canals.

Los Arenales groundwater body has an area of 2,400 km^2, with 96 villages in the provinces of Valladolid, Segovia and Ávila, with 46,000 souls. MAR activities started in 2002, with a special development in three areas: Santiuste Basin, Carracillo Council and Alcazarén Area, with smaller isolated developments. This study focuses in the first one, which first started and the clogging processes have the highest variability. The topologic scheme for the first case with the main components of the water resources management structure is displayer in the figure 1.

Santiuste basin´s MAR activity started in 2002, as a response to the provisional declaration of over-exploitation for Los Arenales aquifer (Segovia, Spain). The former Spanish Ministry of

Agriculture (MAPA) reacted performing different MAR facilities and also set up a groundwater quality monitoring network.

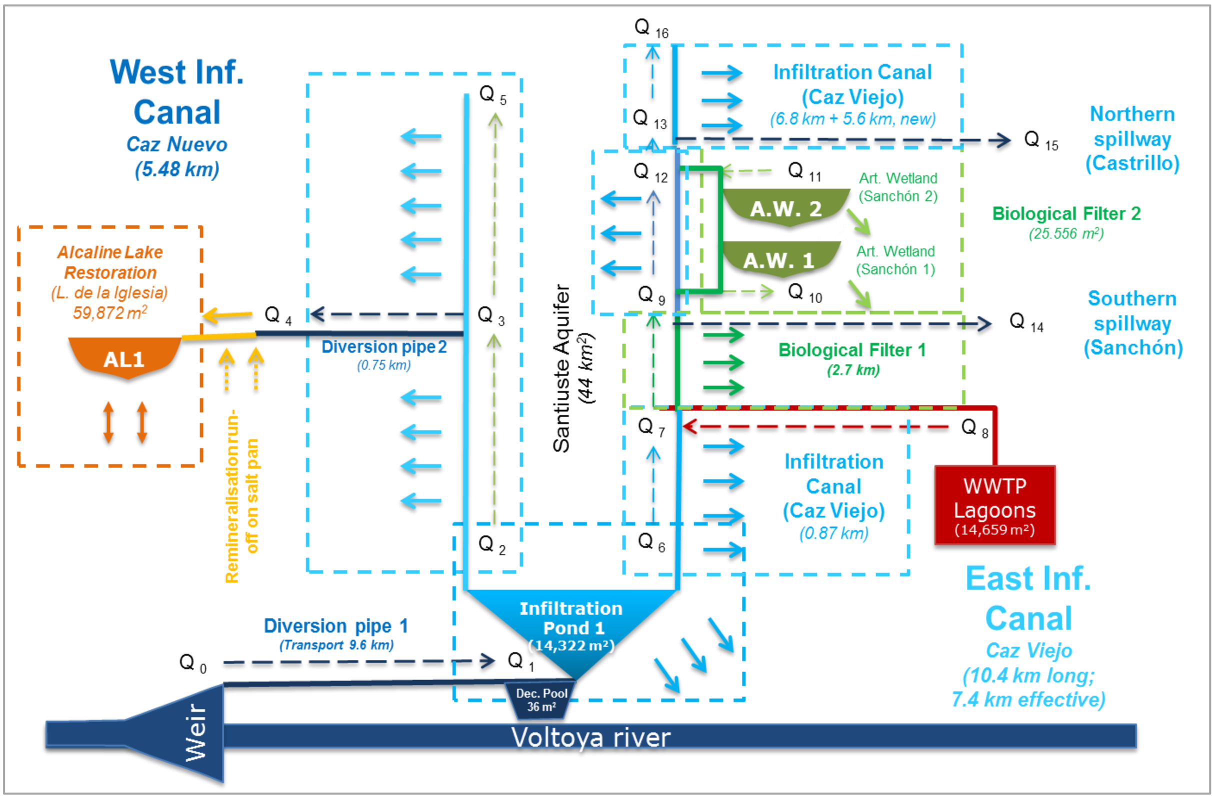
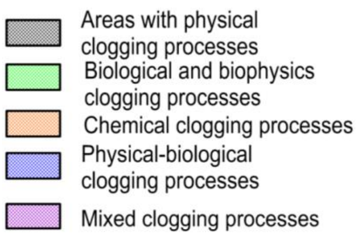


Figure 1. MAR system for Santiuste basin, Los Arenales Aquifer. Topologic scheme. Taken from MARSOL 2015a.

The activities in permanent development in the area have leaded to a classification of the complex clogging processes in different stages: by binocular microscope, serial radiometric images taken at the infiltration ponds and canals, chemical analysis, interaction models, sequential gauging tests, infiltration tests, etc.

Five main types of clogging have been individualized in the MAR canals and ponds, with many different combinations:

1. Areas with physical clogging processes
2. Biological and biophysics clogging processes
3. Chemical clogging processes
4. Physical-biological clogging processes
5. Mixed clogging processes



Figures 2 a) to f). Physical clogging processes (a); biological and biophysics (b); chemical processes (carbonates) (c); vegetated canal bed showing whitish crust (d); physical-biological (e) and biological (filamentous algae colonies) (f).

A detailed description of Santiuste basin can be found in the IAH MAR Commission clogging monograph [Fernández-Escalante, 2013, in Martin R. (coordinator)].

Multi-variable statistics for macro-constituent hydrochemical analyses of groundwater sampled at control points along the MAR system network are presented as Table 1 and represent groundwater chemistry at depth less than 50 m below ground level.

Table 1. Chemical analysis. Values expressed in meq/l. Notice: Cationic index (C.I.); Anionic index (A.I.) and Bases Interchange Index (B.I.I.). Out of bounds (OOB).

RCH	X	Y	depth	Clog type	EC (μS/cm)	pH	r Na	r K	r Ca	r Mg	r Cl	r HCO_3	r SO_4	r NO_3	r Na+K	r Ca+Mg	C.I.	A.I.	B.I.I.
rch-1	366002	4571760	7	OOB	975	7.20	1.96	0.18	2.89	4.69	1.21	5.77	2.17	1.42	2.14	7.58	0.282	0.586	6.762
rch-2	366758	4569620	9.1	OOB	748	8.00	0.70	0.20	2.59	4.03	1.47	3.28	1.29	1.61	0.90	6.63	0.136	0.841	5.329
rch-3	367488	4568356	30	3	1310	7.90	2.26	0.13	4.94	7.40	2.62	5.77	3.33	2.89	2.39	12.34	0.194	1.032	8.726
rch-4	369959	4567090	37	OOB	1396	8.00	1.57	0.15	9.08	4.94	2.82	5.39	2.46	3.68	1.72	14.02	0.123	0.979	9.518
rch-5	369306	4566315	20.6	4	1486	7.40	4.35	0.43	7.53	5.43	1.30	5.33	3.50	4.37	4.78	12.96	0.369	0.900	8.700
rch-6	369753	4567100	150	Depth	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
rch-7	369313	4562496	n/a	2	1096	8.20	2.44	0.20	2.84	6.91	1.72	6.26	2.50	1.69	2.64	9.75	0.271	0.674	7.586
rch-8	367302	4565377	4.05	OOB	2210	8.10	4.61	2.97	5.09	13.66	4.91	9.31	9.22	1.87	7.58	18.75	0.404	1.518	10.890
rch-9	368918	4564508	30	1	1488	8.40	3.70	0.31	4.89	10.28	3.13	6.16	4.93	2.11	4.00	15.17	0.264	1.309	8.098
rch-10	370783	4562750	28	OOB	592	7.8	1.09	0.08	2.69	2.14	0.65	3.16	1.62	0.73	1.16	4.83	0.241	0.719	3.571
rch-11	369313	4562496	30	1	1729	8.00	4.22	0.41	6.74	8.31	3.89	5.44	4.73	4.89	4.63	15.05	0.308	1.584	10.172
rch-12	369254	4561547	30	1	1535	8.60	3.09	1.30	2.45	7.40	2.74	5.59	3.89	3.95	4.39	9.85	0.446	1.186	9.115
rch-13	369291	4560515	9.7	4	1437	7.90	3.44	0.10	6.99	4.94	3.44	5.20	3.08	3.00	3.54	11.92	0.297	1.255	8.164
rch-14	369033	4559716	14.2	1	1389	8.00	3.74	0.92	1.90	9.46	3.53	9.08	2.67	1.13	4.66	11.36	0.410	0.682	9.782
rch-15	369209	4558512	11.2	1	1414	7.80	3.35	0.26	4.34	8.80	2.82	5.80	2.37	3.76	3.61	13.14	0.274	0.895	9.229
rch-16	369339	4558514	20	1	1147	7.80	3.83	0.49	5.59	2.96	1.86	5.57	2.48	2.08	4.31	8.55	0.505	0.779	6.663
rch-17	369837	4557330	17	1	932	8.10	1.74	0.13	4.29	4.20	1.61	6.75	1.15	0.47	1.87	8.49	0.220	0.408	6.993
rch-18	368902	4557236	9	OOB	1063	8.00	2.13	0.20	5.14	4.28	2.68	6.08	1.56	0.87	2.34	9.42	0.248	0.698	7.171
rch-19	370606	4556014	13.9	OOB	456	7.50	0.52	0.05	2.74	0.58	0.56	1.84	0.65	1.27	0.57	3.32	0.173	0.659	3.096
rch-20	368002	4555865	10.2	OOB	734	8.10	2.00	0.10	2.35	2.71	1.83	4.97	0.85	0.39	2.10	5.06	0.416	0.541	5.037
rch-21	369545	4559797	20	2	1119	7.80	3.57	0.08	4.49	4.36	2.14	6.59	2.04	1.06	3.64	8.85	0.412	0.635	6.918
rch-22	370391	4559822	150	Depth	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
rch-23	368631	4559366	400	Depth	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
rch-24	368537	4556643	0	OOB	829	7.80	1.65	0.10	5.09	1.81	1.35	4.95	0.56	1.66	1.76	6.90	0.254	0.387	5.897
rch-25	370648	4560956	20.9	OOB	727	8.10	2.61	0.15	2.00	1.97	1.69	3.13	2.64	0.05	2.76	3.97	0.696	1.385	2.774

2. Materials and Methods

Identification of the dominant clogging mechanism affecting the MAR facility has been done through characterization of physical, chemical and biological clogging processes and their synergistic combinations along Santiuste basin. The procedure consisted on the direct sampling in 34 stations, and also the proper activity of the country work such as visual inspection using magnifier and/or microscope, reaction to acid tests, chemical analyses of samples, radiometric images, photographs and unstable parameters determinations, in special the Total Dissolved Oxygen (TDO). These data were determined by means of a pH meter (Hanna Instruments HI 9018) and a multi-parametric meter with PH/ORP/EC/DO sensors (HI 9828) and through field titration.

According to the spatial distribution of key processes and combinations thereof, an initial mapping from the field work and the results of the 34 clogging sampling stations (figure 3) has been done, overlapping the clogging processes over the MAR facilities cartography. There have been differentiated five sorts of clogging processes already exposed in the previous paragraph.

Additionally, thermographic camera imagery has been implemented since 2010 for the detection and characterization of clogging processes. The Therma-Cam E2, developed by Flir systems, has been employed in order to study the distribution of clogging through temperature differences between clogged and non-clogged zones. These zones show different thermal profiles when visualized. Background information is presented in Fernández and Prieto (2013) where is also displayed an initial clogging characterization cartography for the 2010 situation.

The visual inspection has been a key to define the main process affecting the infiltration capacity at the bottom of the MAR structures. Figure 3 contains photos of clogging profiles.

The main procedure to check the relationship between clogging and groundwater quality has been the application of a multivariable geo-statistical analyses. The study of the variability has been done by a Probability Density Function (PDF) due to the fact that the system is considered to be a variable rather than constant, and a sensitivity analysis to rank the possible effect of the different groundwater components in the different sorts of clogging.

Among the different methods available to fit a distribution to data, has been applied the maximum likelihood estimation (Frey and Burmaster, 1999), method most widely used and also used in the present work. Maximum likelihood estimation is used for finding the parameter values of a distribution that maximize the probability of obtaining a particular set of data, in this case, the most abundant component related with the different appearance of clogging processes. If several distributions are tested, the one with the highest likelihood will accordingly have the best fit (Westrell, 2004). The PDFs adjustment for component concentrations has been done by means of a log-normal distribution, according to some author´s recommendations (NHMRC–NRMMC, 2011; Petterson et al., 2006; Westrell, 2004).

The development of graphics of normal probability and histograms allow information concerning the distribution of the data and their adjustment as a previous stage to accept a hypothesis of normality (accused bias, bimodality, isolated extreme values, etc.) (Grima, 2016). The sensitivity analysis procedures used were based on methods described by van Gerwen (2000). Then, input parameters are assessed one by one by their interest held at its modal (or median for uniform PDFs) or at zero values, while leaving all other transformation process model and dose-response function parameters unchanged. It can therefore be a valuable tool to evaluate the events/phenomena guiding the clogging distribution.

In order to evaluate the change in the risk output, the result obtained removing the factor/treatment, holding it at its modal, has been compared with the result obtained in the initial risk characterization. This comparison is performed by means of calculating the factor sensitivity (FS) for each component, using the worst-case sensitivity calculation (Zwietering and van Gerwen, 2000), dividing the new median (50^{th} percentile) risk estimate by the initial median risk estimate with a $\log_{10}$ transformation:

$$FS = \log 10 \text{ (new median risk / initial median risk)} \qquad (1)$$

High FS values indicate high sensitivity to variations, and show that changes of factors in process steps have profound effects on the final result. For a first analysis, every effect smaller than a factor of 10 (FS = 1) has been neglected, according to Zwietering and van Gerwen, 2000, in order to search for the factors mainly influencing the clogging distribution.

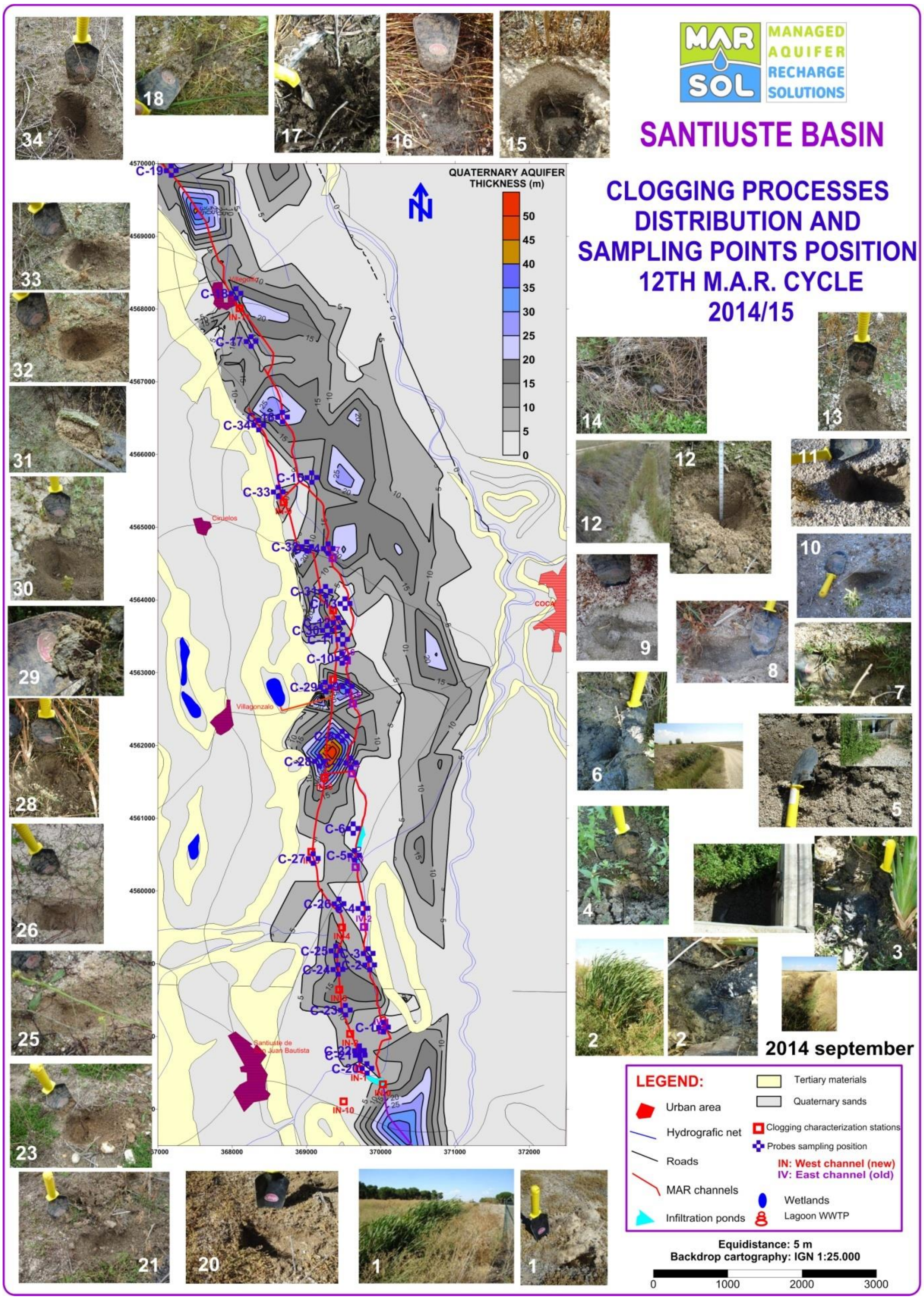


Figure 3. Network to study the clogging processes at Santiuste basin MAR system and sampling/data collection for the situation of 2014 September.

3. Results and discussion

According to the methods explained in the previous paragraph, 34 detailed studies have been conducted in determined stations, providing an initial classification for the most often clogging process affecting each stretch of the MAR canals and infiltration ponds in Santiuste basin´s facilities. Five sorts of clogging have been established, in order to improve the existing range of clogging types mentioned in previous references (Fernández and Prieto, 2013). Those areas presenting a remarkable combination of processes of different origin have been included in the 5th class (mixed clogging processes), in order to simplify the calculations. The results of the field campaigns (figure 3) are presented in the table 2.

Table 2. Clogging characterization. New properties pit profiles and determination of major clogging processes detected in the current clogging network stations, 2015 September. Position in figure 3.

tation	tation	Date	x	y	z	Main clogging process	Observations
C-1	IV-1	03-09-14	370007	4558001	799	Physical	Cake and physical
C-2		03-09-14	369842	4558835	797	Biological	Biological
C-3		03-09-14	369825	4558988	793	Biological and physical	Biological and physical by layers (*lemnas*)
C-4	IV-2	03-09-14	369768	4559590	790	Biological and physical	Sludges, *lemnas*
C-5	IV-3	03-09-14	369672	4560300	788	Biological	Organic matter and *lemnas*
C-6		03-09-14	369660	4560657	785	Biological and physical	*Lemnas*, banded profile
C-7	IV-4	03-09-14	369647	4561534	781	Physical, chemical and biological	Banded profile: physical, clear sand soil and biological. Carbonate and OM clods
C-8		03-09-14	369540	4561893	785	Physical, chemical and biological	Banded profile: clear sand + carbonates, OM clods
C-9	IV-5	03-09-14	369619	4562553	800	Biological, physical & chemical	Banded profile: "Rubens" seeds + clear sand + carbonates, OM clods, physical (grey color)
C-10	IV-6	03-09-14	369556	4562927	792	Physical, biological and chemical	Cake, OM and carbonates. Un-banded profile
C-11		03-09-14	369570	4563181	790	Physical, biological and chemical	Cake, OM and carbonates and gravel. Un-banded profile
C-12	IN-8	29-09-14	369517	4563406	781	Physical	Banded profile: cake, physical and gravel.
C-13		29-09-14	369609	4563658	781	Physical	Banded profile: Cake, physical and gravel
C-14	IV-7	29-09-14	369403	4564395	781	Physical-biological	Horizon A (with clay and OM). Reduction conditions
C-15		29-09-14	369206	4565346	781	Biological-physical	Banded profile: biological, clear sand, OM, physical, OM
C-16		29-09-14	368837	4566159	781	Physical, chemical and biological	Cake, carbonates, OM
C-17		29-09-14	368446	4567175	772	Biological and chemical	Biological film, carbonates and OM
C-18	IN-11	29-09-14	368261	4567819	770	Chemical –biological & physical	Banded layer: ash-grey-black layer, carbonates, OM clods
C-19		29-09-14	367445	4569472	762		
C-20	IN-1	03-09-14	369781	4557457	769	Physical	Ash-colored layer
C-21		03-09-14	369696	4557634	806	Biological-physical	Physical, vectors and OM
C-22	IN-2	29-09-13	369687	4557696	795	Biophysical	"Crust"
C-23	IN-3	29-09-14	369514	4558239	793	Biophysical	"Crust"
C-24	IN-3	29-09-14	369427	4558783	789	-	-
C-25		29-09-14	369405	4559032	791	Physical	Gravel and cream-colored banded
C-26	IN-4	29-09-14	369457	4559658	789	Biophysical	OM clods, banded with white and cream-colored layers
C-27	IN-5	29-09-14	369131	4560267	789	Biophysical	
C-28	IN-6	29-09-14	369236	4561562	789	Biological-physical/Biophysical?	Tangle of weed, clay and gravel, OM.
C-29	IN-7	29-09-14	369331	4562551	786	Biophysical / Chemical?	Filamentous algae. Clay and gravel.
C-30		29-09-14	369372	4563306	784	Biophysical / Chemical?	Filamentous algae. Banded layers
C-31		29-09-14	369359	4563828	780	Biological film-physical	Biological film. Clear sand, dark layer at 8cm depth.
C-32		29-09-14	369123	4564426	778	Biological film-physical	Biological film. Clear sand, dark layer at 8cm depth.
C-33	IN-9	29-09-14	368764	4565163	779	Biological & physical	Biological (green) film. Alternative dark-clear layers
C-34		29-09-14	368524	4566058	773	Biophysical & chemical	Carbonates?

According to the spatial distribution of the key processes and combinations thereof, an initial mapping for characterization of clogging types, updating the scheme commenced in 2009 March situation (Fernández Escalante, in Martin R., 2013) and upgraded in Fernández and Prieto, 2013. This new mapping presents more accurate contacts and new combinations of clogging, in order to monitor the general evolution of the system and to propose measures, what thus represents a DSS for the cleaning and maintenance stages.

Figure 4 represents the clogging processes distribution along Santiuste basin. There are some modifications with respect to the previous referenced characterizations, due to the fact that, as a general rule, the process is becoming more complex and new clogging combinations are appearing in the field. The entrance of sand adhered to the bottom of the canals is causing banded profiles while previously the combinations were more simplistic below the surface cake. The alternation of dark and clear lenses is making the process more and more complex.

Once characterized the clogging distribution in the area according to the presence of major processes, the next stage has been the comparison between stretches of certain clogging processes and the groundwater cartographies in the area, firstly attending to the groundwater quality in the preoperational phase.

Table 3. Groundwater analyses for the wells in the monitoring network which can be correlated with clogging types by their proximity. Preoperational stage: Position, depth of each well, clogging type: Areas with physical clogging processes (1); biological and biophysics clogging processes (2); chemical clogging processes (3); physical-biological clogging processes (4) leaving the mixed clogging processes. Column CI corresponds to cationic index; AI is the anionic index; BII is the Bases Interchange Index.

RCH	X	Y	Depth	Clog type	EC (µS/cm)	pH	r Na	r K	r Ca	r Mg	r Cl	r HCO_3	r SO_4	r NO_3	r Na+K	r Ca+Mg	C.I.	A.I.	B.I.I.	TDO (ppm)
rch-9	368918	4564508	30	1	1488	8.40	3.70	0.31	4.89	10.28	3.13	6.16	4.93	2.11	4.00	15.17	0.264	1.309	8.098	5.55
rch-11	369313	4562496	30	1	1729	8.00	4.22	0.41	6.74	8.31	3.89	5.44	4.73	4.89	4.63	15.05	0.308	1.584	10.172	1.3
rch-12	369254	4561547	30	1	1535	8.60	3.09	1.30	2.45	7.40	2.74	5.59	3.89	3.95	4.39	9.85	0.446	1.186	9.115	3.01
rch-14	369033	4559716	14.2	1	1389	8.00	3.74	0.92	1.90	9.46	3.53	9.08	2.67	1.13	4.66	11.36	0.410	0.682	9.782	3.07
rch-15	369209	4558512	11.2	1	1414	7.80	3.35	0.26	4.34	8.80	2.82	5.80	2.37	3.76	3.61	13.14	0.274	0.895	9.229	5.430
rch-16	369339	4558514	20	1	1147	7.80	3.83	0.49	5.59	2.96	1.86	5.57	2.48	2.08	4.31	8.55	0.505	0.779	6.663	5.31
rch-17	369837	4557330	17	1	932	8.10	1.74	0.13	4.29	4.20	1.61	6.75	1.15	0.47	1.87	8.49	0.220	0.408	6.993	6.24
rch-7	369313	4562496	n/a	2	1096	8.20	2.44	0.20	2.84	6.91	1.72	6.26	2.50	1.69	2.64	9.75	0.271	0.674	7.586	5.51
rch-21	369545	4559797	20	2	1119	7.80	3.57	0.08	4.49	4.36	2.14	6.59	2.04	1.06	3.64	8.85	0.412	0.635	6.918	6.18
rch-3	367488	4568356	30	3	1310	7.90	2.26	0.13	4.94	7.40	2.62	5.77	3.33	2.89	2.39	12.34	0.194	1.032	8.726	6.73
rch-5	369306	4566315	20.6	4	1486	7.40	4.35	0.43	7.53	5.43	1.30	5.33	3.50	4.37	4.78	12.96	0.369	0.900	8.700	8.09
rch-13	369291	4560515	9.7	4	1437	7.90	3.44	0.10	6.99	4.94	3.44	5.20	3.08	3.00	3.54	11.92	0.297	1.255	8.164	6

According to the exposed methodology, a Multivariable Geo-statistical Analysis (MGA) has been conducted. The statistical treatment representation by means of Scatter and Box-plot diagrams are enclosed in the appendix 1 for the analysis performed in the closest wells and the different sorts of clogging:

1. Areas with physical clogging processes
2. Biological and biophysics clogging processes
3. Chemical clogging processes

4. Physical-biological clogging processes

The MGA has provided a set of histograms relating to the main parameters measured in groundwater and the clogging process associated has been charted. The parameters represented have been the pH, sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulphate, nitrates, Na+K, Ca+Mg (all of them in Molal Concentration), the Cationic Index, the Anionic Index, the Base Interchange Index and finally the total of dissolved oxygen. The histograms and the box charts for all the samples are attached as figures 4 and 6.

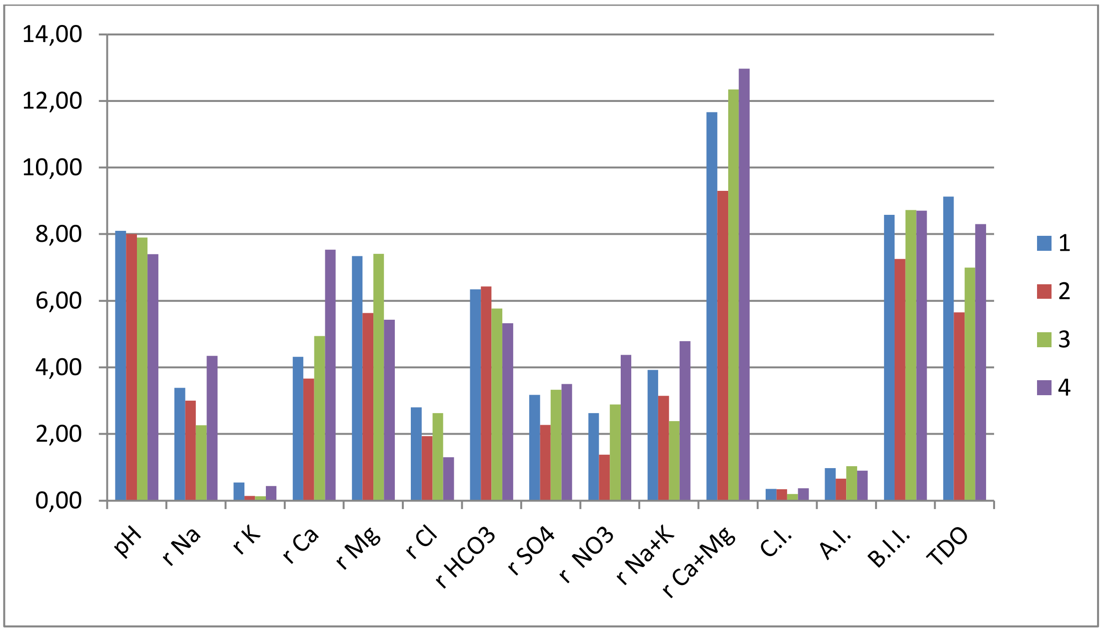


Figure 4. Histogram charting for the whole wells analyzed (mean values) grouped according to their associated clogging processes.

The relation between clogging types and groundwater quality might have a solid connection for this specific demo-site, taking into account that the groundwater table is close to the surface, with a mean depth of 6 m.

It is worth mentioning that the clogging process is becoming increasingly complex. New combinations of clogging are appearing in the field; however some areas show enhanced preferential clogging development.

External processes bring multiple superimposed profiles due to sand deposited by the wind fossilizing previous clogging profiles, which brings the necessity of frequently updated characterizations. It entails the need for the revision of the clogging contours of the maps of clogging distribution and the increase of costs too.

The study of the main compounds in the charts and in the comparison between maps has released the following observations:

Regarding **pH**, the measures collected oscillate in a narrow interval between 7.4 and 8.6, with higher values in winter than in the summer time.

The histogram for mean values presents a pH reduction alike with the four categories, the highest pH for physical clogging (sort 1) and the lowest for physical-biological processes (sort 4).

Regarding **bicarbonates**, the values measured ranges between 5.20 and 9.08 meq/l. The concentration usually increases along the MAR canal, with maximum values in the Northern area, where have been detected carbonate precipitations, crusts of calcite and other chemical clogging.

The SMA indicates a larger presence of biological and biophysics (2) and physical (1) associated to bicarbonates. The concordance with chemical clogging is scarce.

The isolines distribution is congruent with, at least, the sodium+potassium and the calcium+magnesium maps, with a certain resemblance with the one of chlorides.

Regarding **Sulphates**, the values measured ranges between 1.15 and 4.93 meq/l. The maximum sulphates concentration are located in areas with an abundant presence of "mixed" clogging (purple) and physical processes (1).

The SMA indicates a larger presence of chemical clogging (1) associated to sulphates, being the minimum values related to biological and biophysics clogging (2). The sulphates could be behaving as biocides.

Regarding **chlorides**, the values determined ranges between 1.30 and 3.89 meq/l. The maximum values are concentrated close to wetland fossilized areas, which include a high sulphates concentration too due to the presence of gypsum in the west border of the basin.

The areas with minimum concentration have developed, mostly, chemical clogging (3).

The SMA indicates a larger presence of physical clogging associated to chlorides (1). Oddly enough the chemical clogging presents a scarce linkage, due to the fact that some isolated wells in the center of the basin have extreme chloride concentrations.

Regarding **sodium and potassium**, the intervals ranges between 1.74 and 4.35 and 0.08 and 1.30 meq/l respectively. The mean highest concentrations are associated to physical-biological clogging processes (4).

The singular maximum values are placed in the Northern area, where there is an important concentration of chemical clogging processes (3). The Southern zone presents high values associated to physical processes (1).

Regarding **calcium and magnesium**, the intervals ranges between 1.90 and 7.53 and 2.96 and 10.28 meq/l respectively. The distribution is equivalent to the previous case for alkaline ions, except for the chemical clogging processes, which have a solid dependence with these components higher than the previous case.

The SMA results indicate a maximum relation with physical-biological clogging (4) and minimum with biological-biophysical (2).

Regarding **Nitrates**, the values measured ranges between 0.47 and 4.89 meq/l. The maximum nitrates concentration appears in areas with physical and biological clogging (4) and filamentous algae colonies, specially in the West channel and in the South area.

The SMA indicates a larger presence of chemical clogging (3) for mean values of nitrate.

Regarding **conductivity**, the interval ranges between 932 and 1,729 μS/cm with a certain relation with marls and gypsum outcrops.

Regarding the Cationic Index (CI) and the Anionic Index (AI), the values measured and analyzed do not present differences large enough to drive conclusions. The trends display minimum concentrations of chemical clogging processes (3) associated to cations, and biological and biophysics clogging processes (2) to anions, similarly to the ICB trend.

Regarding the Total Dissolved Oxygen, the data collected are between 3.3 and 8.9 ppm. The maximum values are related to physical clogging processes (1), and the minimum for biological and biophysics clogging processes (2). This observation is coherent with the water origin.

The clogging process is becoming more and more complex. New clogging combinations are appearing in the field and some areas are prone to enhance preferential clogging development.

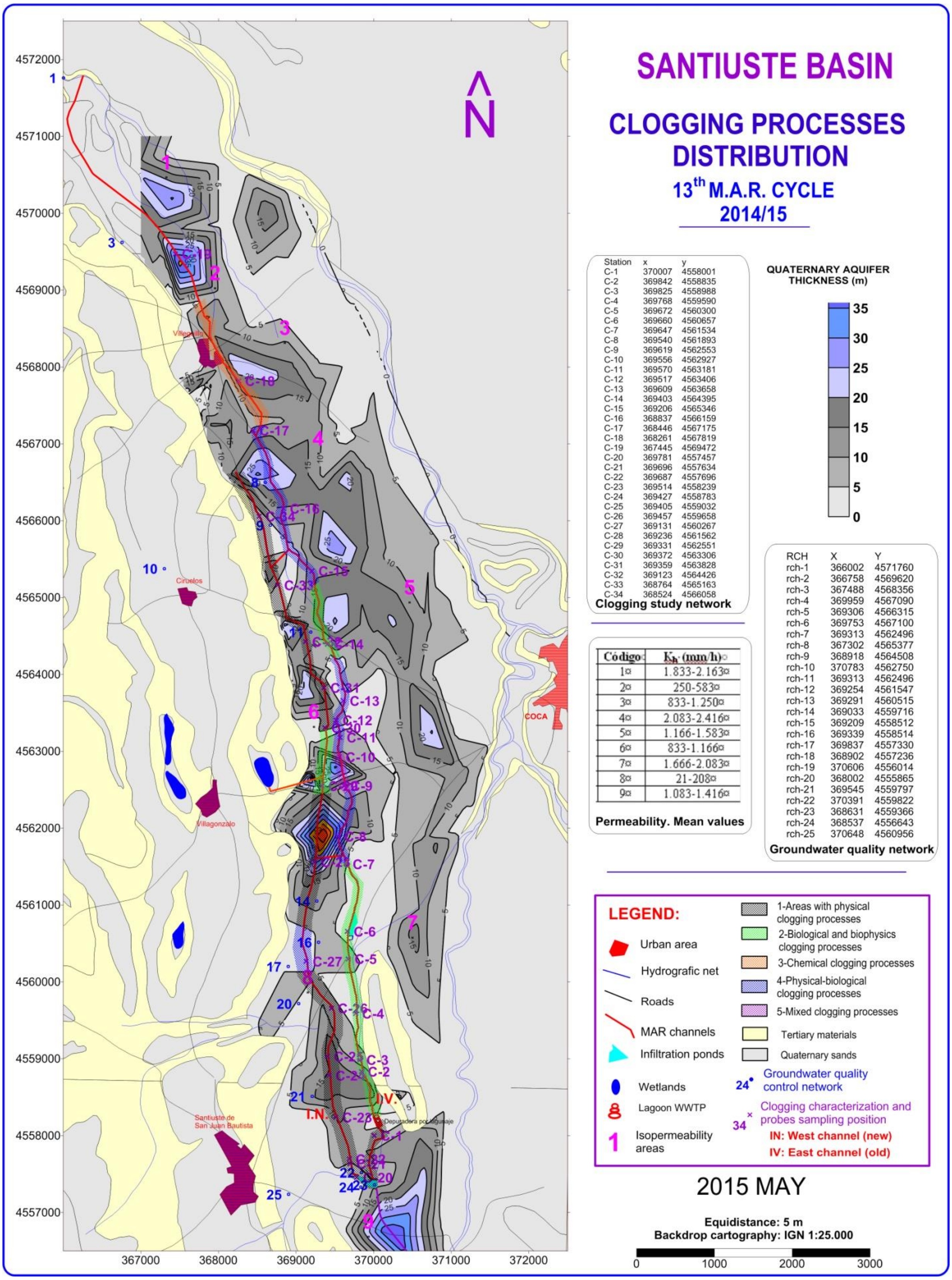


Figure 5. Cartography for Santiuste basin MAR devices and clogging processes distribution according to their nature for May 2015 situation. The map also exposes geological materials, the position of clogging stations, groundwater quality network, permeability distribution in the area and other singular elements. Graphic scale (Modified from MARSOL, 2015a).

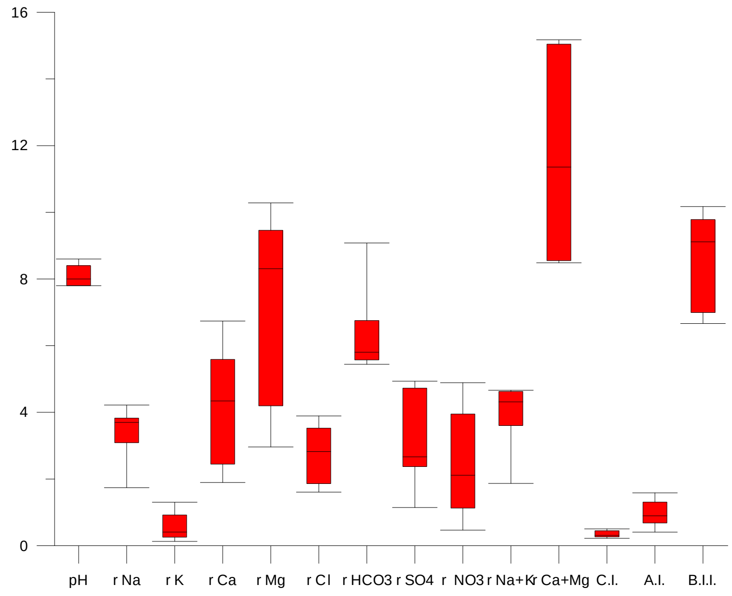


Figure 6. Box-plot charting for the whole wells analyzed for 15 chemical parameters.

5. Conclusions

The clogging process is becoming more and more complex, e.g. multiple superimposed profiles due to external geodynamic processes (banded profiles) and new clogging combinations are appearing in the field. Moreover some areas are prone of preferential clogging development.

There is a bi-directional influence of MAR water in the groundwater and the opposite. The fact that groundwater has a direct action on clogging processes might not be a general rule, but it is likely to happen in MAR facilities with a shallow water table.

In short, there is a interaction between the water employed for recharge, the native groundwater and the geological conditions of each specific area, what remarks the statement that clogging is the result of the interaction between many different elements and processes, not only recharge water and the receiving medium.

There are many different clogging processes which require a good characterization. They have been grouped in five typologies:

1. Areas with physical clogging processes
2. Biological and biophysics clogging processes
3. Chemical clogging processes
4. Physical-biological clogging processes
5. Mixed clogging processes

According to the Multivariable Geostatistical Analisys (MGA) conducted, there is a relation between groundwater compounds and clogging types:

1. The first sort of clogging (1) is specially related to high concentrations of calcium, magnesium, TDO and basic pH values.
2. The second (2) has the maximum correlation with pH and bicarbonates.
3. The third (3) has a bigger appearance with the interaction with groundwater with high concentration of calcium, magnesium, sulphates and nitrates.
4. The fourth (4) sodium, calcium, nitrates and dissolved oxygen.

The pH of the recharge water is neutralized by interaction with rocks opposite areas along the channels where reactive soils have been identified to provide pH buffering. Although changes are modest, the results are good, in general.

Clogging treatment must be considered an integral action rather than in response to a system failure, as there is a complex relationship between all clogging types, recharge water, groundwater quality variations and the specific geological conditions for each point.

The knowledge of the distribution of the incipient clogging processes allows improved designs and scheduled maintenance operations to become more efficiently and the application of the Best Technological Solutions for prevention, cleaning and maintenance.

The alternation of dark and clear lenses, even layers, makes the process more and more difficult and the cleaning costs are increasing considerably as the activity continues.

Modifications to the design of the infiltration canals and basins have been made by trial and error using the best scientific judgment, due to the limited information in the literature on clogging remediation. After each modification testing and monitoring is carried out to gauge the success or otherwise of the modification.

The design changes and management parameters must be created "*a la carte*", depending on the intricacies, climate and characteristics of each system.

Acknowledgments: This article have been developed and written within the framework of MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought FP7, www.marsol.eu, GA 119120), financed by the European Commission and Tragsa Group.

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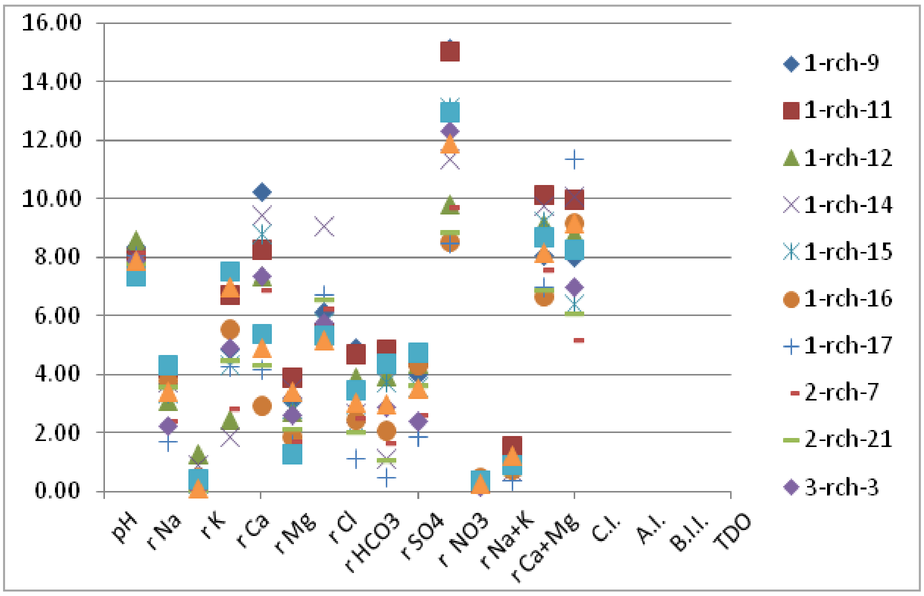
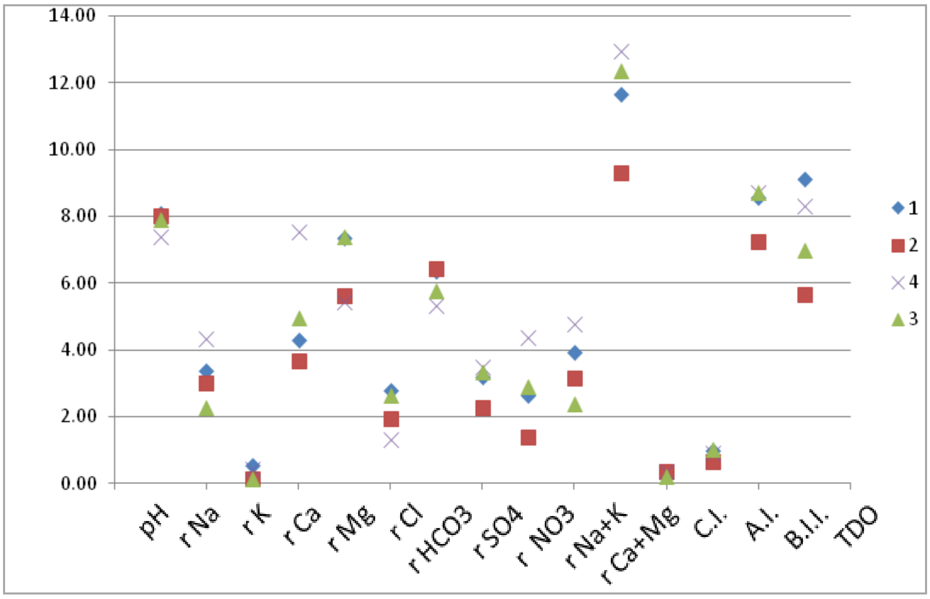
Appendix 1. MULTIVARIABLE STATISTICAL ANALYSES. CHARTING. Mean values





Topic 10. MAR & REGULATIONS

Extended Abstract for Proceedings of ISMAR10 **Topic No: 10 (031#)**

Retrospective on 10 years of risk-based guidelines for managed aquifer recharge

Peter Dillon[1,2,3,*], Declan Page[1], Joanne Vanderzalm[1], Simon Toze[1], Craig Simmons[2], Russell Martin[3], Karen Johnston[4], Simon Higginson[5], Greg Ingleton[6], Bruce Naumann[7], Yvonne Thomson[8], Stephen Parsons[9], David Cunliffe[10], Ryan Morris[11] and Grant Hose[12]

[1] CSIRO Land and Water, Adelaide, Australia, declan.page@csiro.au; Joanne.Vanderzalm@csiro.au; and Brisbane, Australia; Simon.Toze@csiro.au
[2] NCGRT, Flinders University of South Australia, Adelaide Australia; Craig.Simmons@groundwater.com.au
[3] WGA, Adelaide, Australia, RMartin@wga.com.au
[4] Managed Recharge, Perth Australia; karen.johnston@managedRecharge.com.au
[5] Water Authority, Perth, Australia; Simon.Higginson@watercorporation.com.au
[6] SA Water Corporation, Adelaide, Australia; Greg.Ingleton@sawater.com.au
[7] City of Salisbury, Adelaide, Australia; BNaumann@salisbury.sa.gov.au
[8] Department of Water and Environmental Regulation, Perth, Australia; Yvonne.Thomson@water.wa.gov.au
[9] Jacobs Pty Ltd, Melbourne, Australia; Stephen.Parsons2@jacobs.com
[10] SA Health Department, Adelaide, Australia; David.cunliffe@sa.gov.au
[11] Origin Energy Pty Ltd, Brisbane, Australia; Ryan.Morris@upstream.originenergy.com.au
[12] Maquarie University, Sydney, Australia; grant.hose@mq.edu.au
* Correspondence: pdillon500@gmail.com. Tel +61 419 820 927

Summary: In 2009 the Australian Managed Aquifer Recharge Guidelines were published to become the world's first MAR Guidelines based on risk-management principles. These same principles underpin the World Health Organisation's Water Safety Plans. In 2015 a survey of Australian MAR project proponents, consultants and regulators revealed that in those states advancing MAR, the guidelines were considered valuable for giving certainty on approval processes. They were also considered to be pragmatic to use, but there were also comments on onerous data requirements. The rate of uptake of MAR has varied widely among Australian state jurisdictions, for reasons that are not explained by the drivers for and feasibility of MAR. The states where MAR has progressed are those that have adopted the Guidelines into state regulatory processes. It was originally expected that these guidelines would be reviewed and revised after about five years. This would cover experience with any hazards that had not been considered in the guidelines, and also any new scientific developments, and advances in monitoring and control methods. As such revision has not yet occurred, this paper was prepared to overview the guidelines, review ten years of experience since their release, identify issues and suggest improvements for consideration in their revision by Australian water regulators. The full paper is also intended for information of regulators in other countries considering adopting or developing their own guidelines. The paper also discusses factors affecting their international applicability, including on monitoring, control and analytical capabilities for micropollutants required for implementation.

Keywords: Environment protection, health protection, safety, risk, ecosystems, contaminants, recycling, drinking water, regulation, governance.

EXTENDED ABSTRACT

The MAR Guidelines were initially unique also in that they were not simply a set of numerical standards for water quality parameters considered fit for recharge. The Guidelines reflect that aquifers are biochemical reactors and local information on aquifer mineralogy and structure and ambient groundwater quality are needed in order to determine the quality of recharge water that would result in acceptable quality of recovered water, protection of the aquifer and related ecosystems, and sustainable operation. They also account for pressure, flow rate, volumes and levels in confined, semi-confined and unconfined aquifers, and address energy and greenhouse gas considerations. They regard clogging and recovery efficiency as matters for the proponent to address, but provide advisory information on managing these operational issues that impact most on the proponent.

The following experiences and research and have provided sources of information that reflect on the adequacy of the MAR Guidelines and suggest potential improvements for future inclusion:

- A survey on MAR in Australia by NCGRT in 2015 with 134 respondents from all states
- Victorian Civil and Administrative Tribunal ruling in 2017 on reinjection into a geothermal aquifer of spent geothermal water
- Responses made since 2015 to the detection of per- and poly-fluoroalkyl substances (PFAS) in stormwater and aquifers in aquifer storage and recovery projects
- Experience in reinjection of desalinated, deoxygenated associated saline water from coal seam gas wells into a fresh water aquifer capable for use as drinking water supplies in Queensland
- Experience in reinjection of dewatering water from iron ore mines for reinjection of brine for groundwater-dependent salina protection and for storage of brackish water for mineral processing water supplies in Western Australia
- Experience in injection of advanced-treated recycled water into deep aquifers beneath Perth that contribute to public drinking water supplies
- Lack of confidence in managing water quality, quantity and reliability of a recharge project on the Darling River in New South Wales for a drinking water supply for Broken Hill , that resulted in an alternative project being selected at 4 times the cost and with higher vulnerability to drought.
- Experience with cumulative impacts of aquifer storage and recovery schemes resulting in uncapped 3rd party wells overflowing in South Australia
- Potential for problems of rising water table due to expansion of water sensitive urban design with high reliance on stormwater infiltration systems in South Australia unbalanced by increased evapotranspiration from increased tree coverage.
- Research on deep well injection of brines from oil wells in USA suggests that fluid injection between 2km and 4km in depth may be inducing seismicity with only marginal increases in pore pressure, suggesting that more explicit consideration of such risk for aquifer storage and recovery using deep wells in relevant geological settings.
- Research has yielded improved genomics techniques to allow ecological impacts on aquifers and their connected ecosystems to be determined with higher reliability and reduced cost
- Research has also resulted in improved methods to assess the sources and fate of pathogens recharged to aquifers to allow improved public health risk assessment

As a result of this work, the framework for the guidelines has been found in general to be effective and pragmatic. One additional hazard is recommended to be added, that of water temperature. This is an environmental hazard when injecting water into geothermal aquifers. It also needs to be accounted for in cases where the aquifer is relied on for biodegradation or inactivation of organic chemicals or pathogenic microorganisms in the recharged water in order to meet the water quality requirements prior to recovery. Further, more direct consideration is warranted of cumulative impacts of multiple MAR operations in close proximity that have potential to adversely impact on groundwater pressures or water quality. More thought also needs to be given as to whether expansion of water sensitive urban design that relies on infiltration of stormwater to unconfined aquifers is needed, particularly in relation to cumulative impacts of multiple facilities. Advances in research, in detection of pathogens, in developing methods to validate pathogen removal at field scale, and in evaluating ecosystem changes also present opportunities for future refinements to Guidelines.

A manuscript has been submitted to the MDPI journal *Water* that provides more detailed information on the original guidelines, methods used and results. If this is accepted it will be published with other papers originating at ISMAR10 in a special issue of this open access journal at https://www.mdpi.com/journal/water/special_issues/ISMAR10_2019.

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Extended Abstract for Proceedings of ISMAR10 **Topic No: 10 (109#)**

Underground Transfer of Floods for Irrigation (UTFI): Global to field scale assessments

Alam, Mohammad Faiz[1]; Pavelic, Paul[2]; Sikka, Alok[1] and Sharma, Navneet[1]

[1]International Water Management Institute (IWMI), Delhi, India
[2] International Water Management Institute (IWMI), Vientiane, Lao PDR
*correspondence: m.alam@cgiar.org

EXTENDED ABSTRACT

Dealing with inherent challenges associated with intra- and inter- year water resource variability, which are expected to intensify under climate change and manifested as extreme flood and drought events, are amongst the most critical water management challenges globally. Most river basins around the world routinely face difficulty in balancing between water availability and water demand across time and/or space. Water storage infrastructure plays an important role in balancing gaps between water supply and demand. Groundwater storage, with its high storage, buffering capacity, reliability and accessibility provides a potentially attractive water storage option.

One way of utilising groundwater storage to balance water variability is through an approach know as "*Underground Transfer of Floods for Irrigation*" (UTFI) [1]. UTFI provides a nature-based approach to co-manage floods and droughts at the river basin scale [1, 2]. It involves targeted groundwater recharge of seasonal excess surface water flows that potentially pose a flood risk to mitigate downstream flooding and increase groundwater storage. Here, we provide a multi-scalar assessment of UTFI suitability feasibility at the global scale, economic feasibility at river basin scale and performance assessment of a pilot trial at the village scale.

Biophysical suitability assessment is a critical first step in UTFI planning to identify potential regions and basins where UTFI could be potentially implemented. A UTFI suitability assessment was conducted on a grid scale resolution of 30 arcminutes (i.e. approximately 55 × 55 km at the equator) to give an understanding of the wider applicability and potential of UTFI across the globe. Analysis was done using a multi-criteria spatial suitability approach [3]. Multiple datasets covering flood, drought and hydrogeology related variables were grouped into three categories that cover water supply, water demand and aquifer storage. The results of the analysis showed that regions of high UTFI suitability are distributed across with world with South Asia, East Asia, South East Asia and Sub-Saharan Africa having the highest UTFI potential. About 622 million hectares of crop land, with 3.8 billion people residing in these areas is classified as areas of high UTFI suitability. Aggregation of UTFI suitability levels at the river basin scale reveals high suitability across 16 of the 100 largest basins of world, with some of the major basins in Asia (Ganges, Chao Phraya, Mekong), Sub-Saharan Africa (Volta, Awash, Tana, Niger), Latin America

(Sao Francisco, Magdalena, San Juan) and North America (Sacramento, Brazos) classified as high suitability for UTFI.

Assessing whether the overall benefits of UTFI outweigh the costs associated with UTFI implementation is an important indicator to support decision making. Economic analysis was performed for three basins showing high UTFI suitability in different sub-regions: Awash basin in Ethiopia, Ramganga basin (part of Ganges basin) in India and Chao Phraya basin in Thailand [3]. A generalized and replicable economic framework was developed and applied in each basin. In the analysis, total costs of UTFI were divided into infrastructure cost, land use cost, and recovery cost. Total benefits were divided into two parts: flood damage reduction and increased water availability for irrigation used for increasing crop production. The results were summarised in terms of 3 economic indicators: Benefit Cost Ratio (BCR), Internal Return Ratio (IRR) and Net Present Value (NPV). Economic analysis shows high economic feasibility if investments into UTFI are directed towards geographic areas of high suitability with IRR values ranging from 20 to 122%. However, major benefits vary driven by contrasting regional contexts with additional crop production being the predominant benefit in the Awash and Ramganga basins, whilst for the Chao Phraya basin flood mitigation is the major benefit. At the same time, results show that significant costs would be required to set up UTFI infrastructure (US$ 336 – 1,041 million) over the vast scales of the river basins. The high cost associated with UTFI could be minimized by incremental staging of projects in sub-catchments, with lessons learnt from earlier phases taken into account in later phases.

UTFI was piloted at Jiwai Jadid village in the Ramganga basin, India [4]. Piloting was done to analyse the performance of UTFI in the field and generate the knowledge required to support upscaling UTFI in similar setting of intensively irrigated, high yielding alluvial aquifer settings. As land availability is a serious constraint due to high population density and intensive year-round cultivation in the region, UTFI pilot made use of unused pond in the village to install UTFI infrastructure consisting of 10 gravity-fed recharge wells. Detailed operation and monitoring protocol was prepared to guide the monitoring of the physical performance of the pilot system. Result shows that pilot recharged on average of 45,000 m^3 of water of over recharge season of ~ 70 days from 2016-18 [5]. However, there is high inter-year variation in recharge rates observed with highest recharge of around 62,000 m^3 taking place in 2017 (at average recharge rate of 775 m^3 day^{-1}) and lowest recharge of around 26,000 m^3 in 2018 (at average recharge rate of 283 m^3 day^{-1}). The inter-year variation in recharge rate is a function of number of factors including the magnitude and intensity of rainfall, hydraulic gradient available, quality of recharge water and frequency/extent of de-clogging operations. The recharged water from pilot system is sufficient to irrigate between 7.5 and 17.7 ha of crop land (rabi wheat with an irrigation requirement of ~ 350 mm). Recharge from UTFI on average represents ~ 3% village total recharge, reflecting the limitation of one pilot structure in the high storage/transmissivity setting. Groundwater table response to recharge was confounded number of factors including rainfall, intensive pumping, canal and river flows. Distinct mounding from UTFI was only visible in 2017 and was limited to 0.8 metres or less and was most clearly evidenced at the beginning of the season when recharge rates were highest. Based on the performance of pilot, the number of structures required to recharge 10-50 % of excess monsoonal flow in the Ramganga basin range from 13,014 – 65,068 with corresponding land requirement of 3,416 - 17,080 hectares.

The information and knowledge from the studies carried out at multiple scales are useful in early identification of the likely prospects for UTFI and provide the basis and framework for more detailed implementation and research at the country, basin and village scales.

Key Words: Recharge, Flood, Drought, Site Suitability, Economics.

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Paper for ISMAR10 symposium. ***Topic No: 10 (154#)***

Managed aquifer recharge in Brazil: current state of the legal framework

Suênio A. F. da Silva[1], Victor S. G. Baptista[1], Victor H. R. Coelho[1], Nelson O. L. Caicedo[1] and Cristiano das N. Almeida[1]*

[1] Department of Civil and Environmental Engineering, Federal University of Paraíba, João Pessoa, 58051-900, Brazil; sueniof@gmail.com, victorsgb@gmail.com, victor-coelho@hotmail.com, nlcaicedo@yahoo.com.br, almeida74br@yahoo.com.br
* Correspondence: almeida74br@yahoo.com.br; Tel.: +55-83-3216-7684

Abstract: Managed Aquifer Recharge (MAR) can be defined as any process that employs engineering principles to introduce surface water into aquifers in an intentional and planned manner. Currently, some experimental studies and projects using MAR techniques have been discussed in Brazil to overcome different water management challenges. However, Federal and State legal framework in Brazil regarding MAR are still scarce and non-well defined. Therefore, the aim of this study is to present a survey and diagnosis of the legal framework regarding MAR in Brazil at State and Federal levels. An extensive collection and analysis were carried out to assess: 1) how detailed MAR is addressed; 2) what kind of support is given to MAR implementation; and 3) the legal challenges. Collected information shows that there are twenty-six legal provisions regarding MAR Federal and State levels. The first law that mentioned the term MAR in Brazil dates from the early 1990s. Sixteen federative unions, which include the Federal District (DF, acronym in Portuguese), mention some MAR aspects in their legal framework. Only the laws and regulations of four Federal States (DF, Espírito Santo, Pernambuco and Maranhão) mention of MAR methodologies to be adopted. Overall, DF has more significant advances in comparison to other Brazilian states because it also considers – without specific parameters – the necessity of a post-recovery treatment process to assure the water quality required for final consumption. However, even considering a significant number of legal provisions that mention MAR aspects, none of them encourages its implementation in Brazil as a feasible project. Moreover, specific conditions about quantitative and qualitative parameters for MAR implementation are not covered at both Federal and State levels. In conclusion, this study highlights the need to create a more detailed legal framework regarding MAR to induce its use in Brazil.

Keywords: MAR; Federal, States, survey; diagnosis, project.

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1. Introduction

Managed Aquifer Recharge (MAR) represents a set of planned techniques to introduce surface water – including wastewater – into aquifers [1]. The implementation of this type of technology can provide many benefits to sustainable water management, which include: 1) the maximisation of the natural water storage [2]; 2) the improvement of the groundwater quality [3];

3) the reduction of possible salt-water intrusion [4]; and 4) the decreasing in the number of flood events [5].

Over the past years, the implementation of MAR strategies has proved its ability to replenish aquifers and augment groundwater supplies in many parts of the world. Recently, the study carried out by Dillon et al. [6] presented in detail the main advancements of all the major types of MAR implemented worldwide in the last sixty years. Moreover, they also summarised the important role of many regions and countries in providing successful MAR strategies, especially in the United States, Australia, India, and Europe. More specifically, the study carried by Valverde et al. [7] in Latin America identified that the number of MAR schemes over the region has grown in the past few years, although the number is still very small when compared to the aforementioned countries and regions. They also recognised that most MAR study cases in the region were found in Brazil, accounting for >60% of the total cases. Furthermore, they expect that the application of MAR will grow further in Latin America as a reliable tool to address challenges related to climate, population, and economic changes. In Brazil, the increasing number of international ongoing projects (e.g. BRAMAR, SMART-Control, and DIGIRES) is evidence of attempts to implement MAR schemes to reduce the pressure on subsurface resources and mitigate the water shortage.

Currently, many MAR strategies are available, but the design of each technique depends on the local conditions [8,9]. For instance, Coelho et al. [10] illustrated how the analyses applied for frequently underrated data may allow further MAR strategies to be proposed in a complex estuarine and urban system. Moreover, many other studies have concentrated efforts to define MAR site suitability mapping at the regional scale by using multicriteria analysis and mathematical modelling [11–14]. However, besides the knowledge of local and regional conditions to implement MAR strategies, it is also important to assure that the recharge techniques do not compromise any of the protection aims related to water bodies and water uses, as laid down at local and national scale legislations [15,16]. Because of the increasing interest in this type of technology, it is important that MAR is facilitated via a regulatory framework. This regulatory framework must include guidance for protecting public health and the environment while maintaining or enhancing beneficial uses of aquifers for future generations [17]. Nowadays, some countries such as Australia, the United States, and France have available robust summaries and reviews of regulatory frameworks and guidelines to assist the implementation of MAR designs [8,16,18].

To our knowledge, the present National Brazilian Water Resources Policy (PNRH, acronym in Portuguese) does not specify requirements for MAR schemes even in a broad frame. Moreover, studies focusing on the review of other existing Brazilian legislation – from local to a national scale – regarding MAR activities were not performed yet. Considering the lack of information to support the broad audience interested in implementing MAR strategies in Brazil, the aim of this study is to present the preliminary results of a survey and diagnosis of the legal framework in Brazil at State and Federal levels.

2. Materials and Methods

2.1. Regional setting

Brazil is the largest country in Latin America and the fifth-largest country in the world in area, covering approximately 8.5 M km^2. The Brazilian territory has five official geographical regions, namely: North (N), North-east (NE), Central-west (CW), Southeast (SE), and South (S). The regions are divided into twenty-seven Federative Units (UF, acronym in Portuguese), being twenty-six States and one Federal District (DF, acronym in Portuguese). Each State is endowed with legal personality and certain administrative autonomy. The country has different water availability conditions, including water-scarce areas in the North-east region characterised by a semi-arid climate and water-surplus areas in the North region where the Amazon rainforest is located, for example.

2.2. Data collection and analysis

This study performed an extensive collection of information and subsequent analysis of MAR related legal basis at State and Federal levels. For this purpose, it was used the official electronic database available on the State and Federal websites. The approach adopted in this study considers that the regulations should contain the following steps proposed by Yuan et al. [8]: planning, operation, and design. In our research, we considered if the following six key elements for MAR implementation were contemplated in the legal framework:

- Source of recharge water (planning);
- Ultimate uses of recovered water (planning).
- Recharge site (design);
- Recharge methods (design);
- Water treatments (design);
- Monitoring (operation).

These six key elements were used to analyse the details of the legal devices based on the steps of planning, design and operation of MAR. After the analysing the legal details, the level of support of each legal device for the decision-making process to implement MAR was observed. Then, the national resolutions were discussed considering well-established MAR guidelines from other countries as a reference. Finally, the advances and challenges of MAR implementation in Brazil were discussed in the legal sphere.

3. Results and discussion

3.1. MAR legislation in the national context

In Brazil, the PNRH is established by the Law 9.433 published in 1997. It is noted that the referred law makes no mention of the term MAR. However, in item I of article 2, the law highlights that one of its objectives is the need to "ensure the current and future generations the necessary availability of water, in quality standards appropriate to their respective uses" [19]. Therefore, although the term MAR is not expressed in the PNRH, the abovementioned objective of the law provides a legal bias for the use of this planning technique for the water resources.

The national Resolution 15 of the National Water Resources Council (CNRH, acronym in Portuguese), published in 2001, is the first Act mentioning the term MAR. This resolution establishes the guidelines for groundwater management, with the term MAR exposed in Article 6. This article provides that the State Water Resources Management Systems should guide the municipalities for the promotion of integrated management of groundwater. These guidelines should contain mechanisms to stimulate the adoption of both water reuse and artificial recharge schemes with the objective to increase water availability and water quality [20].

Only in December 2013, the CNRH regulated the implementation of MAR with Resolution 153, establishing criteria and guidelines. According to this resolution, MAR strategies can be implemented with the following objectives [21]:

- Water storage to guarantee water security,
- Stabilisation/increasing of groundwater levels in aquifers to regularise seasonal fluctuations,
- Compensation of effects induced by over-abstraction in aquifers,
- Controls the saline intrusion in coastal aquifers,
- Controls soil subsidence hazards.

The Resolution 153/2013 of the CNRH also indicates that the implementation of MAR can be based on two different designs. The first design includes surface water infiltration techniques, such as sand and underground dams, infiltration ponds, ditch, channels, and the combination between them. Conversely, the second design includes direct injection wells. According to this resolution, the implementation of MAR strategies depends on preliminary studies demonstrating the technical, economic, sanitary, and environmental feasibility of the project. Moreover, the resolution 153/2013 assigns the authorisation of such implementation to the state agencies responsible for water resources management.

Anticipating the guidelines established by the resolution of the CNRH published in 2013, the Resolution number 396 of the National Environment Council (CONAMA, acronym in Portuguese), published in 2008, provides the classification and environmental guidelines for the groundwater quality framework, evidencing the requirement of the physicochemical parameters of the surface water injected into the ground. This resolution also evidences that the artificial recharge to prevent salt-water intrusion in aquifers cannot reduce the original quality of the groundwater. On the other hand, for contaminated aquifers, this resolution mentions that the injection of water should provide its remediation, with the aims to maintain or improve the standards for further uses based on the quality control verified by the competent agencies. Thus, the CONAMA resolution clearly exposes that MAR implementation should be exclusively adopted to improve the quality of the aquifer, without any negative consequence. Therefore, the implementation of such a strategy requires a continuous monitoring program of the groundwater quality.

Figure 1 shows the progress of the main national resolutions in Brazil that reference MAR schemes. It is possible to observe that the first mention of MAR was nearly 20 years ago; however the criteria for implementation were only recently established by Resolution 153 of the CNRH in 2013.

Figure 1. Resolutions in the national context of the National Water Resources Council (CNRH) and National Environment Council (CONAMA) addressing Managed Aquifer Recharge (MAR).

3.2. MAR legislation in the Brazilian Federative Units

The legal framework for MAR was analysed in each one of the twenty-six Federative units in Brazil considering the six key elements proposed by Yuan et al. [8]. These six key elements were carefully observed considering the level of detail and support of the legislation for MAR implementation in each state. For a better organisation of the results, the analysis was performed separating the information by the five official regions of Brazil. The legislation of 10 analysed Federative Units do not present any mention of MAR, as shown in Figure 2. On the other hand, 17 Federative Units present some type of mention to MAR. The North region has the greatest absolute number of states without legal support of MAR, four. This amount represents 57% of the total states in region North. On the other hand, the regions Central-west, Southeast, and South have only one state without references of MAR in its legislation.

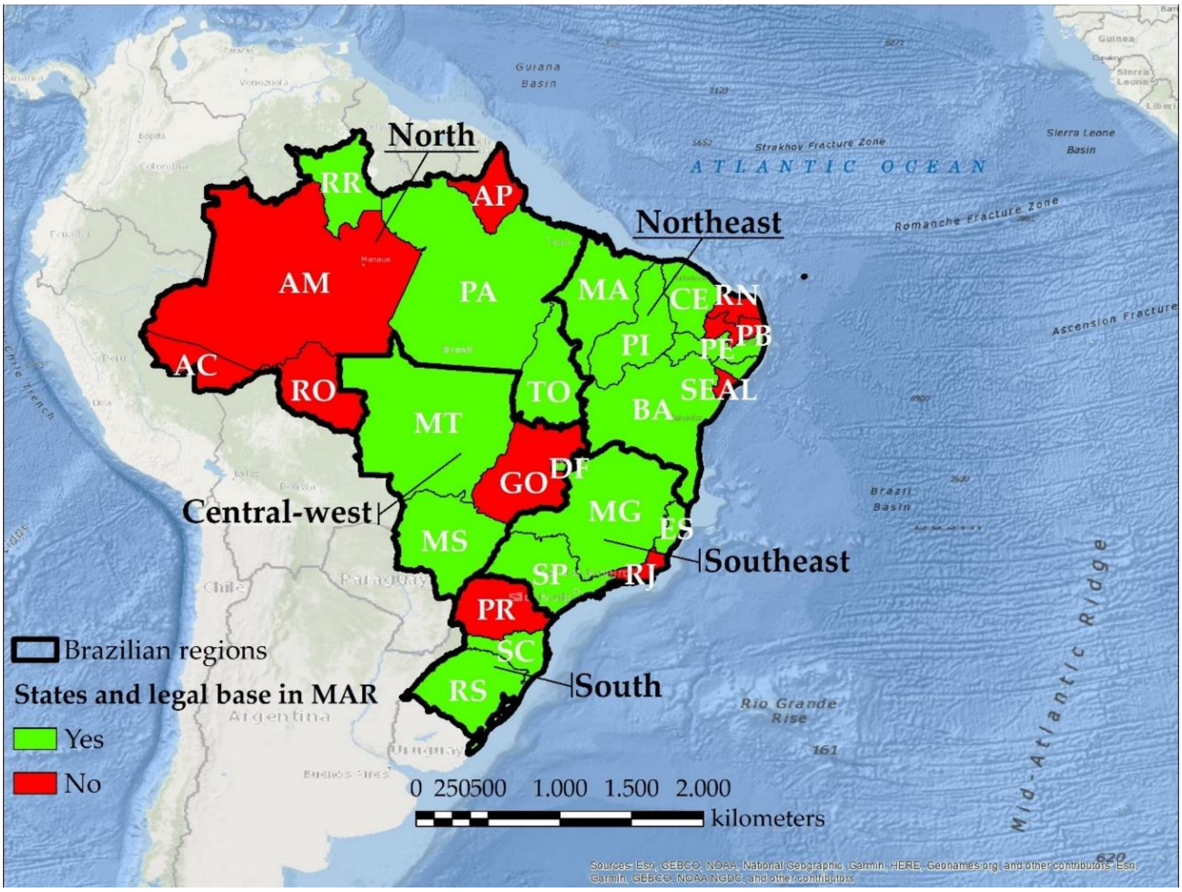

Figure 2. Federative Units that mention and no mention of Managed Aquifer Recharge in its legislation.

Table 1 shows, in chronological order, the number of legislations in region N that mention MAR. It is possible to observe that only three states mention MAR in its legislation, but all of them without any detail or support. The first mention was in 2001 in the state of Pará (PA), while the last reference was made in 2008 in the same state.

Table 1. MAR legal framework of the Brazilian Federative Units located in region North.

Year	FU	Law/Decree/Resolution	Detailing	Support
2001	PA	Number 6.381	Only mention to MAR	No parameter description
2002	TO	Number 1.307	Only mention to MAR	No parameter description
2005	TO	Number 2.432	Only mention to MAR	No parameter description
2006	RR	Number 547	Only mention to MAR	No parameter description
2008	PA	Number 003	Only mention to MAR	No parameter description

FU: Federative Union, PA: Pará, TO: Tocantins, RR: Roraima.

Table 2 shows the states in the Brazilian Northeast region that addresses MAR in some legislation. In total, six states of the Northeast region deal with MAR on its legal basis, while three of them do not present any kind of mention. The three states without information of MAR are Sergipe (SE), Paraíba (PB), and Rio Grande do Norte (RN). The first state of the region Northeast to reference MAR in its legal basis was Pernambuco (PE) in 1998, but the first one citing some specific methods was Maranhão (MA) in 2012. It is possible to observe some advances between the legal basis of the states located in the Northeast region when compared to that one in region North.

Table 2. MAR legal framework of the Brazilian Federative Units located in region North-east.

Year	FU	Law/Decree/Resolution	Detailing	Support
1998	PE	Number 20.423	Only mention to MAR	No parameter description
2000	PI	Number 5.165	Only mention to MAR	No parameter description
2009	AL	Number 7.094	Only mention to MAR	No parameter description
2009	BA	Number 11.612	Support and execution	No parameter description
2010	PI	Number 14.145	Need to implement MAR	No parameter description
2012	CE	Number 31.077	Only mention to MAR	No parameter description
2012	MA	Number 28.008	Specify methods	No parameter description

FU: Federative Union, PE: Pernambuco, PI: Piauí, AL: Alagoas, BA: Bahia, CE: Ceará, MA: Maranhão.

São Paulo (SP) was the first state in Brazil to presents some mention of MAR in 1991 (Table 3), i.e. seven years before PE, the second state. In SP, the MAR strategies were authorised by the Department of Water and Electric Energy (DAEE) to be implemented in the state even before the PNRH. However, like most states, the legislation in SP does not specify recharge methods or description of parameters for MAR implementation. The same superficial guidelines are also found in the other two states of the Southeast region, Espírito Santo (ES) and Minas Gerais (MG). It is worth highlighting that the legislation of Rio de Janeiro state does present any mention to MAR, but a draft law pending for approval is in process.

Table 3. MAR legal framework of the Brazilian Federative Units located in region Southeast (SE).

Year	FU	Law/Decree/Resolution	Detailing	Support
1991	SP	Number 32.771	Only mention to MAR	No parameter description
2000	ES	Number 6.295	Only mention to MAR	No parameter description
2000	MG	Number 13.771	Only mention to MAR	No parameter description
2017	ES	Number 002	Only mention to MAR	No parameter description

FU: Federative Union, SP: São Paulo, ES: Espírito Santo, MG: Minas Gerais.

There are two legal provisions legislating MAR in the Brazilian S region (Table 4). Rio Grande do Sul (RS) regulates the groundwater management and conservation by a decree that allows MAR implementation if approved by the competent state agency. The resolution established by the Santa Catarina (SC) state water council does not present any MAR detailing, which includes a description of fundamental parameters for project implementation. In accordance to other Brazilian legal provisions, the aforementioned resolution of the SC state highlights that MAR is conditioned to the maintenance of groundwater quality conservation.

Table 4. MAR legal framework of the Brazilian Federative Units located in region South (S).

Year	FU	Law/Decree/Resolution	Detailing	Support
2002	RS	Number 42.047	Highlight the need for approval	No parameter description
2014	SC	Number 02	Only mention to MAR	No parameter description

FU: Federative Union, RS: Rio Grande do Sul, SC: Santa Catarina.

Table 5 shows that all Central-west states present MAR in its legal provisions except one – Goiás (GO). Special attention is given to Distrito Federal (DF), which established with the Law

3.793/2006 a system of aquifer artificial recharge. By this law, the use of MAR became mandatory in the DF for all new residential, commercial, or industrial architectural projects, with the technical specificities for implementation and operation defined by the competent agency of the DF. However, this law was revoked eleven years after by the complementary Law 929/2017, which regulates the rainwater harvesting with the objective to retain water in the buildings located in the DF. The complementary law establishes that the license for construction of areas equal to or higher than 600 m² is conditioned to MAR implementation. According to the law of the DF, the impossibility of MAR implementation should be carefully justified by technical report during the construction licensing process.

In general, it is observed that Law n° 929/2017 of the DF presents detailed information of the permeability rates, rain return period to the MAR project, output runoff limits, among others. These facts show that this law is considerably more advanced than the legal provisions of other Brazilian states, also partially covering key elements of MAR such as the sources of water recharge, recharge sites, and possible recharge methods. Another legal framework supporting MAR schemes in the DF is the Decree 35.363/2014 (Tab. 5), which defines the permeability rate in local director plans. The decree admits MAR implementation in real state units using the permeability rate as a criterion. For instance, infiltration trenches are cited as a recharge method. In contrast to DF, the states of Mato Grosso do Sul (MS) and Mato Grosso (MT) follow the same text of legislation quoted in other states of the country.

Table 5. MAR legal framework of the Brazilian Federative Units located in region Central-west (CW).

Year	FU	Law/Decree/Resolution	Detailing	Support
2006	DF	Number 3.793 (Revoked)	Requires the use of MAR in projects	No parameter description
2006	MS	Number 3.183	Only mention to MAR	No parameter description
2011	MT	Number 9.612	Only mention to MAR	No parameter description
2014	DF	Number 35.363	Use of infiltration galleries for rainwater	No parameter description
2017	DF	Number 929	Restrictions to permeability and flow rate	Rainwater harvesting

FU: Federative Union, DF: Federal District, MS: Mato Grosso do Sul, MT: Mato Grosso.

3.3. National resolutions and international guidelines

The two current main resolutions in Brazil with more information for MAR are: (1) Resolution 153/2013 of the CNRH and Resolution 396/2008 of the CONAMA. The first mentioned resolution establishes criteria and guidelines for MAR, where are clearly presented two recharge conceptions: from the surface, and at depth. To exemplify, the legislation of the CNRH mention the following techniques: dams, channels, trenches, and injection wells. However, the resolution of the CNRH shows that implementation of the aforementioned techniques is subject to precedent studies that demonstrate its viability. Such studies should contain at least the hydrogeological characterisation of the area where the MAR will be implemented, as well as the characterisation and design of the proposed project. The resolution also mentions that, depending on the specificity of the project, studies on the physicochemical and bacteriological characterisation of the surface water to be recharged and groundwater of the aquifers are required for the state agencies responsible for the water resources management. In addition, depending on the specificities of the project, the state water or management agencies can also request the assessment of possible qualitative and quantitative impacts caused in the aquifers, once the CNRH resolution determines that the MAR implement cannot cause negative changes in the quality of the groundwater. A similar observation is also present in Resolution 396 of the CONAMA since 2008, which highlights that the artificial recharge cannot change the acceptable classes of water previously established.

According to Resolution 396/2008 of the CONAMA, the injection of surface water into aquifers for remediation purposes should maintain or improve the quality standards for the main uses, as well as prevent any environmental risks. The same resolution also establishes the need for implementation of specific groundwater quality monitoring programs in the case of artificial recharge schemes located in areas with restriction and control for groundwater use. CONAMA defines six classes of groundwater in its Resolution 396, varying in sequential order according to the level of anthropogenic disturbances in the water quality of the aquifer (Table 6). For the poorer class of groundwater (class 5), direct injection is allowed and highly recommended if monitored and controlled by competent governmental agencies. However, hydrogeological studies carried by the interested parties demonstrating non-alteration of the class of groundwater quality condition (local and surroundings) are necessary. Thus, it is understood that the infiltrated or injected water by MAR schemes is subjected to Resolution 396/2008 of the CONAMA. However, it is worth highlighting that some gaps regarding the water quality to be used in MAR implementations are still present and need to be filled, such as the description of hydrogeological parameters for monitoring.

Table 6. Classification of the groundwater quality based on the CONAMA Resolution number 396/2008.

Classes	Description
Special	Aquifers destinated to preserve ecosystems in integral protection conservation units and directly linked to contributing surface water bodies with high-quality.
1	Aquifers without alteration of quality by human activities and no need for treatment because of its natural hydrogeochemical characteristics.
2	Aquifers without alteration of quality by human activities and that may require treatment due to its natural characteristics, depending on the use.
3	Aquifers with alteration of quality by human activities that no require treatment due to these changes but need treatment for specific uses due to its natural features.
4	Aquifers with alteration of quality by anthropogenic activities that can be only used without treatment for less restrictive uses.
5	Aquifers with alteration of quality by anthropogenic activities that can be only used for activities without water quality requirements for use.

The most detailed regulatory documents regarding water reuse as a source for MAR schemes are from the California and Florida states in the United States of America, as well as the Australian water reuse guidelines for MAR [8]. In California, the regulation launched in 2014 by the California Department of Public Health [22] deals with groundwater replenishment by treated wastewater for potable indirect reuse via surface and subsurface application [8]. For instance, this regulation in California establishes strict limits to control nitrogen compounds and pathogenic microorganisms that demand further advanced methods of wastewater treatment and monitoring in order to be used as a recharge water source. Furthermore, the aforementioned regulation in California also obligates the construction of wells for water quality monitoring and the occurrence of a public audience before the project implementation and operation. For surface applications, soil aquifer treatment (SAT) application is mentioned in the Californians legislation, with the total organic carbon an essential parameter used for evaluation. Strong emphasis for a continuous recharge water quality monitoring is given by the regulation.

The Florida Administrative Code has a chapter (62-610) entitled Reuse of Reclaimed Water and Land Application that highlights important issues for MAR implementation. The referred code details that the treated wastewater can be used for some MAR projects such as infiltration basins and injection wells with the use of Aquifer Storage and Recovery (ASR) technique [23]. Two levels of treatment are defined in Florida regulation: (1) the main treatment and disinfection, and (2) the full treatment and disinfection. According to the Florida regulation, nitrate concentration and hydraulic load rates (representative percolation tests to simulate real conditions) are important parameters to be monitored in infiltration basin projects. For ASR wells, the total dissolved solids must be monitored together with other microbiological parameters depending on the project scope. Other restrictions and criteria are also described in the Florida Administrative Code, such as (1) limits of recharge for humid environments, (2) protective distances from replenishment potable water wells, (3) runoff and subsurface drainage control, (4) access control to the project site and establishment of limits.

The Australian Guidelines for Water Reuse provides information regarding many types of aquifer recharge, MAR benefits, and preventive measures regarding the identification and risk assessment evaluation of MAR projects [24]. The main objective of this Australian document is the establishment of general principles for MAR conceptual design and implementation. In opposite to the Californian and Floridian regulations, the Australian document does not specify any water quality monitoring parameters. System operational guidelines and ideal monitoring frequency are not described as well. The document establishes an assessment and management of risks for MAR projects, where two types are descript [8].

3.4. Legal framework details, supports, advances, and challenges

The analysis of the Brazilian state regulations mentioning MAR shows that most of them do not regulate or focus on the key elements for MAR conceptual design and implementation. In general, the laws, decrees and regulations converge in respect of the need for preliminary feasibility studies for MAR; although clear descriptions of criteria that should qualify such studies are nonexistent. The legislation of the Maranhão state located in region North-east makes mention to two specific MAR techniques: infiltration ponds and pumping wells. Among all Brazilian federative units, the legislation of the Federal District is the more advanced and detailed to support MAR schemes.

The Federal Resolution 396/2008 of CONAMA refers to the use of the recharge water to reduce salt-water intrusion risks into coastal aquifers. Thus, this national resolution presents in part some key elements of MAR considered in this study, including recharge methods, recharge locations, water quality monitoring, and the end uses from the recovered water. Furthermore, the surface-water injected or infiltrated into the aquifer are subject to the classes of groundwater quality established by the resolution, according to the prevailing uses. The CONAMA's resolution highlights a list of parameters to monitor the quality of the groundwater with the respective maximum values permitted according to each prevailing uses. However, the national resolution (396/2008) does not inform the possible recharge water sources. Hence, the resolution 396/2008 bases the concept and design of MAR specifically on the water quality (physical-chemical and microbiological) parameters.

Under Federal Resolution 153/2013, which specifically deals with MAR in the Brazilian territory, those responsible for artificial recharge system operation should maintain a record of the system's behaviour. This must include: (1) volumes of water introduced into the aquifer by type of recharge; (2) infiltration rates during the MAR operation; (3) recharge surface water and aquifer groundwater quality monitoring; (4) groundwater level monitoring; (5) rainfall and evaporation records in the area; and (6) recharge effects in the supply systems within the influence area of the MAR scheme. These key-points are important for MAR planning, design, and operation. However, some gaps need to be filled in order to promote better support for MAR in Brazil. For instance, the obligation of studies demonstrating the feasibility of MAR established by the resolution 153/2013 are relevant but need to be more detailed to not become the implementation subjective and compromise the MAR system. Resolution 153/2013 considers the parameters established by CONAMA; however, some questions remain regarding technical, economic, health, and environmental regulatory criteria, and how these may restrict MAR implementation.

5. Conclusions

Twenty-six legal provisions, including resolutions, laws and decrees (state and federal) were found in Brazil mentioning MAR. Overall, the legal framework of the Brazilian states does not present details regarding key elements of MAR, with the exception of the Federal District. Therefore, the legal framework from the Brazilian states does not properly support the steps of planning, design and operation of MAR. The national Resolution 396/2008 partially assures some MAR key elements related to water quality monitoring and final uses of recovered water. In accordance with the international legal basis, the Brazilian federal resolutions focus primarily on the importance of water quality maintenance and monitoring for MAR implementation. The advance and consolidation of MAR schemes in Brazil depend on the definition of detailed and in-depth descriptions of technical, economic, health, and environmental regulatory criteria at national-scale to support MAR implementation.

Acknowledgments: The authors would like to acknowledge the financial support from the Brazilian Innovation Agency (FINEP) granted to the BRAMAR (BRAzil Managed Aquifer Recharge, grant no. 557/2013) project. The authors are also grateful to the Brazilian Council for Scientific and Technological Development (CNPq) for financial support.

Author Contributions: "S.A.F.S., V.S.G.B., and C.N.A. conceived and designed the study; S.A.F.S., V.S.G.B., C.N.A., V.H.R.C., and N.O.L.C. analysed and discussed the data; S.A.F.S., V.S.G.B., and V.H.R.C. wrote the paper."

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed aquifer recharge
ASR: Aquifer storage and recovery
ASTR: Aquifer storage, transport and recovery
BRAMAR: Brazil Managed Aquifer Recharge
PNRH: Brazilian National Water Resources Policy
CNRH: Brazilian National Water Resources Council
CONAMA: Brazilian National Environment Council
SAT: Soil-Aquifer treatment
DAEE: São Paulo Department of Water and Electric Energy

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Paper for ISMAR10 symposium. ***Topic No: 10 (183#)***

The Legal Basis Under Idaho, USA, Law for Private Managed Aquifer Recharge and the Subsequent Rediversion of Such Recharged Water

Kent W. Foster[1]*

[1]Attorney Emeritus and Member, Board of Recharge Development Corporation
*Correspondence: kwf1941@gmail.com; Tel.: +01-208-521-3479

Abstract: The State of Idaho, USA, has abundant natural water resources, including the Snake River and its tributaries which overlie the Eastern Snake Plain Aquifer (ESPA). Uses of natural flow surface water resources in Idaho began in the mid nineteenth century. Idaho became an "appropriation doctrine" state with the adoption of the state constitution in 1890. Water rights are appropriated by diversion of water from the public source of supply and application thereof to a beneficial purpose under a permit system. Recharge Development Corporation (RDC) has been organized to conduct incentivized private managed aquifer recharge (MAR) using surface water flows which would otherwise escape the basin. The goal is to enable continuation of groundwater pumping for beneficial purposes. Such recharged water moves relatively slowly through the aquifer so that the aquifer can essentially function much the same as a surface reservoir. RDC refers to the space within the aquifer in which recharged water is stored as "Aquifer Recharge Units" (ARUs), each one representing one acre foot of space in which water can be measured both in and out. This paper addresses the questions of whether or not available water can legally be stored in the ESPA the same as in a surface reservoir, and can water accruing to ARUs legally be sold or leased for beneficial uses.

Keywords: legal basis; managed aquifer recharge (MAR); aquifer recharge units (ARUs).

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1. Introduction

This author is one of the legal advisors to Recharge Development Corporation, (RDC), an Idaho Corporation organized and existing to provide technical advice and assistance in the implementation of incentivized managed aquifer recharge (IMAR) of available water resources and recovery and use of such water within the State of Idaho. RDC is closely associated with a nonprofit corporation named Eastern Snake Plain Aquifer Recharge, Inc. (ESPAR), organized under Idaho law for the purpose of working directly with water users and water user entities to provide water, intentionally stored in an underground aquifer known as the Eastern Snake Plain Aquifer (ESPA) through incentivized managed aquifer recharge processes, for their use and benefit.

This paper addresses the legality under Idaho law of some of the major activities of RDC and ESPAR and some of the important legal issues affecting the work and objectives of the two corporations. Specifically, this paper addresses the rights of land owners overlying the ESPA to block the efforts of RDC and ESPAR to introduce recharge water into the ESPA, store it therein, convey it through the aquifer, and re-divert it from that aquifer for beneficial uses. These issues have not yet been specifically dealt with by either the Idaho Department of Water Resources (IDWR) or the Idaho courts. It is known that in connection with the construction of some of the surface reservoirs on the Snake River, analogous concepts arose and resulted in increasing the storage in natural lakes and creating additional rights to the added stored water.

The conclusions of this paper are that landowners likely do not have the right to block recharge and storage of water in the aquifer beneath their lands, and that the storage of water within the aquifer and use of the aquifer in the same manner as a surface reservoir is likely also legal so long as those recharging and recovering such water hold the necessary permits or licenses. Commingling recharged water with existing water within the ESPA and then recovering and using water at a different location may present legal hurdles under Idaho statutory law. However, the commingling of natural stream flow and storage water under the existing surface water distribution protocols are both ubiquitous and complex and arguably rely on the same legal principles that RDC is seeking to apply to groundwater allocations and deliveries.

2. Materials and Methods

This paper does not focus on materials. The methods used to accomplish recharge of the ESPA and recovery of the recharged water consist of diverting surface water supplies when available into acceptable areas above the ESPA where the water can percolate and enter the aquifer to be stored therein through such facilities as canals, ditches, ponds and gravel pits. Water quality standards enforced by the Idaho Department of Environmental Quality are met for all recharge sites and all water recharged is measured into the ESPA and reports of the quantities recharged are made.

3. Discussion

The results are that the conveyance of water to the recharge areas and allowing the water to sink into porous materials has been successful in accomplishing the objective of recharging the ESPA. Most of the water used for recharge is of relatively clean and uncontaminated quality and has been further filtered through the layers of soil, sand, gravel and rock so that by the time it commingles with the water already existing in the aquifer it is of drinking water quality. Because the recharged water is measured into aquifer recharge units (ARUs) it can then be used for mitigation purposes or even measured if it is withdrawn for some other specific use.

3.1 The State of Idaho, USA, has abundant natural water resources, including the Snake River and its tributaries which overlie the Eastern Snake Plain Aquifer (ESPA)

Idaho was the forty-third state admitted into the United States of America. It is located in the northwestern portion of the United States, sharing its northern border with the country of Canada, its western border with the states of Washington and Oregon, its eastern border with the states of Montana and Wyoming, and its southern border with the states of Utah and Nevada. Idaho is the thirteenth largest state in the United States, extending some four hundred eighty-three miles north and south and three hundred ten miles east and west in the southern portion of the state. The northern border with Canada is only some forty-five miles in length.

The citizens of the state of Idaho are very fortunate that their state has exceptional and substantial surface and ground water supplies. The state's major river is the Snake River, which rises in western Wyoming and flows into eastern Idaho where it is joined by a major tributary known as the Henry's Fork (or North Fork) of the Snake River. Together with the contributions from other tributary streams, rivers and springs the Snake River flows across the entire State of Idaho and then turns north to form borders with the States of Oregon and Washington on the west side. It then flows into the State of Washington where it ultimately joins the Columbia River. A large portion of the Snake River and many of its tributaries overlie a huge broken basalt aquifer system located in the eastern and southern portions of Idaho which is connected to and receives water from and contributes water to an extensive aquifer system known as the "Eastern Snake Plain Aquifer" (ESPA).

3.2 Uses of natural flow surface water resources in Idaho began in the mid-nineteenth century

Water use in Idaho, primarily from the surface rivers and streams for irrigation of agricultural crops, began in earnest when pioneer groups entered the Idaho Territory in the 1860s, 1870s and 1880s. When the pioneers arrived, they found a typical arid environment requiring that water be diverted from the natural streams and applied to the land in order to cause crops to grow. There was not adequate precipitation during the growing season to permit crops to sprout and mature without irrigation. Within a short period of time the pioneer groups began to construct canal systems. The land was fertile and arable but the large Snake River plain was high desert. Soon there were canal companies and then irrigation districts formed to construct and manage extensive irrigation canal and ditch systems.

3.3 Idaho became an "appropriation doctrine" state with the adoption of its state constitution in 1890. Water rights are appropriated by diversion of water from the public source of supply and application thereof to a beneficial purpose under a permit system

In the western United States, the first uses of water diverted from natural streams were primarily for mining purposes. In that mining industry, the model for water distribution among competing water users became "first in time is first in right". As a result of the use of that model in the mining industry, most of the western states adopted its use in the distribution of water from the natural streams for other uses, including irrigation of agricultural lands and the same model made its way into the organizational documents establishing the State of Idaho.

Idaho, like most other western states became an "appropriation doctrine" state rather than a "riparian doctrine" state. That is, to first obtain or acquire a right to divert and use water from the public source of supply, one must "appropriate" it. The right does not arise merely because of its location near or adjoining a water source as in the case of a "riparian" right.

3.4 Measurement of water flowing in the Snake River and its tributaries began in the early 1900s. By the mid-1950s, the major spring flows emanating from the ESPA into the Snake River approximately doubled. From that time such spring flows steadily diminished due to groundwater pumping and sprinkler irrigation as well as policy changes in management which resulted in more water escaping from the basin. About 1.8 million acre-feet per year, on average, escapes from the basin, usually during springtime high water flows. Many court and administrative proceedings, referred to as "water calls" or "delivery calls" have been initiated in recent years to cut off or reduce pumping of groundwater from the ESPA because of reduced spring flows

Commencing in about 1902, governmental measuring of the discharge from the major springs near American Falls and at "Thousand Springs" began and has continued ever since. From then until about 1957, the spring discharges at both locations approximately doubled. From about 1957 until just the last few years, the same spring discharges have steadily and very substantially diminished, although these discharges have not decreased to the levels at which they were measured in the early 1900s.

The increase in spring flows for more than fifty years accompanied larger and larger diversions and applications of the water used for flood irrigation of the land upstream as it was developed for the raising of agricultural crops and as the canal systems were constructed and improved. After the Second World War, as many of the young men from Idaho who had served in the armed services of the United States returned to farming, technological advances began to find increased application to farming practices, particularly the drilling of deep wells to access the groundwater resources and the implementation of sprinkler irrigation systems and practices. The drilling of deep wells and the application of irrigation water through sprinkling systems increased fairly rapidly until about 1980.

3.5 An adjudication proceeding (court determination) of all surface and groundwater rights within the Snake River Basin was initiated in November, 1987, and substantially concluded in August, 2014, legally adjudicating all rights to the beneficial use of water within the basin except for small exempted uses

When the well drilling and sprinkler irrigation events commenced in earnest, the electrical power company that supplied the power to operate the numerous wells and sprinkler systems encouraged the drilling of deep wells and the installation of electric pumps and the sprinkling systems which continued to improve crop yields and the efficiencies of crop production. After all, the company was selling more electrical power. But when it began to become apparent that the pumping of the wells and sprinkling of crops, especially when conversion from flood irrigation to sprinkler irrigation became quite popular, had a negative impact on spring discharges, litigation ensued and controversy, especially as instigated and prosecuted by the power company, became frequent and a dreaded specter. The power company which had been responsible for encouragement of the changes occurring in groundwater uses and irrigation and other water use practices became more concerned about minimum stream flows to protect hydro-power production, and sought a moratorium on appropriations of groundwater rights and a court adjudication of water rights to surface flows and groundwater.

The irrigation water users themselves are natural competitors with each other and are notoriously reluctant to use financial resources to hire lawyers to litigate. The state's Governor and his staff and most of the legislators in the state sought an out-of-court settlement of the matter and eventually the litigation was resolved with an agreement for the state to enforce against the groundwater users a minimum flow in the Snake River at the "Murphy Gage" near the site of the old hydropower plant on the river at Swan Falls, and to also commence the Snake River Basin Adjudication, one of the largest adjudication proceedings that had ever occurred in the United States.

The adjudication proceeding was commenced by IDWR in the fall of 1987 with the objective of obtaining a final court determination (a decree) of all water rights to surface and groundwater sources within the Snake River Basin and was substantially completed in August of 2014 after the expenditure of significant amounts of financial resources by the state, municipal governments, developers, manufacturers, commercial establishments, the power company, and individual water users.

Various water user entities, including "fish farmers" who had for several decades relied upon the use of the pristine water quality flows that emanated from the canyon walls in the "thousand Springs" reach of the river, then began filing "water calls" or "water delivery calls"[23] to prevent diversions of ground water from wells which they claimed were reducing the flows of the springs upon which they had relied for fish propagation

3.6 Recharge Development Corporation (RDC) and Eastern Snake Plain Aquifer Recharge Corporation (ESPAR) have been organized to conduct incentivized private MAR using surface water flows which would otherwise escape the basin

This article earlier briefly describes some of the history of the development of surface water irrigation in the upper Snake River Valley and its impact on the major spring contributions to the Snake River near American Falls and further downstream in the Thousand Springs reach near Hagerman.

Many of those who are familiar with the perceived issues have observed for a long time that surface flows of the main stem of the Snake River past Milner Dam[24] have, on average over many years, exceeded 1.8 million acre-feet of water, usually during the spring of the year, when, because of snow melt and heavy spring rains, the river flows are often abnormally high so that a

[23] A "water call" or a "water delivery call" is an administrative proceeding before IDWR under its "Conjunctive Management Rules" requesting the Director of IDWR to issue orders requiring groundwater pumpers to curtail or cease groundwater diversions which the petitioner asserts are interfering with or reducing (materially injuring) spring flows or other senior priority water rights claimed by the petitioner.

[24]Milner Dam is a dam on the Snake River about nine miles downstream from the City of Burley and is the downstream end of diversions from the river within Water District 01. It serves as part of the diversion structures for the main canal of the south side project (Twin Falls Canal Company) and the north side projects (Northside Canal Company and Milner-Gooding Canal Company). For several decades it has been thought by most administrators and water users that there is no legal requirement for any water to be released past Milner Dam. However; there have been large amounts of water that have escaped past Milner Dam almost every year for more than one hundred years, usually in the spring of the year.

great deal of surface water escapes the basin without being used within WD01. If any or all of the escaped volumes could be held back and used to recharge the ESPA, the effects of groundwater pumping on WD01 stream flows could be significantly mitigated. After all, it is largely only the top twenty to fifty feet of the aquifer that provides water for the spring discharges that are so important to the fish farmers, the downstream irrigators, and other water users. Those diverting groundwater from deep wells would not then need to have their water supply cut off or curtailed, at least to the extent they have been threatened in recent years.

3.7 Recharge Development Corporation (RDC) and Eastern Snake Plain Aquifer Recharge

In 1978, the Idaho Legislature began dealing with recharge of the aquifer system through statutory enactment. Having been amended twice, the Idaho statutory law, as most recently amended in 2009 and codified at Idaho Code, Sec. 42-234, now provides encouragement of the optimum development and augmentation of the water resources of the state.

We have referred to the practices of some of the fish farmers in the Hagerman area as well as some of the members of the SWC filing petitions with IDWR for delivery calls. In 1994, IDWR, under the Idaho Administrative Procedure Act (IDAPA), promulgated a set of "Rules for Conjunctive Management of Surface and Ground Water Resources" establishing the rules under which delivery calls are to be filed and processed. (IDAPA 37.03.11). Rules nos. 42 ("Determining Material Injury and Reasonableness of Water Diversion), 43 ("Mitigation Plans") and 50 ("Areas Determined to have a Common Ground Water Supply") were promulgated as of the same date. Under Rule 50, IDWR established the Eastern Snake Plain Aquifer (ESPA).

The Idaho Legislature also enacted Chapter 52 of Title 42 of the Idaho Code entitled "Ground Water Districts" in 1995 to permit the organization of such districts to provide a means for groundwater users within particular geographic areas to raise funds and to cooperate with each other in addressing issues common to all users of groundwater within the boundaries of the particular geographical area, especially the delivery calls and curtailment orders. Nine such districts have been organized and cover virtually all the farmland that relies on groundwater within Water District 01. The nine all became affiliated with IGWA soon after they were organized and IGWA essentially speaks on behalf of all nine in most matters which affect the ground water districts in common.

Both before and while all this organizational effort was occurring, a group of large canal companies and irrigation districts from southern Idaho who rely primarily on surface water supplies and storage water from Bureau of Reclamation reservoirs and who were responsible for filing some of the water delivery calls with IDWR, formed themselves into an organization called the "Surface Water Coalition" (SWC). The lobbying before the Idaho Legislature and participation in the administrative and court proceedings became very intense and adversarial and both sides found such actions to be quite expensive. During all of this time both sides gave a great deal of lip service to aquifer recharge as one potential solution to the controversy. Other steps were taken as well; for example, IGWA and some of its members who were the subject to curtailment orders issued by IDWR began purchasing large amounts of storage water supplies from whomever had some available and used it for mitigation in connection with such curtailment orders. Eventually, IGWA and some of its members even purchased one of the major fish farms and took it out of production so as to remove the further threat of the use of the water rights of the enterprise to support more delivery calls. Many of the water rights of the fish farmers were prior in time to most of the water rights for the wells of the groundwater irrigators.

Then in 2015, with the encouragement of several legislators, the governor, and IDWR, IGWA and SWC negotiated an agreement, the major provision of which was that the groundwater users of the ESPA within groundwater districts would reduce diversions by 240,000 acre-feet per year. When IGWA divided up this amount among its members, it resulted in a reduction in diversion of roughly a thirteen percent reduction in groundwater pumping each year for a period of five years. The parties selected nineteen wells as "sentinel wells" which would be monitored to determine if the agreement was accomplishing the desired result of improving aquifer levels. Between the reduction in groundwater pumping of 240,000 acre-feet and the recharge efforts of the IWRB, it was believed that over time the aquifer could be returned to approximately 1990 groundwater levels. The reductions required of ground water districts and their individual members have been done in different ways. In 2018, a number of Idaho cities entered into a similar agreement with SWC to reduce or mitigate for some 7,625 acre-feet of water per year and contribute to this effort.

In 2014, a group of former water rights administrators, attorneys, and farmers organized themselves into an entity which eventually took the name "Recharge Development Corporation" (RDC) with the belief that if RDC or a subsequently organized entity known as Eastern Snake Plain Aquifer Recharge, Inc. (ESPAR), composed primarily of surface and ground water users, could obtain the necessary authority and develop a number of recharge sites, private managed aquifer recharge (MAR) could be made available to individual ground water users to provide water for satisfying their individual mitigation obligations under the 2015 agreement between SWC and IGWA. Under that agreement, a groundwater user can either reduce his diversions by approximately thirteen percent or provide the amount of ground water needed for his reduction as a substitute or as mitigation for the required reduction. Of course, a reduction in pumping of thirteen percent can have a very detrimental impact on an individual's farming operation.

RDC conceived the idea of quantifying water recharged by it or ESPAR in Aquifer Recharge Units or ARUs. Each ARU is space within the aquifer which will hold one acre-foot of recharged water. Although recharged water eventually escapes from the ESPA over varying time frames through the aforementioned springs, it has been determined by expert hydrogeologists, working with the state's ground water model, approximately fifty percent of the water recharged to the aquifer remains available in the aquifer after a period of five years. The concept proposed by RDC is that if an individual acquires sufficient ARUs, then, to the extent they are filled in a given year, he may use them himself or to satisfy his mitigation requirement, or save them for a future time, or sell or lease the water with which they are filled. Some of the ground water districts and even some canal companies and irrigation districts have acquired ARUs for the benefit of their members or shareholders. We call the process of obtaining and using ARUs in this manner "Incentivized Private Managed Aquifer Recharge (IMAR)."

To date, the amounts stored in ARUs which have been submitted as the required mitigation for some individuals and some entities have been accepted by SWC and IGWA as appropriate contributions required under the terms of the 2015 agreement for both the 2017 and 2018 water years. IDWR has not yet made any determination of the value or validity of such ARUs and there are several potential legal issues that have, as yet, not been formally addressed by IDWR or the Idaho courts. Such legal issues might include: (1) whether a land owner can legally prevent the use for recharge and recovery purposes of water placed by such recharge efforts in the ESPA beneath his land, (2) whether the aquifer system can legally be used under Idaho Code, Section 42-105 as a vehicle for commingling recharged water so it may be recovered at another location within the ESPA, and (3) whether the ESPA can be treated as the legal equivalent of a surface reservoir, for example, by the United States Bureau of Reclamation. We will comment on each of these potential issues in the order listed above.

3.8 Laws related to Managed Aquifer Recharge

There is a particularly thorough law review article by John G. Sprankling, 55 UCLA Law Review 979, (April 2008), entitled "OWNING THE CENTER OF THE EARTH" in which he considers and criticizes the origin and validity of the old English doctrine of "cujus est solum, ejus est usque ad coelum et ad inferos" which made its way into the common law of many of the states of the United States because it was included in the commentaries of William Blackstone in 1766. In English the doctrine states that a landowner's title extends to everything between the land surface and the center of the planet as well as everything between the land surface and the heavens. Sprankling calls the doctrine "poetic hyperbole" and shows that it has been essentially done away with in most American jurisdictions so far as the extension of land ownership into the air. He claims that the doctrine with respect to the center of the earth is merely dicta in most jurisdictions because the doctrine never forms the logical basis of any court holding. He then criticizes most statutory statements of the doctrine calling them “confusing”. He says the confusion is even “more pronounced in jurisdictions such as Alabama, California, Georgia, and Idaho” (supra at p. 1002).

With respect to groundwater, he concludes that the “center of the earth” theory has been abandoned or is ignored in most jurisdictions. He points out that in many jurisdictions, title to groundwater is vested by statute in the state. That is certainly true in Idaho (Idaho Code, Sec. 42-226). The Idaho Court has not dealt specifically with this depth of land ownership and control issue (the cujus doctrine) in any reported cases but it is likely that Idaho would view the issue much like the courts of Colorado and Arizona as explained in recent decisions from those jurisdictions.

Justice Hobbs of the Supreme Court of Colorado, a noted judicial expert on water law, authored the opinion in the case of *Board of County Commissioners of the County of Park, et al v. Park County Sportsmen's Ranch, LLP*, 45 P.3d 693 (2002). In that case, the county took the position that the ranch had no right to place artificially recharged water beneath the surface of the lands of the county and that such action would be a trespass making the ranch liable for damages. Citing decisions of the Ohio Supreme Court, the Arizona Supreme Court and the California Supreme Court, Justice Hobbs rejected the application of the “cujus doctrine” with respect to artificial recharge of water into the underlying aquifer.

In the Arizona case, *South West Sand & Gravel, Inc. v. Central Arizona Water Conservation District*, 221 Ariz. 309; 212 P. 3d 1 (2008), The sand and gravel company claimed a taking by the conservation district for recharging the aquifer beneath its gravel pit which would raise the water level so high as to interfere with the sand and gravel company's ability to remove sand and gravel. In rejecting the claim of the sand and gravel company, the court gave no real efficacy to the “cujus doctrine” so far as the sand and gravel company's power to preclude recharge and increased groundwater levels and denied damages for trespass, nuisance, etc., as the court favorably cited the Colorado case referenced above. The court said the law was clear in Arizona that landowners do not own the groundwater below their property and the state is free to regulate its withdrawal and use.

Regardless of what these courts may have said regarding the “cujus doctrine” previously, at least with respect to recharging water into the ground water aquifer, neither the Colorado court nor the Arizona court seemed to have any compunctions about ignoring the doctrine with respect to using an aquifer for recharging water.

With respect to commingling water introduced from a surface supply into an existing aquifer and then recovering such water at another location through pumping, Idaho does have an analogous statute for commingling surface water, allowed by Idaho Code, Section 42-105.

One question that arises is what is the definition of a ‘waterway’? And, could an aquifer be considered a “waterway”. In trying to describe a “waterway”, one would naturally envision a surface stream of water, with banks, and not a surface lake or pond or reservoir or an underground aquifer. The Idaho Court has never defined the term “waterway” and there is no definition in the statute itself.

However, in Chapter 17 of Title 42 of the Idaho Code (the chapter creating, governing the operation of, and setting forth many of the duties and the authority of IDWR, there is a list of definitions in Section 42-1731, number (13) thereof which does define the term “waterway” as a river, stream, creek, lake or spring, or a portion thereof, and shall not include any tributary thereof.

Could this definition include the subsurface flows (or underlying aquifer) that is interconnected to the Snake River and its surface tributaries? The Snake River and probably all of its surface tributaries are certainly connected to the ESPA, and in certain reaches, the surface rivers and streams are tributary to the ESPA, but in other reaches, the ESPA or portions of it are tributary to the Snake River or one or more of its surface tributaries.

Black's Law Dictionary, Fourth Edition, defines “waterway” as “water course”, based on an old Oregon Supreme Court case. It then defines “water course” as a running stream of water; a natural stream fed from permanent or natural sources, including rivers, creeks, runs, and rivulets.

There must be a stream, usually flowing in a particular direction, though it need not flow continuously. It may sometimes be dry.

The two cases we have referenced above, specifically dealing with artificial aquifer recharge do not, for the most part, focus on specific statutory language, but neither the Arizona court (in the *South West Sand & Gravel* case) nor the Colorado court (in the *Park County Sportsmen's Ranch* case), seemed to have any trouble deciding that an aquifer should be treated the same as a natural river or stream or rather a reservoir, for purposes of artificial recharge. The Arizona Court does reference one Arizona statute which states: "Arizona law has historically recognized that the owner of stored waters has the right to use a natural stream to move and store water." (221 Ariz. at 314, 212 P.3d at 5) Also, referring to previous Arizona cases, the Arizona court stated: "This court declined to recognize any legal distinction between CAP water introduced for water recharge and the river's natural flow." (221 Ariz. at 315, 212 P.3d at 7).

Justice Hobbs of the Colorado court uses the terms "water bearing formation" and "natural water bearing formations" instead of the term we quoted from the Idaho statutes, i.e., "waterway." The terms he uses do not appear to be found in the relevant Colorado statutes. The only term in the Colorado statutes relating to the composition or structure of the aquifer appears to be "water course" which would essentially mean the same as the Idaho statutory term "waterways." It is not clear why the Colorado Supreme Court decided to use the term "water bearing formations", but in doing so the Colorado court states: "In sum, the holders of water use rights may employ underground as well as surface water bearing formations in the state for the placement of water into, occupation of water in, conveyance of water through, and withdrawal of water from the natural water bearing formations in the exercise of water use rights. (45 P.3d at 710). And further: "Thus, PCSR would not need the consent of the landowners or an easement, nor would it have to pay just compensation to them, and no trespass occurs simply as the result of water moving into an aquifer and being contained or migrating in the course of the aquifer's functioning underneath the lands of another. (45 P.3d at 713-714). And finally: "Artificial recharge in the course of implementing either an augmentation or storage plan utilizing an aquifer is practically indistinguishable from the conveyance of appropriated water in the natural surface channel across the property of others. (45 P.3d at 14).

If the IDWR or the Idaho courts concluded that the terms "water bearing formations" and "waterways" were for all practical purposes equivalent in meaning, then there would probably be no legal reason not to rely upon Idaho Code, Sec. 42-105 for authority to commingle and then recover water recharged into the aquifer as well as turned into and then reclaimed from the channel of a natural surface stream. Certainly there is no difference in principle or in practical application. Perhaps the best argument however would be to focus on the aquifer as a reservoir rather than a "waterway" or "water course". While there is no Idaho statute designating the ESPA or any aquifer within the state as a reservoir, neither is there any statutory authority prohibiting such designation. If recharge water is introduced into the aquifer which is treated the same as a reservoir, there is no need to even consider the provisions of Idaho Code, Sec. 42-105.

The United States Bureau of Reclamation (BOR) operates the dams and reservoirs within WD01 not only for storage of water for supplemental irrigation purposes, but also for flood control purposes. It seems to be quite difficult to predict spring high water flows accurately enough to always release the exact amounts of water to prevent flooding and yet store all the water that may be available for irrigation storage. There have been many times over the years when the BOR has been criticized for releasing too much water for flood control when with hindsight much more could have been stored in the reservoirs for supplemental irrigation. If most or all of the water released for flood control had been used for recharge of the aquifer, the flood control benefits would be the same, but the water would not have been lost downstream and hence would have remained available for irrigation. If used for recharge, the full storage entitlements of the canal companies and irrigation districts could still be delivered through groundwater pumping. If it turned out that the reservoirs still filled, even though there had been flood control releases recharged, there is always a market for the recharged water because it would still be available in the ESPA. There is plenty of space available for storage in the ESPA through MAR and most of the guess work inherent in deciding how much water to release for flood control purposes would no longer be a factor.

As we have pointed out, Idaho has no statutory authority at present to provide or to prohibit this potential benefit. Preliminary discussions with BOR and IDWR in which this concept has been proposed seem to have been positive and are proceeding. Whether statutory authority would be required has yet to be thoroughly considered. Arguably it would not be necessary, although the State of Washington has effectively made all its aquifers the equivalent of surface reservoirs through legislation. It is interesting to note that the state of Washington has, by statute, designated aquifers within that state as reservoirs. The Washington statute, chapter 90.54 RCW (2) (a) provides that a "reservoir" includes, in addition to any surface reservoir, any naturally occurring underground geological formation where water is collected and stored for subsequent use as part of an underground artificial storage and recovery project.

We note that the Colorado case we have cited above and discussed mentions that two underground reservoir sites have already been designated on the Platt River drainage and of course the decision of the Colorado Court obviating the "cujus doctrine" as a possible legal barrier to movement of recharged water through or storage of recharged water in aquifers clarifies that such is legal in that state. *Board of County Commissioners of County of Park v. Park County Sportsmen's Ranch, LLP,* supra.

Also, the Arizona case we have cited and discussed above makes it clear that in Arizona, surface water may be placed in (recharged) into and stored in an aquifer (which is equivalent to an "existing natural water course" or, we would argue, a reservoir) thus accomplishing the very same thing as a surface reservoir. *South West Sand & Gravel, Inc. v. Central Arizona Water Conservation Dist.*, supra.

4. Conclusions

In conclusion, it is probable that the IDWR or the Idaho courts would ignore the "cujus doctrine" and follow the same logic as the Colorado and Arizona courts with respect to ownership and control of the aquifer (the ESPA) underlying most of the land in southern and eastern Idaho. While we believe IDWR and the Idaho courts could very well follow the holdings in the Colorado and Arizona cases we have cited with respect to whether the ESPA constitutes a "waterway" under Idaho Code, Sec. 42-105, the statutory language in that section and in Idaho Code, section 42-1731(13) creates a possible hurdle that would require surmounting. We doubt that either IDWR or the Idaho courts would find a serious legal problem with treating the ESPA as a reservoir so long as all permitting or other requirements under its "Conjunctive Management Rules" were met with respect to the water to be stored therein.

Abbreviations

The following abbreviations are used in this manuscript:
ESPA: Eastern Snake Plain Aquifer
RDC: Recharge Development Corporation
ARU: Aquifer Recharge Unit
ESPAR: Eastern Snake Plain Aquifer Recharge, Inc.
IMAR: Incentivized Managed Aquifer Recharge
IGWA: Idaho Ground Water Appropriators, Inc.

Conflicts of Interest: The author declares no conflict of interest.

Paper for ISMAR10 symposium **Topic No: 10 (232#)**

MARSOL Policy Brief. Essentials on Managed Aquifer Recharge for policy makers and water managers

Schüth, Christoph[1]; Roehl, Karl Ernst[1]; Fernández-Escalante, Enrique[2]; Guttman, Joseph[3] and Lobo Ferreira, João Paulo[4]

[1] TU Darmstadt, Germany
[2] TRAGSA, Spain
[3] MEKOROT, Israel
[4] LNEC, Portugal
*Correspondence : schueth@geo.tu-darmstadt.de

Abstract: The European Water Framework Directive (2000/60/EC) considers 'artificial recharge' of groundwater as one of the water management tools that can be used by EU Member States to achieve a good groundwater status. It has to be ensured, however, that the necessary regulatory controls are in place to warrant that such practices do not compromise quality objectives established for the recharged or augmented groundwater body. It is also acknowledged by the Groundwater Directive (2006/118/EC) that it is not technically feasible to prevent all input of hazardous substances into groundwater, in particular minor amounts which are considered to be environmentally insignificant and thus do not present a risk to groundwater quality. For such cases the Groundwater Directive, under Article 6(3) (d), introduces a series of exemptions. Artificial recharge is considered as one of these exemptions. MARSOL suggests a Regulatory Framework based on risk assessment, control mechanisms and monitoring as a tool which can facilitate the application of the Water Framework and Groundwater Directives on MAR. It is the intention of such a regulatory framework to provide clear guidelines to Member States on the application of MAR techniques.

Keywords: MAR, regulations, MARSOL, WFD, policy.

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1. Introduction

The main objective of the EU FP7 project MARSOL was to demonstrate that MAR is a sound, safe and sustainable strategy that can be applied with great confidence. With this, MARSOL aimed to stimulate the use of reclaimed water and other alternative water sources in MAR and to optimize WRM through storage of excess water to be recovered in times of shortage. MARSOL operated eight demonstration sites in six countries around the Mediterranean (Portugal, Spain, Italy, Greece, Malta, Israel) applying various technologies, i.e. infiltration ponds, river bed infiltration, direct injection wells, canals, river bank filtration, to infiltrate various water sources, i.e. river water, surface runoff, treated waste water, desalinated sea-water.

This article intends dissemination of last results. It does not intend being a scientific article, but rather a dissemination mean of MAR improvements achieved during the project´s duration.

2. MARSOL Policy Brief

Essentials on Managed Aquifer Recharge for policy makers and water managers

Water scarcity is one of the key issues our society faces today. Although there is enough freshwater on our planet, it is unevenly distributed and often not properly managed. Despite uncertainties in global climate projections, the anticipated reduction of renewable freshwater resources can be as high as 50% within the next 100 years hitting regions that already suffer from water scarcity and droughts. At the same time, large water quantities are lost to the sea as surface runoff and river discharge, discharge of treated and untreated wastewater, or discharge of excess water from various sources during periods of low demand. These alternative water resources in principal can be used to increase water availability in general, in periods of high demand, or as a strategic reserve.

Water sources for MAR and technical solutions

Available water sources for MAR include storm water, surface runoff, treated waste water, water from streams and lakes, groundwater from remote aquifers, or desalinated water. These water sources have different qualities and require different technical solutions for infiltration and recovery. Various technical designs are available and a vast experience with the operation of such sites has been gained. In principle, direct injection of water through wells, or indirect infiltration through surface ponds, infiltration basins, ditches, wetlands, river beds, or shafts are applied. Operational times of installations range from 50 years in the case of the Menashe site in Israel, where runoff water is infiltrated, to recent installations. It was demonstrated that the technical solutions are well understood, operate efficiently, and are cost effective.

What is Managed Aquifer Recharge?

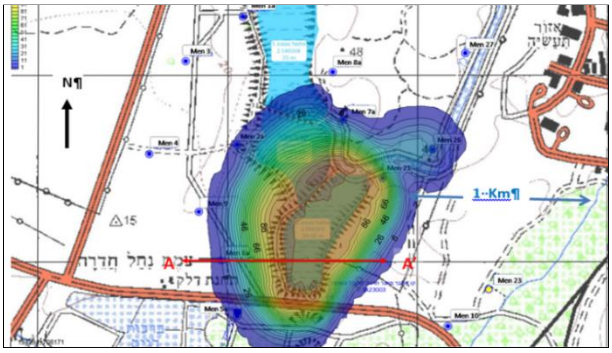
Managed Aquifer Recharge (MAR) refers to the intentional infiltration of excess water into the subsurface through engineered systems for temporal storage or to influence gradients. Water can be recovered in times of high demand. In principal, large storage capacity is available in shallow aquifers, either due to thick unsaturated zones or due to already depleted water resources in extensively exploited aquifers. In addition, water quality can be improved due to chemical and biological reactions during flow of the infiltrated water through the unsaturated and saturated zone. MAR can be a key Water Resources Management tool for tackling water scarcity in Europe, and in water scarce regions worldwide by linking water reclamation, water reuse and integrated

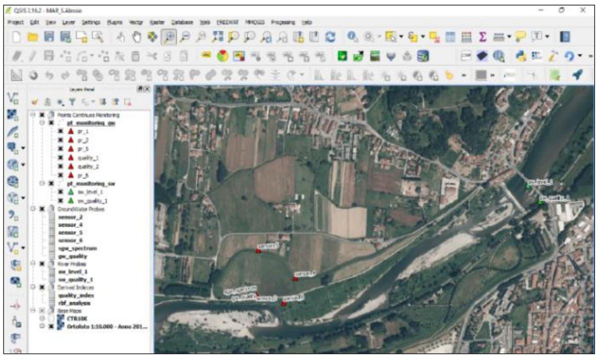
Monitoring and modelling of MAR sites

Monitoring of MAR sites is crucial for performance evaluation and management of sites. Various monitoring tools were applied in MARSOL, targeting hydrodynamics in the saturated and unsaturated zone, water quality and clogging issues. Collecting data in high spatial and temporal resolution and making them available in real time requires appropriate data transmission and storage techniques. Wireless sensor networks including suitable data storage and visualization techniques, i.e. web based data management platforms, allow to feed decision support systems (DSS). Monitoring is typically accompanied by modelling that allows an outlook on the performance of a certain MAR approach in the future. In addition modelling allows evaluating alternative scenarios for MAR operation and enables MAR optimization (predictive tool).

What are the costs?

MAR operations have to be economically feasible and apply simple engineered solutions that are easy to maintain, otherwise it will not be implemented. The financial feasibility of MAR projects depends on a number of parameters affecting their costs, such as capital expenses and operating costs, and the revenues potentially derived from the sales of the water for a variety of uses. However, water has also social and environmental values that are difficult to quantify. The benefit of a MAR project should not be solely based on market revenues. MAR projects can improve the quality of lives of the people benefiting from an increased availability of water, and recharged water can contribute to sustained ecosystem services. A thorough cost-benefit analysis is required to justify a MAR installation. However, MARSOL could prove that MAR can be a cost effective tool.



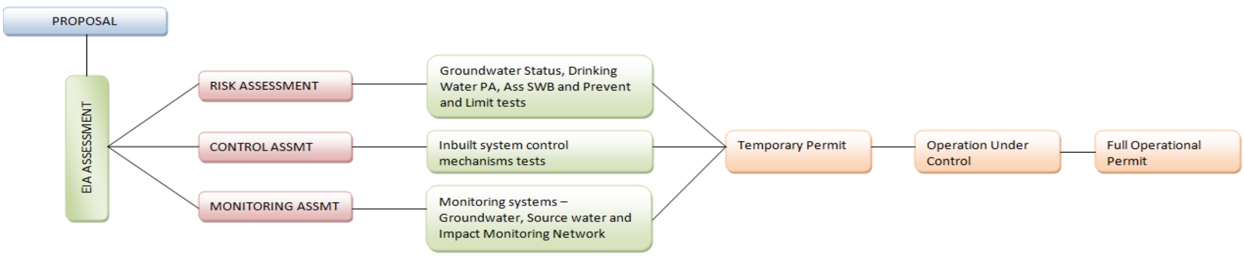


Legal Framework

The Water Framework Directive (2000/60/EC) considers 'artificial recharge' of ground-water as one of the water management tools that can be used by EU Member States to achieve a good groundwater status. It has to be ensured, however, that the necessary regulatory controls are in place to warrant that such practices do not compromise quality objectives established for the recharged or augmented groundwater body. It is also acknowledged by the Groundwater Directive (2006/118/EC) that it is not technically feasible to prevent all input of hazardous substances into groundwater, in particular minor amounts which are considered to be environmentally insignificant and thus do not present a risk to groundwater quality. For such cases the Groundwater Directive, under Article 6(3) (d), introduces a series of exemptions. Artificial recharge is considered as one of these exemptions. MARSOL suggests a Regulatory Framework based on risk assessment, control mechanisms and monitoring as a tool which can facilitate the application of the Water Framework and Groundwater Directives on MAR. It is the intention of such a regulatory framework to provide clear guidelines to Member States on the application of MAR techniques.

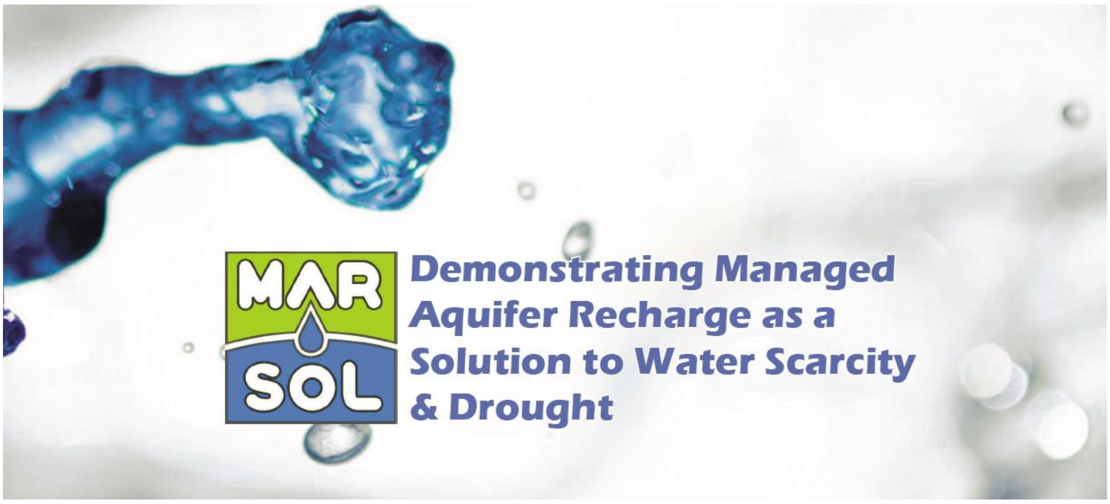
The MARSOL project

The main objective of the EU FP7 project MARSOL was to demonstrate that MAR is a sound, safe and sustainable strategy that can be applied with great confidence. With this, MARSOL aimed to stimulate the use of reclaimed water and other alternative water sources in MAR and to optimize WRM through storage of excess water to be recovered in times of shortage. MARSOL operated eight demonstration sites in six countries around the Mediterranean (Portugal, Spain, Italy, Greece, Malta, Israel) applying various technologies, i.e. infiltration ponds, river bed infiltration, direct injection wells, canals, river bank filtration, to infiltrate various water sources, i.e. river water, surface runoff, treated waste water, desalinated sea-water.



What about water quality?

Quality aspects of water sources used for MAR are of major concern. Especially the presence of micropollutants, such as pharmaceuticals, in treated waste water and in receiving surface waters has to be considered. In particular direct MAR methods using such waters, i.e. injection of reclaimed water through wells directly into the saturated zone, may have a high risk to contaminate native groundwater and typically require a thorough pretreatment or long retention times in the aquifer before recovery. By infiltrating water through the unsaturated zone, MARSOL could show that natural attenuation processes for contaminants can substantially improve water quality. The capacity to retain pollutants in indirect MAR techniques, however, differs considerably depending on the hydraulic and geochemical factors on each specific site.



The MARSOL Partners:

The MARSOL project received funding from the European Union's Seventh Framework Program for Research, Technological Development and Demonstration under grant agreement no 619120. The information in this document reflects only the authors' views and the European Union is not liable for any use that may be made of the information contained therein.

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Topic 11. MAR AND MONITORING

Paper for ISMAR10 symposium. ***Topic No: 11 (065#)***

Investigating a Strategic Aquifer Storage and Recovery Scheme in the Sherwood Sandstone to Improve Resilience

Price, Victoria M.[1]; Stanley-Jones, Hannah[2]; Watson, Sally[1]; Buckley, James[1] and Rippon, Peter[1]

[1] Mott MacDonald
[2] Anglian Water Services
* Correspondence: victoria.m.price@mottmac.com; Tel.: +44 1223 463748

Abstract: Water Resources East, led by Anglian Water, aims to develop a long-term strategy to meet the water resource requirements for the East of England until 2085, including domestic, industrial and agricultural supply. An aquifer storage and recovery scheme in the Sherwood Sandstone Group (SSG) aquifer in Lincolnshire, UK was considered as a supply option. Water abstracted from surface water during periods of high flow would be treated and recharged into the confined SSG at 250-440m below ground level. Recharged water would remain in the confined SSG until required for supply. The proposed wellfield extends c.40km along the banks of the River Trent. An investigation was undertaken to consider the potential impacts of the scheme on identified receptors as well as potential constraints on the wellfield construction and borehole spacing. The UK Environment Agency's East Midlands-Yorkshire regional groundwater model was adapted to simulate different operational schemes and their potential impacts. Results from the modelling were used to inform the maximum recharge rates at each borehole, optimise the wellfield layout and maximise the capacity of the scheme. Modelling indicated that maximum scheme size comprises 18 boreholes, recharging at 42Ml/d and abstracting at 46Ml/d.

Keywords: Modelling; aquifer storage and recovery.

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1. Introduction

Anglian Water is a water company which delivers potable water across the east of England, UK. Eastern England includes some of the driest areas of the country, which receive less than 700mm of rainfall per year. Additionally, population increases with concurrent increases in demand and potential adverse impacts due to climate change are predicted to lead to large deficits in water supply in the future.

While the regulator (Environment Agency) requires water resources management plans to be developed every five years, a more ambitious long-term strategy was required for the east of England, which encompasses industrial, agricultural and environmental requirements as well as domestic supply. Hence, Anglian Water led the Water Resources East (WRE) project, which included stakeholders across the east of England, with the intention of developing long-term strategic water supply projects, which can be used in the long term to deliver a reliable, affordable and sustainable system of supply across the east of England. A water resource simulator was used as part of the robust decision-making process to determine which options should be developed to meet demand until 2085. Information from the WRE project was also used to inform the Water Resources Management Plan for the 2020-2045 planning period (WRMP19).

As part of WRE, an aquifer storage and recovery (ASR) scheme was considered to increase water available for use in the Sherwood Sandstone Group (SSG) aquifer in the lower Trent valley (Figure). The focus of the proposed scheme was to supply water for 18 months during a severe drought; it was assumed for the purposes of the investigation that the drought would occur once every five years. As a result, the proposed ASR scheme comprised five years of recharge during winter months followed by continual abstraction for a period of 18 months during a severe drought. During recharge, water would be abstracted from the River Trent, treated and recharged via a wellfield. When required, water would be abstracted from the same wellfield, treated to potable standards then pumped to supply.

Investigations were required to:

- ensure that the ASR scheme meets the environmental permitting requirements; and
- inform the scheme yield and restrictions on wellfield construction.

The study area is 40km long between Town A and Town B adjacent to the River Trent (Figure), which flows northwards to discharge to the Humber Estuary near Kingston upon Hull. The geology comprises approximately 250m of easterly dipping SSG, which is confined in the study area by up to 200m of the Mercia Mudstone Group (MMG). To the west, the MMG thins and the SSG crops out approximately 10-15km to the west of the study area.

The investigation reported here was focussed on the hydraulic properties of the aquifer to provide a high level feasibility assessment of the proposed ASR scheme. Although water quality was recognised as an important issue for the proposed ASR scheme, it did not form part of this study.

2. Method

In the absence of field testing data and given the time constraints of the project, groundwater modelling was used to:

- Define the capacity of the scheme;
- Assess the impact of the scheme on identified receptors; and
- Consider the potential movement of poor quality recharge water towards nearby abstraction boreholes.

Results from the modelling were used to inform the capital and operational expenditure of the option as well as investigate potential environmental risks.

2.1. Scheme constraints

Through discussion with the UK's Environment Agency, who are the permitting authority for the proposed ASR scheme, the following uncertainties were identified:

- Potential impact of abstraction during the recovery phase on streams across the SSG outcrop (10-15km west of the recharge site);
- Destination for poorer quality recharge water abstracted from the River Trent during the recharge and storage phases; and
- Potential to entrain poor quality native groundwater during periods of recovery.

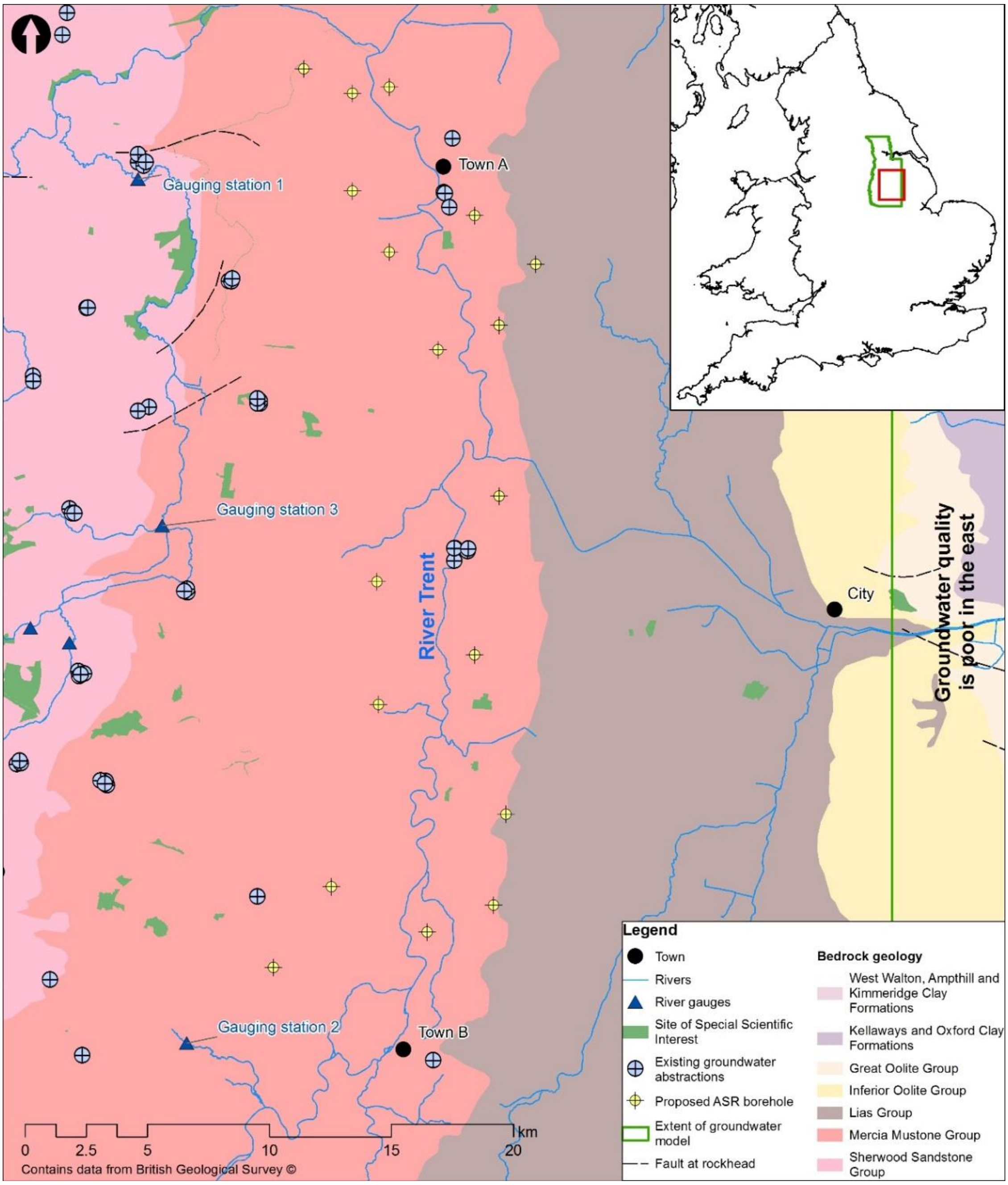


Figure 1. Study area.

Receptors that may be affected by the proposed ASR scheme comprised public water supply abstractions within the SSG and surface water features on the unconfined SSG (Figure). Many of the streams which flow across the unconfined SSG are subject to ongoing investigations to assess impacts of abstraction on river flows and Water Framework Directive (WFD) compliance.

Further information was also required by Anglian Water to define the scheme capacity and wellfield design, including the potential for adverse geotechnical impacts and changes in groundwater levels at neighbouring abstraction boreholes. In determining the scheme capacity, the following additional considerations were made:

- Drawdown during abstraction and deepest advisable pumping levels;
- Groundwater level rise during recharge and limits on pressurisation; and
- Potential for groundwater discharge and losses to streams and rivers on the unconfined SSG.

Assessment criteria were identified for the modelling as shown in Table .

Table 1: Assessment criteria.

Assessment point	Assessment criteria (recharge)	Assessment criteria (abstraction)
Proposed ASR borehole	Groundwater level rise above ground level during recharge should not exceed 20% of the thickness of the MMG [1]	Modelled drawdown during abstraction should not be below 10m above the top of the SSG
Stream gauges		Modelled losses from any stream should not exceed 2% of the modelled historical flow.
Neighbouring groundwater abstractions	Groundwater level rise above ground level during recharge should not exceed 20% of the thickness of the MMG [1]. Recharge water should not reach other groundwater abstractions in the study area.	Modelled drawdown during abstraction should not be below 10m above the top of the SSG

2.2. Modelling

The study area is within the UK Environment Agency's East Midlands-Yorkshire (EMY) regional groundwater MODFLOW model [2, 3]. The regional groundwater model is considered to be the most up to date and comprehensive understanding of the groundwater flow regime for the SSG. Groundwater flow is simulated between 1839 and March 2012. The model extends from York in the north to Grantham in the south and from the edge of the sandstone outcrop in the west to the assumed limit of groundwater flow in the east.

The impacts of the proposed ASR scheme were investigated initially using the historical model as this was considered to show a wide range of potential hydrogeological conditions, particularly during of low groundwater levels. Further refinements were then made using the Recent Actual model run, which simulates the abstraction conditions from 2007-2012 and represents the groundwater flow regime that is thought to be most likely to occur in the future. In both cases, a range of climatic conditions were modelled using the recharge file generated from the historical climate data.

MODPATH [4] was used to investigate the advection of water to the abstraction boreholes to understand if the poor quality water in the east of the model area might be entrained in the recovered water. MODPATH uses particles, which are released either at the start or end of the simulation. The particles show the advection of water through the aquifer and hence can be used to understand the origin or fate of the abstracted and recharge water.

In particle tracking, the particles were released at a distance of 200m from the modelled ASR boreholes. Reverse particle tracking was used to understand the origin of the water near the boreholes and, hence, whether poor quality water at the eastern boundary of the model might be entrained in the recovered water.

During the modelling, the recharge and abstraction rates for the proposed ASR wellfield (Figure) were varied through an iterative process until the criteria in Table were met at all sites. Initially, a 21 borehole wellfield was simulated with the same abstraction and recharge rates at each borehole. Boreholes were distributed across the study area by choosing sites that:

- Do not contain a surface water body or onshore oil field;
- Are within 250m of a road and 4km of the River Trent;
- Are located in the confined Sherwood Sandstone; and

- Are at least 2km from a public water supply borehole, 500m from a geological fault, and 250m from a Site of Special Scientific Interest.

3. Results

3.1. Groundwater levels

Groundwater modelling indicated that the limitation on the scheme capacity was the volume of water that can be recharged without exceeding the groundwater rise criteria, and not the amount of drawdown at each borehole during abstraction. Due to the consistently high groundwater levels during recharge at three specific boreholes, the decision was made to exclude these from the study as they exceeded the pressurisation criteria. This reduced the total number of boreholes from 21 to 18. In almost every remaining borehole, the recharge quantity was adjusted without exceeding the permissible pressure in the MMG. Recharge rates varied from 0.8 to 4.0Ml/d for the boreholes. Figure provides an example of the modelled groundwater levels at the ASR borehole compared with the maximum pressurisation value and minimum permissible drawdown; this figure is typical of the results obtained from all boreholes within the proposed wellfield.

The modelled drawdown and pressurisation levels in the boreholes do not take into account well losses and short term aquifer losses in and around individual boreholes. Well losses and short term aquifer losses could raise the pressure levels significantly above the acceptable levels indicated in Table . For example, using the B and C values obtained from step test data (B=0.0132dm^{-2} and C=1x10^{-6}d^{2}m^{-5}) at one of Anglian Water's groundwater sources within the study area, the potential additional increase in groundwater level could range from 11.1 m to 70.5m.

Further optimisation of the wellfield and the duration and rate of recharge could be used to reduce the impact of potential well losses on the modelled groundwater levels at the proposed ASR boreholes. Such optimisation would be best carried out following pilot testing to obtain information on well losses during recharge and abstraction.

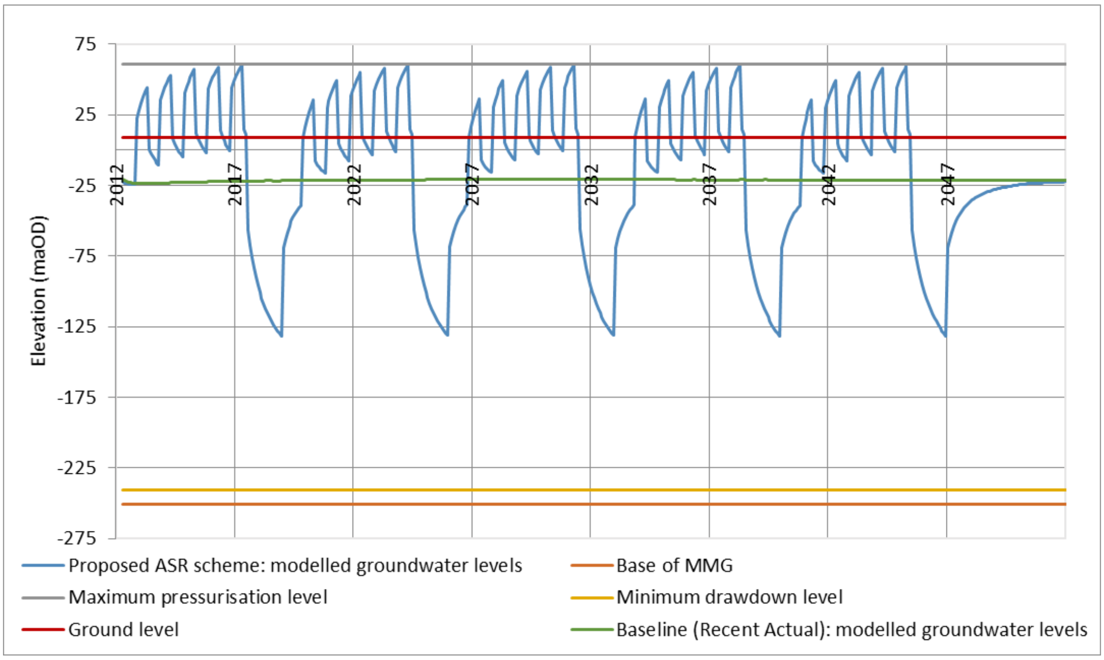


Figure 2. Modelled impact of proposed ASR scheme on groundwater levels.

3.2. Stream flows

Both abstraction and recharge were found to affect the streams on the unconfined SSG. However, given the ongoing National Environment Programme low flow studies on some of the streams, it was considered that the potential impacts of the proposed scheme during abstraction were more likely to constrain the capacity of the scheme.

The difference between the modelled stream flows, with simulation of the ASR scheme, and the baseline model stream flows were used to assess the effects of the ASR scheme and adjustments were made to borehole recharge and abstraction rates to reduce the modelled impacts. The modelled changes in stream flow for the final model simulation are summarized in Table and an example of the model results is provided in Figure 3. The final model simulation was deemed to have met the stream flow assessment criteria outlined in Table 2.

Table 2: Summary of simulated impacts on streams.

River gauge	Recent actual model results (maximum as % of baseline)		Historical model results (maximum as % of baseline)		Likely effect on WFD objective
	Increase in stream flow	Decrease in stream flow	Increase in stream flow	Decrease in stream flow	
Gauging station 1	5%.	3.5%.	5%.	4.5%.	Potential for adverse impact on stream during abstraction periods which occur during a severe drought.
Gauging station 2	7.5%.	3%	8%.	4%.	
Gauging station 3	1.8%.	0.5%.	2.2%.	1.5%.	No adverse impact expected

3.3. Particle tracking

The results of the particle tracking demonstrate that the water abstracted from the boreholes originates close to the boreholes and that no water from the eastern boundary, where water quality is poorer, is expected to be abstracted. A typical example of the modelled particle traces is shown in Figure 4. The particle traces suggest that the water abstracted from the boreholes is likely to be the same as the water that is used for recharge. Additionally, the particle traces suggest that the existing abstraction boreholes external to the proposed ASR wellfield are unlikely to abstract water that has been recharged.

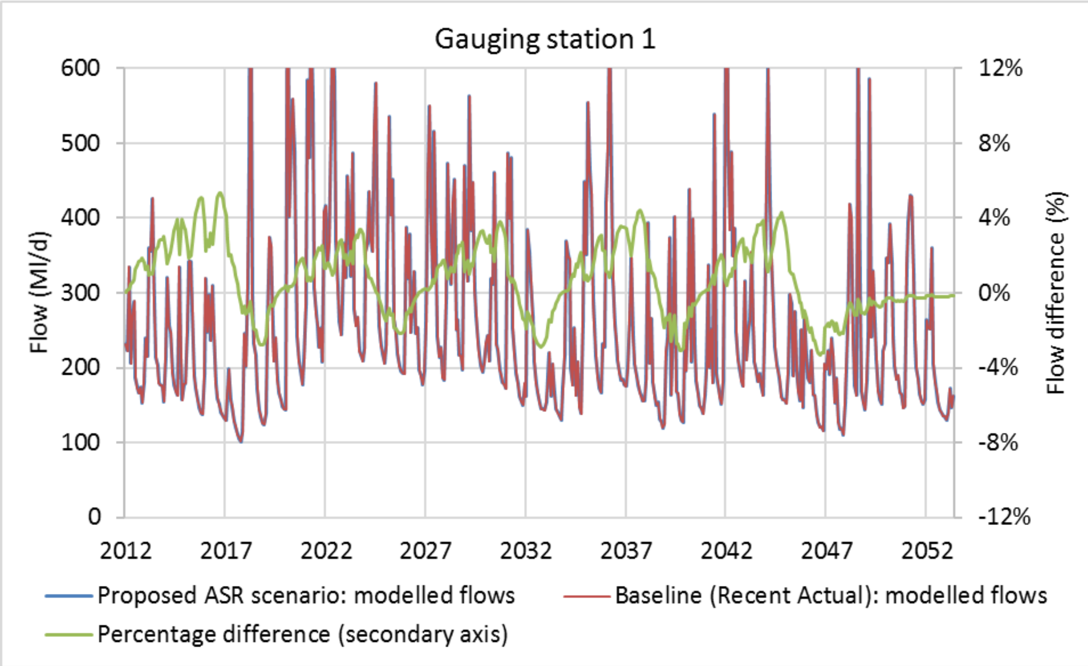
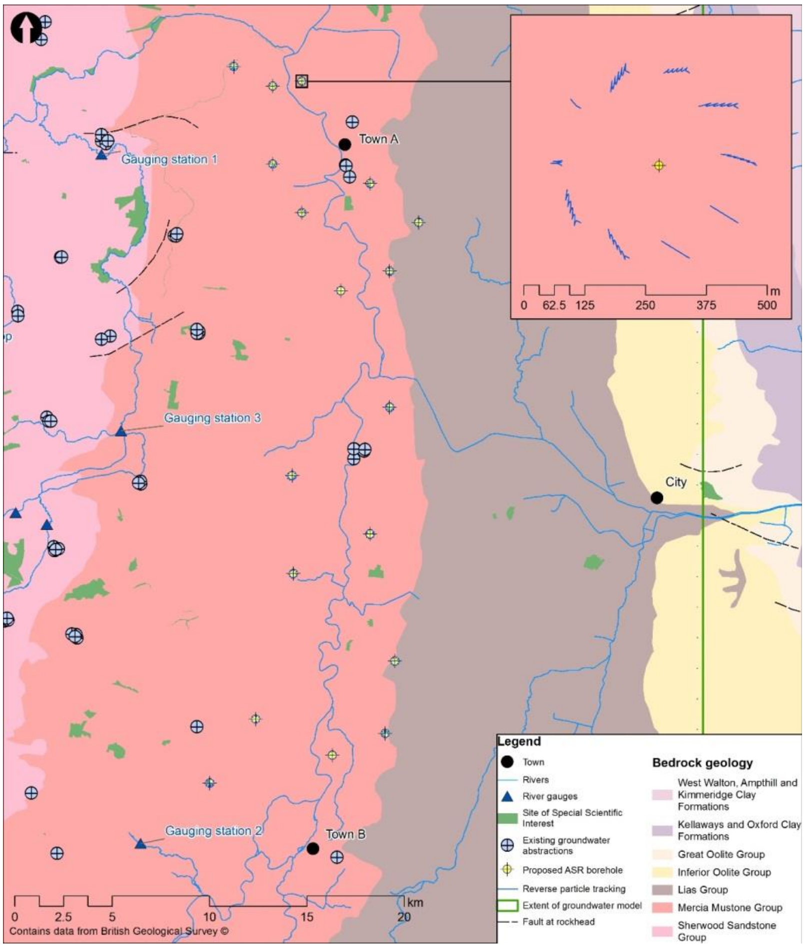


Figure 3. Modelled impact of proposed ASR scheme on river flows.



Note: MODPATH particles were released 200m from the borehole in the model. Hence, the lines show the movement of those particles from their starting point.

Figure 4. Modelled particle traces for proposed ASR scheme.

3.3. Scheme design

Using the results of the model, the refined ASR scheme is illustrated in Figure, and assumed:

- Water will be available from the River Trent for recharge at 42Ml/d from November to April (winter), with no recharge outside this period; and
- Abstraction will occur at 46Ml/d for a continuous period of 18 months during a severe drought, and no recharge will take place during this period.

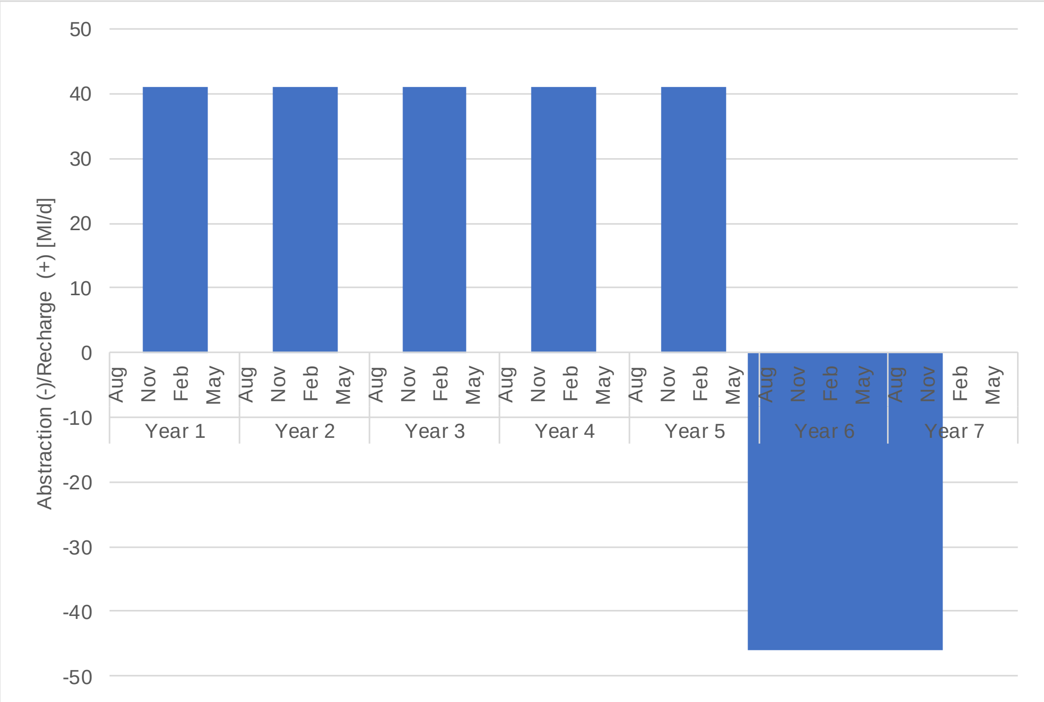


Figure 5. Proposed operation of ASR scheme

4. Discussion

Groundwater modelling was used to investigate the feasibility of an ASR scheme in a confined sandstone aquifer (SSG), including consideration of the movement of water to and from the ASR wellfield, potential impacts on environmental receptors at outcrop and an investigation into hydraulic properties at the proposed wellfield. Using an existing regional groundwater model, developed for the Environment Agency, to simulate the proposed ASR scheme was a robust method to provide a high-level understanding of the potential consequences of both abstraction and recharge. The model allowed the proposed scheme to be optimised to ensure that there were no adverse impacts on streams flows across the outcrop whilst maximising recharge during periods of high flows. Modelling was a cost-effective method of assessing possible risks at an early stage of the proposed scheme development.

Whilst the modelling was a useful tool in highlighting potential issues, future work will use pilot testing to obtain field data on well losses during recharge and water quality changes as a result of recharge. These data can then be used to improve the model and further optimise the proposed scheme whilst ensuring that the environment is not adversely affected.

In a future where water resources are predicted to become scarcer and demand is increasing, an ASR scheme may provide part of the solution to delivering drinking water to the east of England.

Acknowledgments: The study was funded by Anglian Water Services.

Author Contributions: Victoria Price wrote the paper, developed the methodology and managed the modelling; Hannah Stanley-Jones provided the data for the modelling and the purpose and constraints of the scheme; Sally Watson directed the investigation and reviewed the paper; James Buckley ran the models; and Peter Rippon provided technical expertise on borehole characterisation and wellfield design.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
ASR: Aquifer Storage and Recovery
EMY: East Midlands-York
MMG: Mercia Mudstone Group
SSG: Sherwood Sandstone Group
WFD: Water Framework Directive
WRE: Water Resources East.

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Extended abstract for ISMAR10 symposium. ***Topic No: 11 (102#)***

New methods for microbiological monitoring at riverbank filtration sites

Yasmin Adomat[1]*, Gerit-Hartmut Orzechowski[1], Marc Pelger[1], Robert Haas[2], Rico Bartak[2], Zsuzsanna ÁgnesNagy-Kovács[3], Joep Appels[4] and Thomas Grischek[1]

[1] Division of Water Sciences, University of Applied Sciences Dresden, Germany
[2] DREWAG NETZ GmbH, Dresden, Germany
[3] Budapest Waterworks Ltd, Hungary
[4] MicroLAN B. V., Waalwijk, Netherlands
*Correspondence: yasmin.adomat@htw-dresden.de; Tel.: +49-351-462-3944

Abstract: Water suppliers aim to achieve microbiological stability throughout their supply system by regular monitoring of water quality. Monitoring temporal biomass dynamics at high frequency is time consuming due to the labor-intensive nature and limitations of conventional, cultivation-based detection methods. The goal of this study was to assess the value of new rapid monitoring methods for quantifying and characterizing dynamic fluctuations in bacterial biomass. Using flow cytometry and two highly precise enzymatic detection methods, bacterial biomass related parameters were monitored at three riverbank filtration sites. Additionally, the treatment capacity of an ultrafiltration pilot plant was researched using online flow-cytometry. The results provide insights into microbiological quality of treated water and emphasize the value of rapid, easy and sensitive alternatives to traditional bacterial monitoring techniques.

Keywords: online flow-cytometry, enzymatic activity, riverbank filtration, ultrafiltration, ATP.

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1. Introduction

Water produced at riverbank filtration (RBF) sites is commonly monitored for the absence of pathogen indicator organisms like *Escherichia coli (E.coli)*, total coliforms (TC), *enterococci* and *clostridium* using cultivation-based methods with targeted growth media [1]. Additionally, heterotrophic plate counts (HPC) with non-specific media are frequently assessed. Although there is no evidence of a link between HPC results and health risk it is of major importance to assess data of microbiological growth during drinking water treatment and to detect changes in bacterial concentration and composition of monitored water [2–4]. The HPC method has been introduced more than 100 years ago but since then no general performance and interpretation of data was developed resulting in differences concerning sample incubation times, temperatures and acceptable critical thresholds across the world [5]. Despite time intensive laboratory procedures and incubation, the HPC method only detects a fraction of the total bacterial cells in water samples. This is due to the fact that only a small portion of bacteria species present in aquatic samples is culturable under laboratory conditions [6]. In the past decade significant advances in rapid cultivation-independent techniques, mostly fluorescence-based methods, have been developed. These methods focus on direct measurements of indigenous bacterial growth or enzymatic activity.

In this study flow-cytometry (FCM), two enzymatic detection methods (intracellular adenosine triphosphate, *alkaline phosphatase*) were used to analyze the total microbiological concentrations after different treatment processes in samples of three RBF treatment sites. The aim was to assess the applicability of each method in routine monitoring programs and also to compare the methods with each other and with HPC data. Additionally, an ultrafiltration pilot plant was monitored using online FCM with the goal to assess the pilot plants performance and to test if a continuous measurement of bacterial removal is possible.

2. Materials and Methods

2.1. Sample collection and microbiological characterization

Samples were collected from (dis)continuously operated sample taps from the RBF waterworks Dresden-Hosterwitz (DH), Dresden-Tolkewitz (DT), Csepel Island, Hungary (CI) and various RBF wells at Szentendre Island, Hungary using 5 mL, 15 mL and 1 L sterilized sample bottles. Prior to sampling at discontinuously operated taps, a disinfection-step with ethanol (98 %) and flame sterilization was employed followed by a 3 min flushing interval before samples were collected. Afterwards, each sample was transported to the laboratory for analysis within 12 h of sampling.

Intracellular adenosine phosphate (ATP) was determined using a luminesce-based Clean-Trace ATP water test kit (3M Inc, USA). Based on an enzymatic reaction (firefly *luciferase*), total and extracellular ATP were measured in relative light units (RLU) as per the manufacturer's instructions. Using a fully automatic operating system called BACTcontrol (microLAN, Waalwijk, Netherlands), total enzymatic activity (TEA) was also analyzed by measuring the specific activity of *alkaline phosphatase* (ALP) as an indicator for the presence of bacteria. Prior to each measurement, the water sample was pumped at 0.2-1 ml/sec through a 0.45 µm ceramic filter into a reactor chamber. While constantly stirring, the concentrated water sample was incubated for 20 min at 45 ± 0.1 °C. During incubation the enzymatic activity of ALP was detected in methylumbelliferone (MUF, in pmol MUF/(min 100 mL) by a fluorimeter which was pre-calibrated using a standard concentration of 1000 nM MUF. Flow-cytometry analysis was carried out with a BactoSense (Sigrist, Switzerland) flow-cytometer equipped with a 488 nm solid-state laser and an optional continuous/discontinuous sampling port. Sample volumes of 260 µL were drawn at a flow rate of 200-400 mL/min and mixed with fluorescent stain (SYBR® Green, propidiumiodide). After incubation (10 min, 37 °C), samples were analyzed (FL1 channel at 525 nm, FL3 channel at 721 nm) using fixed gates to separate cells and background signals and additionally to distinguish between so-called high (HNA) and low (LNA) nucleic acid content bacteria.

2.2. Ultrafiltration pilot plant and online FCM measurements

The ultrafiltration pilot plant was operated at DH with a treatment capacity of 20 m^3/h. Using either bank filtrate, Elbe river water or flocculated Elbe river water as feed supply, water was pumped (30 m^3/h) directly into a storage tank (1.9 m^3) through a supply pipe. Ultrafiltration was processed by using two membrane modules consisting of polyvinylidene difluoride (PVDF) with different pore sizes of 20 nm and 18 nm and operated at a flux of 40-80 L/(m^2 h) at 1.5 bar. Online FCM sampling was realized using an automatic programmed magnetic-valve system. Water samples were drawn using an online sampling option of the BactoSense flow-cytometer and analyzed applying the same method which is outlined in section 2.1. The cleaning process of the membrane modules was adjusted every 30 min by backwashing. Taking into account backwash cycles to avoid a sampling of backwash water, samples were drawn by flushing the FCM system for 2 min and analyzed within a cycle of 105 min.

3. Results

3. 2. Correlation of new methods and conventional cultivation-based methods during RBF treatment

FCM and TEA provided positive bacterial counts for all water samples with an average maximum Pearson correlation coefficient observed of R = 0.89 for the ICC/TEA ratio showing there was a high correlation between ICC and ALP-TEA. To elucidate potential links between FCM and TEA related results, an example is given in Figure 1 (BC sampling campaign). $1.5 \cdot 10^5$ ICC/mL were detected using FCM during RBF with corresponding TEA values of 70 pmol/min. Biomass concentration increased further in open aeration towers by 4 % to $1.6 \cdot 10^5$ ICC/mL and 86 pmol/min due to process-related external biomass entries. Ozone eliminates most intact organisms to $1.2 \cdot 10^3$ ICC/ml and 25 pmol/min based on its high redox potential, but at the same time this process also provides organic substrate: dead cell material to still intact organisms. As a result a minor biomass increase was detected using FCM to $2.4 \cdot 10^4$ ICC/ml. This relationship however could not be observed with the BACTcontrol method where TEA slightly decreased to 23 pmol/min. There was no significant impact of UV-disinfection on ICC cells observed. Intact cells decreased by 16 % to $2.0 \cdot 10^4$ ICC/ml due to UV-C treatment, only damages the bacterial genome but no impact on bacterial cell membranes is achieved. Final disinfection using ClO_2 reduced ICC by 96 % to $7.1 \cdot 10^2$ ICC/ml, TEA was detected with 18 pmol/min which is in accordance with other studies [7,8].

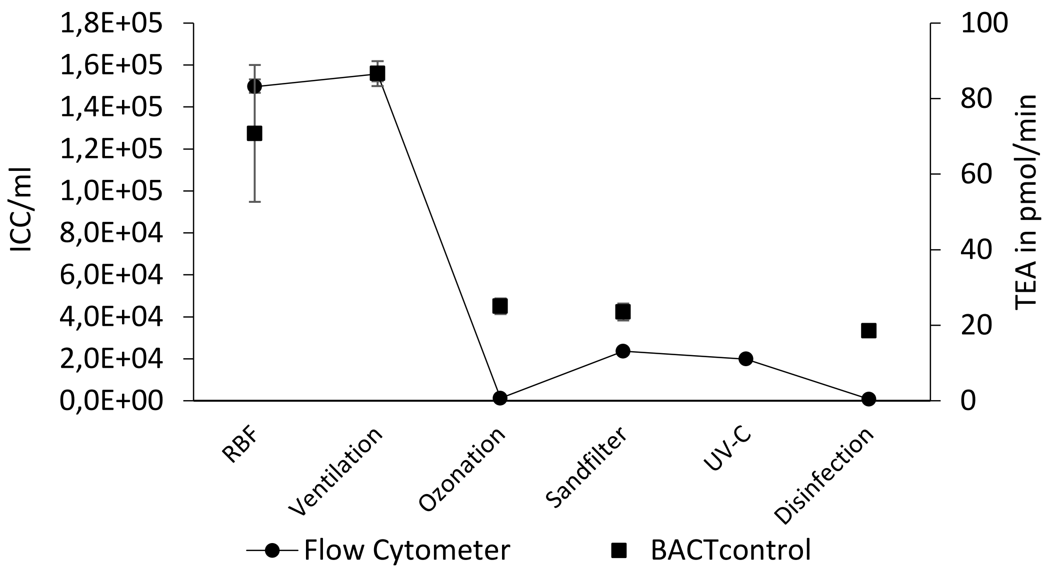

Figure 1. Comparison of FCM intact cell count (ICC, n = 5) with total enzymatic activity (TEA, n = 3) in CI (9th May 2019).

The attenuation of bacteria, viruses and protozoa during RBF is attained trough processes such as filtration, straining, and sorption which are influenced by aquifer material composition, temperature, supply of oxygen or organic/inorganic nutrients and travel time in the aquifer [1,9,10].

The results shown in Figure 2 confirm the correlation between the attenuation of microorganisms and travel time in the aquifer. ICC decreased by 1.10 log units to $1.4 \cdot 10^5$ ICC/ml in well BF1 while ICC in well BF4 with a travel time of 100…220 days decreased by 1.61 log units to $5.0 \cdot 10^4$ ICC/ml. The limit of detection using the HPC method is also demonstrated in Figure 1. While 220 MPN/ml and 48 MPN/ml were determined in Danube river water, no colonies could be detected in water from the RBF wells. These results suggest that new rapid microbiological methods (e.g. FCM) could be powerful tools for monitoring general water quality during treatment and distribution, as well as for the design and optimization of RBF sites.

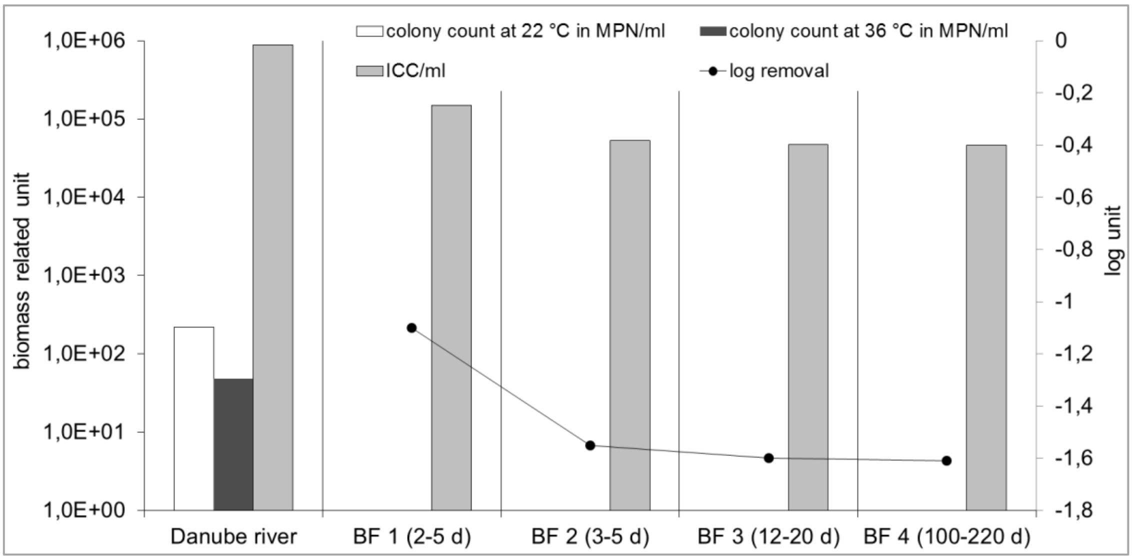

Figure 2. ICC monitored in various RBF wells in Budapest and their travel times in days, BF 1 = Csepel waterplant, well No. 1, BF 2 = Tahi 1, well No. 5, BF 3 = Tahi 2 well No. 5, BF 4 = Szigetujfalu, well No. 7, HPC data were provided by Budapest Water Works Ltd.

3. 3. Ultrafiltration pilot plant and online FCM measurements

During operation of the ultrafiltration pilot plant, bacteria and other particulate matter were efficiently retained independent from feed water quality. Figure 3 shows online FCM measurement result for using flocculated river water as feed water. The total cell count (TCC) in flocculated river water was constantly fluctuating between $3.8{\cdot}10^6$ and $1.3{\cdot}10^6$ TCC/ml caused by e. g. rainfall events or sunlight [11]. TCCs in Permeate 1 range from $6.5{\cdot}10^4$ to $1.9{\cdot}10^5$ TCC/ml and in Permeate 2 from $4.4{\cdot}10^4$ to $9.9{\cdot}10^4$ TCC/ml. Different results for different membrane units depend on membrane material, area per module and pore size. The observed values are in a normal range due to bacterial regrowth after treatment. Cell numbers in the range from 10^4 to 10^5 cells/ml of diverse microbial populations confirmed to be normal in previous studies [12].

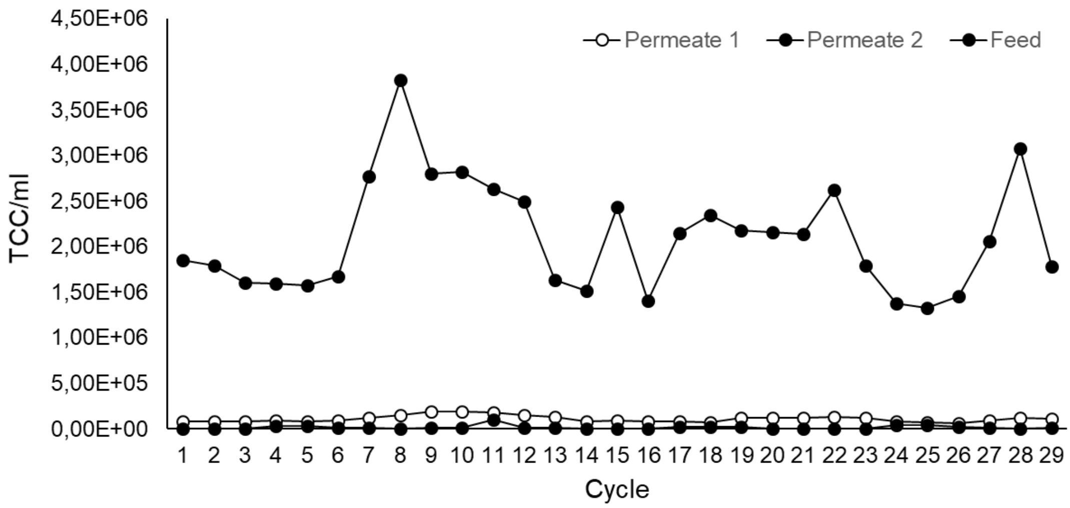

Figure 3. Continuous determination of total cell count (TCC) in flocculated Elbe river water (feed), Permeate 1 and Permeate 2 (9th-11th November 2018).

4. Discussion

In this study, the applicability of new microbiological methods for monitoring water quality parameters at RBF sites was investigated. Despite a good correlation between FCM and TEA values, several differences were observed, e. g. TEA values decreased from 25 to 23 pmol/min after sand filtration (Figure 1.), unlike the ICC trend. This could be caused by the nature of enzymatic methods. Enzymatic activity is generally bound to specific enzymatic concentration which is mostly dependent on bacterial state of growth while no information about species, size or number of a general population pattern is obtained. ALP activity is especially high in the exponential stage of growth [13]. The probability of exponential growth in smaller bacterial communities is lower due to its limited number of microbiological species which is confirmed in Figure 1. Besides concentration enzymatic processes are also dependent on specific reaction conditions which can be disturbed by interfering substances such as iron and manganese compounds. This was observed during ATP measurements in RBF well water samples (not shown in Figure 2) which usually contain higher concentrations of dissolved iron and manganese.

Furthermore, the removal of microorganisms was correlating with travel time, proven by FCM and HPC measurements for various RBF wells in Budapest. The observed log removal rates for bacteria during RBF were in agreement with average values of 1.5…3.5 [13]. Despite the short travel time of 2…5 d in BF1 the removal rate of 1.10 log units is only slightly lower than values found at other RBF sites [14,15]. No colony counts were detected by HPC or TEA (not shown in Figure 3), indicating limitations of these methods, whereas for FCM and ATP methods a low limit of detection was proven and a high efficiency to assess microbiological dynamics during RBF.

Results from the ultrafiltration pilot plant study confirmed on one hand that online sensors are of advantage for microbiological monitoring, could improve risk assessment of water treatment steps offering more frequent sampling and early warning technologies. On the other hand, the results indicate that ultrafiltration is an efficient barrier against microorganisms, especially with regard to the combination of RBF and ultrafiltration. By applying RBF as a pretreatment step for ultrafiltration, less chemicals are needed for disinfection and membrane backwashing.

Funding: All primary data was collected within the AquaNES project. This project has received funding from the European Union´s Horizon 2020 Research and Innovation Program under grant no. 689450.

Acknowledgments: The authors gratefully acknowledge support from the DREWAG NETZ GmbH, Budapest Waterworks Ltd, Hungary, microLAN B. V.

Author Contributions: Y.A. reviewed previous literature and prepared the article draft, T.G. initiated the research and acquired the funding, Y.A., G.O. and M.P. carried out measurements, R.H., R.B. and Z.N. organized sampling campaigns and operation of treatment facilities, J.A. introduced TEA measurements and provided the device, all authors reviewed the final manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

ALP: *Alkaline phosphatase*
ATP: Adenosine triphosphate
FCM: Flow cytometry
RBF: Riverbank filtration
TEA: Total enzymatic activity

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Paper for ISMAR10 symposium. ***Topic No: 11 (242#)***

Numerical modeling of pumping test data at an artificial recharge site in Kuwait

Amitabha Mukhopadhyay[1]*

[1] Water Research Centre, Kuwait Institute for Scientific Research, PO Box 24885, Safat 13109, Kuwait.
* Correspondence: amukhop@kisr.edu.kw; Tel.: +965-2498-9892

Abstract: A pilot scale injection- recovery experiment in the Dammam Formation aquifer is currently on progress at a site located in the Kabd area of Kuwait to assess the feasibility of artificial recharge of the aquifer at this site. One injection-recovery well, also called as Aquifer Storage and Recovery (ASR) well, and six monitoring wells have been drilled at the site for this purpose. Prior to the start of the experiment, a 192-hour pumping test (96 hours of pumping followed by 96 hours of recovery) has been conducted in the ASR well. The water level data collected from the ASR well and the monitoring wells have been used for the calibration of a numerical model that has been set up for the simulation of the injection-recovery experiment. The calibration process has highlighted the fractured nature of the Dammam Formation aquifer at the selected site. It has indicated that the ASR well and five of the monitoring wells are located along or close to a fracture zone. The simulation of the subsequent recharge – recovery experiment using the calibrated model has, however, suggested that the longer injection and recovery activity affects a larger volume of the aquifer resulting in the reduction of the overall influence of the fracture zone.

Keywords: Aquifer Storage and Recovery (ASR), Groundwater Management, Fractured Rock, Dammam Formation, Kuwait Group, Kuwait.

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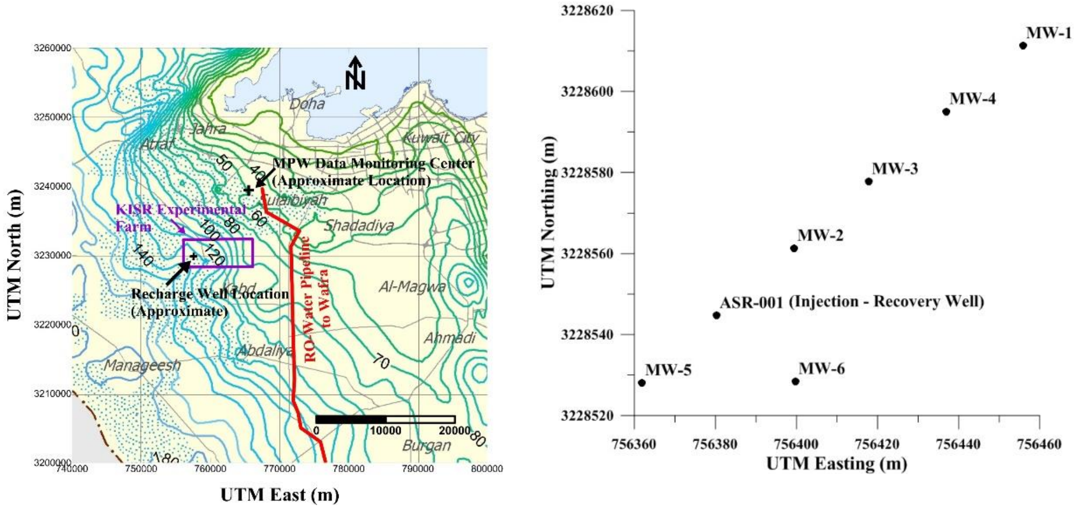
1. Introduction

A pilot scale recharge – recovery experiment through one well is currently ongoing at Kabd area of Kuwait to assess the feasibility of artificial recharge of the karstic dolomitic limestone aquifer known as the Dammam Formation. Membrane (reverse osmosis; RO) treated municipal wastewater is being used for injection. To derive the hydraulic parameters of the aquifer, a pumping test (96 hours of pumping followed by 96 hours of recovery period) with pumping at the rate of 200 Igpm (1309 m^3/d) was conducted in the injection – recovery well (designated as the Aquifer Storage and Recovery well – ASR-001) prior to the experiment. The location of the recharge site and the distribution of the wells are shown in Figure. 1. Except for the monitoring well MW-3, which was completed in the clayey aquitard constituting the lowest part of the Kuwait Group sediments overlying the Dammam Formation Aquifer, all other wells were completed within the Dammam Formation aquifer. A numerical model has been developed for the evaluation of the recharge – recovery experiment. The water level data collected from the pumping and the monitoring wells during the pumping test have been used for calibrating the model. The results are reported here.



(a)

(b)

Figure 1. (a) Location of the recharge site; and (b) arrangement of the recharge wells.

2. Materials and Methods

2.1 Site Geology and Hydrology

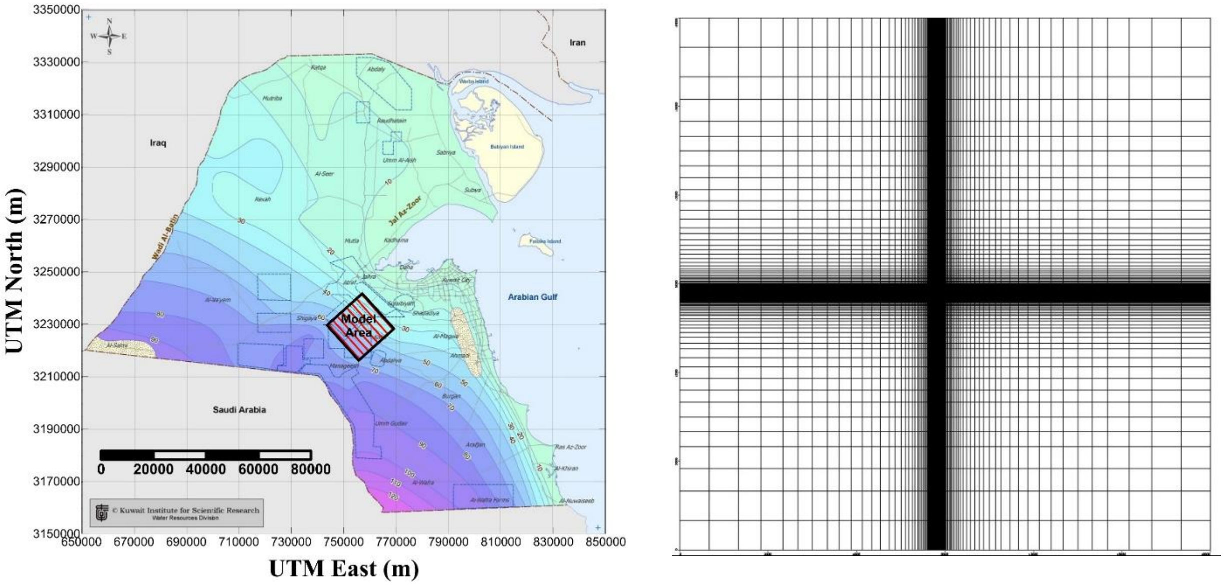
The hydrogeology of Kuwait has been discussed in details by Omar et al. [1] and Mukhopadhyay et al. [2]. At the selected recharge site, the target aquifer, the Dammam Formation, is at a depth of 195 m from the surface. It is unconformably overlain by the clastic Kuwait Group aquifer. The water level in the well is at 96 m below the surface.

2.2 Model Setup

The Classic interface of the Visual MODFLOW software (Build 4.6.9.168) [3] has been used for the modeling of the recharge – recovery experiment. A rectangular area of size 18 km x 18 km with the injection and the monitoring wells located approximately at its center has been chosen as the area to be modeled. This has allowed the modeled area boundaries to be at an enough distance to remain unaffected by the injection – recovery operation conducted at the site. The northeastern and the southwestern boundaries of the area are aligned approximately parallel to the regional equipotential lines. (Figure 2a). The area has been subdivided into 167 rows and 336 columns. The widths of the rows and the columns vary from 0.625 m near the wells to 1000 m near the model boundaries (Figure 2b). The ASR well and four monitoring wells (except Wells MW-1 and MW-6) are aligned on a row (Row No. 89). Well MW-1 is located in Row No. 90 (i.e., in the row adjacent to the one along which other five wells are located). Well MW-6, located at the intersection of Row 105 and Column 123, is transverse to the Row 89.

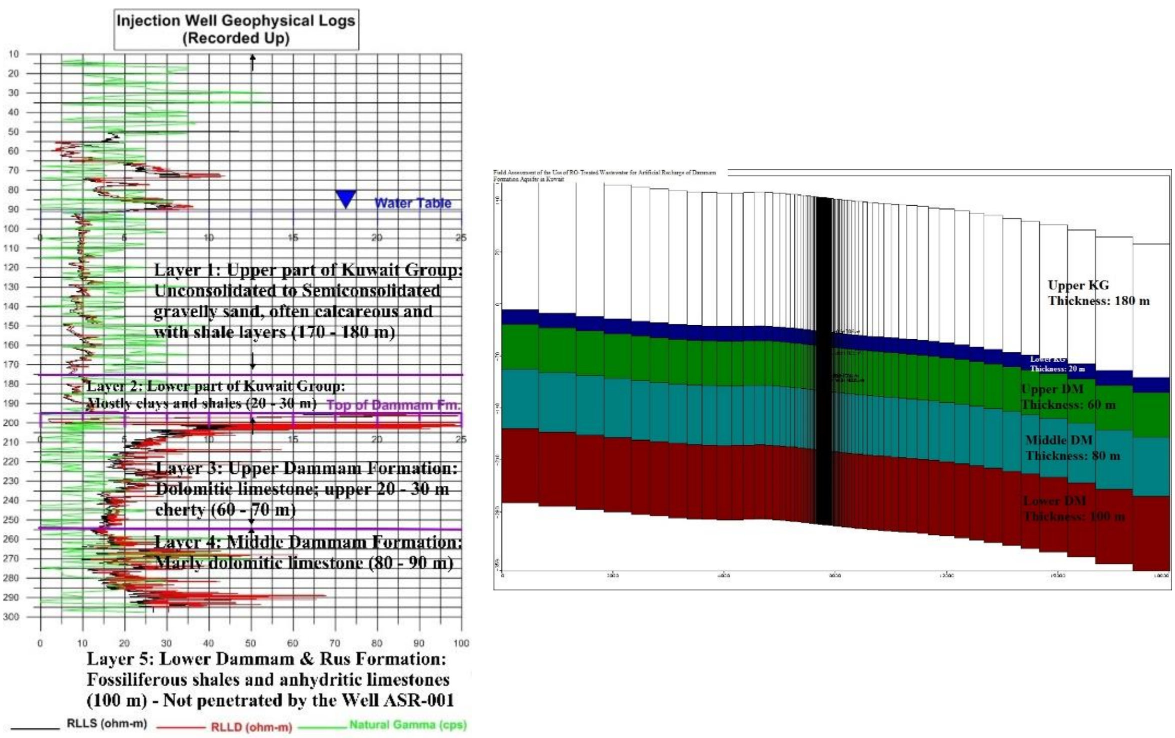
Based on the lithological and geophysical logs of the ASR well and the six monitoring wells and the conventional cores covering the Dammam Formation recovered from the well MW-6, the vertical thickness covered by the model was divided into five layers as shown in Figure 3.

Constant heads were assigned for the southwestern and the northeastern boundaries of the model and the initial heads for grid centers were based on the potentiometric heads as shown in Figure 3a. Initially, the model grid was populated with uniform hydraulic conductivity and storage coefficient values based on the interpretation of the pumping test data and numerical modeling previously carried out in Kuwait [4-8]. The model calibration mainly involved adjustment of the hydraulic conductivity and in some cases, of the storage coefficient, so that the calculated heads matched with the observed heads in the pumping and the monitoring wells during the pumping test.



(a) (b)

Figure 2. (a) The location of the modeled area with potentiometric head distribution in the targeted aquifer; (b) the model grid.



(a) (b)

Figure 3. (a) Composite geophysical log of Well ASR-001 with descriptions of the model layers; (b) Vertical layering in the model along Row No. 89.

3. Results

The hydraulic conductivity values were modified through several runs (but still keeping them within a reasonable range of the values derived from pumping test) to obtain a good match with the pumping test data. It was, however, impossible to get a reasonable match with the observed data from the observation wells even when a good match was obtained for the pumping well. The results of such a run are presented in Figure 4 and the hydraulic conductivity and the storage coefficient values used in the run are presented in Table 1.

Through many trials and errors, it was realized that to obtain a reasonable match for all the wells, the existence of a high conductive zone (fracture) connecting the pumping well with the monitoring wells MW-01, MW-02, MW-04 and MW-05 was needed to be assumed. Such a fracture zone (F – F′) that extends through the Layers 3 and 4 (Upper and Middle Dammam Formation), with high but varying hydraulic conductivity along Row 89 (width 0.625 m) is depicted in Figure 5. This is a reasonable assumption, as the Dammam Formation is known to be karstic in nature, especially in the southern parts of Kuwait [1-2]. The hydraulic conductivity values used in this run are presented in Table 1. The results of the run are presented in graphical manner in Figure 6 where the observed water levels during the pumping test are compared with the calculated heads. It can be observed that though the exact match with the individual observed water level data may not be good, the overall similarity with the trend of changes in water level as the pumping test progressed and during the recovery period, is very good in all the wells. This is further elaborated in Table 2. The results suggest that a high conductivity zone does exist more or less along the line connecting the wells MW-5, ASR-001, MW-2, MW-3, MW-4 and MW-1. In view of the various scales of heterogeneity generally present in a karstic aquifer [9], the hydrogeological model suggested for the recharge site, based on this modelling study, cannot, however, be taken as an unique one; but only as one of the most plausible ones.

The single fracture model was further adjusted with respect to the hydraulic conductivities and storage coefficients to obtain acceptable matches with the observed head variation in the injection and the monitoring wells during the four cycles of the recharge and recovery operations carried out in the ASR well. The modified hydraulic conductivities and the storage coefficients are presented in Table 1 and the results are shown in Figure 7. It can be observed from Table 1 that as the radius of influence for injection and pumping has increased with the extended period of operation, the influence of the fracture zone has diminished as indicated by the lower hydraulic conductivity required for this zone for a good match between the observed and the simulated heads.

4. Discussion

From the results presented above, it is apparent that the Dammam Formation aquifer is fractured at the recharge site and the ASR well and five of the six monitoring wells are located along or very near to one of the fracture zones. Simulation of the artificial recharge experiment using the model calibrated with the pumping test data has, however, revealed that during the artificial recharge experiment, as the pumping or injection duration increases, larger volumes of aquifer around the ASR well are affected. The rise and drawdown of the water levels in the wells under such circumstances are determined more by the conductivity values averaged over the increased radius of influence rather than the conductivity of a single fracture.

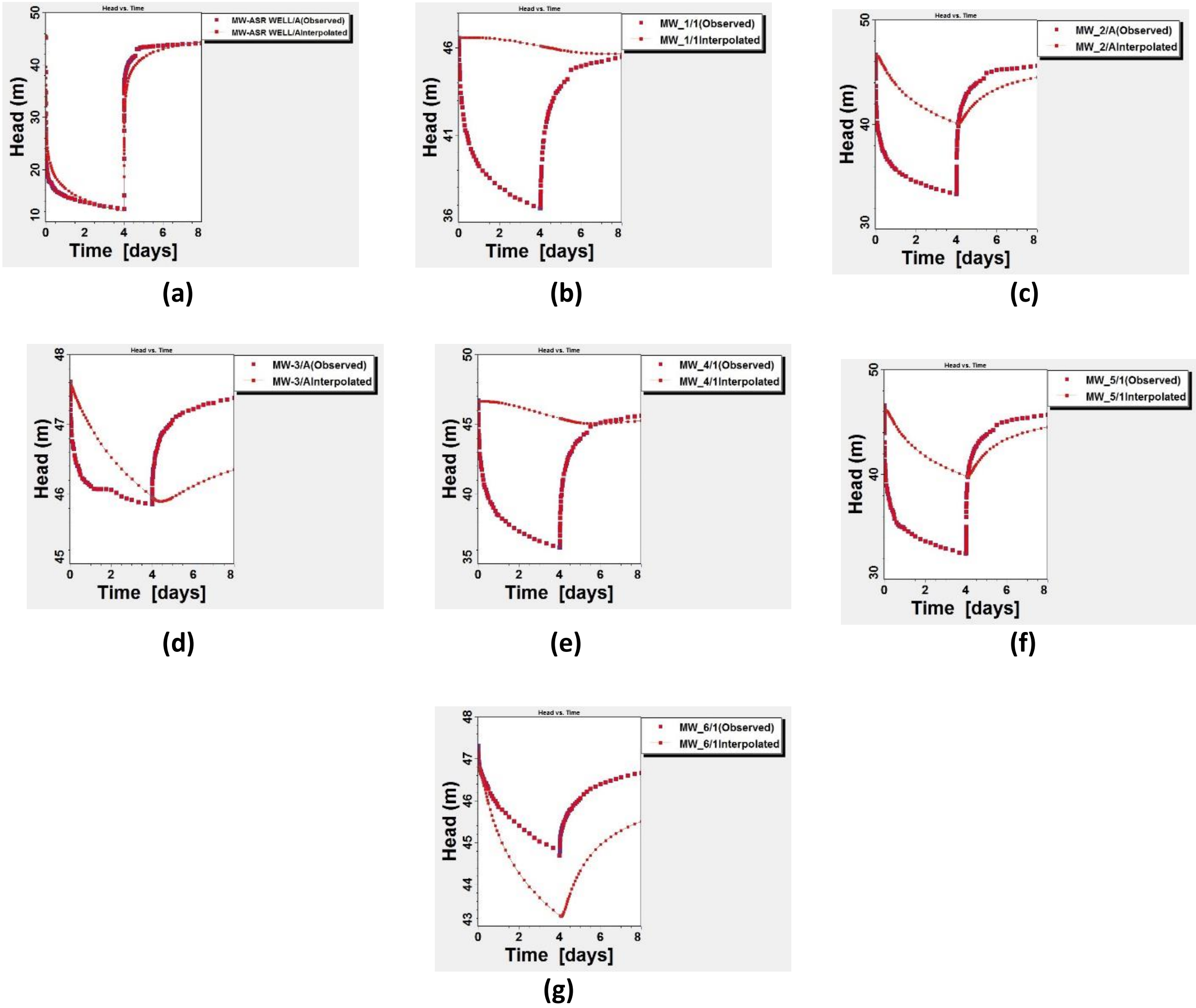


Figure 4. Observed (Unconnected Larger Red Squares) versus calculated heads (Connected Smaller Red Squares) in the wells at the pumping test site; (a) Well ASR-001; (b) Well MW-01; (c) Well MW-02; (d) Well MW-03; (e) Well MW-04; (f) Well MW-05; and (g) Well MW-06 for a run without assuming the presence of a fracture.

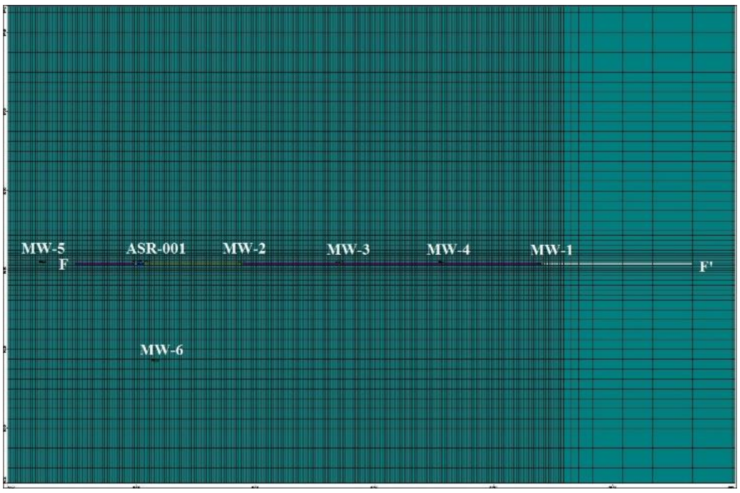


Figure 5. Model grid near the ASR well and the monitoring wells with possible distribution of high conductivity (fracture) zones.

Table 1. Calibrated Values of Hydraulic Conductivity, Specific Storage and Specific Yield for Different Model Runs for the Pilot Scale ASR Site in Kuwait

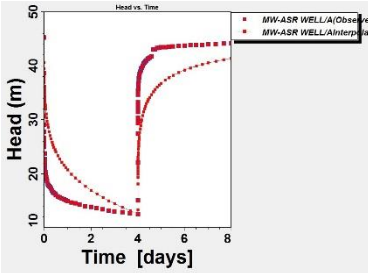
Layer/Zone	Pumping Test Run without a Fracture					Pumping Test Run with a Fracture					Injection – Recovery Run with a Fracture				
	Kx [m/d]	Ky [m/d]	Kz [m/d]	Specific Storage (1/m)	Specific Yield	Kx [m/d]	Ky [m/d]	Kz [m/d]	Specific Storage (1/m)	Specific Yield	Kx [m/d]	Ky [m/d]	Kz [m/d]	Specific Storage (1/m)	Specific Yield
Layer 1	1.5	1.5	0.15	-	0.1	1.5	1.5	0.15	-	0.1	1.5	1.5	0.15	-	0.1
Layer 2	0.0001	0.0001	1.00E-05	4.50E-08	-	0.00081	0.00081	1.40E-05	4.50E-08	-	0.0075	0.0075	0.0001	1.0E-08	-
Layer 3 (southwest)	0.2	0.2	0.02	0.0004	-	0.09	0.09	0.009	0.0004	-	0.3	0.3	0.03	1E-5	-
Layer 3 (central)	0.2	0.2	0.02	0.0004	-	0.09	0.09	0.009	0.0004	-	0.3	0.3	0.03	1.5E-5	-
Layer 3 (northeast)	0.2	0.2	0.02	0.0004	-	0.09	0.09	0.009	0.0004	-	0.08	0.08	0.008	2E-5	-
Layer 4	0.5	0.5	0.05	0.001	-	0.36	0.36	0.036	0.001	-	0.35	0.35	0.035	0.0001	0.0001
Layer 5	0.05	0.05	0.005	0.0004	-	0.05	0.05	0.05	0.0004	-	0.05	0.05	0.005	0.0004	0.0004
Fracture – Zone 1	-	-	-	-	-	100	100	0.001	*	-	10	10	0.001	*	-
Fracture - Zone 2	-	-	-	-	-	50	50	0.0005	*	-	5	5	0.0005	*	-
Fracture – Zone 3	-	-	-	-	-	18	18	0.00018	*	-	2.5	2.5	0.00025	*	-
Fracture – Zone 4	-	-	-	-	-	0.9	0.9	0.00009	*	-	0.8	0.8	0.00008	*	-
Fracture – Zone 5	-	-	-	-	-	0.5	0.5	0.00005	*	-	-	-	-	-	-

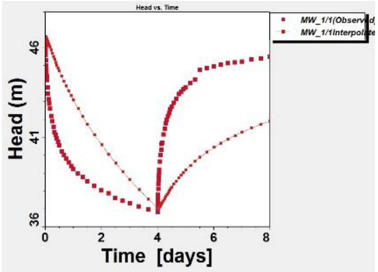
* The specific storage in the fracture zones have been assumed to be the same as for the layer in which the fracture is located though it may not be strictly correct

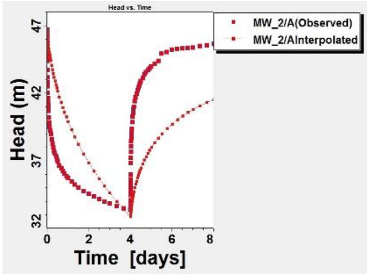
Table 2. Statistical Data on Runs with and without the Assumption of the Presence of a Fracture

Well Name	Run without Fracture									Run with Fracture								
	No. of Data Points	Max. Residual (m)	Min. Residual (m)	Residual Mean (m)	Abs. Residual Mean (m)	Standard Error of the Estimate (m)	Root Mean Square (m)	Norm. RMS (%)	Corr. Coeff.	No. of Data Points	Max. Residual (m)	Min. Residual (m)	Residual Mean (m)	Abs. Residual Mean (m)	Standard Error of the Estimate (m)	Root Mean Square (m)	Norm. RMS (%)	Corr. Coeff.
ASR-001	1020	-7.927	0.004	0.05	3.483	0.132	4.21	12.976	**0.929**	1020	13.032	0.024	0.017	8.062	0.275	8.794	27.102	**0.625**
MW-01	1020	9.286	0.012	4.661	4.661	0.103	5.697	58.433	**0.091**	1020	-4.892	-0.005	-0.238	2.451	0.093	2.98	30.563	**0.664**
MW-02	1020	8.309	0.001	3.214	4.06	0.118	4.947	37.206	**0.431**	1020	-6.498	-0.001	-0.707	4.043	0.139	4.496	33.811	**0.529**
MW-03	1020	-1.134	0	-0.049	0.581	0.022	0.691	39.48	**0.415**	1020	-1.31	0	-0.123	0.627	0.023	0.75	42.887	**0.386**
MW-04	1020	9.261	0.001	4.571	4.601	0.106	5.685	54.096	**0.168**	1020	-5.425	0	-0.507	2.943	0.108	3.485	33.163	**0.606**
MW-05	1020	9.115	-0.005	3.438	4.29	0.126	5.29	37.53	**0.41**	1020	-7.989	-0.005	-0.726	4.665	0.163	5.262	37.355	**0.452**
MW-06	1020	-2.149	-0.008	-1.119	1.119	0.023	1.34	51.146	**0.938**	1020	-0.997	0	-0.4	0.426	0.012	0.552	21.058	**0.907**
All Wells	5100	9.286	0.001	3.187	4.219	0.057	5.195	15.221	**0.861**	5100	13.032	0	-0.432	4.433	0.075	5.408	15.845	**0.737**
Monitoring Wells only	4080	9.286	0.001	3.971	4.403	0.058	5.414	38.058	**0.402**	4080	-7.989	0	-0.544	3.525	0.064	4.151	29.182	**0.568**

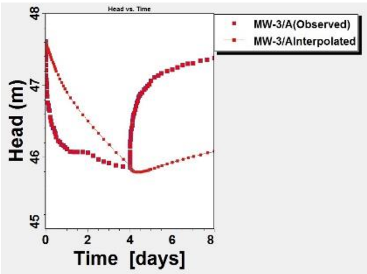
It may be observed from Table 2 that with the assumption of a fracture, though the quality of the match between the observed and the calculated heads deteriorated to some extent for the wells ASR-001, MW-03 and MW-06, the match quality improved moderately to substantially for the wells MW-01, MW-02, MW-04 and MW-05. The overall match between the observed and the model calculated head values for the monitoring wells, however, improved with the assumption of the presence of a fracture (as can be seen from the last two rows of the table) if the Well ASR-001 is not considered

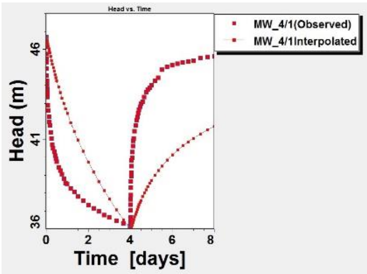


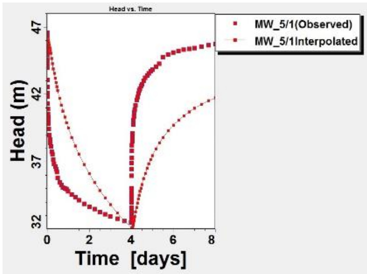




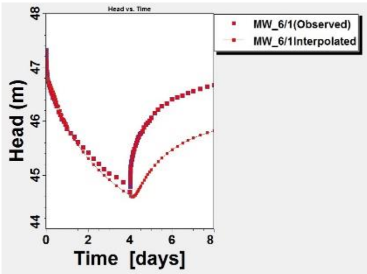
(a) **(b)** **(c)**





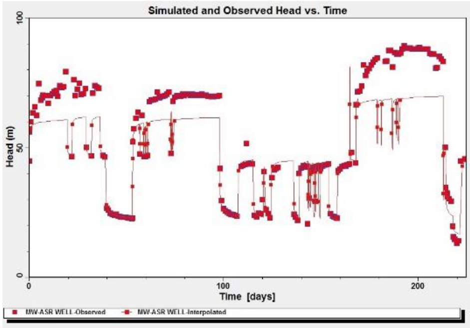


(d) **(e)** **(f)**



(g)

Figure 6. Observed (Unconnected Larger Red Squares) versus calculated heads (Connected Smaller Red Squares) in the wells at the pumping test site; (a) Well ASR-001; (b) Well MW-01; (c) Well MW-02; (d) Well MW-03; (e) Well MW-04; (f) Well MW-05; and (g) Well MW-06 for a run with the assumption of the presence of a fracture zone along Row 89.



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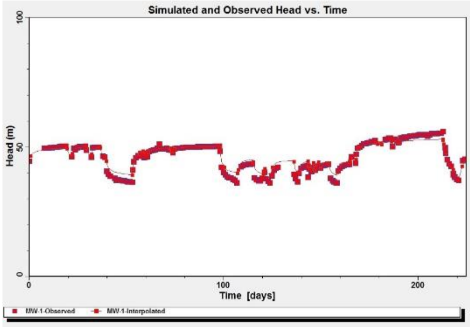

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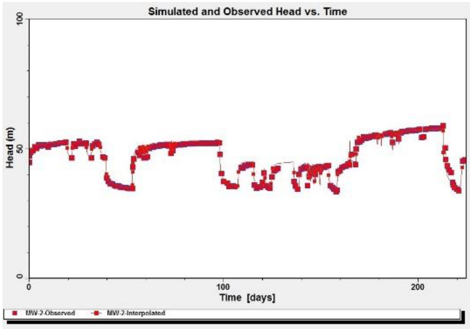

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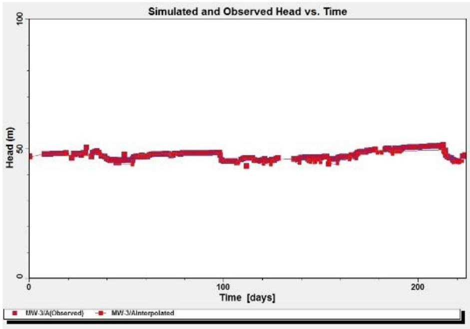

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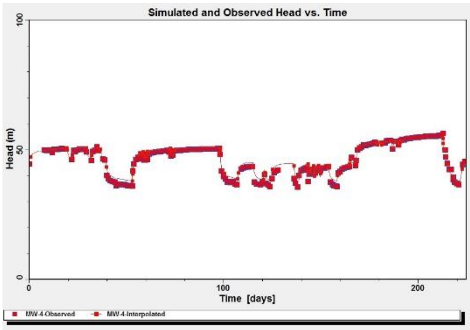

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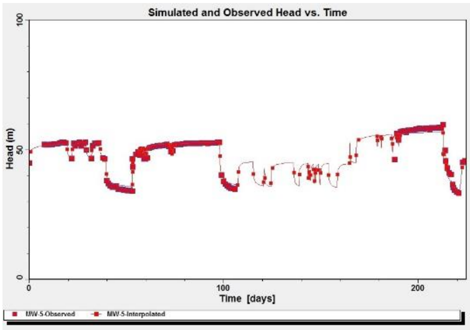

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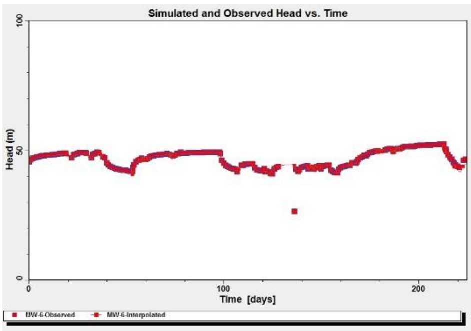

(g)

Figure 7. Observed (Blue Triangles) versus simulated heads (Red Squares) against time in the wells at the recharge site during the injection – recovery experiment using the modified single fracture model; (a) Well ASR-001; (b) Well MW-01; (c) Well MW-02; (d) Well MW-03; (e) Well MW-04; (f) Well MW-05; and (g) Well MW-06. The heads in Well ASR-001 are higher than the simulated ones because of possible air clogging, as the injection pipe could not be kept full due to inadequate supply of water. The possibility of clogging from fine particles or biofilms/crusts was less as the RO process removed most of the fine particles and microbes and the injection water passed through a sand filter before reaching the wellhead.

In view of the above, for the planning of a long-term recharge – recovery operation, an estimated weighted hydraulic conductivity of a fractured aquifer should possibly be enough. During the implementation of a full scale aquifer recharge field in a fractured aquifer, it would be, however, advisable to develop the field in steps through assessment of the hydraulic conditions (including locations, trends and density of fractures) and the extent of mixing of the injected and the native groundwater around the last batch of the recharge wells drilled. The numerical model should be updated at every step with the data from the previous cycles of injection and recovery. The planning of the next series of step-off recharge-recovery wells around the existing ones should be done, based on this assessment and results of the model runs.

Acknowledgments: This study has been undertaken under the Water Resources Development and Management (WRDM) Program of the Water Research Centre (WRC) of Kuwait Institute for Scientific Research (KISR) and partially funded by the Ministry of Electricity and Water (MEW), Kuwait (Contract Number: 4616-2013/2014). No fund has, however, been granted for the publication of the article in an open access journal. The permissions for the publication of the paper from the managements of MEW and KISR are gratefully acknowledged.

Conflicts of Interest: The author declares that there is no conflict of interest. The funding sponsor (MEW) had no role in the design of the study, in the collection, analyses, or interpretation of data and in the writing of the manuscript. It has, however, given permission to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
ASR: Aquifer Storage and Recovery
KISR: Kuwait Institute for Scientific Research
MEW: Ministry of Electricity and Water
WRC: Water Research Center
WRDM: Water Resources Development and Management.

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Topic 12. MAR AND MODELING

Paper for ISMAR10 symposium. ***Topic No: 12 (148#)***

Smart framework for real-time monitoring and control of subsurface processes in managed aquifer recharge applications: project outlook

Jana Glass[1*]; Catalin Stefan[1]; Christoph Sprenger[2]; Ronjon Chakrabarti[3]; Suzana Montenegro[4]; Cristiano Almeida[5]; Panos Papanastasiou[6]; Stylianou Marinos[6]; Jean-Christoph Maréchal[7]; Thomas Schneider[8]; Alexandre Duzan[9] and Géraldine Picot-Colbeaux[7]

[1] Research Group INOWAS, Department of Hydrosciences, Technische Universität Dresden, Germany
[2] Berlin Centre of Competence for Water gGmbH, Berlin, Germany
[3] adelphi research gGmbH, Berlin, Germany
[4] Federal University of Pernambuco, Department of Civil Engineering, Recife, Brazil
[5] Universidade Federal da Paraíba, Department of Civil and Environmental Engineering, João Pessoa, Brazil
[6] University of Cyprus, Nireas- IWRC and Department of Civil and Environmental Engineering, Cyprus
[7] BRGM, French Geological Survey, Montpellier, France
[8] Umwelt- und Ingenieurtechnik GmbH, Dresden, Germany
[9] SUEZ Eau France, Hyères les Palmiers, France
***** Correspondence: jana.glass@tu-dresden.de; Tel.: +49351 46344146

Abstract: Despite its financial and ecological benefits, the contribution of MAR to safe water supply at global scale is still limited due to various reasons. Especially the lack of data on associated risks and the absence of proper monitoring at some MAR facilities reduces the level of public trust, raises questions about the impact of MAR on the affected ecosystem and hinders the optimal operational management. An efficient control of the recharge and recovery processes through simulation-based optimization and control incorporating real-time data would allow water operators to optimize the performance of MAR systems while satisfying economic and environmental constraints. The main objective of the EU-funded project SMART-Control is to reduce the risks in the application of sustainable groundwater management techniques through the development and implementation of an innovative web-based, real-time monitoring and control system in combination with risk assessment and management tools which will allow improving the implementation, management and operational capabilities of MAR facilities. The SMART-Control approach encompasses research, piloting, demonstration, training and technology transfer in one framework where tools developed in previous and ongoing European projects will be enhanced. The core of the project consists of the web-based INOWAS platform, where various analytical and numerical tools for MAR assessment are compiled and which will be enhanced with additional features to assess, monitor and control the occurring processes at MAR facilities. The approach will be tested at six pilot and full-scale MAR schemes in Germany, France, Cyprus and Brazil which ensures that the framework can be applied to various environmental and operational conditions to improve integrated water resources management techniques. SMART-Control will show that despite MAR is a nature-based solution, risks associated with the implementation and operation can be managed and controlled and it will demonstrate that MAR is a safe and reliable technique for integrated water resources management. The web-based platform offers a new scientific approach to analyse the relevant processes in real-time which enables the up-to-date diagnostic for operators, regulators and water managers.

Keywords: Managed aquifer recharge, web-based tools, real-time monitoring and control, risk assessment and management.

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1. Introduction

Enhancing groundwater recharge by storing surplus water in the subsurface in times of high availability followed by recovery in times of high demand represents a low cost technology that increases the resilience of water supply infrastructures to extreme hydro-climatic events. This technique, referred to as managed aquifer recharge (MAR), represents a viable adaptation solution for sustainable water resources management while it reduces the impact of water scarcity by increasing seasonal water availability. MAR can improve food security and reduce harvest failure risks as the resilience against extreme weather events such as droughts is increased. MAR is successfully applied worldwide for the restoration of affected groundwater-dependent ecosystem services [1], including: freshwater production and availability, flood mitigation, prevention of saltwater intrusion, restoration of depleted aquifers, seasonal water storage, improvement of water quality, land renaturation, as well as increasing the aesthetic values of water bodies. In Europe, MAR plays an important role in the development of water supply systems and contributes substantially to the drinking-water production. In Germany, 59 active MAR schemes produce about 750 Mm^3 of freshwater per year, mainly through river bank filtration and direct surface infiltration [2]. In France, the main objective of MAR is to sustain overexploited groundwater aquifers and partially to improve the groundwater quality by infiltration of surface water into polluted or brackish aquifers [3]. Besides Europe, MAR is also widely applied in Australia and the USA while the implementation in Asia, Africa and Latin America is rather low. A recent research initiative in Brazil (BRAMAR) suggests that water reclamation solutions can be applied against water scarcity in the semiarid north-eastern part of the country while rainwater harvesting and subsurface storage could reduce urban runoff and subsequently contribute to flood mitigation.

Despite its financial and ecological benefits, the contribution of MAR to safe water supply at global scale is still limited. The reasons include lack of data on MAR technological costs, hydrogeological site-specific characteristics, the associated risks with operational challenges (e.g. unpredictable quality and quantity of the recharged and recovered water) and the lack of national regulations. Additionally, the absence of proper monitoring at some MAR facilities reduces the level of public trust, raises questions about the impact of MAR on the affected ecosystem and hinders the optimal operational management. Thus, an efficient control of the recharge and recovery processes through simulation-based optimization and control incorporating real-time data would allow water operators to maximize the use of groundwater while satisfying physical, financial, and sustainability constraints.

The critical operational component of MAR systems is the interaction between the infiltrating water and the aquifer. Previous studies investigated the risk associated with the removal of pathogens during storage, the behaviour of organic compounds, the chemical processes influencing the recovered water quality and the reduction of infiltration capacity due to clogging [4–8]. These studies mainly focused on specific risks but it is of paramount importance to assess and manage the arising risks holistically at different implementation stages. The Australian MAR guidelines [9] regulate the risk assessment requirements at the planning stage of MAR facilities and have already been applied outside Australia, e.g. in Berlin. The guidelines provide an excellent basis that can be used to develop risk management frameworks worldwide and advise the application of numerical models to adequately assess the arising risks [10]. However, the lack of detailed and up-to-date data monitoring hinders reliable model setup and calibration for risk assessment in nature-based systems such as MAR facilities. The implementation of real-time monitoring and control systems (RMCS) will therefore enable the assessment and management of risks at MAR sites and decrease model uncertainties.

Within the last two decades, RMCS have been used to improve efficiency in monitoring and management of water quantity and quality, to assess the efficiency of water networks in real-time, to avoid leakage losses and to minimize risk of inadequate water quality [11]. Up to date, the application of RMCS in MAR systems is scarce. Recently, an algorithm was developed to facilitate the operational challenges of MAR systems conducted in a small 2D synthetic aquifer at laboratory scale using near real-time data which enabled improved control [12]. At field scale, supervisory control and data acquisition (SCADA) is used in the Bolivar aquifer storage and recovery scheme, in Australia [13]. Safety approaches for drinking water supply systems are moving from substance-based monitoring to risk assessment and management (RAM, e.g. WHO Water Safety Plans [14]). Application of quantitative microbial risk assessment, sometimes perceived as rather complicated, can be a hurdle especially at smaller utilities where expert knowledge is lacking. These previous works demonstrate that RMCS is a suitable and necessary tool to assess and manage the risks in MAR schemes. The combination of RMCS with RAM tools, modelling and prediction in a generic, open-source and web-based framework as proposed in SMART-Control improves the management and operation of MAR schemes, helps in the assessment of site-specific risks and reduces the risk of failure.

2. The SMART-Control framework

The SMART-Control approach encompasses research, piloting, demonstration, training and technology transfer in one framework to reduce MAR-associated risks and promote MAR as a safe and reliable technology for water resources management. In the frame of SMART-Control, tools developed in previous and ongoing European projects will be enhanced. The core of the project consists of the web-based INOWAS platform[1], where a range of tools with various complexities for MAR assessment are compiled [15,16] and will be enhanced with additional features to assess, monitor and control the occurring processes at MAR facilities (Fig.1).

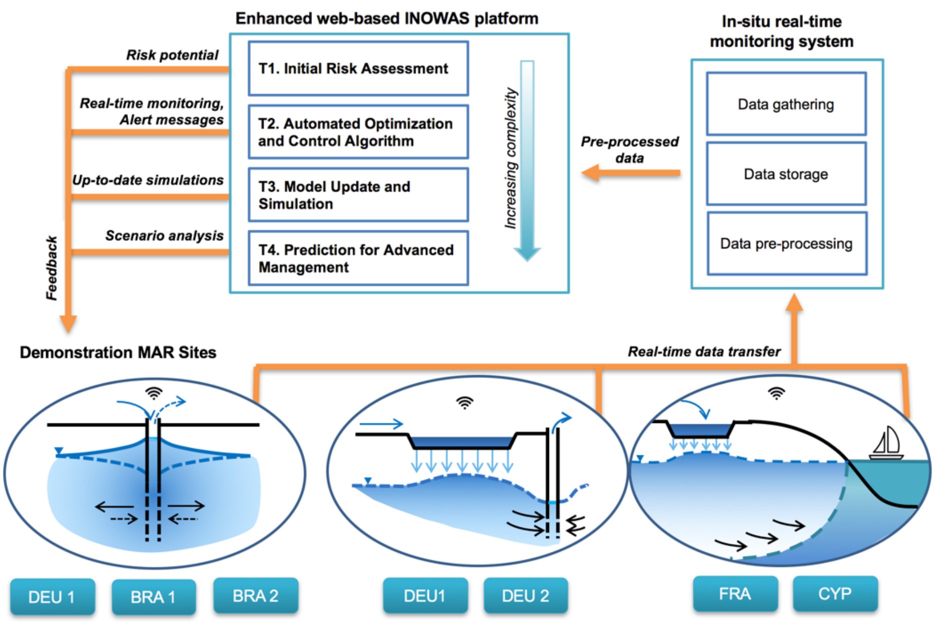

Figure 1. RMCS concept within SMART-Control including the various components of the approach (online sensors, real-time monitoring system, web-based platform) and the MAR demonstration sites.

[1] https://www.inowas.com/

2.1 Web-based INOWAS platform

The INOWAS platform is a free web-service to provide solutions for groundwater-related issues with a special focus on MAR. The web-based platform comprises of various data-driven, analytical and numerical tools and allows for account-based simulations via standard web browsers. The tools are accompanied by a detailed online documentation, example applications and comprehensive background information. For a detailed description of the platform and example analytical tools, see [15] and for the MODFLOW-based numerical tools see [16].

In the frame of SMART-Control, the INOWAS platform will be enhanced with tools of different complexity that foster the real-time monitoring and control of MAR facilities. The initial risk assessment tool (T1), based on guidelines and literature values, will help to evaluate the risk a priori and suggest measures to reduce the risk. Online sensors will be coupled with the real-time monitoring system to collect, store and pre-process the relevant parameters. The tool for automated optimization and control facilitates real-time management and operation of the MAR facility (T2). Besides data visualization, the tool will integrate basic decision rules and control algorithms to identify occurring risks at a MAR scheme. Numerical models are frequently used to plan, optimize and assess MAR facilities [10] but optimal use of modelling results is hindered as models are not frequently calibrated and compared to present observation data. The innovative model update and simulation module (T3) will overcome this issue by integrating real-time observation data into the web-based modelling framework allowing for up-to-date simulations. The prediction for advanced management tool (T4) goes one step further integrating climate change and development scenarios into the scenario analysis.

With the development of open source and web-based tools in combination with real-time monitoring, risk assessment at MAR facilities can be improved. The online sensors measure various operational and water quality parameters including e.g. infiltration water volume, groundwater level, temperature, electrical conductivity, microbial content, chemical oxygen demand, nitrate, total suspended solids and dissolved organic carbon. These parameters encompass the most common operational, chemical and biological parameters that influence the risk at MAR facilities depending on the individual system setup.

2.2 Case study sites

The SMART-Control approach will be first implemented and tested at the pilot MAR facility in Pirna, Germany. The concept will then be deployed and adapted to five additional pilot and full-scale MAR schemes in Germany, France, Cyprus and Brazil encompassing various environmental, socio-economic and technological characteristics to demonstrate the wide applicability of the approach (Table 1).

Table 1. Overview of case study sites including specific objectives and applied modules of the SMART-Control approach.

Case Study	MAR type	T1	T2	T3	T4	SMART-Control objective
Pirna, Germany (DEU1)	ASR well, infiltration pond	x	x	x	x	RMCS system setup, testing and calibration; influence of recharge on water dynamics
Berlin, Germany (DEU2)	Infiltration ponds		x			combination of real-time monitoring of subsurface residence times with high-resolution microbial dynamics
Aquarenova, France (FRA)	Infiltration ponds		x	x	x	prevent saltwater intrusion and monitor saltwater wedge at the Gapeau riverbank
Ezousas, Cyprus (CYP)	Infiltration ponds		x	x	x	setup continuous monitoring system: locate saltwater interface,

				monitor water quality (nitrate)
João Pessoa, Brazil (BRA1)	ASR well	x	x	setup continuous monitoring system: reduce surface runoff during flooding
Recife, Brazil (BRA2)	ASR well	x	x	setup continuous monitoring system: mitigate saltwater intrusion, extreme climatic events

The pilot-scale scheme in Pirna, Germany (DEU1) consists of a small-scale infiltration pond [17] and ASR wells that will be used for system setup, testing and validation of the real-time monitoring and control system as well as of the developed tools.

The full-scale scheme at Berlin, Germany (DEU2) infiltrates pre-treated water from the Havel River in infiltration ponds to increase water supply capacity. At the case study site, the project will focus on real-time microbiological risk assessment using an innovative, fully automated online flow cytometry system. The specific objective is to combine real-time monitoring of subsurface residence times with high-resolution microbial dynamics, both influenced by natural and operational events in a groundwater well used for drinking water production.

The full-scale scheme at Aquarenova, France (FRA) infiltrates water from Roubaud River in the alluvial aquifer to prevent saltwater intrusion induced by excessive water pumping in Hyères-les-Palmier city. The already existing monitoring system will be extended to account for real-time data transfer and to study the saltwater wedge on the left bank of the Gapeau river, which dynamics is so far only poorly understood.

The full-scale scheme at Ezousas, Cyprus (CYP) infiltrates tertiary treated wastewater through ponds to mitigate saltwater intrusion and increase the freshwater availability for irrigation. The MAR facility is currently only monitored manually and within SMART-Control, continuous monitoring using the RMCS will be setup. The specific objectives are to continuously monitor the effect of MAR on saltwater intrusion as well as the local water quality especially with respect to nitrate. Laboratory analysis of e.g. pathogens and heavy metals (copper) will accompany the online monitoring.

The pilot MAR scheme in João Pessoa, Paraiba (BRA1) consists of one ASR well to mitigate extreme climatic events through rainwater harvesting and infiltration into the unconfined aquifer. As no monitoring system exists so far, a RMCS will be installed within SMART-Control to monitor basic operational and water quality parameters.

The pilot MAR scheme in Recife, Pernambuco, Brazil (BRA2) is currently being developed . An ASR well will infiltrate pre-treated rainwater harvested from building roofs into the confined coastal aquifer to reduce the effects of flood events in the urban district as well as saltwater intrusion. Within SMART-Control, the RMCS system will be setup to continuously monitor electrical conductivity and groundwater levels to evaluate the influence of the effect of the tide on the hydraulic load variation and to develop a sustainable groundwater management concept.

The variety of case studies ensures that the SMART-Control approach is applicable to a wide range of MAR facilities and easily adaptable to the local requirements.

3. Outlook and Conclusions

The web-based platform comprises the main outcome of SMART-Control and will include various tools for monitoring, modelling and risk assessment of MAR facilities. The developed tools span various complexities (literature guidelines to numerical modelling and prediction) to cover the demand at a wide range of facilities and will be tested at six MAR plants. In addition, training material will include publicly available online documentation pages and user manuals for the various features of the web-based platform to eliminate application barriers for multiple beneficiaries. The training of end-users and stakeholders through workshops in the participating countries ensures the application of the web-based platform.

A guideline on the transfer of the SMART-Control approach including a cost-benefit analysis (CBA) and a technological transfer concept will allow system operators to quantify the site-specific benefits of the implementation of an advanced monitoring and control concept.

Acknowledgments: The authors would like to thank the EU and the German Federal Ministry of Education and Research (BMBF), the French National Research Agency (ANR), the Paraíba Research Foundation (FAPESQ), the Pernambuco Research Foundation (FACEPE) and the Cyprus Research Promotion Foundation (RPF) for funding in the frame of the collaborative international Consortium SMART-Control financed under the 2017 Joint call developed by the Water Challenges for a Changing World Joint Programme Initiative (Water JPI).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:
ASR: Aquifer storage and recovery
MAR: Managed Aquifer Recharge
RMCS: Real-time monitoring and control system
RAM: risk assessment and management
SCADA: Supervisory Control And Data Acquisition
WHO: World Health Organization

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Paper for ISMAR10 symposium. ***Topic No: 12 (158#)***

Groundwater recharge estimation for sustainable development of groundwater in Kandi Belt of Jammu, India

Vivekanand Singh[1]

[1]Professor, Department of Civil Engineering, National Institute of Technology Patna, Patna, Bihar 800005, India
* vsingh@nitp.ac.in, Tel: +91 7544006310

Abstract: In this paper, groundwater recharge is estimated using soil moisture modelling of unsaturated zone in Kandi belt of Jammu, India. Entire Kandi belt suffers from water scarcity and ground water table is deep. This model considers the subsurface flow component along with the evapotranspiration from the crop or actual evaporation from soil and vegetative covers. The subsurface flow component is represented using one-dimensional Richard's equation with root water uptake as the evapotranspiration from crop. The root water uptake is calculated considering the crop coefficient, potential evaporation, and soil moisture available at different depth and the distribution of the root density along the root zone depth. Conceptualizing the unsaturated zone depth as a vertical soil column comprised of number of cells, in which flow calculated using Darcy's law for the unsaturated flow from one cell to another takes place in accordance with the gradient of the suction head. The unsaturated hydraulic conductivity in such case is computed at the cell face. A strongly implicit finite-difference procedure is used to solve the subsurface flow equation with the suitable initial and boundary conditions. The model is used to simulate a single soil column having different soils (sandy loam, Silty loam and loam) in Kandi belt of Jammu (J & K). Groundwater recharge is estimated for one complete crop year with daily rainfall and pan evaporation data of Jammu. The results show a considerable improvement over the existing method of estimation of groundwater recharge.

Keywords: Groundwater Recharge, Kandi belt of Jammu, Root water uptake, Soil moisture modeling, Numerical modeling.

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1. Introduction

The submontane region of the Himalayas fringing, the Siwalik hills, termed as Bhabhar or Kandi, is a steeply sloping belt of less than 10 to 30 km width, extending discontinuously from Jammu and Kashmir to Assam in India. The tract lying in the outer Himalayas of Jammu division of Jammu and Kashmir, (Fig. 1), is an extension of the Kandi belt in the states of Himachal Pradesh, Punjab, Haryana, and Uttrakhand of India. Towards south and southeast of the Siwalik range, the soil material becomes finer grading from gravel and sand to silt and clay. This gradation of the material to fine sediment almost marks the southern limit of this tract. Hill torrents contain water only during freshets and run dry for most of the time. Vast stretch of boulders and dry streambeds present a very dry look to this tract. On account of its dry look, the tract is locally known as the Kandi belt.

Population in the entire Kandi belt suffers from water scarcity and groundwater table is deep. Agriculture is uneconomic because of poor soils and low moisture content. Groundwater recharge may be the possible solution to cope up this problem in Kandi belt of Jammu. For this purpose, groundwater recharge has to be estimated from this region. Groundwater recharge estimation also plays a crucial role in evaluating weather and climate change, global water cycle, effective management of water resources, agricultural practice and irrigation planning.

Numerous recharge estimation techniques are proposed in the literature with varying degree of success. Most common among them are analysis of saturated and unsaturated zones, water budget considering water table fluctuations, watershed modelling [1]. These models can generally classify as saturated zone, unsaturated zone and surface water based focus of study [2], and can estimate using numerical technique, physical technique and tracer techniques [1]. The saturated models provide the actual groundwater recharge and integrated over large areas but often not reliable [3]. Whereas, unsaturated models provide potential recharge information over a small scale in arid and semiarid regions having thick vadose zone. Even though tracer technique and physical technique provide most reliable recharge estimation, the numerical unsaturated zone modeling got a good attention in recent times [2,4]. Groundwater recharge through the unsaturated zone of a cropped field has been simulated considering that the excess water after the moisture holding capacity of soil, which drains below the root zone reaches the groundwater table [5]. The objective of this study is to estimate the groundwater recharge using soil moisture modelling of single soil column in each type of soil and each type of land use in unsaturated zone and integrate for the entire region for complete year in Kandi belt of Jammu.

2. Study Area

The Kandi belt is the foothill zone of the Siwalik of Jammu and Kashmir. This belt stretches between longitude 74° 21′ to 75° 45′ E and latitude 32° 22′ to 32° 55′ N, except in the west portion, where it lies between latitude 32° 50′ to 33° N. The Kandi belt in J&K is extended between River Ravi in the East and Munawar Tawi on the West within the Jammu and Kathua district as shown in Fig. 1. It lies at the altitude between 300 and 490m above mean sea level.

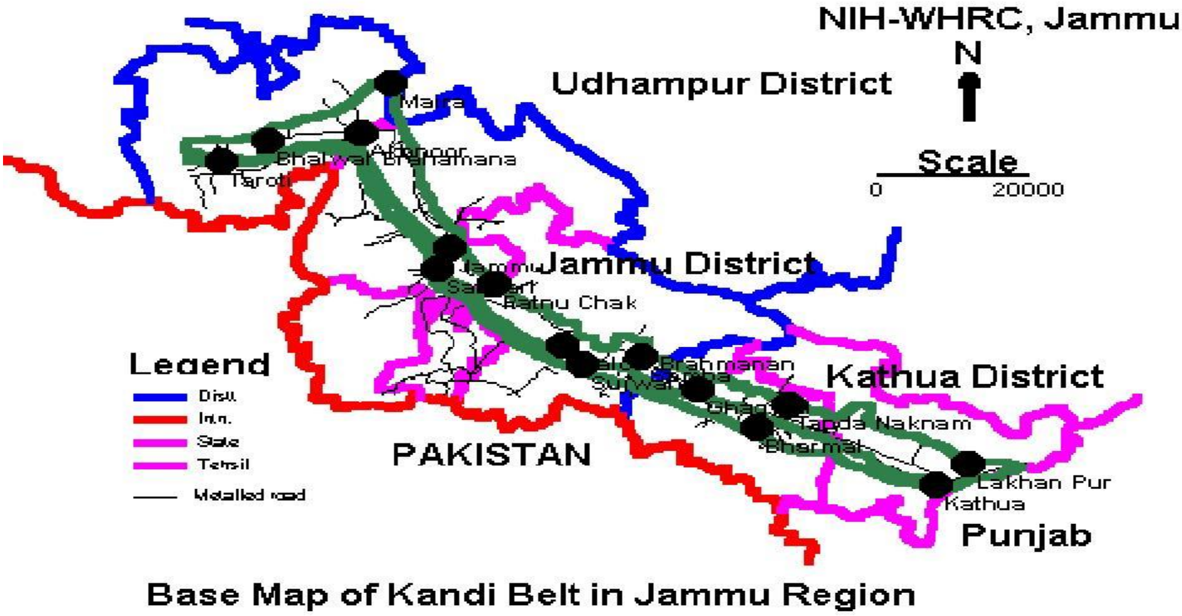

Figure 1: Base map of Kandi Belt in Jammu Region.

Total area of Kandi belt of Jammu is 812 km^2 out of which 499 km^2 is in Jammu and 313 km^2T is in Kathua districts. The Kandi belt experiences subtropical climate, where summers are very hot and winters are cold and dry. Within a year, pan evaporation varies between less than 1 mm/day in January to about 9 mm/day in June. The average annual rainfall is about 1373 mm, of which about 70% is received during the monsoon period, i.e. from June to September. Winter rains are received during January to March due to western disturbances. The area of the different soil types have been given in Table 1. In this study, three types of soil are considered namely sandy loam, silty loam and loam.

Table 1: Types of soil in Kandi belt with area.

S. No.	From Literature		Considered in this Study	
	Soil Types	Area (km^2)	Soil Types	Area (km^2)
1	Sandy Loam	545.96	Sandy Loam	545.96
2	Silty Loam	101.63	Silty Loam	101.63
3	Loam	10.27	Loam	164.41
4	Fine Loam	43.81		
5	Fine Sand	44.09		
6	Alluvium	66.24		
Total Area		812		812

3. Methodology

The movement of soil moisture in unsaturated zone is simulated using one-dimensional mixed form of the Richards equation for subsurface flow in vertical direction with the sink term to account evapotranspiration from the crops. Evapotranspiration from the crops is computed using potential evapotranspiration, crop coefficient, soil moisture status and variation of root density along depth.

3.1 Governing Equations

Special and temporal movement of soil moisture through the unsaturated zone is governed by the mixed form of 1D-Richard's equation, [6]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right)\right] + S(z,t) \qquad (1)$$

in which, θ = volumetric moisture content; ψ = pressure/suction head (cm); and K(ψ)= unsaturated hydraulic conductivity (cm/h); which depends on the suction head, ψ; S(z,t) = Sink term representing the rate of withdrawal of water per unit volume of the soil; and z is distance along z-direction and is taken positive downwards.

A strongly implicit finite-difference scheme [7,8] for the mixed-based formulation of the Richards equation is used to solve the governing equation with suitable initial and boundary conditions. This scheme ensures mass balance in its solution regardless of time step size and nodal spacing, and has no limitations when applied to field problems [9]. It is also easy to incorporate different types of boundary conditions in this scheme.

3.2 Initial and Boundary Conditions

An arbitrary value of soil moisture content as initial condition is selected. Corresponding pressure head and unsaturated hydraulic conductivity (computed using the characteristic relationships) is also specified at all the nodes as the initial conditions,

$$\theta(z,t) = \theta_{ini} \qquad for\ z \geq 0, t = 0 \qquad (2)$$

The depth of irrigation and rainfall and transpiration from the surface is defined as the upper boundary condition. For the subsurface flow resulting from irrigation and rainfall infiltration, the upper BC will change with time. During the initial stage of irrigation/precipitation, a specified depth of ponding ψ (x) = h(x) = depth of water) is considered. Let the imposed pressure head at the surface of ground for the flow domain is ψ_b. The above pressure head ψ_b is used along with the pressure head of first node ψ_1 and pressure head at the second node ψ_2 in the direction of z-axis for the determination of the ground surface flux as given below,

$$V_z\Big|_{z=0} = -K(\psi_b)\left\{\frac{(-8\psi_b + 9\psi_1 - \psi_2)}{3\Delta z}\right\} \qquad (3)$$

When all water gets infiltrated into soil then the upper boundary is changed to the flux type boundary. The flux boundary is taken as the irrigation and rainfall infiltration and actual rate of evaporation at the first node near the ground surface.

For Lower boundary the suction head, ψ values at the bottom are obtained using a simple extrapolation from the interior points if the water table is deep. If the water table is shallow (at the bottom) then the phreatic surface acts as bottom boundary of the system and the pressure head is equal to zero.

3.3 Soil Moisture Characteristics

The following soil moisture characteristics relationships are used in the model [10]:

$$K(\Psi) = K_s \frac{A}{A+|\Psi|^m} \quad \text{and} \quad \theta(\Psi) = \theta_r + \frac{B(\theta_s - \theta_r)}{B+|\Psi|^n} \tag{5}$$

in which, K(ψ) is the unsaturated hydraulic conductivity (cm/h); K_s is the saturated hydraulic conductivity (cm/h); θ(ψ) is the moisture content; θ_s is the saturated moisture content and θ_r is the residual moisture content; A, B, m and n are the constants.

3.4 Root Water Uptake

Atmospheric boundary condition requires specifying rate of potential evapotranspiration, irrigation and precipitation. Potential evapotranspiration, (E_{vpt}) is computed by the equation, $E_{vpt} = K\,E_p$, where E_p is the pan evaporation and K is the consumptive use coefficient. The distribution of the potential evapotranspiration alone the root depth is given as,

$$E_{pdis}(z) = C_{rt} E_{vpt}(0,t) \qquad For \qquad 0 \le z \le d \tag{6}$$

Where $E_{pdis}(z)$ = distribution of potential evapotranspiration based on root density; C_{rt} = coefficient of the root density at depth z and d = depth of the root zone. The actual evapotranspiration is computed based on the available soil moisture at that node and is given as [11]:

$$S(z,t) = \begin{cases} E_{Pdis}\left(\dfrac{\theta - \theta_w}{\theta_f - \theta_w}\right) & For \quad -15800\ cm \le \psi \le -400\ cm \\ E_{Pdis} & For \quad -400\ cm \le \psi \le -50\ cm \\ E_{Pdis}\left(\dfrac{\theta_s - \theta}{\theta_s - \theta_{an}}\right) & For \quad -50\ cm \le \psi \le -\ 0\ cm \end{cases} \tag{7}$$

where, S(z,t) is the actual evapotranspiration from root of the crop (cm) at particular node; θ is the soil moisture; θ_w is the moisture content at wilting point (at ψ = -15800 cm); θ_f is the moisture content at field capacity (at ψ = -400 cm); θ_{an} is the moisture content at anaerobiosis point (at ψ = -50 cm); θ_s is the saturated moisture content.

3.5 Hydrological Properties of Soil of Kandi belt

Field investigations were carried out during February month at five selected locations (Hiranagar, Kathua, Samba, Ratnuchak and Jammu) in the Kandi belt to estimate hydrologic properties of soil. Disturbed and undisturbed soil samples were collected and analyzed in the laboratory. The Guelph permeameter was used in the field to compute the field saturated hydraulic conductivity for different types of soil. Soil characteristic parameters are presented in Table 2. These parameters are computed based on the soil types and saturated hydraulic conductivity and using the SYSTAT software.

Table 2: Parameters of Soil Characteristics in Kandi belt.

S. No.	Types of Soil	K_s (cm/h)	A	M	θ_s	θ_r	B	n
1	Sandy Loam	0.20	95.86	1.338	0.40	0.05	20.73	0.520
2	Silty Loam	0.12	22.48	1.271	0.30	0.04	34.62	0.516
3	Loam	0.10	56.8	1.307	0.3	0.04	7.83	0.432

In this region, Rabi crops are sown during October to November and harvested from April to mid May. Similarly, Kharif crops are sown during June to end July, and harvesting takes place during September to October. The main crop rotation followed in the area is wheat in Rabi season and maize in Kharif season. The complete simulation period is shown in Table 3, which shows the rabi and kharif Season's months and the rotation of the crops. It also shows the date of sowing and harvesting of the crops. Table 4 presents the agricultural details of the crops considered in this study.

Table 3: Simulation Period of Kharif and Rabi Crops and Rotation of Crops.

Rabi Season						Kharif Season					
Wheat (21th Oct – 20th April.)								Maize (15th Jun. – 20th Sept)			
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept

Table 4: Agricultural Details.

	Wheat	Maize
Root Depth (cm)	60	90
Base Period (days)	182	97
Date of Sowing	21tth Oct	15th June
Date of Harvesting	20th April	20th Sept.
Amount of water (mm)	Irrigation plus Rainfall during the period	Irrigation plus Rainfall during the period

4. Results and Discussion

Model is used to compute ground water recharge in Kandi Belt of Jammu region for the complete one-year period of wheat and maize crops and bare soil through a single soil column. These results are integrated for different types of soil and different types of cropping pattern.

4.1 Simulation of wheat

The figure 2 presents the depth of rainfall occurred and applied irrigation water and water infiltrated below the ground surface in the study area during the simulation period of wheat crop. The positive value of water depth is the water applied whereas negative value is the water infiltrated due to irrigation and rainfall. Four numbers of irrigations, each of 7 cm have been applied during the whole simulation period of wheat. It can be seen that the sum of the applied water is equal to the sum of the infiltrated water, though there is little lag between applied water and infiltrated water except 1st irrigation. It shows the water balance in the soil column. The infiltrated water is again distributed to evapotranspiration, soil moisture storage and recharge below the root zone. The water balance in the root zone is also carried out.

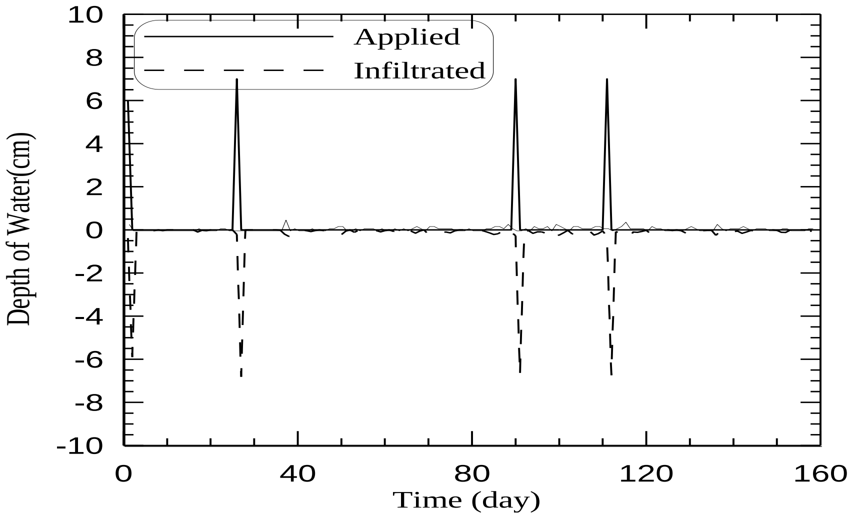

Figure 2: Irrigation and Rain Water Application in wheat.

The cumulative depth of water infiltrated, evapotranspired, stored in root zone and percolated below root zone as the recharge is shown in Fig. 3. There is stepped rise in the infiltrated water, this due to the water applied instantaneously. There is stepped rise in recharge during the period of infiltration. The storage curve shows stepped rise (when water is infiltrated there is rise in storage) but gradual fall (when there is no infiltration, crops takes water gradually from storage). The evapotranspiration shows gradual rise initially and then steep rise in the later stages of crops. Figure 3 shows the water balance in the unsaturated zone. The amount of total water infiltrated, stored, evapotranspired and recharge during the simulation are 38.17, 10.99, 23.54 and 3.64 cm, respectively. About 9.5 % of applied water is recharged below the root zone.

4.2 Simulation of maize

Figure 4 presents the depth of rainfall occurred and applied irrigation water and water infiltrated below the ground surface in the study area during the simulation period. Three numbers of irrigations, each of 7 cm have been applied during the simulation period of maize. It can be seen that the sum of the applied water is equal to the sum of the infiltrated water, though there is little lag between applied water and infiltrated water except 1st irrigation. It shows the water balance in the soil column. The infiltrated water is again distributed to evapotranspiration, soil moisture storage and recharge below the root zone. The water balance in the root zone is also carried out.

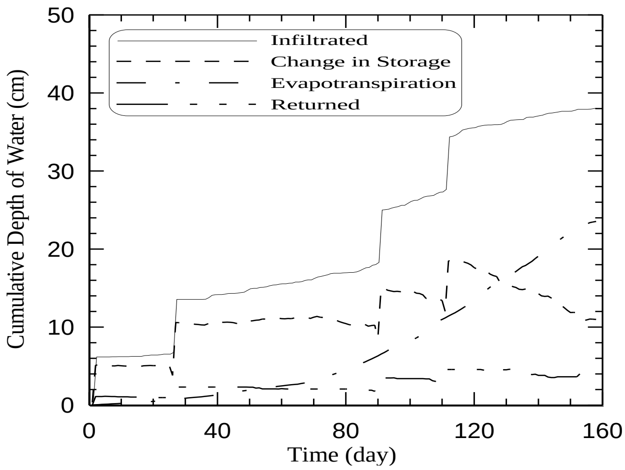

Figure 3. Cumulative depth of infiltrated water, stored, evapotranspired and returned below root zone from wheat.

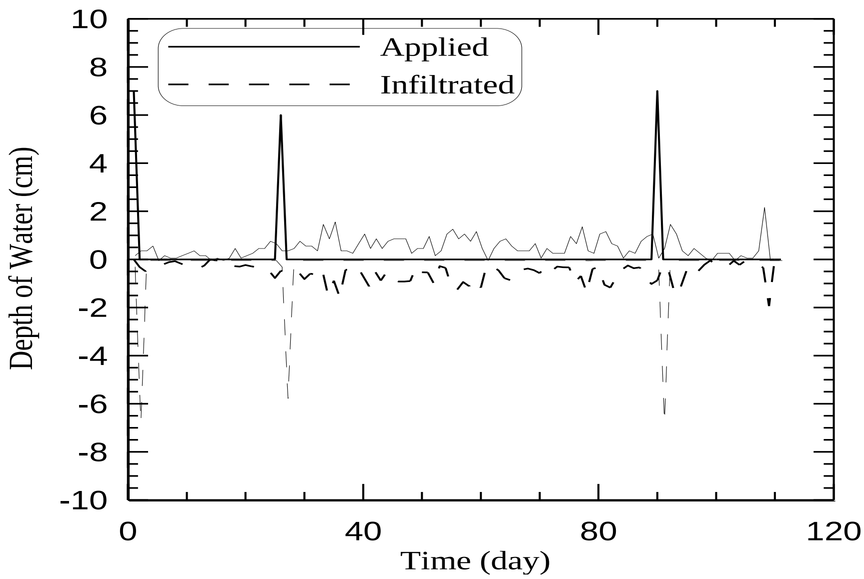

Figure 4: Irrigation and Rain Water Application in Maize.

The cumulative depth of water infiltrated, evapotranspired, stored in root zone and percolated below root zone as the recharge is shown in Fig. 5. It can be seen from this figure that there is stepped rise in the infiltrated water this due to the water applied instantaneously. There is stepped rise in recharge during the period of infiltration. The storage curve shows stepped rise (when water is infiltrated there is rise in storage) but gradual fall (when there is no infiltration, crops takes water gradually from storage). The evapotranspiration shows gradual rise initially and then steep rise in the later stages of crops. Figure 5 shows the water balance in the unsaturated zone. The amount of total water infiltrated, stored, evapotranspired and recharge during the simulation are 78.82, approximately nil, 34.7 and 41.76 cm respectively. Total recharge is 52.98 % of the total applied water below the root zone. This is the kharif season and hence more rainfall causes more recharge.

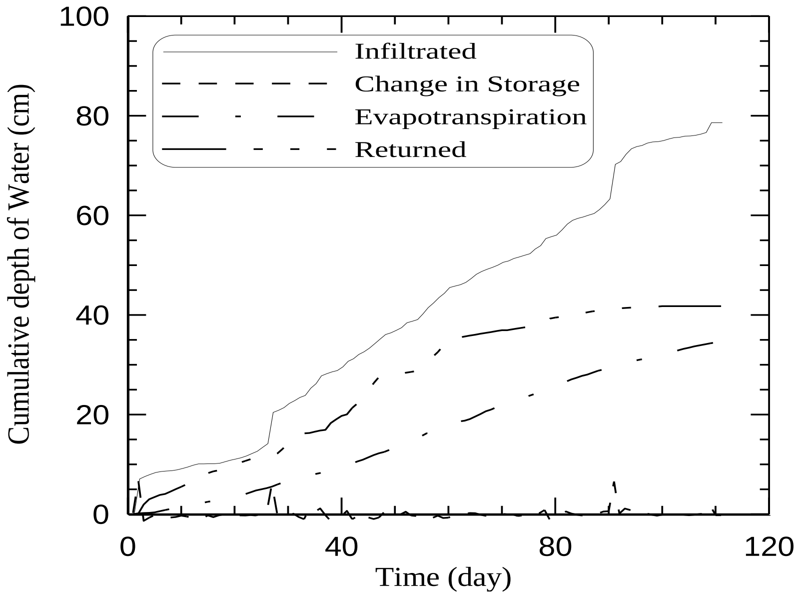

Figure 5: Cumulative depth of water infiltrated, stored, evapotranspired and returned below root zone from maize.

5. Conclusions

The groundwater recharge in the Kandi belt of Jammu have been estimated using soil moisture model of unsaturated zone, which considers the subsurface flow component along with the root water uptake from the crop as the sink term for different types of soil and land use. The root water uptake term has been computed considering the crop coefficient, potential evapotranspiration, and soil moisture available at different depth and the distribution of the root density along the root zone. The model is used to simulate a single soil column having different soils (sandy loam, Silty loam and loam) in Kandi belt of Jammu (J & K). Groundwater recharge is estimated for one complete crop year having crop rotation of wheat and maize with daily rainfall and pan evaporation data of Jammu. It was found that for the wheat crop the total amount applied is infiltrated. The amount of total water infiltrated, stored, evapotranspired and recharge during the simulation were 38.17, 10.99, 23.54 and 3.64 cm, respectively. Similarly for maize crop, the amount of total water infiltrated, stored, evapotranspired and recharge during the simulation are 78.82, approximately nil, 34.7 and 41.76 cm, respectively. Total recharge from wheat crop in rabi season is 9.5 % whereas from maize crop in Kharif season it is 52.98%. Kharif season has more rainfall and hence more recharge than Rabi season.

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Paper for ISMAR10 symposium. **Topic No: 12 (239#)**

Managed Aquifer Recharge Plan based on a surface water-groundwater model for the Santo Domingo Creek, Baja California Sur, Mexico

Jobst Wurl[1] and Miguel Imaz-Lamadrid[1]*

[1] Universidad Autónoma de Baja California Sur, Carretera al Sur Km, 5.5. Mezquitito, La Paz, Baja California Sur C.P. 23080, Mexico.
* Jwurl@uabcs.mx; Tel.: +52-612-123-8800 Ext 4230

Abstract: The Santo Domingo Valley aquifer (SDV) represents the main source of groundwater for the Irrigation District 066, but it is overexploited due to the intense historical extractions that reached up to 230% above the annual average recharge. The cone of depression with levels up to 35m under sea-level has caused the impoverishment of water quality, through seawater intrusion (SWI). For the purpose of planning artificial recharge infrastructure using the excess of surface water, a hydraulic model was developed, as a design tool to forecast scenarios. According to our results, the maximum capacity of natural alluvial infiltration is in the range of 4.3 to 4.7X10^{6}m^3, which would represent a percentage of infiltration between 12.1 and 14.3% of the average volume of runoff for the watershed. Under actual conditions, the amount of SWI from Santo Domingo estuary will increase 3.6 times in 2040. At least 10X10^{6}m^{3}of surface water could be artificially recharged, with infiltration dams constructed at two proposed sites. The groundwater model represents a useful tool to plan the position of recharge dams in order to reduce the effects of over-exploitation of groundwater such as SWI.

Keywords: Recharge dams, coastal areas, modflow modeling, swi2 package, seawater intrusion.

1. Introduction

The SDV aquifer is located in Mexico, in the middle of the state of Baja California Sur; 200 km northwest of the city of La Paz, capital of the state. The main towns within the SDV are Ciudad Constitución and Ciudad Insurgentes with 44,918 and 11,503 inhabitants [1]. The most important economic activity is the agricultural production mainly in the center of SDV (called Irrigation District 066); according to IMTA in the period 2015-2016, the total production of 688 thousand tons was achieved from 30,391 hectares.

Two main geomorphological features in the study area include a nearly plain area with elevations ranging from 0 to 70 masl to the west and a mountain range known as Sierra de La Giganta to the east, which ranges from 70 to 1500 masl. Rainfall in the state of Baja California Sur occurs mainly in summer due to the effect of tropical cyclones and to a lesser degree in winter; winter rains represent about 30% of total precipitation [2]. The annual total precipitation ranges from 50 to 150 mm in the western portion and 150 to 300 mm in the mountain part of SDV [3].

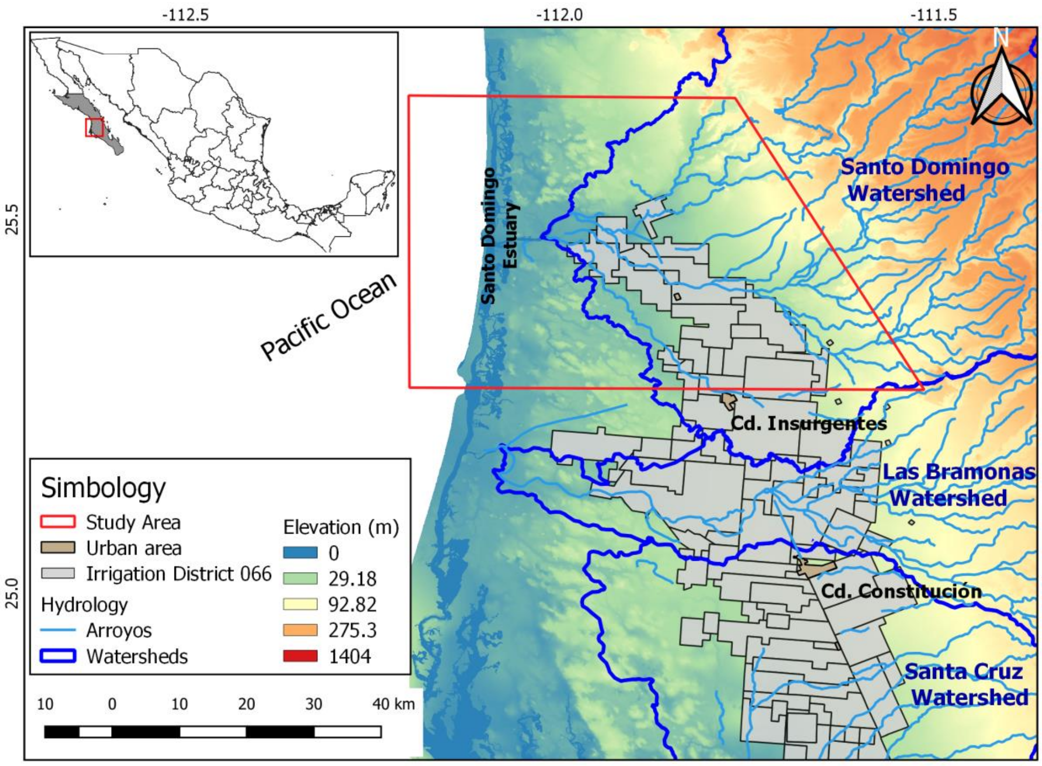

Figure 1. Topographic map of the Santo Domingo Valley (main basins, important populations and the polygon of the Irrigation District 066).

1.1. Geological framework

The study area is characterized by the Sierra de la Giganta to the east, formed by Miocene volcanic rocks of andesitic composition, and rhyolitic tuffs (SGM, 2000)[4]. To the west, the upper part of the sedimentary basin is filled with sediments with ages ranging from the Upper Cretaceous to the Quaternary according to SGM (2000) [4].

The upper deposits correspond to a set of alluvial and eolic deposits of the Quaternary, with a maximum thickness of 75 m [5]. A sequence of medium to fine grain sandstones interbedded with fossiliferous limestone of the Pliocene and with a maximum thickness of 120 m is underlying the upper units. Finally, a sedimentary unit of shales and mudstones of the Upper Cretaceous-Eocene represents the underground limit of the main aquifer.

1.2. Hydrology

The SDV covers three watersheds: Santo Domingo, Las Bramonas and Santa Cruz. Due to its desert climate, no permanent river exists. The surface water flows towards the Pacific coast, partly infiltrating into the porous aquifers. The Santo Domingo Creek has a length of 138 km and a runoff coefficient of 0 to 5%. Constructed in 2014 in the upper part of the wathershed, La Higuerilla Dam has a storage capacity of $7.89x10^6m^3$ of water (short time retention volume of 13.710^6m^3). This volume of storage water can be used as a source of freshwater to be infiltrated in two recharge dams planned to be located downstream of Santo Domingo Creek (see Figure 3). According to our calculations both recharge dams have may have a capacity of $10x10^6m^3$.

1.3. Definition of the Aquifer System

The Quaternary sediments and the sedimentary rocks from the Pliocene form the main porous aquifer. These units represent 70% of the surface of the study area with a maximum thickness of 140m [7, 8, 9]. The fractured aquifer includes tertiary consolidated rocks (volcanic and epiclastic rocks of the Comondú Formation and Quaternary volcanic rocks), which are interdigitated with the sedimentary units in the eastern side of the sedimentary basin. The unconfined aquifer system of SDV is limited by an underlying low permeability unit from the Upper Cretaceous-Eocene.

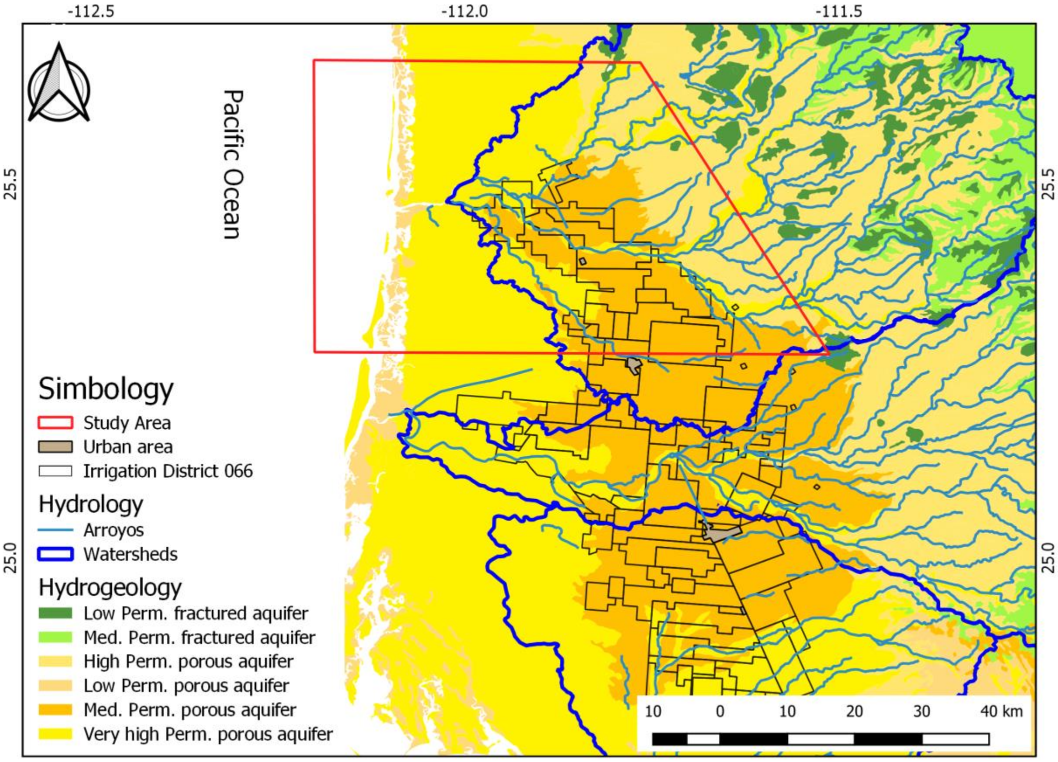

Figure 2. Hydrogeological map of the Valley of Santo Domingo.

2. Materials and Methods

The groundwater model of the main aquifer was constructed using Model Muse [6], which incorporates Modflow-2005. Using a finite difference approach, the mesh consisted of three layers with cell sizes of 250x250 m near the coastline and 2 X 2 km in the rest of the model (Table 1). The model has an extension of 2450 km² and covers the northern area of SDV (Figure 1). The simulation of the SWI was realized using Modflow in combination with SWI2 package. Stream runoff and riverbed infiltration were introduced, using the Stream Flow Routine (STR) package. In the manual calibration process, hydraulic conductivity values and recharge were changed by zones to achieve a concordance between the observed and simulated hydraulic head levels during the period 2010–2016.

Table 1. Vertical discretization of the model.

Layer	Depth (m under surface)	Aquifer	Representing lithology
1	43 to 118m	Alluvial sediments, sandstones, fossiliferous limestone	Porous aquifer with high permeability
2	10 to 90m	Sandstones, fossiliferous limestone	Porous Aquifer of moderate permeability
3	10 to 90m	Shales and mudstones	Porous aquifer with very low permeability

The topographic surface was obtained from an ASTER GDEM 30m. The thicknesses of all layers were reinterpreted from the model proposed by SEMARNAT (1996) [5] and from Wurl et al. (2017) [9]. The groundwater flow from the Sierra de la Giganta was modeled by fixed cells, which were adjusted according to the variation of historic levels; to the south, the model was limited by a flow barrier.

2.1. Time steps

The calibration was carried out in time steps of one day for the period 2010-2016. Each year was divided into three periods taking into account the distribution of precipitation per year. The first period (from February to July) is characterized by little or no precipitation. The second period (from August to September) has the highest rainfall rate due to the approach of tropical cyclones and finally the third period (from October to January) with rainfall events towards the end of the cyclonic season causing occasionally runoff in the streams. After calibration, groundwater levels were simulated for 2040.

2.2. Hydraulic parameters.

For the shallower aquifers, the hydraulic conductivity was obtained from the analysis of soil samples. In case of deeper aquifers, hydraulic conductivity values were obtained from [10], according to the lithology. Values of specific storage and specific yield were obtained from [15, 16] (Table 2).

Table 2. Hydraulic parameters used for the modeling of the case studies.

Layer	Simulated Aquifer	Hydraulic conductivity (m/d)	Specific storage (m-1)	Specific yield
1	Alluvial sediments, sandstones, fossiliferous limestone	1.6 - 34	0.0009	0.26
2	Sandstone, Fossiliferous Limestone	1.0	0.0002	0.06
3	Shales and mudstones	0.05	$1X10^{-5}$	0.02

The MODFLOW module Stream Routine (STR) was used to simulate the infiltration through runoff generated by the creeks. The average annual runoff volumes were calculated by multiplying the area of the watershed by their average annual rainfall. This result was multiplied by the runoff coefficient (table 3) obtained from the SIATL portal of INEGI and introduced into the STR package.

Table 3. Modeling of runoff volume in Santo Domingo watershed.

Watershed	Area (Km^2)	Average Annual Precipitation (mm/year)	Runoff Coefficient (%)	Runoff volume ($1X10^6m^3$)
Santo Domingo	4119	161	5	33.1

The horizontal flow recharge was simulated using the Time-Variant Specified-Head (CHD) package, assigning fixed levels for the simulation periods. The vertical recharge and irrigation return was simulated by the recharge package (RCH). The values within this package were modified in order to reach the calibration point, always taking into consideration the annual average recharge reported by CONAGUA [8, 11, 12]. The recharge values applied by RCH were $65X10^6m^3$ for the model. The extractions were simulated using the Well (WELL) package of MODFLOW, based on the database provided by CONAGUA. 167 wells with an extraction volume of $53X10^6m^3$ were included.

2.3. Modeling of seawater intrusion.

The simulation of SWI was performed using the SWI2 package. The package uses the result of hydraulic modeling to interpret the position of the freshwater-saltwater interface. To carry out this process, it was simulated based on two zones with a dimensionless density of "0" for freshwater (zone 1) and 0.025 for saltwater (zone 2). The ocean was modeled as a fixed level "0" constant in all simulation periods. The initial Z surface was modeled using the Ghyben-Herzberg equation calculated after the starting heads.

3. Results and discussion

The model was calibrated for the period 2010-2016 and evaluated, based on a linear regression between the simulated and observed values (Figure 3). A total of 100 control points were defined to evaluate the calibrated model. With an average variation of 1.18m, (maximum of 8.47m, and an R^2 of 0.9896), the calibration criteria defined by Welst et al. (2012) [13] and Hill (1988) [14] were fulfilled.

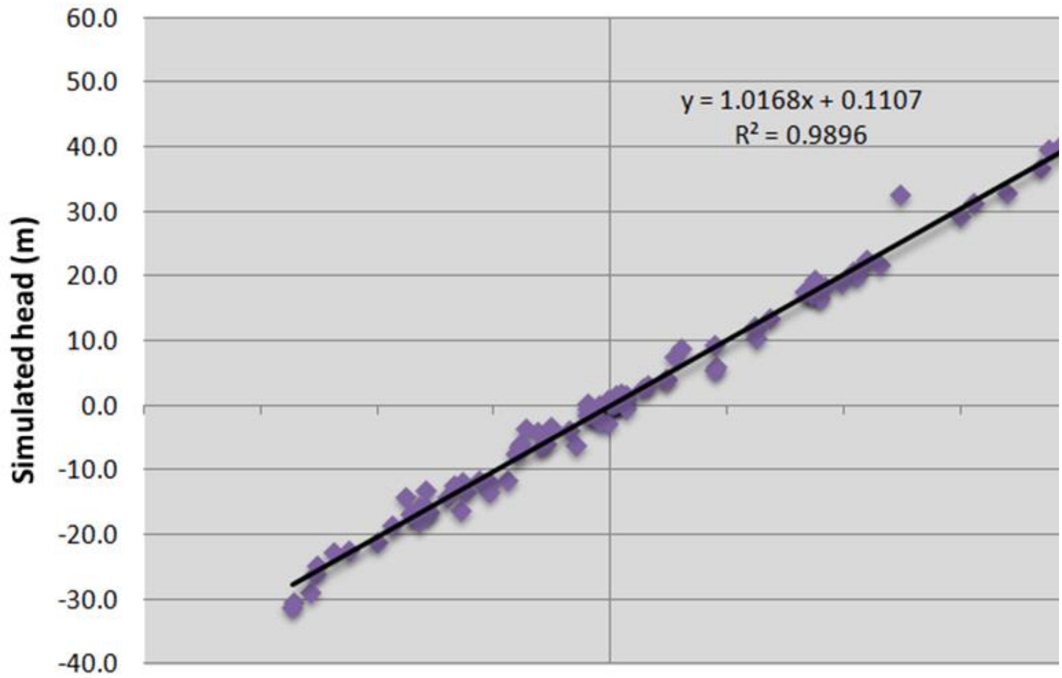

Figure 3. Comparison between simulated and observed heads for the model.

The initial groundwater table is given in Figure 4.

The evolution of groundwater levels for the period 2017-2040 resulted as follows: With respect to the year 2017, the model indicates an average reduction of the groundwater table of -0.67 m with a minimum of -13.66 m. The higher levels are observed mainly in the areas surrounding the main streams. Towards the coast, the levels tend to be stable with maximum reductions of -2 m. In the eastern part (mountain area), reductions are observed between -4 and -6 m. The most intense reductions are expected towards the southern part of the model, where the highest density of extraction wells is found.

According to the model, the maximum natural capacity of alluvial infiltration is in a range of 4.3 to 4.7X10^6 m^3, which would represent a percentage of infiltration of 12.1-14.3% of the average volume of runoff for the Santo Domingo watershed. With respect to the evolution of the saline wedge for 2017-2040, the maximum advances are observed in the area of the Santo Domingo estuary and with less intensity in the coastal zone. However, in the area of the estuary, the advance was even greater due to upconing caused by pumping. The migration landwards of the saline wedge is in a range of 0 to 490 m while in the estuary the maximum advance is 576 m. Under actual conditions, the amount of SWI from Santo Domingo estuary will increase 3.6 times in 2040. At least $10X10^6 m^3$ of surface water could be artificially infiltrated with the proposed infiltration dams.

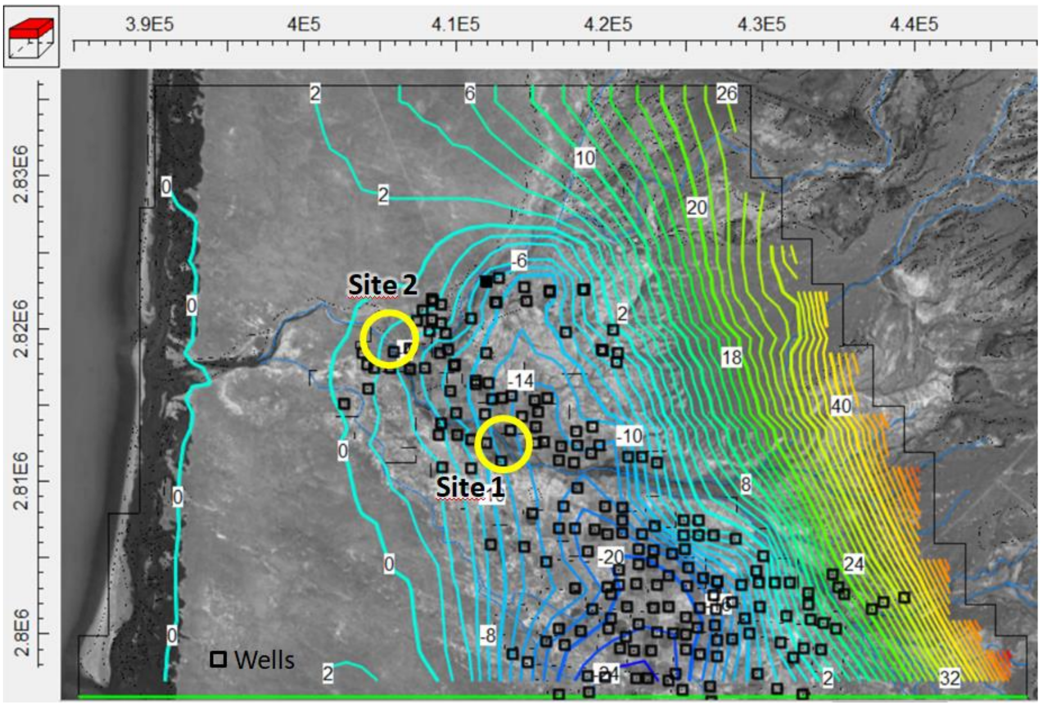

Figure 4. Starting heads (2010), extraction wells and the position of the two proposed infiltration dams.

5. Conclusion

The groundwater model represents a useful tool to plan the position of recharge dams in order to reduce the effects of over-exploitation of groundwater such as seawater intrusion. This model forms an essential part of a managed aquifer recharge plan with the goal to partly recharge the aquifer and to stop the inflow of seawater.

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Paper for ISMAR10 symposium. **Topic No: 12 (244#)**

Artificial Recharge of a Karst Groundwater System in a Developing Country

El Khoury Ibrahim[1], Chalhoub Lara[1], Yazbeck Remy[1] and Naji Khoury[1]

[1] Undergraduate research assistant, Notre Dame University, Zouk Mosbeh, Lebanon

*Correspodence: nnkhoury@gmail.com; naji.khoury@ndu.edu.lb

Abstract: Water exploitation is increasing worldwide. Engineers can assist in the development and management of groundwater resources in order to assure safe and efficient use of these resources. It is possible, under suitable conditions, to supplement an aquifer's natural recharge thereby adding to its safe yield capacity, a process called artificial recharge. Artificial recharge requires knowledge of site specific geological and hydrogeological parameters including an aquifer's hydraulic conductivity. In this study managed aquifer recharge was tested for a Jurassic (karstic) aquifer, located in Douma-Lebanon (34°13'28.00" N and 35°51'4.00" E), using the hydrogeological aspects of the site and assessing source water availability. Knowledge from existing literature and the results of the audio magnetotellurics (AMT) study were used to identify the subsurface hydro-lithologic environment including the aquifer units, their depth of occurrence and hydraulic conductivity. Four subsurface layers were inferred from resistivity versus depth measurements at several locations in the study area and a J4 formation was identified as a potential aquifer. The site suitability for augmenting the groundwater reservoir was tested by modeling the aquifer using USGS MODFLOW Flex. Dual wells (water discharge and recharge) tapping the potential J4 aquifer were modeled. The models showed a significant decrease in the generated drawdown levels, from -19.16 m to -9.8 m in some zones. Artificial aquifer recharge can also be achieved by means of the river diversion method. A sample structural design showed the results of diverting a flow of 5.2 m^3/s from the Al Jaouz River into the aquifer from a diversion head work structure (weir) of 0.8 m height, 2.5 m top width and 3 m base width. The water ran through an alluvial channel (canal) of 2 m depth and 1.5 m width to injection wells situated in close proximity to the river channel. These wells pump the diverted river water into the aquifer, potentially at a deeper level than the access points for the pumping wells. Following artificial recharge, the drawdown values decreased to a range of -7 to -9.91 m.

Key words: Aquifer, Managed Aquifer Recharge, artificial recharge, karstic formation, groundwater, geophysics, hydrogeology.

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1. Introduction

Freshwater supplies depend on various sources such as rainwater, water stored in rivers, lakes and soil, treated wastewater, desalinated sea water and groundwater. Groundwater represents the largest source of unfrozen freshwater on earth. Lebanon, however, has yet to complete a comprehensive groundwater assessment program. In 2016 the Lebanese Republic Ministry of Energy and Water, in collaboration with the United Nations Development Program (UNDP), completed a large study as a national guideline for rainwater harvesting systems [1]. A complementary study on available water resources in Lebanon provided a projection of the changing climate which agreed that droughts are likely to recur with greater frequency while warmer temperatures will speed up evaporation from water and land surfaces [2]. In Lebanon almost 70% of the aquifers are karstic in nature with the deepest Jurassic aquifers reaching 1000 to 1500 m. The relatively low availability and long-term mismanagement of its water resources mean Lebanon is depleting its underground water reservoirs, which comprise 53% of the country's available freshwater. Because the rate of these withdrawals now surpasses the rate of groundwater recharge, these aquifers are in overdraft. This situation presents unique challenges for the management of groundwater resources because the demands made on the resource are not met by current rates of groundwater recharge. Aquifer recharge occurs naturally through infiltration mechanisms as part of the hydrologic cycle and can be enhanced artificially by increasing the water supply available for recharge. Given the hydrostratigraphic nature of aquifers in Lebanon, groundwater replenishment by means of well infiltration can be efficient [3]. In this study audio magnetotellurics (AMT) is used to investigate the hydrostratigraphic conditions in the Jurassic formations of Douma, Lebanon. This technique incorporates naturally occurring electrical and magnetic fields to measure the electrical resistivity of the subsurface layers [4]. Field data are analyzed along with the published Dar Zarrouk parameters, yielding estimates of the aquifer's hydraulic parameters. The proposed recharge scheme relies on a designed diversion headwork in order to incorporate a fraction of the available freshwater supplied by the nearby Joauz river. Finally, a thorough conceptual methodology is developed for assessing the viability of the aforementioned recharge scheme in Jurassic aquifers using USGS MODFLOW. Model and hydrological data are derived based on a simplified water budget assessment of the watershed delineating the proposed location.

2. Methodology

2.1. Geological and geophysical studies

The geologic strata of the studied site are identified below by reference to the simplified stratigraphy and hydrostratigraphy of Lebanon adapted from Walley (1995) and Abbud and Aker (1986), documented in a study by the UNDP [4] (p.43):

- Kimmeridgian–J6: approximately 50 to 80 m thick, consisting primarily of pale massive fractured micritic, dolomitic limestone with chert (Bikfaya formation).
- Oxfordian–J5: approximately 50 to 100 m thick, consisting primarily of brown to yellow detrital limestone, basalts, tuff pyroclastics, with marls and shale (Bhannes formation).
- Callovian-Bathonian-Bajocian-Aalenian–J4: approximately 1000 to 1500 m thick, consisting primarily of pale gray fractured limestone, dolomite and dolostones, yellow detrital limestone, basalts and tuff pyroclastics, interbedded with local marls, chert and volcanics (Kesrouane formation).

The site considered in this study falls within areas of high karst exposure (HKE) where the karst is well developed, visible and easily identified. In this context (AMT) is performed within the studied area at 34°12'28.8"N 35°51'05.2"E and 34°12'28.3"N 35°51'05.0"E. AMT is a geophysical method used in groundwater exploration to map the geologic structure of the earth for a depth of 30 m to 2 km utilizing naturally occurring currents with frequencies in the audio range 0.1 Hz to 8,000 Hz [5]. StrataGem EH4, a magnetotellurics instrument, was used to measure ground resistivity. AMT measurements, documented in Figure 1, which shows the resistivity variations with depth below ground surface which are used to identify the subsurface layers.

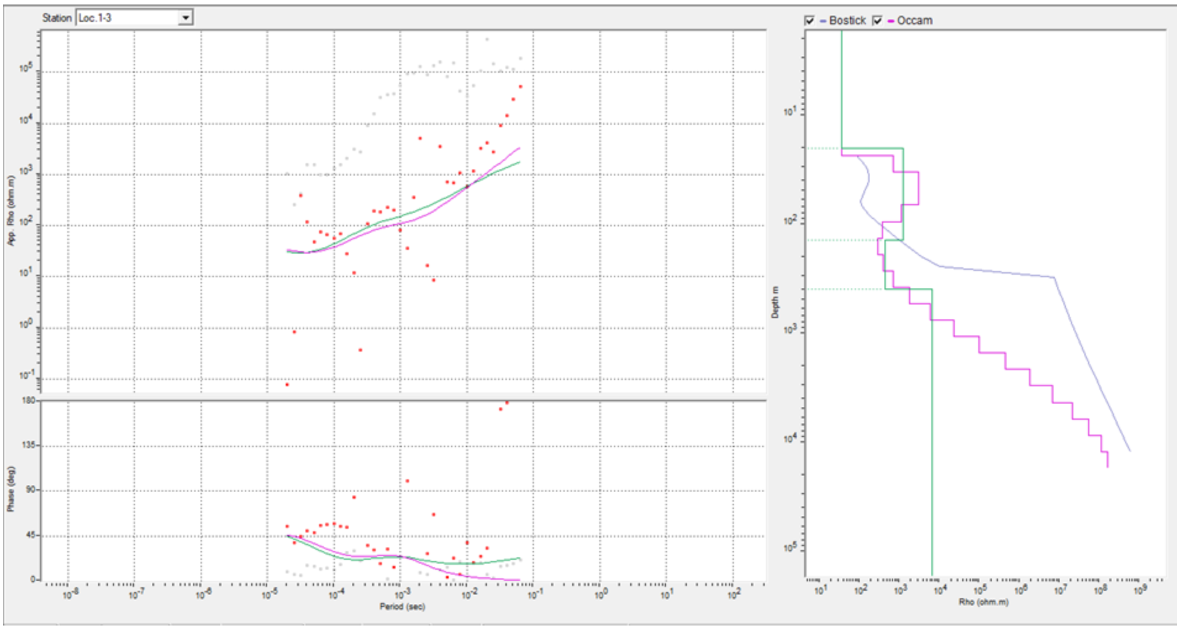

Figure 1. Resistivity variations with depth from StrataGem EH4 data.

The first layer with a depth up to 150 m in depth has a resistivity value of 1500 ohms.m. Beneath this layer, the principal aquifer extends from 150 m to 400 m in depth; it constitutes a single layer of mainly fractured rock and is considered a good aquifer for artificial recharge practices since it has a moderate resistivity value (650 ohms.m). The next layer has a high resistivity value of 7000 ohms.m. It can be inferred from the interpreted magnetotelluric data and the geological information provided in the literature that a layer of J5 and J6 formation extends up to 150 m below ground surface. Below this layer and extending up to 1000 m is a layer of J4 formation consisting of highly fractured rock that can be classified as an aquifer. Table 1 summarizes the identified subsurface layers from AMT soundings interpretation.

Table 1. Subsurface layers with their respective resistivity.

Depth Range (m)	Resistivity (ohms.m)
0-20	400
20-150	1500
150-400	650
400-1000	7000

2.2. Correlations between Hydraulic Properties and Geo-electric Data

In order to find the aquifer's hydraulic parameters, a pump test should be conducted. Since this conventional test is time consuming and expensive, alternative geophysical methods can be incorporated with pump test data results to find the aquifer's hydraulic parameters in locations where a pump test cannot be performed [6].

AMT data provide a resistivity versus depth profile that can be used to estimate the aquifer characteristics. Aquifer transmissivity is estimated from geophysical data applying the Dar Zarrouk parameters whereby transmissivity can be directly linked to the transverse resistance or the longitudinal conductance using the resistivity measured at surface [7]. Since no pump test results are available for the tested aquifer, it is suitable to correlate data obtained in this area with data found in aquifers having similar geological formations such as those studied by Joel et al. (2016) in Nigeria[8]. For an average resistivity value of 650 ohms.m and an aquifer depth of 250 m, the longitudinal conductance is calculated as 0.38 Ω^{-1} using the Dar Zarrouk parameters. Referring to Figure 2, the transmissivity is calculated as 194.9 m^2/day using the direct relationship established between the transmissivity and the longitudinal conductance $T = 490.3L_c + 6.3259$. The hydraulic conductivity is obtained using the transmissivity and has a value of 0.78 m/day.

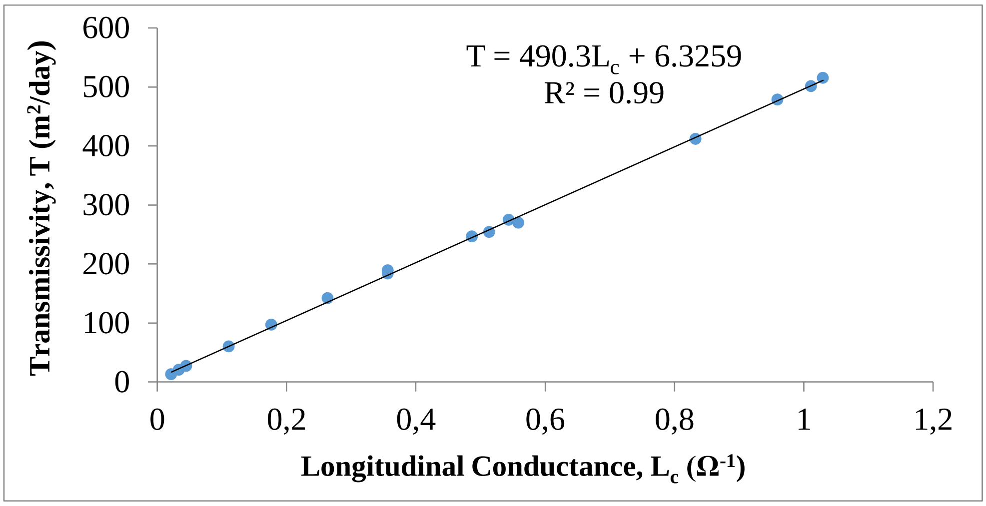

Figure 2. Transmissivity versus longitudinal conductance (Joel et al. ,2016)

2.3. Visual MODFLOW Flex

The integration of finite difference mathematical models as a tool to assess the aquifer performance is demonstrated in this study using Visual MODFLOW Flex 2015. MODFLOW allows a three-dimensional representation of the aquifer's geometry and boundary conditions as well as input of its hydraulic properties. A matrix of uniformly spaced grids is generated and solved. This discretization process represents an effective way to examine the aquifer's response to groundwater management practices.

2.4. River Site Exploration

River flow Q is determined by measuring water heads using a Pitot tube at different points along the section of the Al Jaouz River located at 34°13'12.55" N and 35°50'38.99" E. The average width of the river section is L = 8.5 m while the average river bed height is h = 0.67 m. The average volumetric flow is then determined with a result of 5.2 m^3/s.

2.5. Design of Artificial Recharge Structures

One of the main objectives in this study is determining the possibility of diverting available water from the Al Jaouz River course into the aquifer as a supply for artificial recharge. Diversion head works are hydraulic structures constructed along the head of a channel to divert water from the river into the canal and ensure a continuous supply of water with a minimum head. A vertical drop weir was designed following Bligh's theory while the alluvial channel design was based on Kennedy's theory. Both designs were based on the estimated average volumetric rate of 5.2 m^3/s. The final design parameters for the vertical drop weir wall included a weir height of 1.27 m, a top width of 2.53 m and a base width of 3.15 m, while those of the alluvial channel included a depth D of 2 m and a width B of 1.5 m

2.6. Groundwater Modeling and Artificial Recharge

The Al Jaouz River's watershed is delineated using GIS software package ArcMap. Figure 3 shows the watershed surface, the river path and the locations (dotted points) where the AMT subsurface investigation and river data collection are conducted.

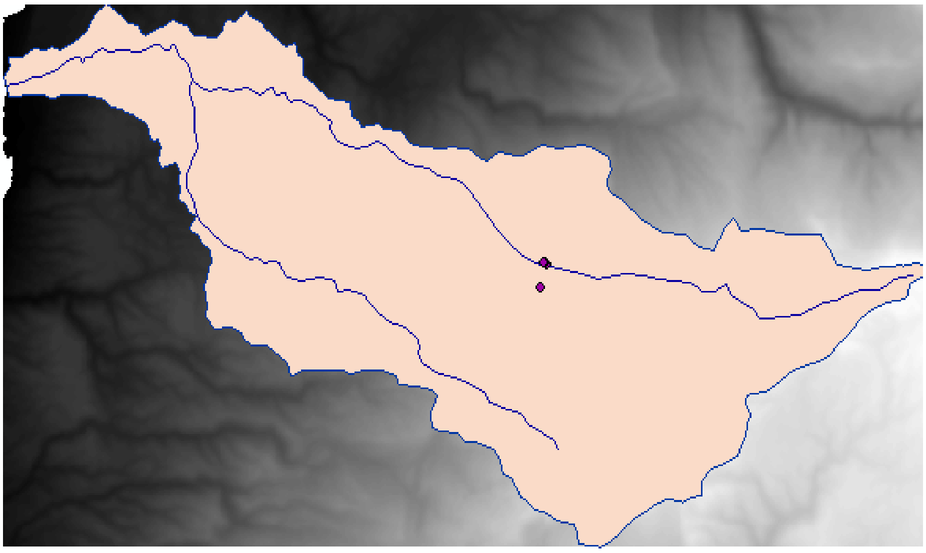

Figure 3. Digitized map of the watershed and investigated sites (ArcMap Output).

Groundwater flow of Douma's aquifer is simulated using Visual MODFLOW Flex 2015. The modeled section for artificial recharge is limited to the extent of the Jurassic formation outcrops including the J6, J5 and J4 strata. Data pertaining to the aquifer's geometry are assigned using developed GIS maps of the ground surface and subsequent layers. The overlapping J6 and J5 formation layers, each having a thickness of approximately 180 m, are both modeled as aquicludes with a hydraulic conductivity of 0.0001 m/d. The underlying J4 formation strata is assigned a hydraulic conductivity of 0.78 m/d (deduced from the preceding resistivity analysis) and modeled to a depth of 600 m, see Figure 4. Artificial recharge is induced by means of a recharge shaft with injection wells piercing through the impervious layers to the J4 formation layer, see Figure 5. Four dual wells are modeled to reach 250 m below the riverbed level in order to tap into the thickness of a potentially unsaturated zone of the aquifer. The evaluation of the storage potential and replenishment capacity of the J4 sub-surface layer is governed by the extent of recharge volumes accommodated. In the first stage of the analysis, the aquifer drawdown is predicted assuming a discharge of 500 m^3/day across each of four wells for a period of 12 months. Aquifer replenishment is accomplished by using the previously modeled wells and infiltrating a volume of 500 m^3/day of available water in each of the wells for a period of 5 months.

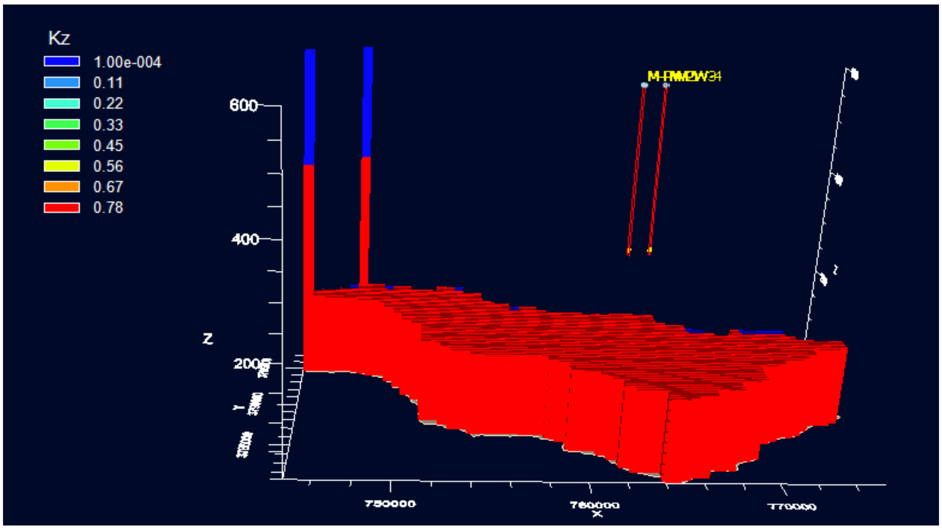

Figure 4. Assigned Vertical Hydraulic Conductivity K_z.

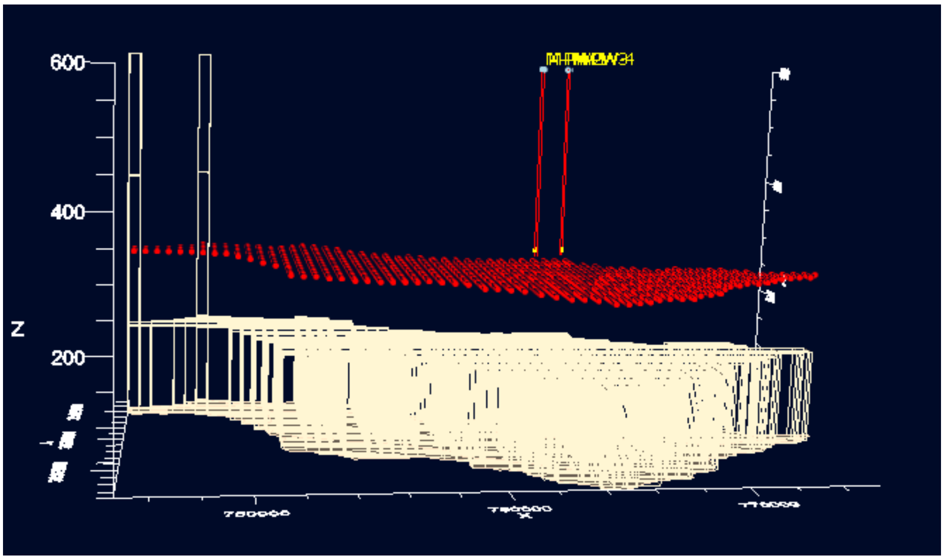

Figure 5. Assigned dual wells and groundwater level at 250 m.

3. Results and Discussions

Changes in the water heads under transient state are generated and the extent of the aquifer drawdown is shown in Figure 6. Drawdown values as high as -16.04 to -19.16 m are noted in the zones of water discharge across the injection wells. The influence of drawdown extends beyond the location of the wells to values ranging from -3.56 to -0.45 m. When aquifer replenishment is applied, drawdown values decrease to a range of -7 to -9.91 m near zones of water recharge and discharge. The drawdown recovery affected some outermost boundaries of the studied area where water levels increased to 1.73 m, see Figure 7.

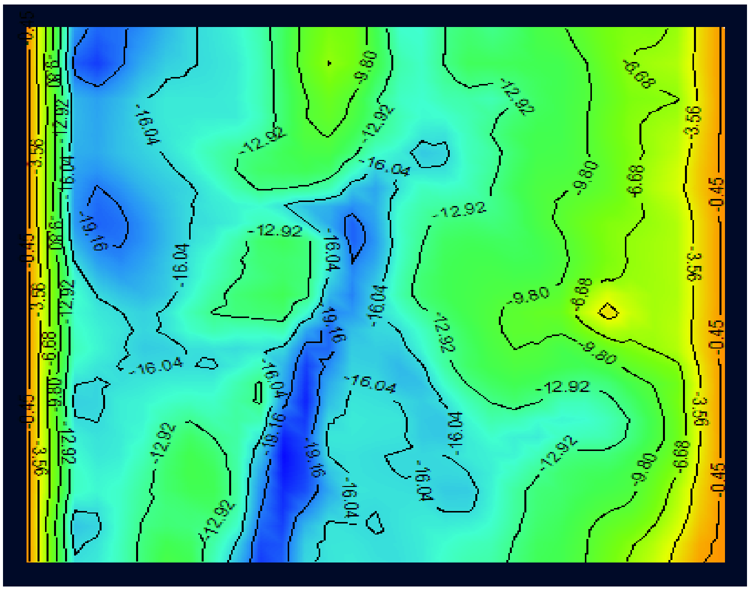

Figure 6. Drawdown Contours following groundwater abstraction (MODLFOW output)

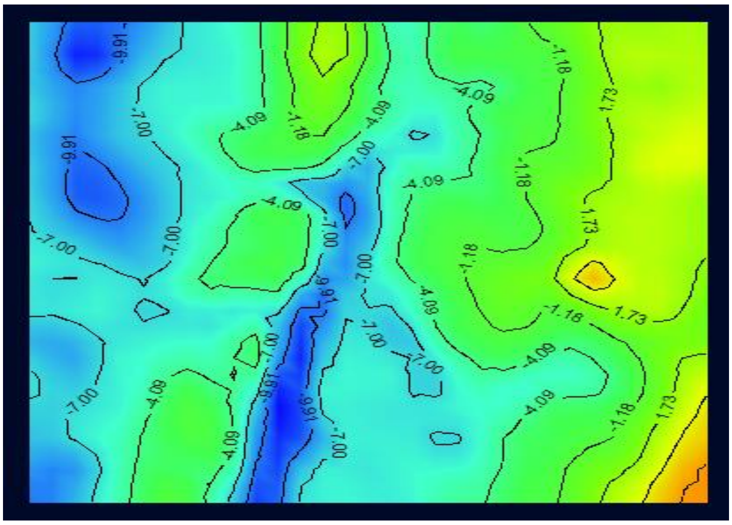

Figure 7. Drawdown Contours following artificial recharge (MODLFOW output).

The last national assessment of groundwater resources in Lebanon was conducted in 1970. In 2014, a new study managed by the UNDP was published in partnership with the Lebanese Ministry of Energy and Water. The study provided a thorough re-assessment of the existing data on water resources. It also provided a re-evaluation of the water budget across several groundwater basins. Among the identified Jurassic basins, the Kesrouan Jurassic basin, (basin 16) was classified in the Mediterranean province [4] (p.53). Groundwater level data in various basins were garnered during a one-year monitoring program and results showed most of the interior groundwater basins in the Mediterranean Province, which were not in direct contact with the sea, exhibited a severe decline in groundwater levels primarily due to over-exploitation. For instance Sir ed Dannieh – Ain Yaacoub Basin (Basin 13), which includes a J4 aquifer, experienced a water level drop of about 27 m [4] (p.12). The drawdown values, documented previously in Figure 7, indicate the susceptibility of the tested aquifer to severe water abstraction practices and can be correlated to those obtained by the UNDP.

The UNDP study also evaluated the potential of using artificial recharge in various ground water basins with different hydrostratigraphic features. The Kesrouan Jurassic basin was documented as one of the candidate sites for utilizing surface water, in this case the Jouaz river, as a source of recharge. The UNDP [4] (p.82) study estimated the Jouaz river discharge rate at an average of 5.88 m^3/s (2011-2012 cycle) while in this study it was found to be 5.22 m^3/s (2018 cycle).

The total volume of recharge water the Kesrouan Jurassic basin could potentially receive varies between 6.9 to 13.7 MCM/year with an estimated effective recharge of 1.1 to 2.25 MCM/year (2011-2012 cycle) as suggested by UNDP [4] (p.84). The preliminary assessment of artificial recharge suggested water injection by gravity wells as both cost efficient and environmentally viable. In 2017 Lukas Rolf completed a Master’s Thesis at Utrecht University wherein he defined multiple criteria to assess the suitability of karstic aquifer sites for Managed Aquifer Recharge (MAR) projects in Lebanon. His study was based on the deliverables provided by UNDP (2014) and suggested the implementation of artificial recharge schemes in nine potential sites should not only consider the availability of water resources but should follow a multi-criteria evaluation of the potential alternatives, including social economic and environmental aspects. The Kesrouan groundwater basin in proximity to the Abou Ali River exposed to J4 formations demonstrated a mild performance with an average score of 0.54 for the different weighted criteria considered in the assessment of site suitability [3] (p.34). The Kesrouan groundwater basin scored particularly well in the criteria “source water” with a score of 0.73 suggesting high water availability and low bacterial contamination potential. However, the site's performance was extremely poor when using MAR technique, scoring only 0.12 [3] (p.34).

The assessment of drawdown contours following water replenishment in this study suggest the aquifer would respond rapidly to water storage and recovery events. However, a correlation between groundwater level data from this study cannot be fully established with those from the UNDP study and Rolf's study. The results obtained in this study can be attributed to the fact that previously published studies suggest the necessity of groundwater level monitoring in managed aquifer recharge projects and groundwater modeling practices. Current data on groundwater flow patterns and changes in the aquifer head are necessary to identify the boundary zonation of the aquifer affected by water discharge courses.

The periodic monitoring of water levels in the field would help determine the effect of artificial recharge on the natural ground water system depending on the method of artificial recharge and the hydrogeology of the area. It should also be noted that developing groundwater models using USGS MODFLOW requires calibration of the generated model by ensuring compatibility between the observed water heads in the siteand those calculated by the model.

4. Conclusions

Geologic and hydrological features of Jurassic aquifer formations in Douma were studied. Audio-Magentotelluric (AMT) soundings were performed at a site with an elevation of 860 m, located at 34^{o}13'28.00" N and 35^{o}51'4.00" E. Surface resistivity versus depth data from geophysical measurements was used to map subsurface layers of the existing aquifer and detect potential presence of groundwater. Four layers and their depths were inferred from the resistivity variations and a potential aquifer was delineated in the Jurassic J4 formation with a thickness of 250 m. The hydraulic properties of the water bearing strata were determined from the geophysical data correlated with previously published literature using Dar Zarrouk parameters. A design of a river diversion headwork and alluvial channel recharge shaft was suggested in order to provide water supply to injection wells that could be constructed to tap into phreatic aquifers where water levels are much deeper. The availability of source water was assessed by investigating the flow supply of the nearby Al Jaouz River. The estimated hydraulic properties were used to model the aquifer in Visual MODFLOW Flex. Finally, the storage potential of subsurface reservoirs was tested by modeling dual wells (water discharge and recharge) tapping the potential J4 aquifer. The generated drawdown maps suggested the subsurface reservoirs could substantially respond to artificially induced water.

Acknowledgements

Part of this project was funded by NSF – PEER project 2-514. Authors would also like to express our sincere gratitude to Mrs. Yara Maalouf and Mr. Elie Lahoud for their help during the field exploration.

Author Contributions

N.Kh., El Kh. I., Ch.L., and Y.R. conceived the presented topic. El Kh. I. devised the main conceptual ideas and proof outline. N.Kh. conceived and planned the experiments. N.Kh., El Kh. I., Ch.L., and Y.R. performed the experiments. N.Kh. modeled the AMT soundings retrieved in the field. N.Kh. and Ch.L. analyzed the AMT modeled data to determine the subsurface layers and the location of a potential water bearing stratum. Ch.L. incorporated the geophysical data was incorporated with previously published pump test results to estimate the aquifer's hydraulic conductivity. El Kh. I., Ch.L., and Y.R. collected and analyzed the various digitized maps pertaining to the studied watershed. El Kh. I designed the aquifer model using Visual MODFLOW Flex and the computational framework. El Kh. I performed the numerical simulation of artificial recharge and interpreted the results. Y. R. performed the numerical calculations for the suggested hydraulic structures. El Kh. I. and Ch.L. took the lead in writing the manuscript. El Kh. I., Ch.L. and Y.R. helped shape the manuscript. N. Kh. supervised the project and corrected the final manuscript.

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Topic 13. MAR AND ECOSYSTEMS

Paper for ISMAR10 symposium. ***Topic No: 16 (019)***

Vulnerability of the aquifer system from the Nhartanda Valley (City of Tete, Mozambique)

Ameno BDJ Bande [1]; Isabel MHR Antunes [2*] and Acacia GR Naves[3]

[1] Pedagogic University, Delegação de Tete, Mozambique; ameno1000@yahoo.com.br
[2] ICT/University of Minho, Campus de Gualtar, 4710 - 057 Braga, Portugal; imantunes@dct.uminho.pt
[3] Centro de Investigaciones Científicas Avanzadas (CICA), E.T.S.E. Camiños, Canais e Portos, University of Coruña, Spain; acacia.naves@udc.es
* Correspondence: imantunes@dct.uminho.pt; Tel.: +351 253 604390

Abstract: Water is an essential resource and must occur in appropriate quantity and quality. The main objective of this research is the vulnerability assessment of the aquifer system in the Nhartanda Valley (City of Tete, Mozambique). Groundwater is collected from the aquifer for public water supply system of the old city of Tete and a traditional agro-livestock farm, which is irrigated by artesian wells. In situ water determinations and laboratory analysis have been performed to assess water quality in the study area. Groundwater vulnerability was determined through the application of GOD and DRASTIC indexes. The vulnerability indexes of the Nhartanda Valley aquifer vary from moderate-high to very high. During hot and humid seasons, the vulnerability index may reach to extreme levels, being reached relatively quickly by harmful organisms and substances. A specific set of actions and measures are necessary for the protection of Nhartanda Valley aquifer, which necessarily must involve social and environmental awareness of civil society and local population. The better knowledge of the system is essential to support decision makers on sustainable management of the water resources and protection and remediation strategies for the aquifer. The identification of the most vulnerable areas has generated basic information for that.

Keywords: Groundwater; Vulnerability; GOD; DRASTIC; Nhartanda Valley; Mozambique.

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1. Introduction

Groundwater is one of the most important sources of drinking water due to the reduced chance of surface water pollution and is considered as the only safe water source for domestic, industrial, and agricultural activities [1-3]. However, groundwater quantity and quality are being threatened by increasing demands due to population growth and agricultural/industrial activities, on the one hand, and increased pollution from the discharge of wastewater, on the other hand.

The protection and conservation of groundwater resources is very important, particularly in arid and semi-arid regions where water resources are more limited. The effects of rapid population growth, urbanization and diversification of economic and agricultural activities contribute to the quantitative (scarcity, overexploitation) and qualitative degradation of groundwater (pollution, chemical degradation) [4].

Groundwater management encompasses a broad range of activities including prevention of groundwater contamination. Increasing groundwater contamination around the world has triggered the concept of "aquifer vulnerability", which has been widely used for three or four decades by researchers and policy makers to protect groundwater pollution [5].

Assessment of aquifer vulnerability is an important step in order to implement any management groundwater plans and protecting these water sources [6-8]. However, only a few recent studies have focused on the performance of vulnerability assessment methods [5]. The methods for assessing groundwater vulnerability can be divided in index methods, statistical methods and process methods [9]. Parametric methods such as DRASTIC and GOD were developed to assess groundwater vulnerability [7; 10-16].

The Nhartanda Valley aquifer system, in City of Tete (Mozambique), is exposed to a lack of sewage treatment plants and intensive agricultural activities. In the area, there isn´t any waste management system and wastes are deposited irregularly in the valley and surrounding areas, as well as in its main source of recharge - the Zambezi River. Consequently, there is an increased vulnerability of the aquifer and a deterioration of water quality, which is the main source of human water consumption for the "old" city of Tete.

This study aims to evaluate the vulnerability of groundwater in the Nhartanda Valley aquifer using the GOD and DRASTIC indices. The identification of the most vulnerable areas will generate information to support preventive water use and quality control measures. The management of water resources allows the development of proposals for actions to monitor the quantity and quality of groundwater by local and national policy makers.

2. Materials and Methods

2.1. Study area – Nhartanda Valley

The Nhartanda Valley is located in Southern Africa, center of Mozambique, in the southern part of the City of Tete (Figure 1). City of Tete is a large urban area which and hosts ~2.74 million inhabitants. The Nhartanda Valley occupies an area of 6.76 km^2, corresponding to 2.2 % of the surface of the City of Tete, which is approximately 314 km^2.

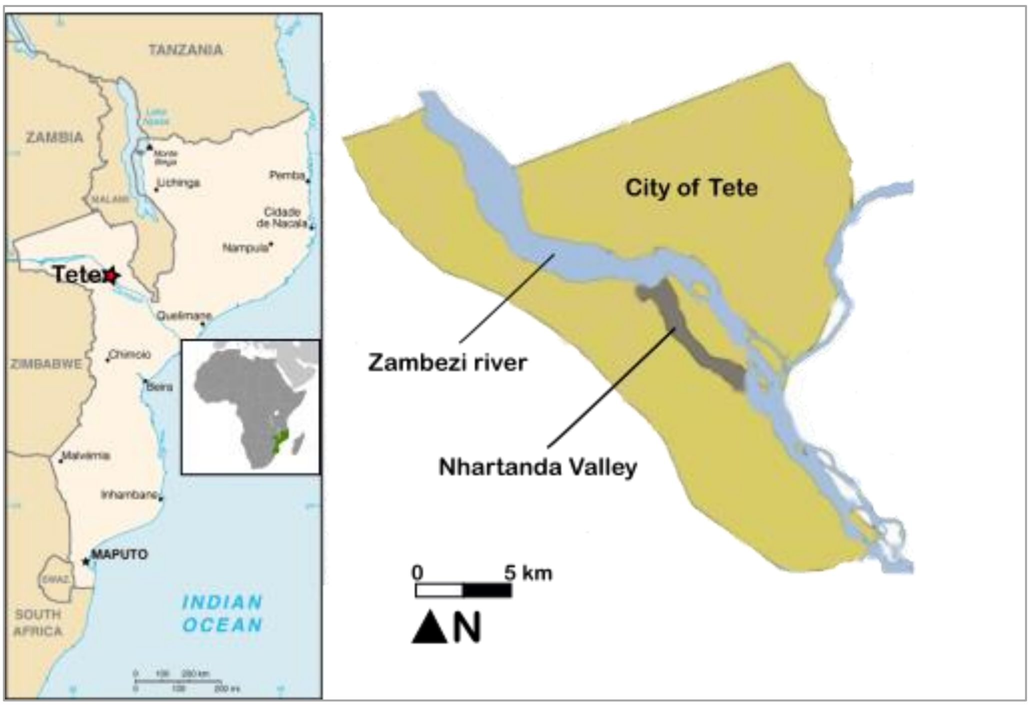

Figure 1. Geographic setting of the Nhartanda Valley (City of Tete, Mozambique) and Zambezi River.

City of Tete faces a set of serious structural issues of access to water such as a precarious public water supply system - large losses, pressure drawdown, and lack of investment in the network management, water rationing and a poor sewerage system [17]. Historically, the public water supply in the area relies mainly on surface water reservoirs and groundwater. Nevertheless, repeated droughts have caused groundwater abstraction increase in the last few decades, and it was identified as a risk for the groundwater quality and quantity.

The region is included in the northern Mozambique climatic region, dominated by a typical tropical dry climate [18] and constitutes a typical climatic hotspot facing demographic and groundwater over-abstraction pressures in southern hemisphere countries [19]. The relative air humidity reaches the lowest values at the end of the dry season and its maximum in January/February, where the annual average value does not exceed 65 %. Average annual temperatures are generally high, on the order of 28° C, and annual maximum rainfall rarely reaches or exceeds 800 mm [20]. Frequent climatic extreme events generate urban drainage issues which associated to urbanization implies that large water volumes are not available to recharge local aquifers. The combination of high temperature and low rainfall characterizes this part of Mozambique's zone as one of the most arid in the country. The extreme dryness of this climate results from the weak oceanic influence, coupled with the high average annual temperatures, where the altitude effect is not enough to make the climate wetter [18]. Additionally, the increase of impervious surface due to urbanization causes drainage issues, when frequent climatic extreme events take place, and reduces the recharge of local aquifers.

The study area occurs in the watershed of the Zambezi River. The Zambezi river rises in the mountains of Kalene Hill, northwestern Zambia, at an altitude of 1 450 m. It traverses a total of 2700 km, orientated W-E, and flows into the Indian Ocean in the Zambezian Province (Mozambique). The Nhartanda Valley is a fluvial plain of Zambezi river, orientated NW/SE. The topography of the valley shows a slight slope converging towards the central region.

The occupation of the Nhartanda valley is dominated by agro-livestock activities, residential areas, services and handmade ceramic factories. All the valley area is exposed to diffuse and local pollution sources related to the lack of wastewater treatment plants in the city and adjacent areas of the Nhartanda Valley, which influence the water quality.

Mozambique presents two major geological units: (i) Precambrian, subdivided into inferior or archaic - *Rhodesian Craton* - with 200 Ma, consisting of metamorphic rocks from magmatic and sedimentary protoliths, and Superior - *Mozambique Belt* - with 500 Ma, and (ii) Phanerozoic represented mainly by sedimentary rocks, with 300-700 Ma, and subdivided into: Karroo, Jurassic, Cretaceous, Tertiary and Quaternary [18]. The Nhartanda Valley is composed of Phanerozoic sedimentary formations belonging to the Quaternary [17].

In the valley area, there is a several number of deep drilled wells with very large pumping rates and many shallow wells, most of them illegal, which also presents large pumping rates. This scenario led to dramatic piezometric drawdowns which make evident an unsustainable management of aquifer resources. Otherwise, anthropogenic activities developed along the Nhartanda Valley and adjacent areas may be or become a threat to the groundwater quality and constitute a hazard to the population consuming it directly or indirectly.

2.2. Vulnerability Methods

The GOD vulnerability method determines the intrinsic vulnerability. Hence, it does not consider the type of pollutant. It is based on the designation of indices between 0 and 1 to the following variables: *groundwater occurrence including recharge* (G), *overlaying aquifer lithology* (O) and *depth to groundwater* (D). The index is calculated according to the equation: $V_{index} = G_r * O_r * D_r$ [21-25]. This is an easy and quick assessment method to map the groundwater vulnerability for contamination as the classical models assume some generic contaminants. This model has relatively lesser parameters in comparison to pragmatic models such as DRASTIC.

The DRASTIC method was developed by the US Environmental Protection Agency to evaluate the groundwater pollution potential for the entire USA [26]. It considers the hydrogeological pattern, which depends on the major geological and hydrological factors that affect and control the groundwater flow [27-28]. DRASTIC is the acronym of seven hydrological parameters: *Depth to water* (D), *net Recharge* (R), *Aquifer media* (A), *Soil media* (S), *Topography* (T), *Impact of the vadose zone* (I) and *hydraulic Conductivity* (C). The depth of groundwater is very important because it determines the vertical and/or perpendicular distance which a pollutant must run to reach the aquifer. The vulnerability decreases with the increase of the distance between of surface and groundwater, because deeper water levels imply longer times for contaminants to reach the aquifer. Net groundwater recharge can affect the vertical transport of pollutants to the aquifer and their dilution and dispersion once in the aquifer. It depends on precipitation, topographic slope and soil permeability [29]. Soil texture properties affect the amount of water infiltrated from surface to groundwater levels [30]. Topography also influence groundwater infiltration processes. The decrease of topographic slope reduces runoff, promotes water retention and infiltration and, consequently, increases potential contamination. The potential pollution attenuation of vadose zone depends on its permeability and sediment characteristics. The attenuation processes which may take place within the vadose zone are biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion. Those processes tend to decrease with depth. Aquifer hydraulic conductivity determines the velocity of pollutant migration and dispersion once it goes in the aquifer.

The index can be calculated using the following equation:

$$DRASTIC_{index} = D_rD_w * R_rR_w * A_rA_w * S_rSw * T_rT_w * I_rI_w * C_rD_w$$

The rating score (r) varies from 1 to 10, based on their relative effect on aquifer vulnerability, and the weight (w) varies from 1 to 5, reflecting the relative importance of each parameter. It is an index that indicates the potential pollution of groundwater resources. The higher value, the greater pollution risk is (Table 1).

Table 1. Evaluation of degrees of vulnerability DRASTIC [31].

DRASTIC index	vulnerability
1-100	low
101-140	moderate
141-200	high
> 200	very high

3. Results

The GOD index and DRASTIC index have been calculated for wells and boreholes of the Nhartanda Valley area, respectively.

3.1. GOD Index

The vulnerability to water pollution of Nhartanda Valley, through the application of the GOD methodology, varies from medium to high, with a predominance of the highest vulnerability class. In order to allow a more detailed evaluation, these classes were subdivided into subclasses: (i) moderate-medium, (ii) moderate-high and (iii) medium-high. It is observed that 9.1 % of the Nhartanda Valley is considered as an area of medium vulnerability, while 90.9 % is of high vulnerability. Of the latter, 80 % of the area has a moderately high vulnerability.

The areas with a moderate-to-medium vulnerability occur concentrated in the northwest of Nhartanda Valley. That is an area of low population density, which promotes a reduced number of contamination sources. The zones of high vulnerability coincide with recharge areas and central Nhartanda Valley.

3.2. DRASTIC Index

The intrinsic vulnerability to pollution of the Nhartanda Valley aquifer system has been determined by calculating the DRASTIC index value following previously presented methodology. The values for each parameter have been defined according to data of boreholes of the water supply system of the City of Tete. The groundwater depth was obtained from available data of piezometric head of the boreholes just after drilling. Predominant soil texture in the study area are alluvial soils, with a sand-loamy and clay texture, resulted from Zambezi river flood materials. The clay properties contribute to pollutant natural attenuation, increasing the retention capacity of the unsaturated zone and, consequently, decreasing the vertical pollutant movement. The topographic slope in the valley is neglectable. However, the valley is lower than adjacent areas and, thus, contaminants from east and west adjacent areas converge to the valley increasing the groundwater potential pollution. The unsaturated zone of the study area contains altered soil with predominant fine sand, clay and locally silts, and with the depth increase a fine to medium sand material [17].

4. Discussion

Evolution of groundwater vulnerability assessment methods over the past 35-40 years reveals that the two index-based qualitative methods - DRASTIC and GOD - that evolved during late-1980s, are the pioneering qualitative methods for groundwater vulnerability assessment [5]. The GOD and DRASTIC methods are very efficient in estimating the vulnerability to groundwater contamination. However, these methods are restricted by qualitative and subjectivity aspects. Nevertheless, they are important tools to be used, especially by decision makers and public administration, in order to decide the activities to be implemented or restricted in an area.

According to the uniformity of study area characteristics, the GOD and DRASTIC vulnerability maps are practically homogeneous. The GOD map is very homogeneous with most of the area with a vulnerability index of 0.63, showing a general high vulnerability. DRASTIC method vulnerability resulted in a qualitative map showing a high and very high vulnerability in the Nhartanda Valley. The vulnerability indices determined by the two methods - GOD and DRASTIC - clearly demonstrate that the aquifer is characterized by a high to very high vulnerability and sometimes can reach extreme levels.

Comparing both vulnerability methods, GOD index considers three parameters in its evaluation, while DRASTIC evaluates seven parameters. DRASTIC methodology is the most detailed analysis, since the knowledge of the studied area will promote a prediction of the subsoil behavior against possible sources of pollution. However, the two methodologies showed a similar vulnerability response to area of the aquifer system of the Nhartanda Valley.

The presence of potential contaminant activities along the valley and adjacent areas associated with Zambezi river pollution contribute to the degradation of water quality. The high vulnerability indexes indicate that water is easily affected by bacteria and viruses and other substances that will contaminate the water, according to defined parametric values for drinking water and agriculture.

5. Conclusions

A global risk assessment methodology has been used to determine groundwater vulnerability to contamination from anthropogenic activities in the Nhartanda Valley area. A deep study of hydrological, hydrogeological and land uses of the study area has been carried out. The GOD index and DRASTIC index have been calculated for wells and boreholes of the Nhartanda Valley.

The vulnerability to water pollution of Nhartanda Valley, through the application of the GOD methodology, varies from medium to high. The 9.1 % of the study area is considered of medium vulnerability, while 90.9 % is of high vulnerability. Of the latter, 80 % of the area has a moderately high vulnerability. The vulnerability of the aquifer, through the application of the DRASTIC methodology, varies from high to very high, corresponding to 40 % and 60 % of the area, respectively. The two methodologies have shown a similar vulnerability response in the aquifer of the Nhartanda Valley and have demonstrated that the aquifer is characterized by a high to very high vulnerability.

The presence of potential contaminant activities along the valley and adjacent areas, associated with Zambezi river pollution, contribute to the degradation of water quality. The high vulnerability indexes that water is easily and relatively quickly affected by bacteria and viruses and other substances that contaminate the water, according to defined parametric values for drinking water and agriculture.

A specific set of actions and measures are necessary and urgent for the protection of Nhartanda Valley aquifer; which main function is to provide drinking water to City of Tete population. Those actions must also involve social and environmental awareness of civil society and local population.

The better knowledge of the hydrological and hydrogeological system is essential to support decision makers on sustainable management of the water resources and protection and remediation strategies for the aquifer. The identification of the most vulnerable areas has generated basic information to water use planning, quality control monitoring and designing of measures for aquifer protection and remediation.

Acknowledgments: This work is co-funded by the European Union through the European Regional Development Fund, based on COMPETE 2020 (Programa Operacional da Competitividade e Internacionalização), project ICT (UID/GEO/04683/2013) with reference POCI-01-0145-FEDER-007690 and national funds provided by Fundação para a Ciência e Tecnologia

Author Contributions: All the authors have equally contributed to the study. ABDJ Bande and IMHR Antunes conceived and designed the experiments; ABDJ Bande performed the field work and determinations; ABDJ Bande, IMHR Antunes and AGR Naves analyzed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Topic 14. MAR IN COASTAL AREAS…

Paper for ISMAR10 symposium. ***Topic No: 14 (029#)***

Assessment of aquifer storage and recovery efficiency in coastal aquifers

Mohammad Hasan[1] and Mark Bakker[2]

[1] Water Resources section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands; M.I.Hasan@tudelft.nl
[2] Water Resources section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands ; mark.bakker@tudelft.nl
* Correspondence: hasanbdimran@gmail.com, M.I.Hasan@tudelft.nl; Tel.: +31657676721.

Abstract: Aquifer storage and recovery plays a significant role in effective freshwater management in coastal areas. Recovery of fresh water from an ASR system in a coastal aquifer depends on many factors, including the operating system, salinity, aquifer properties, and the regional hydraulic gradient. 100% recovery efficiency is not possible. The main reason for a decrease in the recovery efficiency is the density difference. As the fresh water is lighter than the saline water, the injected fresh water flows slowly upward to the top of the aquifer. This results in an inclined interface during injection and recovery. Recovery of the fresh water has to be stopped when the interface reaches the bottom of the well to prevent withdrawal of saline water. The rest of the fresh water remains unrecoverable. Moreover, if the storage period is considerable, all fresh water may flow to the top of the aquifer, resulting in a recovery efficiency of zero. Bakker [1] studied aquifer storage and recovery efficiency with a radial model with injection and recovery over the entire aquifer thickness. The objective of this study is to increase the recovery efficiency by injecting and recovering fresh water at different depths in the aquifer. A radially symmetric one-dimensional multi-layer model has been developed. The model has been applied to investigate various scenarios to determine recovery efficiencies of ASR systems in models consisting of one or two layers. A tool is developed that is computationally far more efficient than the salt water intrusion package for MODFLOW. This tool can be applied to assess the feasibility of an ASR scenario and to determine the optimum operation method to maximize recovery efficiency.

Keywords: Aquifer; storage; recovery; efficiency; model.

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1. Introduction

Artificial recharge for storage purpose has been around for over 50 years. US Geological Survey (USGS) started their research on storing fresh water in saline aquifer after world war II [2]. Cederstrom [3] of was the first within the USGS to investigate the storage of fresh water in saline aquifers in Virginia [2]. Nowadays the injection and storage of fresh water into a saline aquifer and subsequent recovery is called ′′aquifer storage and recovery′′ in short "ASR". The amount of recovered fresh water relative to the total injected freshwater is termed the "recovery efficiency" [4]. In this research, ASR settings and operation are revisited to maximize recovery efficiency.

Factors affecting the recovery efficiency can be divided in three categories: stratification density effects, interface dispersion, and ambient groundwater flow [5–7]. The first category of density-dependent stratification includes buoyancy that cause the interface to rotate [6]. This effect can be investigated with the current study by changing the density of the ambient and injected water. Lowry and Anderson [4] studied the effect of advection and dispersion on the recovery efficiency. The presence of a hydraulic gradient may cause the fresh water bubble to shift [8,9]. The recovery efficiency can also be optimized by scheduling a multi-well injection-recovery system [5]. Geochemical factors may also affect the success of an ASR system, but they are not addressed in this study.

The main objective of this study is to develop a new tool to determine the maximum recovery efficiency of an ASR system without the need for a density-dependent flow and transport model. Different cases will be investigated including a single well at different depths and multiple wells simultaneously. All cases are for radial Dupuit interface flow with density effects.

2. Mathematical Derivation

Consider a schematic vertical cross section of an aquifer (Figure 1) and the zones are separated by an interface. Flow is approximated as stratified; which means that water has a constant density in each zone. The Dupuit approximation is adopted for the flow in the aquifer. Many studies (e.g., [10,11]) compared Dupuit solutions to exact solutions for interface flow, showing that the Dupuit approximation is accurate for many practical problems. Density effects are incorporated in Darcy's law. The effects of dispersion and diffusion are neglected.

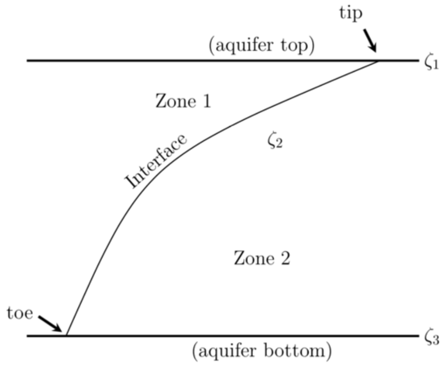

Figure 1. Schematic vertical cross section of an aquifer.

The vertical movement of the interface during injection, storage and recovery is simulated following Bakker [12]. The finite difference method is applied. During time step of the finite difference simulation, the location of the tip and toe of the interface are fixed. At the end of the time step, it is evaluated whether the tip or toe need to move to an adjacent cell using tip toe tracking algorithm.

3. Tip toe tracking

The interface boundary at the top of the aquifer is called the tip and the interface boundary at the bottom of the aquifer is called the toe (Figure 1). The tip and toe tracking algorithm is adopted from Bakker et al. [13].

Let us consider a boundary cell j which contains the toe at the end of a time step (Figure 2) and $ZETA_{j,k}$ is the interface surface of cell j in layer k. The horizontal length of cell j is $DELR_j$ and the bottom elevation of that cell is $BOTM_{j,k}$. The effective porosity of cell j is $SSZ_{j,k}$. The horizontal length and bottom elevation of the next empty cell numbered *j*+1, are $DELR_{j+1}$ and $BOTM_{j+1,k}$, respectively. The effective porosity of the cell is $SSZ_{j+1,k}$.

The main concept of the toe tracking algorithm is that the toe is shifted to the next empty cell when the toe slope exceeds a user-specified value i_{max} termed the toe slope. The condition when the toe moves to the next empty cell is shown in equation (1).

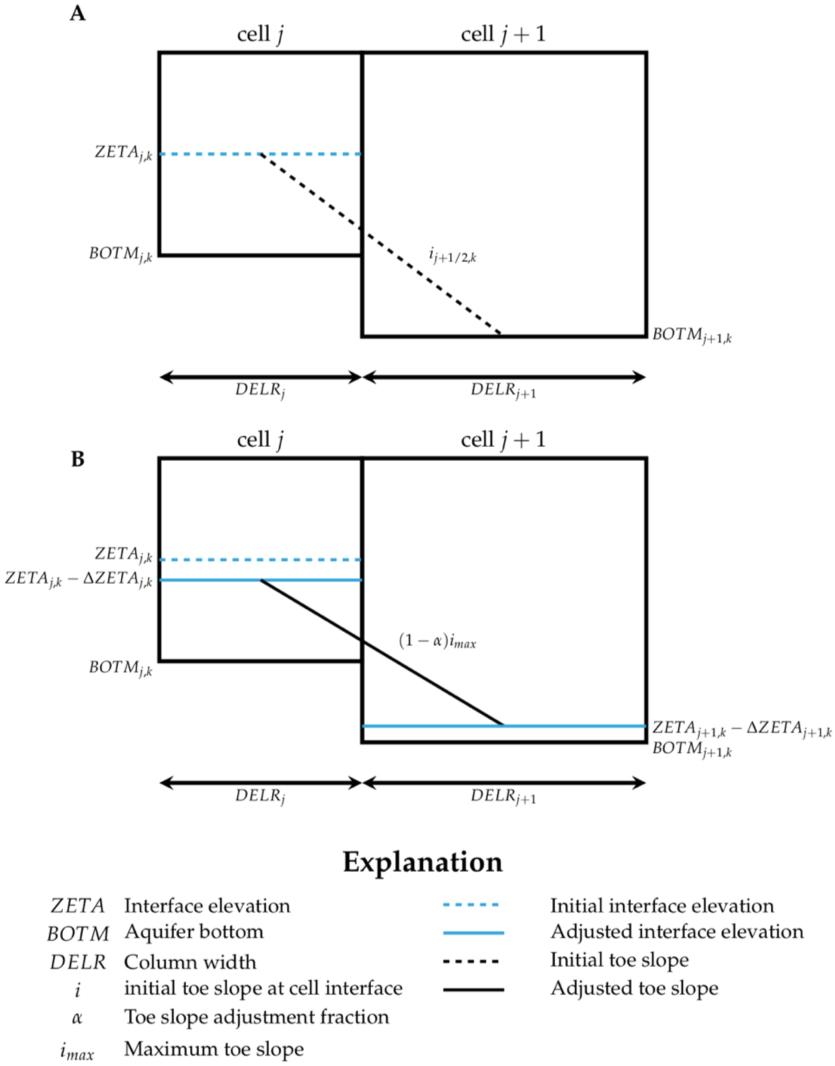

Figure 2. Variables used in the toe tracking algorithm. (Source: [14])

$$i_{j+\frac{1}{2},k} = \frac{ZETA_{\,j,k} - BOTM_{j+1,k}}{\frac{1}{2}(DELR_j + DELR_{j+1})} > i_{max}, \tag{1}$$

when simulated slope $i_{j+\frac{1}{2},k}$ is greater than user specified maximum slope i_{max} the interface is lowered by an amount $\Delta ZETA_{\,j,k}$ in the toe cell *j*, and the toe cell is moved to the next empty cell *j*+1 such that the new slope is $(1-\alpha)i_{max}$. The coefficient α has a default value of 0.1. The calculation of the toe moving from cell from cell *j* to *j*+1 is given below.

$$ZETA_{\,j,k} - BOTM_{\,j+1,k} > \Delta ZETA_{max} = \frac{1}{2}\big(DELR_{\,j,k} + DELR_{j+1,k}\big)i_{max}, \tag{2}$$

After that the $ZETA_{\,j,k}$ should be lowered by $\Delta ZETA_{\,j,k}$, which is given by the expression below.

$$\Delta ZETA_{\ j,k} = \alpha \frac{SSZ_{\ j+1,k} DELR_{j+1}}{SSZ_{\ j,k} DELR_j + SSZ_{j+1,k} DELR_{j+1}} \Delta ZETA_{max}, \tag{3}$$

Likewise, $ZETA_{\ j+1,k}$ is raised above the base $BOTM_{\ j+1,k}$ by $\Delta ZETA_{\ j+1,k}$, which is given by the equation below.

$$\Delta ZETA_{\ j+1,k} = \alpha \frac{SSZ_{j,k} DELR_j}{SSZ_{\ j,k} DELR_j + SSZ_{\ j+1,k} DELR_{j+1}} \Delta ZETA_{max}, \tag{4}$$

The toe tracking algorithm can produce strange results when the slope of the bottom of the aquifer is larger than the user specified toe slope. The minimum depth threshold for moving backward the toe cell when the interface is moving towards the well, is given by the equation below.

$$(ZETA_{\ j+1,k})_{min} = \beta \Delta ZETA_{j+1,k}\ , \tag{5}$$

Here β (BETA) is a coefficient with default value of 0.1.The algorithm for tracking of the tip is similar to that for the toe [13]. The toe and tip slopes need to be estimated.

The toe slope is changed after each time step. This is different than in SWI2. At first the interface slope at the mid depth of the aquifer is calculated after the simulation of a time step. This slope is taken as a reference slope for the new value of the toe slope. Afterwards, some percent of that slope is taken as a toe slope. The percentage varies and depends on the scenario parameter such as hydraulic conductivity, aquifer depth, injection/recovery rate, dimensionless density etc. The variable toe slope has been applied on the one and two layer model.

4. Model result

4.1. Model setup

Consider a 20 meter thick aquifer with a hydraulic conductivity of 10 m/d and a porosity of 0.3. The density of the water in the aquifer is 1025 kg/m^3. The specific storage is 0.0001 m^{-1}. The diameter of the well is 0.2 meter. The flow is radially symmetric. The technique of Langevin [15] is applied to set up the radially symmetric model. Initially a small amount of fresh water is present in all model layers. The model extends far enough radially (about 12 km) so that the boundary of the model does not affect the position of the interface. Water is injected for 15 days. No storage period is considered after injection. Recovery starts immediately after the injection period. The recovery is stopped when the interface reaches the bottom of the well. Ten injection-recovery cycles are simulated to achieve maximum efficiency.

Results of the new model are compared to two other models: the model of Bakker [1] and the SWI2 model results [13]. The single layer results are compared to both models. The multilayer model results are only compared to the SWI2 results. The main difference between the new model and the SWI2 model are that in the SWI2 model a constant tip slope and toe slope are used, while in the new model these are adjusted in each time step.

4.2. Single layer model

Consider ASR in a single aquifer. Injection and recovery is simulated over the entire freshwater thickness. The injection and recovery rate is 2000 m^3/d. The interface positions at the end of the injection period for cycles 1, 5 and 10 are shown in Figure 3 for all three models. The corresponding interface positions at the end of the recovery periods are shown in Figure 4.

Table 1. Deviation (%) in water balance of the new model.

Cycle	End of injection	End of recovery	End of cycle
1	-0.007	-0.001	-0.006
5	-0.002	0.007	0.003
10	0.006	0.016	0.014

All three models give similar results (Figures 3 and 4). The percent error in the water balance of the new model (Table 1) is less than 0.02 percent. The recovery efficiencies for cycles 1, 5 and 10 are shown for the three models in Table 2. The recovery efficiency of the new model and the Bakker [1] model are very similar. In cycle 1, the recovery efficiency of the SWI2 model is significantly lower than the other two models. This is likely caused by the toe slope which is constant in the SWI2 model, and a bit small for early cycles.

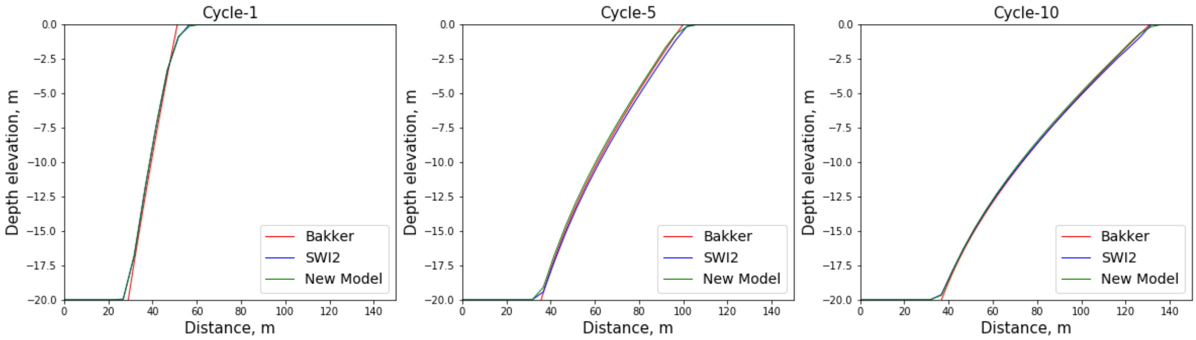

Figure 3. Position of interface at the end of injection of single layer ASR, simulated in three different types of model

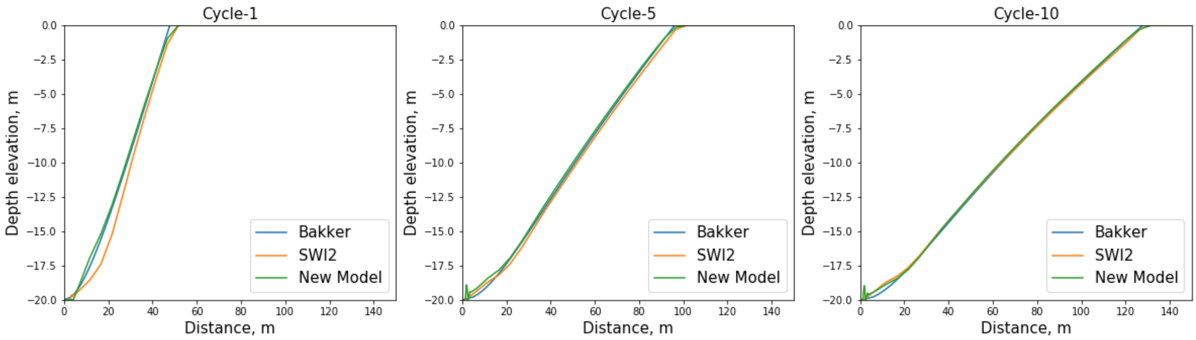

Figure 3. Position of interface at the end of recovery of single layer ASR, simulated in three different types of model

Table 2. Efficiency (%) of single layer ASR on different model.

Cycle	Bakker	SWI2	NEW Model
1	43	34	43
5	70	69	69
10	75	76	74

4.3. Two-layer model case 1

The two-layer model consists of two layers of 10 m thickness. The injection and recovery is simulated in the top layer only. The injection and recovery rate are 2000 m³/d. The resistance between the two layers is equal to half the thickness of the aquifer divided by the vertical hydraulic conductivity, and equals 1 day. ASR is simulated with SWI2 and with the new model.

The interface positions at the end of injection cycles 1, 5 and 10 are shown in Figure 4 and the corresponding interfaces at the end of recovery are shown in Figure 4. Note that the interface shifts slightly from layer 1 to layer 2. The water balance error (Table 3) of the new model is less than 0.03%. The results of SWI2 and the new model are again similar (Figures 5 and 6), the efficiency for both models are also very similar (Table 4).

Table 3. Deviation (%) in water balance of the new model.

Cycle	End of injection	End of recovery	End of cycle
1	0.000	0.029	0.019
5	0.007	0.028	0.021
10	0.010	0.028	0.022

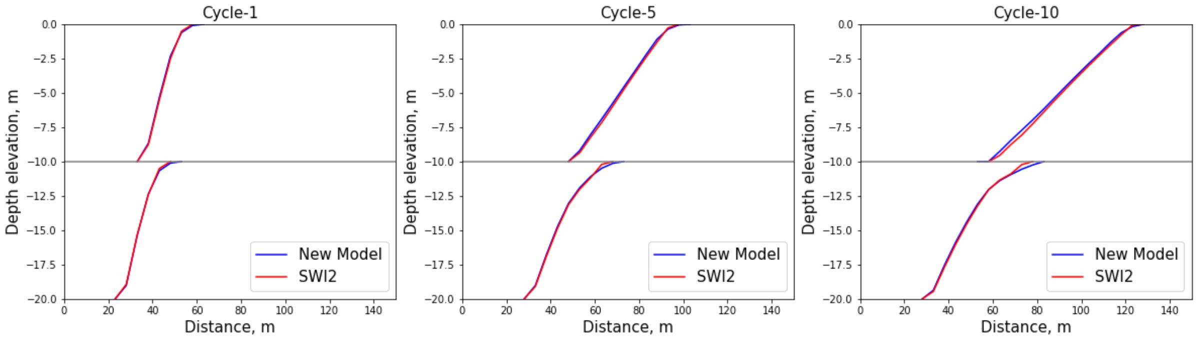

Figure 5. Position of interface at the end of injection of two layer ASR, with injection and recovery in top layer.

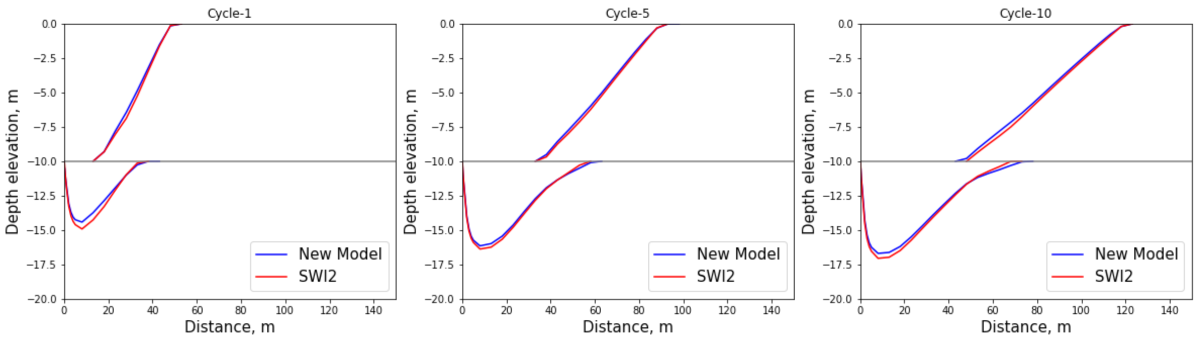

Figure 4. Position of interface at the end of recovery of two ASR layers, with injection and recovery in the top layer.

Table 4. Efficiency (%) of double ASR layers on different model.

Cycle	SWI2	New Model
1	55	57
5	75	75
10	78	79

4.4. Two-layer model case 2

The second case of the two layer model consists again of two layers of 10 m thickness of but now water is injected in the bottom layer at the rate of 2000 m³/d. The recovery is simulated in the top layer only at a rate of 2000 m³/d. The resistance between the layers is the same as in the previous case of two layers and is 1 day.

This two layer ASR case is simulated with the new model and with SWI2. The interface positions at the end of injection cycles 1, 5 and 10 are shown in Figure 5, and the corresponding interfaces at the end of recovery are shown in Figure 6. The water balance error of the new model is slightly larger than for the previous models, but still below 1.2%. The efficiencies are shown in Table 6.

Table 5. Deviation (%) in water balance of the new model.

Cycle	End of injection	End of recovery	End of cycle
1	0.535	1.140	1.131
5	0.251	0.434	0.426
10	0.153	0.226	0.219

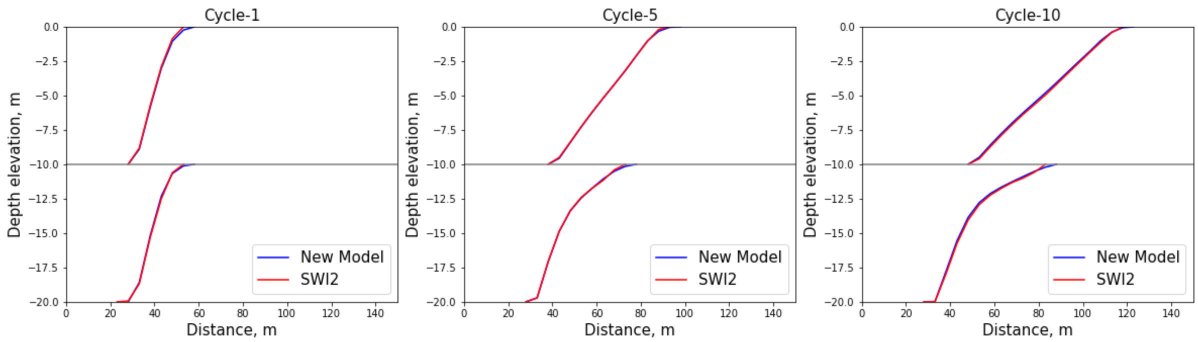

Figure 5. Position of interface at the end of injection of double layer ASR case 2, simulated in two different types of model

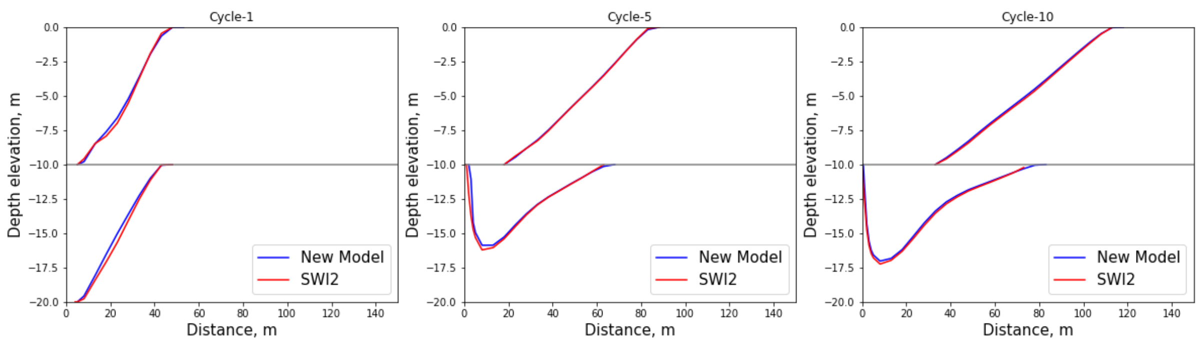

Figure 6. Position of interface at the end of recovery of double layer ASR case 2, simulated in two different types of model

Table 6. Efficiency (%) of double layer ASR case 2 on different model.

Cycle	SWI2	New Model
1	49	54
5	79	81
10	81	81

5. Discussion

A new method was presented for radially symmetric Dupuit interface flow. The method is based on the theory of Bakker [12] for Dupuit interface flow and the theory of Langevin [15] for radially symmetric flow. Injection, storage and recovery of freshwater in saltwater aquifers may be simulated with this method. Aquifer storage and recovery was simulated for models consisting of 1 and 2 layers. The recovery phase involves pumping of the fresh water until the toe of the interface reaches the well bottom. The recovery efficiency for all three cases, as simulated with the new model, is plotted in Figure 7. For these examples, the two-layer model with injection in the bottom layer and recovery from the top layer (except for cycle 1) performs best. The new model produces results very similar to SWI2, but is significantly faster, around ten times faster for the cases considered in this paper. The new model needs further development to deal with an arbitrary number of layers.

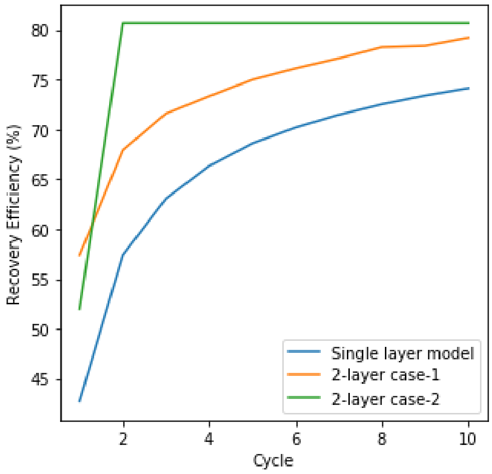

Figure 7. Efficiency of all three model

Acknowledgement

This work is part of the Delta-MAR project, funded by the Urbanizing Deltas of the World program of NWO-WOTRO, w 07.69.107.

Abbreviations

ASR: Aquifer storage and recovery.

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Paper for ISMAR10 symposium ***Topic No: 14 (083#)***

Managed of the ground water aquifer under the Nile delta

Mohamed Abd-El-Mooty[1] ***and*** **Maha Moawad**[2]

[1] Professor of irrigation and Hydraulic department Faculty of Engineering, Alexandria University
[2] Research student in irrigation and Hydraulic department Faculty of Engineering, Alexandria University
*Correspondence: maha_moawad@yahoo.com ; Tel.: 00201093933546

Abstract: Sea level variations have occurred throughout history. Sea level changes are caused by several natural phenomenons such as the rise of global temp causing the melting of ice at the poles and on the mountains. The rise of sea level might drown some low lands in the world. One of the dangerous effect of the sea level rise is the salt water intrusion under the Delta and may be drowned unless certain precautions to be taken. According to the previous researches, the relative rise during the century at the Egyptian coasts might reach 1 m.

This paper presents the expected effect of this rise on the delta. Study of the salt water intrusion under the delta and the necessary precautions to safeguard the coastal area of the delta against drowning are presented .Suggestions to protect the delta against the sea level rise are included in the paper .the groundwater resevoir under the nile delta is studied carefully. Some of this water is pumped for the purpose of irrigation and some of the water percolate towards the sea. The recharge of this reservoir comes from the seepage water of the irrigation system in the delta and the precipitation of the land. This study concentrated on the flow towards this aquifer and the outflow seepage to the sea. Also the salt water intrusion under the delta take big attention in the study presented in this paper. Van der veer solution is used in the analyses of intrusion and determining the aquifer outflow at the sea.

Keywords: Groundwater recharge, saltwater intrusion, low lands.

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1. Introduction

This paper discusses the causes of sea level rise, impacts of sea-level rise, and the expected effect of this rise on the Nile delta. Sea level variations have occurred throughout history and will continue to occur in the future.

Due to the rise of atmospheric temp, the ice in the poles and on the mountains started to melt causing the level of the sea to raise .Many coastal areas in the world is above the existing sea level by one or two meters .This coastal area might be drowned during this century due to the sea rise. The northern part of the Nile delta is between 1.0 - 2.0 m above the existing sea level.

According to the previous studies of different researchers the expected relative sea level rise in the Mediterranean Sea coast of Egypt is between 0.5 m and 1.0 m by the end of the 21st century including the subsidence of the delta land which is about 3 mm per year. Some studies suggest that the sea level rise might be higher than one meter.

This means that the northern part of the delta might be drowned by the sea water. Precautions must be taken against these expected phenomena.

The sea level rise: causes and effect:

A – Causes:

There are many factors causing the rise of the water level. These factors can be summarized as follows Moawad et al (2014):

1. Effect of Increasing CO_2 and Atmospheric Gases.
2. Temperature and greenhouse effect.
3. Thermal expansion of oceans and seas.
4. Melting of glaciers and ice.
5. Sunspot numbers effect.
6. Changing the shape and size of seas and oceans.
7. Atmospheric pressure effect.
8. Effect of salinity of sea water.

Simonett, (1988) suggested that accelerated sea water level rise of 1 or 2 m per century associated with the greenhouse effect would extend the Nile delta shoreline inland to the present 1.0 or 2.0 m contour line above mean sea water level.

Sharaf El Din et al.,(1989) studied the sea water level variation at Alexandria and port said with effect of meteorological parameters by using statistical regression analysis technique for tidal gauges records of Alexandria for the period from (1958 – 1988) and port said from (1924 – 1973).

El-Fishawi, (1990) studied the impact of sea water level rise in estuaries, aquifer and salinity along the Nile delta coast and determined the characteristics of seawater level along the Nile delta coast by using the recorded data of sea water level taken by Coastal Research Institute at Rosetta (1981–1984), Burullus (1972-1990) and Damietta (1972-1976).

Mohamed, M, A. A., (2004), studied the global and local factors which affecting the acceleration of sea water level. He studied the development of artificial neural networks model to estimate sea water level along the northern Egyptian coast from the data of tidal gauges records and weather stations parameters from Alexandria to El-Arish. He found that sea water level rise is strongly dependent on the future rise of global mean temperature that in turn is affected by future increase in concentrations of greenhouse gases, particularlyCo2. Also found the impact of the extreme sea water level rise along the Northern Egyptian coast from Alexandria to Port Said for the year 2050, will cause area land loss of about 5.691 Km2and about 3.664 Km2of agriculture land area will flooded., the population about 12, 036, 000 people will possibly be endangered.

Effects of sea level rise on coastal areas:

B – Effect of sea level rise:

Continued climate change and sea level rise could have many effects on the coastal areas on the long term including Maha et al (2012):

- Inundate wet land and coastal low land.
- Erode of beaches, bay shores, river deltas and salt water intrusion.
- Exacerbate coastal flooding.
- Sea water intrusion and increase salinity of estuaries and aquifers.
- Alter tidal ranges in river and bays.
- Decrease the amount of light reaching the sea floor.

The most serious effects of the sea level rise are the sea water intrusion and the drowning of low coastal lands.

The sea level rise and flooding will have serious impacts on the economic activities such as fishing, agricultural, harbors, tourism etc. In Egypt the agricultural land is irrigated by water coming from the Nile River. A sea level rise or flooding will impact the agricultural production either by loss of land due to submersion or increase of soil salinity. Increase the salinity and temperature of water in the northern lakes, will lead to loss of areas traditionally used for aquaculture and fishing and also a change in the quantity and quality of fish stock.

Sea water intrusion

Seawater intrusion (SWI) occurs in many coastal aquifer around the world and it is a major problem in coastal regions all over the world because these coastal zones are often heavily urbanized. SWI reduces the freshwater storage in coastal aquifers. It is essential to study carefully the effect of the intrusion on the ground water using suitable measures. Due to the expected sea level rise, the need for the analysis of the groundwater under the delta and the sea water intrusion becomes necessary.

It is defined that the movement of saline water into fresh water aquifer and under the coastal low lands occurs. The key to control saltwater intrusion is to maintain a proper balance between water being pumped from the aquifer and freshwater recharged to the aquifer. Figure 1 shows the sea water intrusion.

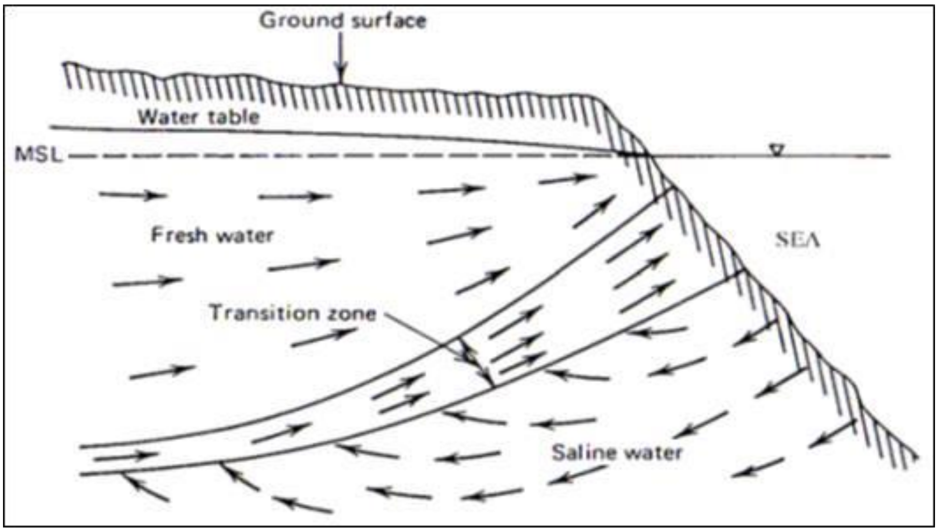


Figure 1. The seawater intrusion, Ranjan (2007)

1.2. Salt water intrusion analysis

Segol et al., (1975) solved the problem of intrusion by using the Galerkin finite element technique in the confined coastal aquifer.

Van der veer (1977) investigated the problem of determining the steady position of an interface and a phreatic surface in a coastal aquifer. He studied the analytical solution for steady interface flow in a coastal aquifer involving a phreatic surface with Precipitation. He assumed that the Fresh groundwater flows towards the sea is at rest, and the upper boundary of the flow region is a phreatic surface with precipitation. He compared the results with the one-dimensional approach according to Badon Ghyben and Herzberg.

Panigrahi et al., (1980) presented a finite difference solution scheme in the unconfined aquifer to solve the problem of intrusion. They assumed that the aquifer with infinite extent with a free surface and the interface along with the width of outflow face are unknown boundaries.

Kashef, (1983) studied the intruded saltwater wedge in the huge artesian delta aquifer. He discussed the methods of salt water control and various techniques of water resources management. Also, he used two unconventional methods for identifying the salt water wedge because of the great variation in the depth of the aquifer.

Padilla, et al., (1997) presented Modeling for sea water intrusion with open boundary conditions; they presented a new numerical approach to describe the fresh water and salt water relationships in coastal aquifers and used a Galerkin finite – element formulation. They solved the problem of saltwater intrusion by using a steady two dimensional vertically averaged finite element model, based on the assumption of horizontal fresh water flow is essentially developed for unconfined coastal aquifers. Also they used the Ghyben –Herzberg principle to estimate the position of the sharp fresh water/ salt water interface for the present single-phase numerical approach.

Izuka, (1998) described a method to estimate the depth to the interface between fresh water and salt water directly from water-level measurements made during drilling of a well that partially penetrates a dynamic fresh-water body. The method is particularly useful where substantial vertical head gradients invalidate Ghyben–Herzberg estimates of interface depth. The method is applied to field data to examine practical problems that may arise.

Aharmouch et al., (2001) described numerical modeling of saltwater interface upconing in a coastal aquifer with Galerkin finite element technique and assumed that a sharp interface assumption between freshwater and saltwater.

Feseker (2006) described numerical studies on saltwater intrusion in a coastal aquifer in northwestern Germany. He showed that the exchange of ground water and surface water is one of the key processes influencing saltwater intrusion.

Kim et al., (2007) presented a simple method to determine the depth of the fresh water–salt water interface in coastal aquifers using two sets of pressure data obtained from the fresh water and salt water zones within a single borehole. This new methodology has the advantage of being simple and low cost. The method used the density difference between fresh water and saline water and can practically be used at coastal aquifers that have a relatively sharp fresh water–salt water interface with a thin transition zone. The applied method was to estimate both short- and long-term variations of the interface at the coastal aquifer on Jeju Island, Korea to estimate the variations in the depth of the interface.

Abdullah et al., (2010) used numerical modeling (SEAWAT 2000) of seawater intrusion and showed that the model is useful in demonstrating the movement of freshwater-seawater interface.

Sriapai et al., (2012) used a physical model to simulate the seawater intrusion into unconfined aquifer near the shoreline and evaluate the effective method to control seawater intrusion.

Lu et al. (2015), derived analytical solutions of the interface toe location in both confined and unconfined coastal systems with a general-head inland boundary condition. It is found that the displacement of the interface toe predicted using a general-head inland boundary is between those of using a constant-head (upper bound) and constant-flux (lower bound) inland boundary, depending on the values of two general-head boundary parameters.

Thomas et al., (2015) presented a simulation of seawater intrusion in coastal confined aquifer using a point collection (Mesh Free method) also they assumed that the diffusion interface between the freshwater and saltwater is transition zone.

2. Materials and Methods

A new proposed mathematical model is prepared. The main purpose of this mathematical model is to get the phreatic surface, the surface between the fresh and salt water and to get the exit area of the fresh water to the sea.

The following assumptions are taken into consideration for solving the governing equations.

- The sharp interface between the fresh and the salt water.
- The Dupuit assumption is employed to vertically integrate the flow equation, reducing it from three-dimensional geometry to two-dimensional geometry.
- As the rate of rain is very small, so the vertical infiltration of the irrigation water is considered instead of the precipitation value in the solution of Van Der.
- Steady state condition is adopted.

2.1. *Fundamental equations*

Depending on the solution given by Van der veer (1977) the following equation is used in the present study

$$q^*=q+NLe \qquad (1)$$

For the case the discharge q* is unknown and height of the phreatic surface is known, in this case, from equation (2) the quantity q* can be calculated.

$$q*= a_1 * k * L_t - [a_1(a_1 - \frac{N}{K})(k * L_t)^2 - a_2(k * h_t)^2]^{0.5} \qquad (2)$$

Where

$$a_0 = \frac{1 - \frac{N}{K}}{\left[1 - \left(\square + \frac{N}{K}\right)\right]} \quad , \quad a_1 = a_0\left(\square + \frac{N}{K}\right) \quad , \quad a_2 = a_0(\square + 1)$$

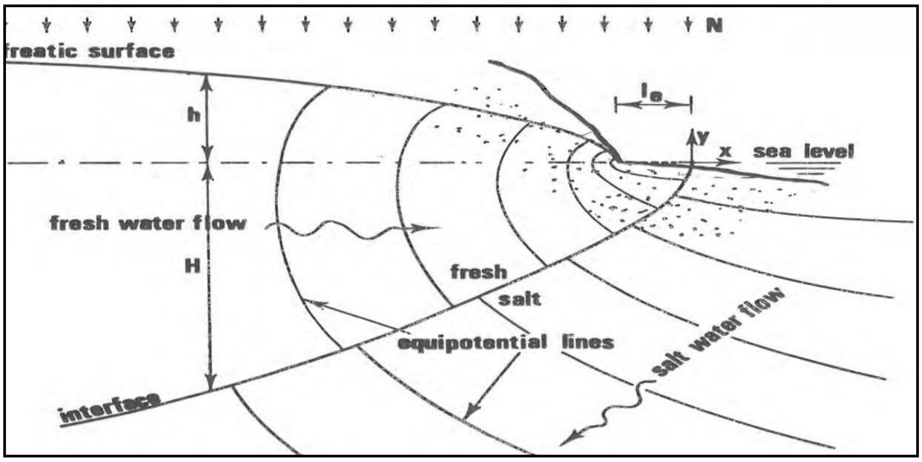


Figure 2. The schematic of the problem.

Interface line

To get the interface line applies the following equation:

$$H \quad = \sqrt{-\left(\frac{N}{K}x^2 + 2\frac{q^*}{K}x\right)/\left(\gamma + \frac{N}{K}\right)(\gamma + 1)} \qquad (3)$$

Phreatic surface

To calculate the position of the phreatic surface use following equation:

$$h = \sqrt{-\left(\frac{N}{K}x^2 + 2\frac{q^*}{K}x\right)\left(\frac{\gamma+\frac{N}{K}}{\gamma+1}\right) - \left(\frac{q^*}{K}\right)^2 \frac{\left(1-\left[\gamma+\frac{N}{K}\right]\right)}{(\gamma+1)\left(1-\frac{N}{K}\right)}} \qquad (4)$$

The width of the fresh water outflow gap

Calculating the out flow gap use the following equation:

i. For the case of no vertical infiltration or precipitation.

$$L_e = \frac{q^*}{2k}\left(\frac{1}{\gamma} - 1\right) \qquad (N = 0) \qquad (5)$$

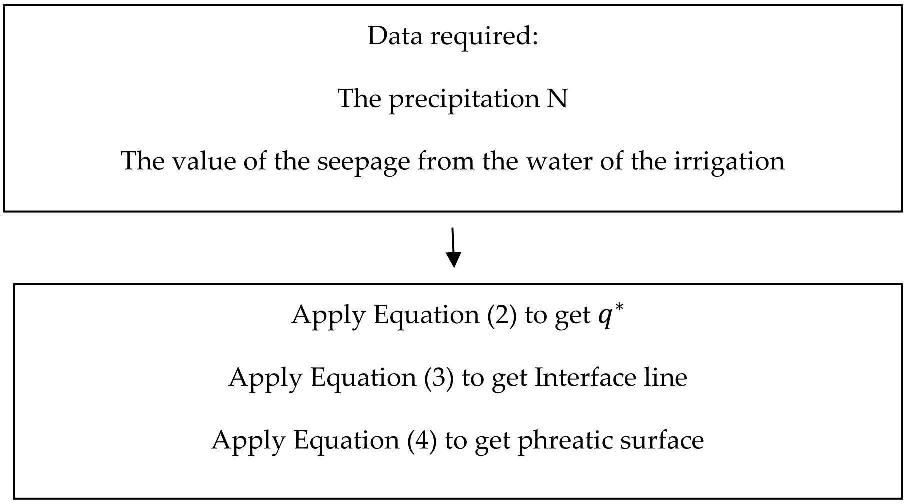
ii. For the case of vertical infiltration or precipitation.

$$l_e = \frac{q^*}{N}\left(1 - \sqrt{1 - \left(\frac{N}{K}\right)\frac{\left(1-\left[\gamma+\frac{N}{K}\right]\right)}{\left(1-\frac{N}{K}\right)\left(\gamma+\frac{N}{K}\right)}}\right) \qquad (N \neq 0) \qquad (6)$$

Where:

ϱ: density
ϒ= (ϱs- ϱf)/ ϱf
K: the coefficient of permeability in the Nile Delta aquifer is relatively high and ranges between 40 and 180 m/day according to the type of the soil it assumed (100 m/day) Kashef, (1983), as an average value for the different types of the soil under the delta
N: is the precipitation and will be taken as the net vertical infiltration water of irrigation. This depends on type of agriculture used. The rise will be taken as the max infiltration (.25 and 0.80 mm/day)
h: height of phreatic surface above sea level
x: distance from the shore line
Le: is the width of the outflow gap
q: is the outflow of fresh water towards the sea.

The flow chart of the proposed model is as follows:



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Results

Phreatic Surface

Interface Line

↓

Print

Figure 3 Flow chart of the model.

2.1. Background

Egypt lies between latitudes 22° and 32° north, and longitudes 25° and 35° east. The North boundary of Egypt is the Mediterranean Sea, and the East is the Red Sea. The South and West are political boundaries with Sudan and Libya, respectively. The total area of Egypt is equal to about one million km^2, about 94% of which is desert. The Nile Delta and its fringes (22,000 km^2) shown in Figure 3, lies between latitudes 30° 05′ and 31° 30′ North, and longitudes 29° 50′ and 32° 15′ East.

3. Discussion

3.1. Case study

At a distance of 20 km North-West of Cairo (Delta Barrage), and at an elevation of 17m above the sea level, the Nile Valley begins to open out into a triangular alluvial Delta with a base length of 275 km along the Mediterranean sea joining Alexandria and Port-Said. The level of the Delta land ranges between +17m above the sea level at the South to less than one meter at the North boundary Moawad et al (2014).

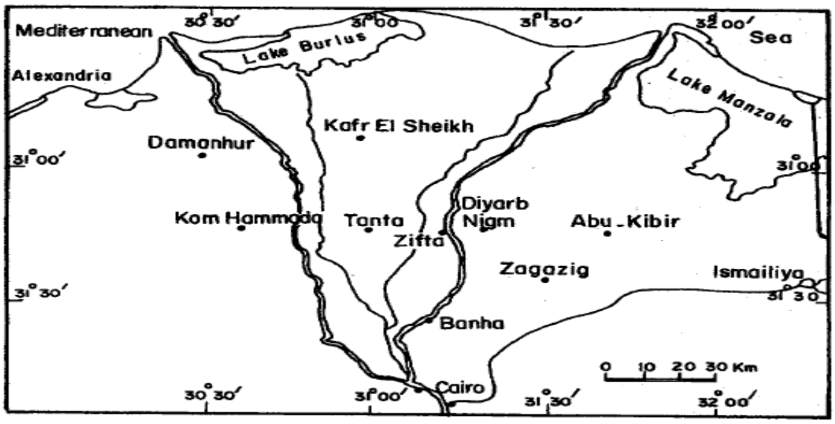

Figure 3. Layout for the Nile delta and its fringes.

The Nile Delta aquifer system is a complex groundwater system. The aquifer systems are recharged from deep percolation of subsurface drainage water and seepage from the main irrigation canals crossing the Nile Delta region. It may also be recharged by any possible flow coming from the Upper Egypt aquifer. The average rate of recharge from the excess irrigation water varies between 0.25 and 1.1 mm day^{-1}. The groundwater aquifer system in the Nile Delta is divided into two major aquifers the semi-confined aquifer and the unconfined aquifer. Figure (4) shows the distribution of these two aquifers within the delta itself and its fringes (eastern and western), El Ramly, (1997).

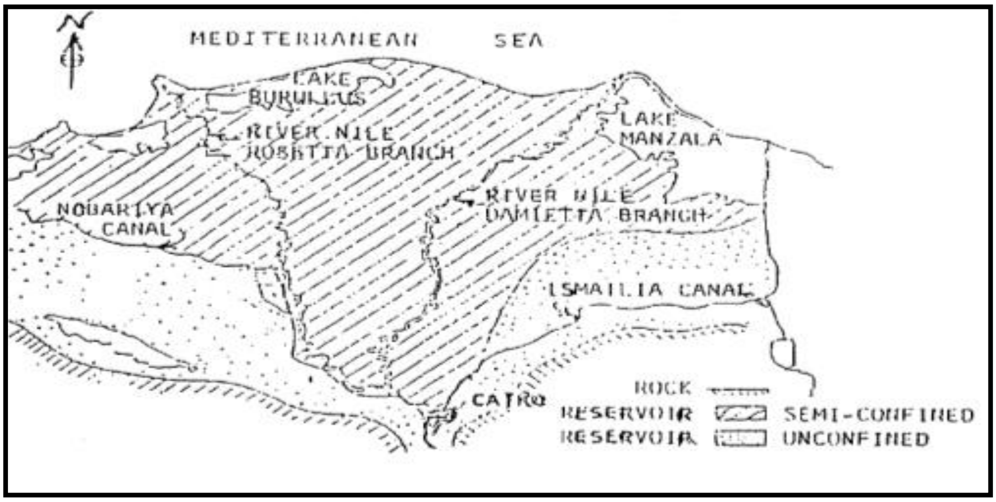

Figure 4. General map of the Nile Delta groundwater reservoir El Ramly, (1997).

The Nile delta aquifer extends over six million acres and is naturally bounded Northward by the Mediterranean Sea and Eastward by the Suez Canal. The Western boundary extends into the desert. At the south, the aquifer demises and seems to be isolated from the aquifer of Upper Egypt by an aquiclude approaching the clay cap near Cairo at El-Manawat. The delta aquifer is increasing in thickness from about 250 meters in the south to about 900 m near the Mediterranean Sea kashef, (1983) Figure (5) shows cross-section in the middle of the Delta.

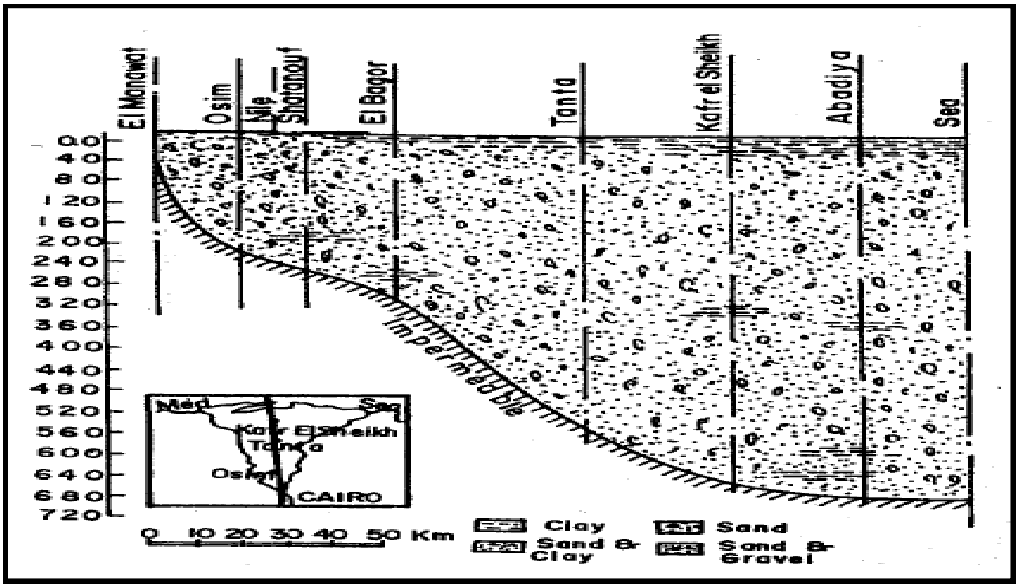

Figure 5. Cross-section in the middle of delta Sherif et al., (2001).

Figure 6 shows the surface counter line in the delta. It varies between 17.0m at Cairo and 1.0m near the coast. The surface of the delta inclines by 4cm/km towards the north.

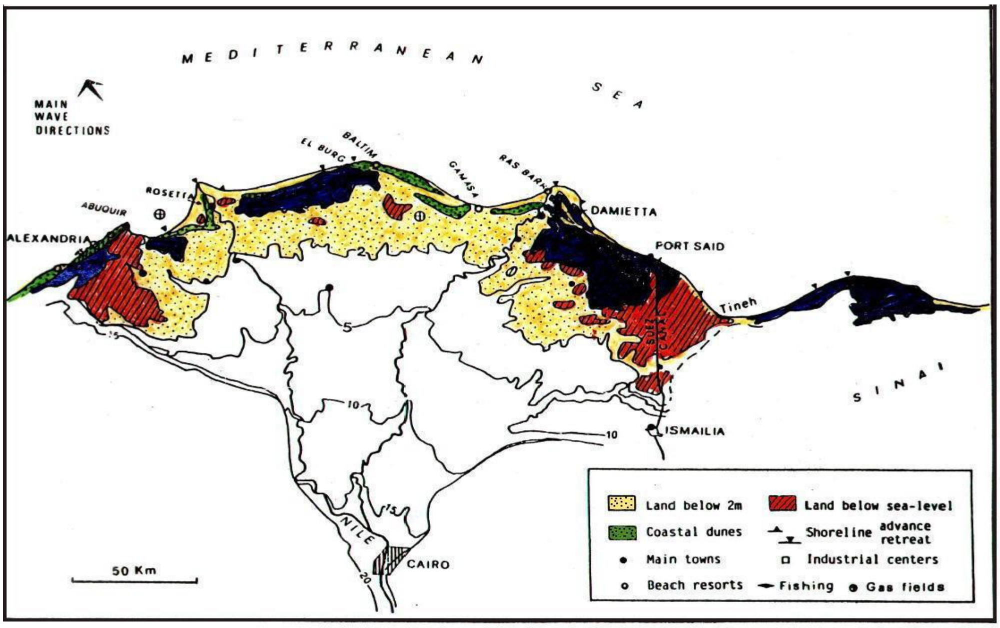

Figure 6. General topography of the Nile delta indicating areas below mean sea level in red and areas below 2m contour level in yellow El Raey (2010).

The sea level is expected to rise up to 0.5-2 m during a century and this will have a direct bad effect on the Nile Delta. The coastal zones of Egypt take a major part of the industrial activities including chemicals, petroleum and tourism distributed among a large number of highly populated economic centers such as the cities of Alexandria, Rosetta, Damietta, Port Said, Suez and Hurghada. Trading and transportation centers are also distributed among a large number of harbors which are considered highly attractive to employment from all over the country including: Alexandria, Idku fishing harbor, Burullus fishing harbor, Damietta commercial harbor and Port Said commercial harbor. The coastal zones are also considered an important source for fisheries and income generation Moawad (2014).

As mentioned before, the serious effects of sea level rise are two main effects: namely drowning the low land adjacent to the coast and the rise of the interface between the fresh and salt water under the delta.

The side effects of this are the destroy of the life of many people living in the low land and the end of many factories, schools, villages, and towns. The ecosystem will be changed in the wet lands, million of people will be immegrated from their homes, agricultural lands will be lost, and ground fresh water will be affected.

In the summer season, the value of precipitation is taken equal to the value of the seepage from the water of the irrigation area and will apply the equation (3) to find the interface line with vertical seepage, and equation (5) to find the out flow gap.

In the winter season, the value of precipitation plus to the value of the seepage from the water of the irrigation area are taken and applied in equation (3) to find the interface line with vertical seepage, and equation (6) to find the out flow gap.

The phreatic surface is assumed to be 1.m below the ground surface as the level of the drainage water surface is taken as a boundary condition.

In aquifers where the tidal range is big enough to allow the sea water to enter and go out the soil of the aquifer, it will effect on the site of the interface line noticeable. In the Nile Delta aquifer which is in tidal range (about 30-40 cm), the interface line will not change significantly.

4. Suggested protection strategies

The sea level might rise above the existing level by 1-2m due to melting of the ice at poles and at the top of the mountains during the century . Therefore, the low lands in the Delta might be drowned due to the sea level rise unless certain precautions to be taken. To protect the Delta, the following steps should take place:

a) The international road should be designed to be safe against seepage and effect of waves to prevent the passing of water from the sea and its level should be increased to at least 4.0 m above the existing sea level, as the case of Mohamed Ali wall to protect El-Meadia.
b) The inlets of the lakes should be controlled by gates to permit the water to go to the sea and prevent it from entering to the lakes.
c) If the inlets of the lakes are not controlled by gates, it should be closed, and pumping stations have to be used as the case of Lake Maryout.
d) If the inlets of the lakes are not controlled, an embankment of height 4m should be made all around the lakes to prevent the sea water from passing through the land.
e) Continuous use of irrigation water is essential in the low land to keep the interface of the salt water down.
f) The sand dunes near the coast should be kept as it is to be a natural defence.

5. Conclusion

The prepared model is useful and sufficient to give full analysis for the sea water intrusion under the delta. The Nile Delta will not be in danger if the above mentioned strategies are applied.

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Extended abstract for ISMAR10 symposium. **Topic No: 14 (098#)**

MAR on the Island of Gotland, Sweden – exploring the potential and feasibility in comparison to alternative measures

Peter Dahlqvist[1]*, Karin Sjöstrand[2,3], Andreas Lindhe[3], Lars Rosén[3], Jakob Nisell[1], Eva Hellstrand[1], Björn Holgersson[1]

[1] Geological Survey of Sweden, Lund/Uppsala, Sweden (SGU)
[2] RISE Research Institutes of Sweden, Lund, Sweden
[3] Chalmers University of Technology, Gothenburg, Sweden
*peter.dahlqvist@sgu.se ; Tel: +46703466058

Keywords: MAR; groundwater; mapping; cost effectiveness; decision-support.

EXTENDED ABSTRACT

1. Introduction

The Island of Gotland, situated in the Baltic Sea 100 km from mainland Sweden, suffers from insufficient water availability. Thin soil layers and lack of coherent reservoirs in the sedimentary bedrock, leads to high precipitation run-off and limited reservoir capacity in both surface and groundwater reservoirs. In addition to an already constrained water supply situation, the total water demand on the island is estimated to increase with more than 40% to the year 2045. To enhance water resource security and close the water supply and demand gap, several alternative measures are investigated on Gotland. Managed Aquifer Recharge (MAR) is explored by identifying suitable areas and estimating their possible contribution to an increased groundwater recharge. MAR is then compared to other measures in terms of costs and water availability potential.

2. Materials and Methods

Mapping of potential MAR locations on Gotland was based on information from hydrogeological investigations including two airborne transient electromagnetic surveys (SkyTEM) [1,2]; MAR investigations within existing well fields [3]; a 3D geological and hydrogeological model of the island; and a national mapping-project for groundwater recharge and storage capacity [4]. Cost-benefit and cost-effectiveness analyses were used to compare MAR to alternative measures.

3. Results

Figure 1 shows areas where the geology is favorable for infiltration and/or groundwater storage, and Figure 2 presents areas with proximity to surface water and/or areas suitable for water storage.

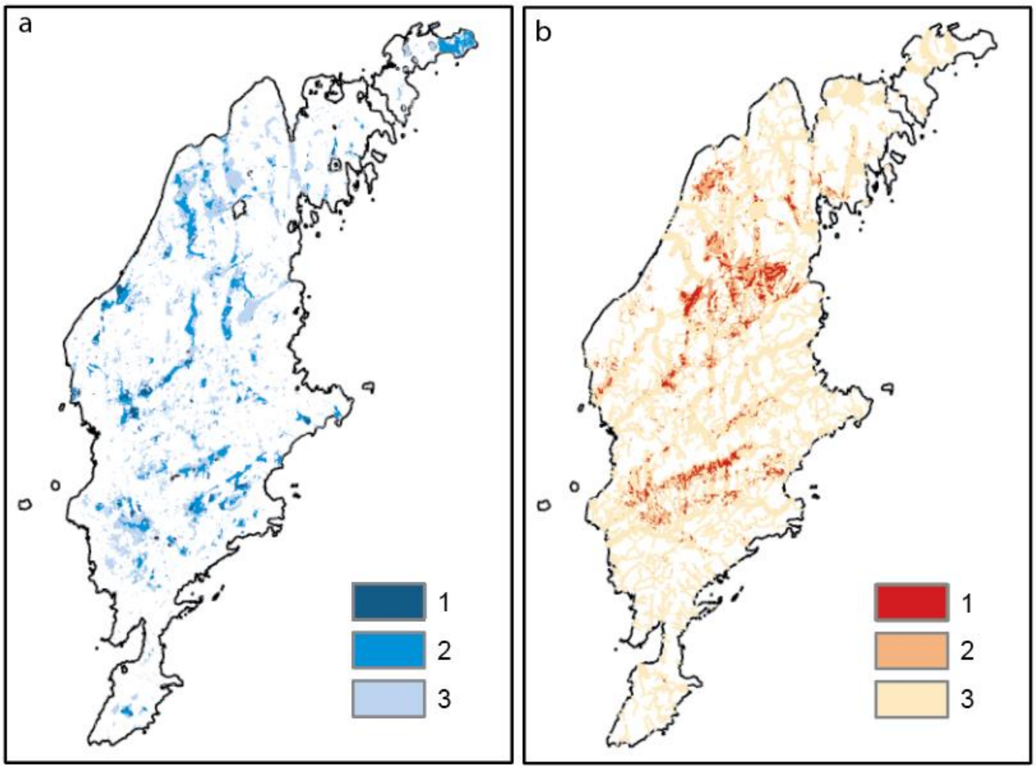

Figure 1. (**a**) Areas suitable for infiltration and groundwater storage; (**b**) Areas with close asset to a source and man-made storage areas. Scale 1:1,200,000.

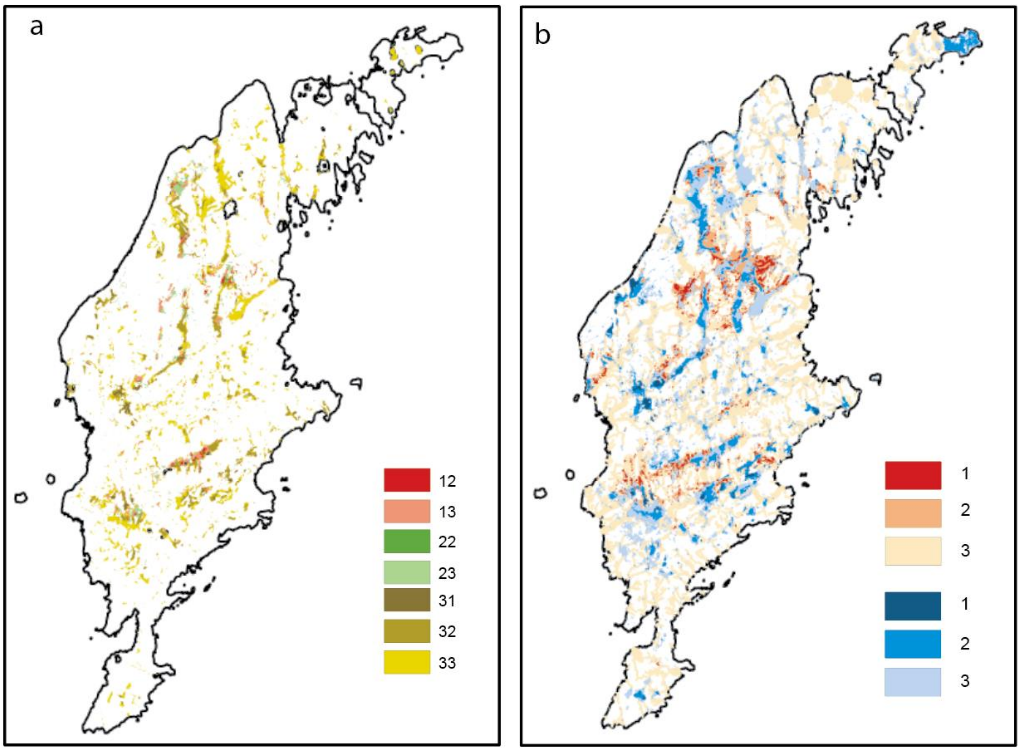

Figure 2. (a) Map with the best areas for infiltration/groundwater storage and source/surface water storage. **(b)** Combination of overlapping datasets. Scale 1:1,200,000.

In Figure 3 MAR is compared to alternative measures in a marginal abatement cost curve. The bar heights represent the cost per unit of water added by each measure (100 SEK ≈ 11 USD).

The bar widths display the annual amount of water made available by each measure in million cubic meters.

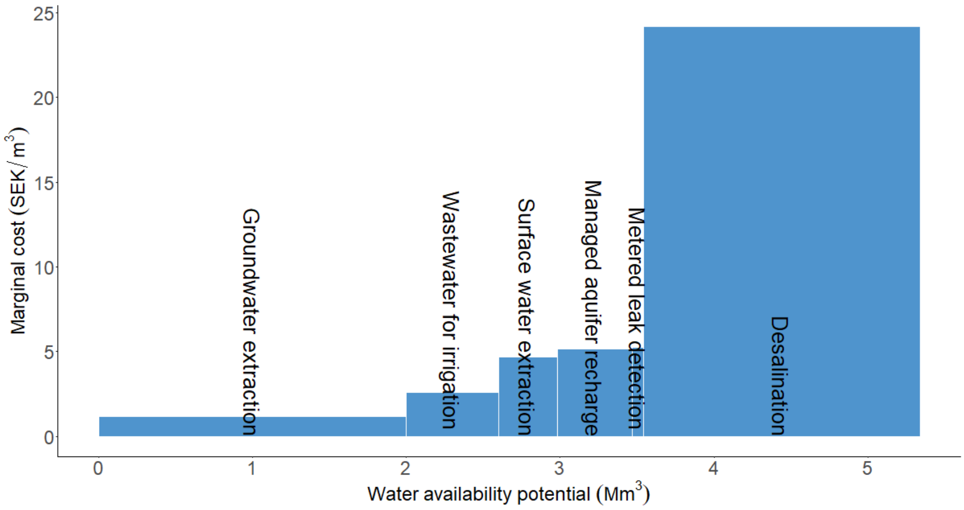

Figure 3 Marginal abatement cost curve for alternative measures on the island of Gotland.

4. Discussion

The presented data and analysis represent an early stage of mapping of MAR areas and estimates of potential and feasibility of MAR on the island of Gotland. There are uncertainties in data and analyses, but within these limitations there is now a rather detailed picture on possible MAR-areas which can be used by the municipality, farmers, industry and other stakeholders. Results from this paper can provide guidance on prioritizations between different MAR types as well as between a variety of alternative measures to improve the water resource security on the island.

5. Conclusions

The main conclusions of this paper are:
good and decent conditions for MAR was found in 7,700 and 22,700 ha respectively, the marginal cost of MAR was low when compared to e.g. desalination, and the water availability potential of MAR may increase when also considering new wellfields.

Acknowledgments: The work was funded by the Marie Skłodowska-Curie grant agreement No 754412; Region Västra Götaland; Region Gotland; The Swedish Agency for Economic and Regional Growth; and the Swedish Research Council Formas contract no 942-2015-130.

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Paper for ISMAR10 symposium. **Topic No: 14 (197#)**

Application and evaluation of an aquifer storage and recovery pilot system in Recife, Brazil

Lucila Fernandes[1]*, Anika Conrad[2], Suzana Montenegro[3], Anderson Paiva[4] and Maria Castro[5]

[1] Federal University of Pernambuco – UFPE, Recife-PE, Brazil; lucila.araujo@gmail.com
[2] adelphi research GmbH, Berlin, Germany; conrad@adelphi.de
[3] Federal University of Pernambuco – UFPE, Recife-PE, Brazil; suzanam.ufpe@gmail.com
[4] Federal University of Pernambuco – UFPE, Recife-PE, Brazil; andersonlrpaiva@gmail.com
[5] Federal University of Pernambuco – UFPE, Recife-PE, Brazil; mariaandradeal@hotmail.com
* Correspondence: lucila.araujo@gmail.com. Tel.: +55 83 99624 1490

Abstract: The rapid growth of the world's population has increased the demand for water. Especially in coastal cities where many of the world's most productive and economic centres are located, groundwater resources are suffering from increasing exploitation. To meet these growing challenges, the Managed Aquifer Recharge (MAR) system has emerged as a nature based solution for improved water management by protecting, enlarging, and using subsurface freshwater resources. In Recife, an ASR pilot system is currently under construction. This paper describes a recharge test that was carried out to determine the recharge rate and to identify the behaviour of the injected water in the brackish aquifer. The recharge pilot plant is located at a public school in the neighbourhood of Pina in the city of Recife/PE. A series of recharge tests were performed to analyse the water level drawdown. The water injection response was analysed in 3 monitoring wells. The results showed a recharge rate lower than that recorded in the literature and a decreasing recharge rate with the improving of the water volume injected. It is expected that these test results will contribute to the improvement of the ASR pilot system.

Keywords: Groundwater static level; Coastal aquifer; Recharge test; Brazil.

1. Introduction

Groundwater is a key natural resource and home to a variety of ecosystems providing valuable services supporting socioeconomic development worldwide [1]. Many ecosystem services have a direct link to groundwater storage, recharge and discharge. The interdependencies between ecosystem services and groundwater are little recognized and valued, neither in decision making and nor management of water resources and river basins. Especially in coastal zones where some of the world's most densely populated, productive and economic centers are located [2], groundwater resources are suffering from increasing exploitation. The issue of overexploitation interferes not only with the aquifer level, but also increases the risk of saltwater intrusion and subsidence. Coastal aquifers are likely to undergo salinization processes in both marine and estuarine areas. These potential sources, coupled with excessive exploitation, cause degradation of underground resources, rendering their waters unfit for various uses, including human consumption [3]. On the other hand, subsidence in addition to causing damages to buildings can render the aquifer useless as a source of fresh water.

Areas such as the Recife Metropolitan Region (RMR) at Brazilian Northeast Coastline, characterized by seasonal water shortages due to alternating wet and dry periods, benefit in particular from improved storage and recovery options, ensuring stable water supply year-round. In addition, recent droughts (1998-1999, 2012-2016) [4] and rising water demand over the last three decades due to steady population growth have created impacts such as overexploitation of groundwater resources, as well as potential subsidence [5], saltwater intrusion [6], and degradation of water quality [7]. At the same time, the RMR is exposed to frequent extreme rain events during 4 to 5 months of the wet season each year [8] and surface runoffs cause urban floods [9]. The MAR and in particular the ASR/ASR-Coastal systems could provide a mitigating solution addressing the abovementioned challenges [10,11].

The main reasons for implementing ASR systems are securing and increasing water supplies through emergency, seasonal and/or long-term storage [12]. The injection of water through deep wells has the advantage over other MAR methods because higher recharge rates are achieved and less land is required. But ASR also has its disadvantages over other MAR methods, which need to be weighed against the advantages of a particular case: The deep well injection requires a higher quality of the injected water, compared to surface recharge systems, to avoid well clogging and protect the groundwater quality [13]. Taking this into account, ASR can be used when storage and retrieval is the primary goal and water treatment of minor importance [14]. The involved costs for well-constructed wells and the high levels of necessary water pre-treatment depending on the available water source can be relatively high.

Currently, the challenge is to improve planning strategies for water resources management through the implementation of a Managed Aquifer Recharge (MAR) system in the Cabo aquifer. [15] demonstrated the feasibility of a pilot scale ASR system for recharging the Cabo aquifer through an injection test in a residential building in Boa Viagem neighbourhood. [10] tested how data monitoring and geological knowledge may allow further use of MAR strategies in the Recife region, asserting that a recharge next to an estuarial area of RMR is possible.

In this paper, we explore the behavior of the injected water in the Cabo aquifer, the second most exploited aquifer of Recife showing partly brackish conditions, by monitoring water level of both the injection well and monitoring wells and determine the recharge rate of the aquifer.

2. Materials and Methods

2.1. Study area

The study area was the Metropolitan Region of Recife (RMR). The RMR is located on the north-eastern coast of Brazil in the state of Pernambuco and includes the city of Recife, capital of Pernambuco and 13 surrounding municipalities [16]. With a total area of 2,768 km², RMR has a population of around 4 million inhabitants [17], with a concentration in neighborhoods such as Boa Viagem and Pina [16]. The pilot site was situated in a public school called Landelino Rocha, in the Pina neighborhood, between coordinates 8°05'35''S, 34°53'01''W.

The climate of the region is hot and humid, with average temperatures above 25°C [18]. The mean annual precipitation is relatively high compared to the semiarid inland with ca. 2,450 mm (1961-1990) [19], and with rain events occurring during the rainy season between March and July (> 250 mm/month).

2.1.1. Hydro-geological conditions

The area of RMR is a multi-layered sedimentary aquifer system located in the estuarine area of the Capibaribe River and includes smaller rivers such as the Beberibe, Tejipió, Jordão and Jiquiá. It includes also substantial mangrove ecosystem, an area which has developed due to the tide penetrating into the estuarine area.

RMR has been geologically formed by rocks of the crystalline basement and meso-cenozoic sediments of the coastal sedimentary basins Paraíba and Pernambuco. Both these basins are separated by a transverse structure of the Pernambuco Lineament with an east-west direction near the UTM 9,105,000 South [20]. The area of interest for this study was located in the Recife plain, south of the Pernambuco Lineament. The elevations of this plain is very low, from 1 to 10 m above sea level [6].

The main aquifers used in RMR for water supply are the Cabo aquifer, the Beberibe aquifer and the Boa Viagem aquifer. The Cabo formation, for which the ASR-Coastal system was conceptualized, is the second most exploited aquifer with the largest number of operating wells in the RMR [20]. It is composed by siliciclastic sediments resulted from the regional basement erosion [6], feldspar-rich conglomerates, siltstones, arkoses, claystones and sandstones. The hydraulic conductivity value is $4.64x10^{-6}$ m/s [21] and storage coefficient value is $1,0x10^{-4}$ [22]. The Cabo formation is overlaid by the Boa Viagem and Barreiras formations, formed by Quaternary sediments. The Boa Viagem formation is an unconfined aquifer characterized by recent and undifferentiated sediments, poorly-sorted deposits of gravel, sand, silts and clay of fluvial and marine origin.

2.2. Procedure of the recharge tests

The determination of the recharge rate was based on water level responses after filling the well with water. The test process distinguishes between single and continuous recharge tests. For the single recharge tests, water was filled into the well using gravity until the top of the well was reached. Subsequently, the injection was stopped, and the response of the water level was monitored by divers. Once a certain drawdown was reached, the well was filled with water again. This procedure was repeated several times. The first 4 tests (#1-4) were completed at a drawdown of about 10 to 15 m, the subsequent tests at 5 m water level difference (#5-8) and at 3 m (#9-10), and the last 13 tests (#11-23) at 1 m. Finally, the well was refilled with water continuously for 1.5 h while keeping the water level at a fixed level below the head of the well. Afterwards, the injection was stopped and the final drawdown (#25) was recorded by a diver until the water level reached the initial static water level. The process of a general single recharge test is visualized further on Figure 2, in the results and discussion section.

To receive an idea of the area of influence of the recharge, divers were installed in a second tube of the injection well (for recovery) as well as in two surrounding wells: a monitoring well at the school (20 m from the injection well) and a well at the residential building Enseada da Barra (150 m from the injection well). The location of the wells can be seen on the site map in Figure 1.

Figure 1. Google Maps (2018): Project site with location of the sensors.

In total, 4 wells have been equipped with sensors measuring water lever. The wells description is shown in Table1.

Table 1. Wells characteristics.

Well	Local	Function	Diameter (mm)	Depth (m)	Filter Lengh (m)	Static Level (m)	Distance from injection (m)
P1	L. R. School	Injection	50	135	127 - 135	35.57	0
P2	L. R. School	Recovery	50	126	104 - 110	34.16	0.20
P3	L. R. School	Monitoring	50	183	145 – 147 153 – 155 167 – 169 175 - 177	35.05	20
P4	E. B. Building	Monitoring	100	-	-	34.65	150

3. Results and discussion

3.1.Recharge rate

The variations of water level over time at the injection well as a response to water recharge are visualized in Figure 2. The individual peaks clearly represent the single recharge tests conducted. The graph also shows that the drawdown of water level took longer with each test conducted, evident in the peaks becoming broader. Consequently, the water recharged into the aquifer decreased over time. In order to maintain recharge rates that are as high as possible over the whole recharge process, the drawdown of each single recharge test was reduced while the tests were increased. The water level course in Figure 2 also shows the continuous recharge from minutes 210 to 300. During this test, a recharge rate of 1.2 L/min could be maintained. The water supply was stopped, and the final drawdown was recorded by the sensors.

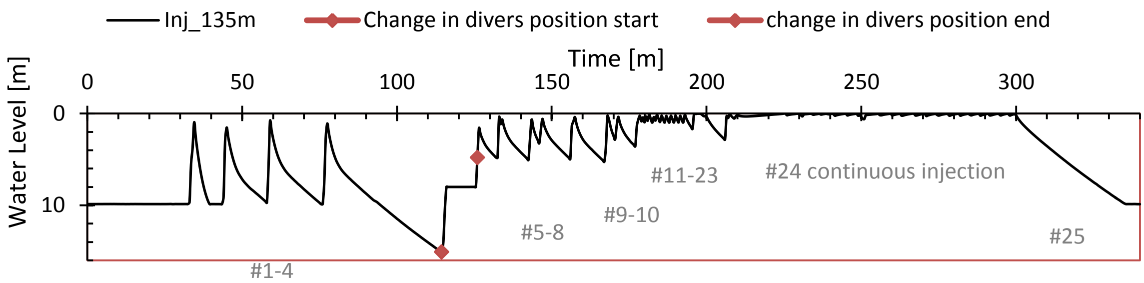

Figure 2. Water level variations in the injection well

In total, the injected water volume within a test time of 5 h was limited due to a decreasing recharge rate with increasing total injected water volume (Figure 2). Approximately 360 L in total could be infiltrated into the aquifer.

In order to investigate the decrease in the recharge rate more closely, the different recharge rates of the first eight tests and the final test (after continuous recharge) are compared in Figure 3, which shows water level variations over time. Based on three selected drawdown curves, mean recharge rates were determined by dividing the curves in different sections. The individual mean recharge rates resulted from the slope of the graph sections determined by building regression lines. It becomes obvious that the drawdown behaviour of the water level during the first recharge test is steeper and thus aquifer recharge was faster than in the remaining tests.

For the first test (#1) an initial mean recharge rate of 5.2 L/min at the first 8 m below the surface and a final 1.5 L/min at 8 to 11 m below the surface could be determined (Figure 3). The next three tests (#2-4) showed similar drawdown behaviour in the first few meters, with a recharge rate of 4.5 L/min. Subsequently, however, the recharge rate was less than half of the rate of the first test, with 0.6 L/min between water level of 5 and 15 m. In the last test (#25), after continuous recharge, the recharge rate finally dropped to 0.5 L/min.

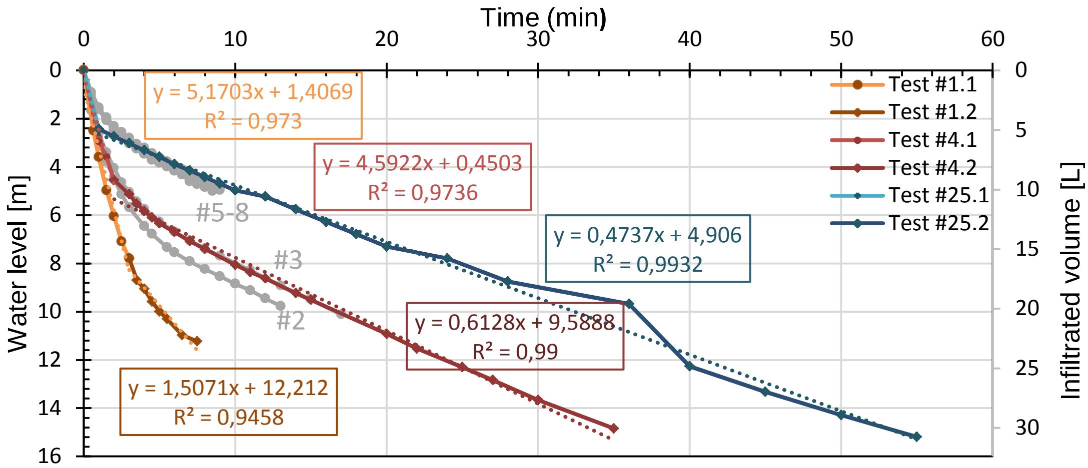

Figure 3. Variation in water level over time of the first seven single recharge tests as well as the continuous recharge test

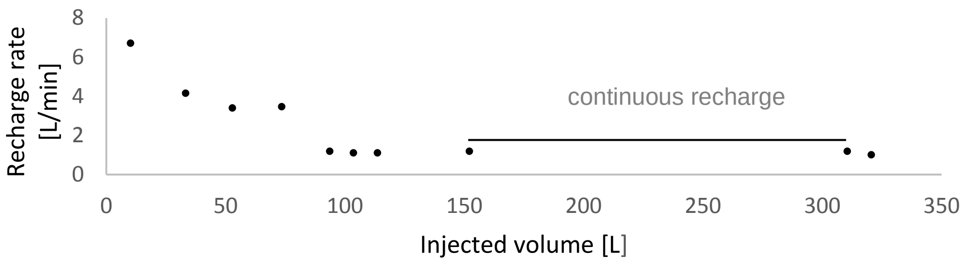

Figure 4. Dependency of the mean recharge rate on the total injected water volume. Seen are the mean recharge rates of 8 selected tests over a water level drawdown from 0 to 5 m (test #1-7 and #24 ascending from left to right)

These results show a clear dependency of the recharge rate on the total injected water volume, as presented in Figure 4. Here, the mean recharge rate of a water level drawdown from 0 to 5 m within the recharge tests (#1-4, #6-8 and 25) over the total water volume injected up to the respective time is shown. The graph shows a clear decline of the recharge rate with increasing injected water volume, approaching a value of about 1.2 L/min after 100 L injection volume.

3.2 Response in monitoring wells

The response in the recovery well was not robust. Due to an over increase in water level in the tube, the diver, which was stationed at around 34.60 m, was no longer able to detect water levels above a depth of 24 m.

Further, no response in water level could be detected at the two monitoring wells, at the school and the residential building Enseada da Barra.

4. Discussion

During the single recharge test series decreasing recharge rates from 6.7 L/min to 1.1 L/min were observed when injecting increased water volume. After the injection of about 100 L a constant recharge rate of about 1.2 L/min was maintained. This initial decrease is most likely due to the accumulation of the initial injected water volume noticed in the second tube of the injecting well. Both tubes are situated in the same borehole and connected via the gravel filter surrounding both screens. During the test series, an increase could be observed in the water level of this slightly shallower tube. Furthermore, air entrainment may have occurred as the well was filled with water in free fall. It is recommended injecting the water via a hose directly below the water level to avoid air entrainment (e.g. [23]). According to [24], this effect usually leads to a decrease of recharge rates within the first few hours. However, [25] was able to maintain a constant injection rate over two weeks, even though he injected the water in free fall above the water level. The continuous recharge test, in which constantly 1.2 L/min were injected, only lasted for 1.5 h. In a subsequent long-term test, it would be interesting to investigate whether this constant recharge rate can be maintained.

The achieved recharge rate of 1.2 L/min is very low compared to data measured in literature. [26] detected a mean recharge rate of 34.5 L/min into the Cabo aquifer, almost 30 times higher. Even though the ASR well investigated by Silva had a screen two times as long as the well studied in the present study, the achieved recharge rate of 1.2 L/min is still several times smaller. Under the simplified consideration that the screen length is directly proportional to the recharge rate, a rate of approximately 17 L/min would have been expected, assuming that all other parameters of both studies are equal. However, when comparing the studies with each another, a further difference becomes apparent: the screen of the well under study is surrounded by fine sandstone with clayey intercalations, whereas the screen of the ASR well investigated by Silva was surrounded by coarse to medium – and thus less dense – sandstone with clayey intercalations. These differences in soil type porosity could explain the lower recharge rate measured at the pilot during the recharge test series. In addition, it is possible that the proportion of clay within the sandstone surrounding the studied injection well was higher than at the well of Silva’s case study.

Furthermore, wells generally used for ASR application contain medium to large diameters [25] and the injection well used by [22] was 4 inches in diameter. Few model and field studies have proven a relatively new ASR approach using a small diameter between 1 inch and 2 inches to be practically applicable for a temporary recharge period [23, 25, 27]. However, these studies have been conducted in alluvial aquifers. In consolidated aquifers with relatively low hydraulic conductivities, such as the Cabo aquifer, a detectable increase in the recharge rate with increasing well diameter is reported [28]. Hence, at the project site containing a relatively low transmissivity it may be more appropriate to use larger diameters to achieve larger recharge rates. Another major reason why larger well diameters should be chosen is the need to install a pump for backwashing and measurement equipment for monitoring.

As a relatively low recharge volume of approximately 360 L could be injected into the aquifer, no significant changes in the water level were detectable at the two monitoring wells distanced 15 m and 150 m from to the injection well.

5. Conclusion

The recharge tests at a 2-inch diameter well showed that recharging the Cabo aquifer is feasible but only under very low injection rates. Groundwater flow simulations could help when investigating whether and when the injected water is recoverable and for which RE. Few potential measures have been discussed that might improve the performance of the studied injection well:

- Increasing the length of the well screen
- Increasing the well diameter
- Selecting a layer of the Cabo aquifer that is composed of coarser materials and less clay

Whether these small injected water volumes are still recoverable after a long storage period needs to be further investigated by, for instance, using groundwater modelling. APAC recently developed a groundwater model for the entire RMR [29] which could be adapted to this case study.

Acknowledgments: The author would like to acknowledge the financial support from Brazilian Innovation Agency (FINEP) grant to the BRAMAR (BRAzil Managed Aquifer Recharge, grant no. 557/2013) project. The authors greatly thank the Foundation for Science and Technology of Pernambuco State (FACEPE), CNPq (Brazilian National Council for Scientific and Technological Development), and UFPE (Federal University of Pernambuco) for the research (PQ and PIBIC) and graduate scholarships. The authors would like to thank also the adelphi research GmbH group for their support. Special thanks are given to Prof. Cristiano Almeida, Victor Baptista, Suênio da Silva and Felipe Lemos, Federal University of Paraíba (UFPB) researchers in the Civil Engineering Department, for their valuable support in the recharge test.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASR: Aquifer Storage and Recovery
MAR: Managed Aquifer Recharge
RMR: Metropolitan region of Recife (Região Metropolitana do Recife)

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Topic 15. MAR AND ENVIRONMENT…

Extended abstract for ISMAR10 symposium. ***Topic No: 15 (015#)***

Methodology for assessing Managed Aquifer Recharge project implementation in Chile

Guimerà, Jordi[1]*; Vilanova, Ester[1]; Pilar Enguita[2] and Adrián Lillo[3]

[1] Amphos 21 Barcelona, Spain
[2] Amphos 21 Santiago de Chile
[3] Dirección General de Aguas, Chile
* Correspondence: jordi.guimera@amphos21.com; Tel.: +34 935830500

Abstract: Managed aquifer recharge (MAR) in Chile is contemplated in the National Water Resources and in the Irrigation strategies as an option to face the shortage of the resource in basins with negative water balance and to increase the reserves in aquifers, to facilitate the water transport and to improve groundwater quality. In addition, MAR is already established in several Chilean regulations. As a result, different individual and private studies of MAR were implemented in Chile in an increasing number from the 70s years to present. The National Water Authority (DGA) commissioned a study to evaluate the most favorable areas for MAR in Chile; to stablish the methodological procedures to apply for a MAR project in Chile and to asses them.

A multicriteria analysis was applied to identify the most favorable areas for MAR. This methodology was developed using those variables of importance for MAR that were available at the national level: soil and aquifer permeability, land uses, slope and existence of rivers. Each variable is represented in a cover map and transformed to harmonized values depending on their degree of favorability. Afterwards the different variables are weighted by their degree of importance with respect the total of variables in the final feasibility analysis. As a result, the different basins were ranked and those where a priori, the MAR strategy has more feasibility potential, were defined.

Keywords: Chile, managed aquifer recharge, water scarcity, GIS analysis, multicriteria analysis, decision support system, decision making tool.

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1. Introduction

There are different international guides that detail the most important criteria and parameters for the selection of areas where managed aquifer recharge (MAR) is viable [1-3]. In addition, several countries have applied Geographic Information Systems (GIS) to determine the most favorable areas automatically based on previously defined criteria. In some of these studies they use remote sensing to map some parameters such as geomorphology or land uses.

The study by Fernández-Escalante *et al* [1] has been carried out within the framework of the DINA-MAR project in Spain. This project has analyzed and evaluated all artificial recharge sites throughout Spain. In addition, a GIS with the selection of potential new sites in Spain is published on the project's website (http://www.dina-mar.es/). It uses 82 different thematic covers (criteria) the main one being the storage capacity of the aquifers. Given that it is designed for a given country, it may not be applicable to many other countries because the information is not equally relevant in nor does it exist with the same degree of detail.

Steinel [2] analyzes all the factors to be taken into account for the implementation of recharging devices in an arid area such as Jordan. The work focused on the collection of flood or alluvial waters but also considers the factors to be taken into account in other recharging devices, such as precipitation, slope, hydraulic infrastructures, soil type, hydrogeology and land use.

The Department of Water Affairs in South Africa has developed a series of methodological Guidelines that summarize previous studies and issue conclusions regarding the criteria to be taken into account and their relative importance [3]. They published the Strategy on Artificial Recharge [4] aiming at the implementation of this technology, at reviewing seven main topics and including the analysis of risk to clogging and uncertainty of hydraulic parameters.

The Hindu Department Indian Central Ground Water Board (CGWB) has also published a MAR Guide [5] and has subsequently developed a Master Plan and an implementation manual, as well as a selection of case studies. Chowdhury selected recharge zones in India through the use of a GIS [6]. The parameters used are five: geomorphology, geology, drainage density, terrain slope and transmissivity, while the work of Saraf and Choudhury [7]-also developed in India-considered only four parameters: geology, geomorphology, linear structures and slope.

Rahman et al. [8], organized the criteria to evaluate favorable zones in Portugal according to three categories: surface characteristics, water quality and characteristics of the aquifer, the latter being the most important. Within these categories, the residence time, depth of water table, aquifer thickness, infiltration rate, slope, chloride and nitrate concentration were considered.

The Water Authority of Chile (DGA) commissioned a methodological study in 2013 to (1) detect the most favorable areas for MAR at the country scale (2) provide the structure of a solicitation project of MAR and (3) provide the structure of the assessment of these projects [9]

1.1 Objectives

The objective of this paper is to define the most suitable locations for MAR projects implementation in Chile. For that, a methodology which is based on collecting already existing information at national scale is developed and implemented in a Geographical Information System. The advantages and limitations of this system are discussed in light of its wide use for the decision-making authorities.

2. Materials and Methods

2.1 Criteria used in literature cases

The first step was to make a selection of the criteria and sub-criteria, that is, the parameters and conditioning values in relation to the installation of new recharging devices. This selection was made based on background information and was applied to the main types of previously selected devices.

These criteria are the same as those used in the Geographic Information System (GIS) for the selection of sites and which were mapped accordingly.

Next, the hierarchical relation of the different criteria and sub-criteria was established. The fourth step was to standardize the maps made. This process allowed converting the values of each map to a common dimensionless scale. In this sense, it is proposed to give three categories to the values of each of the maps: very favorable, moderately favorable, not viable. In the majority of the references consulted, between 2 and 4 classes were used.

Once the values of each of the criteria were standardized, the next step consisted in giving weights relative to the criteria and sub-criteria. There are different methods to consider all the parameters in a joint way. Most are based on giving weights to each of the parameters based on expert opinion. These weights or weighting factors are different for each of the recharging devices.

Before proceeding to the estimation of more favorable areas based on the criterion weighting method, it is necessary to eliminate and exclude those areas or areas that for different reasons do not allow the installation of new recharging devices, among others:

- Due to proximity to the population or environmental ecosystems
- Due to proximity to other recharging facilities
- By environmental or aquifer protection legislation
- Due to the typology of the aquifer
- Due to the vulnerability of the environment or the depth of the water table.

2.2 Weighting and representation of parameters used in this work

The weighting of parameters relies on the selection of the most influential parameters and for which information is available. This weighting will be different depending on the type of recharge device to be evaluated.

Based on the available information, it is proposed to work in Chile on two work scales:

1. Identify at a national level those areas where there is a demand for non-supplied water and that water is available for recharging, and will consider water demand and presence of surface water as main critical parameters

2. Identify at the basin level those areas most favorable to artificial recharge based on surface and underground criteria. This second level of work will only be applied to those basins where the first analysis has shown that recharge is viable and will consider aquifer types, slope, confinement and soil use as main variables.

2.3 GIS project

We propose new potential areas for MAR based on the criteria explained above implemented in a GIS which has been divided into three stages and that are described below:

1) Background Collection
2) Generation of new coverage through spatial analysis
3) Multicriteria Evaluation and Mapping of results

Based on the information collected and the criteria of interest, the variables whose variation in the environment affects the potential of establishing artificial recharge works have been specialized, generating continuous coverage (raster or polygons) where its spatial and / or temporal variation is recorded if required.

GIS tools have been used for proximity analysis, superposition, geostatistical interpolation, among others (when required), as an indirect estimation of the behavior and / or parameters of interest that have contributed to the development of the objective of this study.

In the multicriteria analysis, the generation of thematic coverage has been considered from the categorization of these. Therefore, ranges of favorable values have been established: means, low, null or limiting, depending on the effect generated by the variable on the final indicator.

Subsequently, these categories have been weighted by the degree of importance with respect to the total of variables.

The definitions of the limits of each category and the weights of each variable are the result of the technical analysis, validated in the different workshops of the project. Equation 1 and Figure 1 represent the general equation that defines the multicriteria index and an example scheme of how variables and criteria are organized in the construction of the index, respectively. The final index and each of the spatialized criteria participating in the analysis have been mapped at an appropriate scale.

$$C_j = \sum_{i=1}^{n_j} \frac{v_{ij} p_{ij}}{r_j} * 100 \qquad (1)$$

where, Cj = scoring for criteria j
Vij = variable i for criteria j
pij = weight of variable i in criteria j (between 0 y 1; Σpi = 1)
rj = measurement range of variables for criteria j

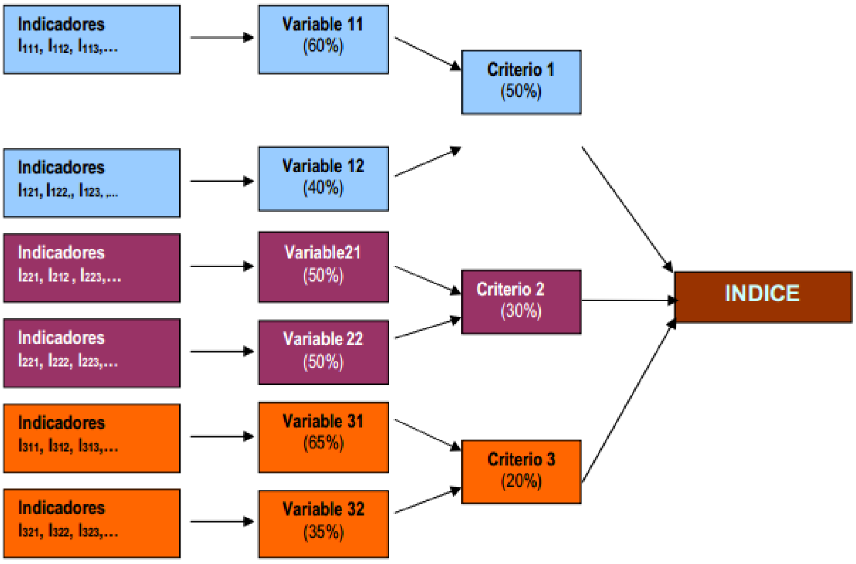

Figure 1. Procedure to identify the most favorable zones

3. Results

Based on the information available and the criteria explained above, we calculate an index, which allows hierarchizing the basins of Chile based on the presence of favorable conditions for artificial recharge. The variables considered in the analysis were permeability, land use, slope and presence of river bed due to the availability of information at national scale.

Permeability was considered at the national level from the Hydrogeological Map of Chile scale 1: 1,000,000, considering as favorable areas the zones identified as formations with primary pososity.

Land use was delineated by means of the Land Use Cadastre CIREN / CONAF, where the favorable areas were the remnants after discarding the areas present in the SNASPE (protected areas), urban areas, agricultural areas, forests, glaciers and water bodies.

The slopes were calculated as a percentage for the entire national territory, from GDEM data of 32 meters resolution, were classified in ranges of 0 -5% (limit in infiltration works), 5-50% (injection works) and greater than 50%. Notwithstanding this, only the first rank was considered as a favorable value in the calculation of the index.

Another factor considered in the preliminary calculation of this index was the presence or absence of riverbeds within each basin.

Finally, the proposed multicriteria index can be defined as follows:

$$index = \frac{AP * 200 + AFR * 200 + PR * 50}{450} \qquad (2)$$

where:

AP are aquifers protected, restricted or overexploited

AFR is the favorable basin area with respect to the maximum favorable area in the studied basins (0 to 1)

PR presence of riverbeds in the basin

The results of this index calculation extended to a total of 100 basins and are indicated in Figure 2. A more complete description may be found in DGA-Amphos 21 (2014).

4. Discussion

The results presented in the former section, have a significant value in terms of decision making but should be taken with caution and as a semiquantitative tool. In fact, it provides a reliable way of categorizing the basins where the Water Authority must focus, yet it relies on the direct information where aquifers in trouble together with the relative dimension where the problem is more prominent. This is the reasoning of weighting by areas, yet it provides available space where the MAR projects can be implemented with respect to the dimension of the basin. The calculation of the index takes into account the presence of riverbeds, which is considered both the source and the location where the MAR projects can be developed. It is a source of water for those permanent and a potential to establish MAR projects when the river is seasonal. This is especially sensitive in the Andean Highlands (Altiplano) and in the Atacama Desert basins, where precipitation occurs through heavy winter storms and the riverbeds may run dry the rest of the year.

The index does not consider however, the hydrological description of the river in terms of availability of water or the distance of the potential zones for MAR projects to the source of water. This type of categorization should be done at a basin scale, when the decision to opt for one or another site must be done. This new index at a more local scale should contemplate the social components of the project as well as a preliminary economical – financial estimation.

5. Conclusions

Decision making tools for categorizing candidate zones for MAR projects in a given country or region of the country are valuable and provide a (semi-)quantitative basis to make informed decisions. Multicriteria analysis implemented in Geographical Information Systems permit to rank areas and to help at deciding which should be given more attention than others. This paper provides an example of application at a very broad scale, that is the whole country of Chile, despite the fact that only those more relevant areas have been presented.

The selection criteria for potential aquifer recharge basins, in Chile the most considered parameters have been the depth of the water table, the permeability / hydraulic conductivity and the aquifer area.

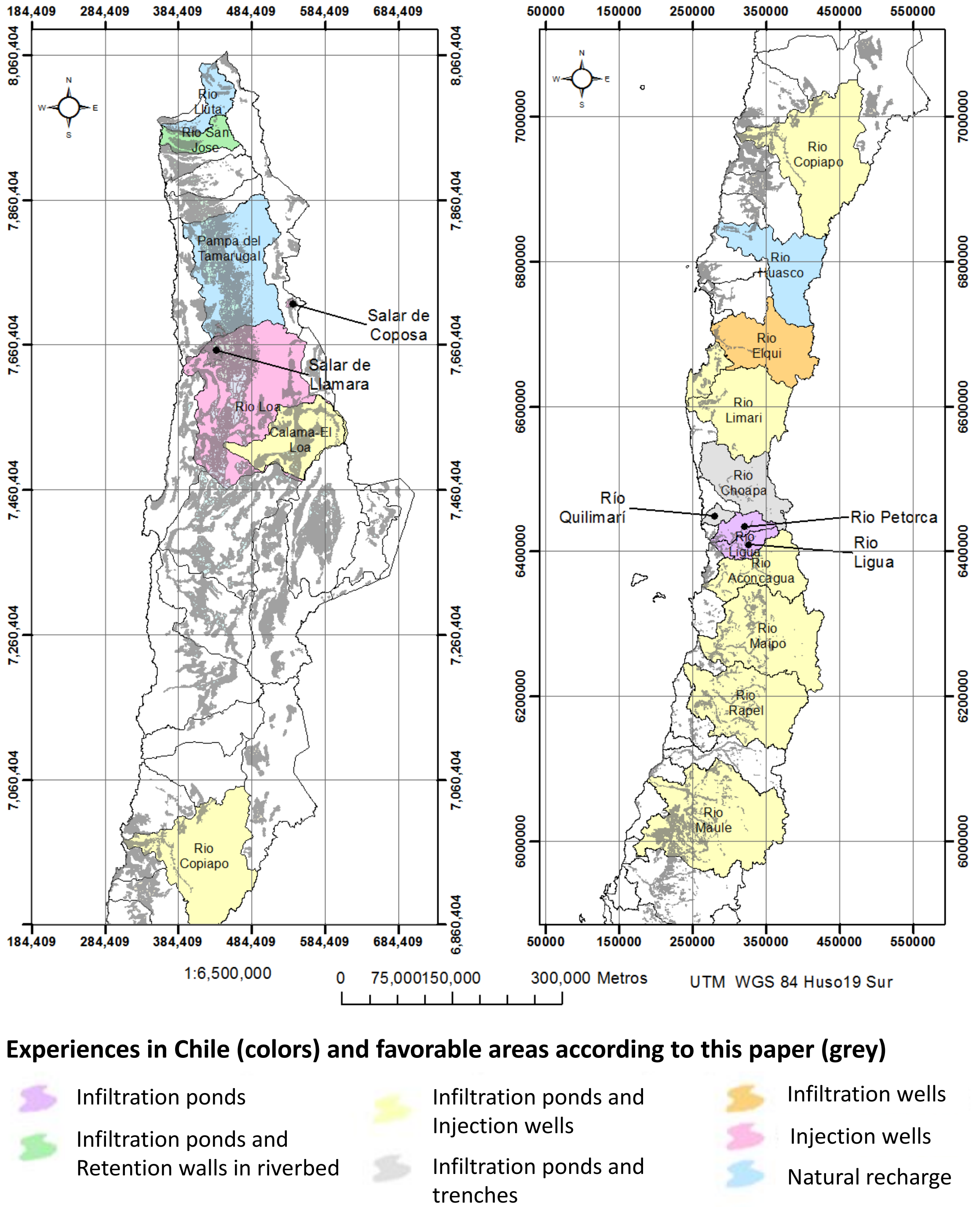

Figure 2. Favorable areas for MAR in Chile

Acknowledgments: This paper was funded by the Water Authority of Chile (Dirección General del Agua) by commissioning the study "DIAGNÓSTICO DE METODOLOGÍA PARA LA PRESENTACIÓN Y ANÁLISIS DE PROYECTOS DE RECARGA ARTIFICIAL DE ACUÍFEROS" sit 34 to Amphos 21 Consulting Chile. Authors wish to thank Daniel Montaner and Georgina Trujillo for their contribution to set up the GIS.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper for ISMAR10 symposium. ***Topic No: 13 (022#)***

Managed Aquifer Recharge to Support Environmental Outcomes on the Katarapko Floodplain

Russell Martin[1], Hayley Whittington[1], Whendee Young[2,] and Ann-Marie Lush[2*]

[1] Wallbridge Gilbert Aztec; rmartin@wga.com.au; hwhittington@wga.com.au
[2] Department for Environnent and Water; Whendee.Young@sa.gov.au; Ann-Marie.Lush@sa.gov.au
*Correspondence: rmartin@wga.com.au; Tel.: +61 438 110 700

Abstract: The health of many riverine floodplains has been in decline for several decades because of river regulation, overallocation, over use and extreme drought. The percentage of healthy trees (River Red Gum, Black Box and River Cooba) on the Katarapko floodplain, an area of approximately 1,300 hectares, dropped from 43% in 2002 to 22% in 2007. The South Australian Riverland Floodplain Integrated Infrastructure Program (SARFIIP) aims to create an interconnected mosaic of manageable floodplains enabling an engineered regime of inundation frequency and duration. Predictions are that groundwater rise in response to managed inundation events could mobilise highly saline groundwater displacing the existing freshwater lenses and increasing salt loads to the river. Injection of freshwater using managed aquifer recharge approaches is being trialed as a potential option to mitigate against the possible displacement of the existing freshwater lenses and to expand zones of lower salinity groundwater. A key knowledge gap for the future design of groundwater management infrastructure on floodplains is validation of injection as a reliable mitigation option. This paper presents the results of the first stage of a managed aquifer recharge trial aimed at assessing the technical feasibility of injecting river water into the floodplain shallow aquifers via bores.

Keywords: Katarapko, floodplain, managed aquifer recharge, groundwater, environmental, river murray, clogging.

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1. Introduction

The South Australian Riverland Floodplain Integrated Infrastructure Program (SARFIIP) aims to create an interconnected mosaic of manageable floodplains between Lock 1 at Blanchetown and the South Australian borders with New South Wales and Victoria. A suite of infrastructure projects has been proposed to improve the ecology of the Pike and Katarapko Floodplains. Proposed groundwater management schemes aim to reduce the regional saline groundwater influx to the floodplain and to protect or enhance the availability of lower salinity groundwater to vegetation.

A major infrastructure component is the construction of an extensive blocking bank on the Katarapko Floodplain to enable periodic inundation behind the blocking bank to enhance infiltration and promote a reserve of freshwater in the underlying shallow saline groundwater system to support vegetation. Two issues have been identified:

1. The infiltrated fresh water will displace some of the shallow saline groundwater, driving it toward the river, increasing the salinity risk to healthy vegetation located between the blocking bank and river; and
2. Vegetation between the blocking bank and river already exhibiting signs of salinity impacts would not benefit from the periodic inundation that would occur behind the blocking bank.

Injection of freshwater into the shallow saline groundwater system has been proposed as a potential option to mitigate the risk of displacing existing freshwater lenses. Additionally, injection of freshwater has the potential to expand into existing zones between the river and blocking bank where the groundwater salinity is high and impacting on vegetation health.

A critical knowledge gap for the future design of groundwater management infrastructure on the floodplain is the validation of injection as a reliable mitigation option for the management of existing, and establishment of new, freshwater lenses. An injection trial is proposed to increase the understanding concerning the technical feasibility of this approach and if this approach can effectively freshen the groundwater noticeably and extensively. In addition to the knowledge gap several key risks were identified when the proposed approach to developing the managed aquifer recharge (MAR) trial on the floodplain.

Clogging associated with the high turbidity water and potential changes in pH between the source and receiving groundwaters are likely to result in chemical precipitation and clogging of the injection well. There are various approaches to managing the turbidity and balancing the pH involving mechanical filtration and treatment which, depending on the source and receiving water quality, can range in cost from tens of thousands of dollars up to hundreds of thousands of dollars. The accessibility of the floodplain, the risk of natural inundation, and the desire of the community to limit hard infrastructure on the floodplain require innovative but simple solutions. To manage the identified risks the project is being delivered in several stages and this paper presents the results of the Stage 1 investigations which has delivered solutions to meet some of the main technical challenges.

2. Approach

The primary objective of Stage 1 is to confirm that a reliable and cost-effective treatment train for the source water can be designed to support the MAR trial. If the treatment train required to achieve the necessary water quality for reinjection proves too expensive, consideration would need to be given to alternative freshening options other than MAR. The following aspects of the preliminary feasibility study were undertaken:

- Analysis of the local hydrogeology, field inspection of potential sites, and review of background data.
- Membrane filtration index assessment to determine filtration requirements of source water for MAR.
- Hydrogeochemical modelling.
- Preliminary specifications for a treatment train that would achieve the required water quality for MAR at a suitable cost.
- Development of a preliminary analytical model to support planning of the trial.

3. Hydrogeological Setting

A review of the geological and hydrogeological setting of the Coonambidgal and Monoman Formations using drillhole data and the airborne electromagnetic (AEM) data has identified that the Coonambidgal Formation contains buried channels and isolated sand lenses which potentially support the existing freshwater zones and are likely to act as preferential flow paths for water infiltrated behind the blocking bank. This interpretation of buried channels and thin sand layers within the Coonambidgal Formation, evident from the AEM data and some existing drillholes, directly connected to the underlying Monoman Formation, presents an alternative conceptualisation of the aquifer system across this portion of the floodplain. Previous studies (SKM and AWE, 2003 Woods, 2015) [1 and 2] have assumed the floodplain comprises a simple layering of thin topsoil (>20 cm), a four-metre-thick sequence of clay (Coonambidgal Formation) and an underlying sequence of sand (Monoman Formation) between 10 to 15 m thick. The interpretation of the floodplain geomorphology at Katarapko identified in this study is consistent with interpretations by Clarke et.al. (2008) [3] in the New South Wales portion of the riverine floodplains.

4. Results

Membrane Filtration Index (MFI) testing was completed to provide a qualitative predictor of clogging. The basic theory behind the MFI testing is to assume that the rate at which a filter becomes clogged at a constant pressure can be used to define a "clogging index" for a specific water at a given temperature (Dillon et. al. 2001) [4]. The results confirmed that without some form of pre-filtering clogging in the injection well would be inevitable.

The water samples were filtered through an 11, 8 and 2.4-micron filter and the resultant filtrate sent to the laboratory for analysis of the suspended solids content. All suspended solids to below the limit of laboratory reporting (LOR), 5 mg/L, were removed with an 11-micron filter. These results indicate that a 25-micron bag filter should remove up to 90% of the filterable solids. However, these results are for a one-off sample event and the temporal variability in suspended solids loading is not known therefore, for the trial a 10-micron bag filter will be used to ensure turbidity levels of the source water are maintained below 5 NTU.

Hydrogeochemical modelling using PHREEQC of the mixing between the source and receiving groundwater has identified iron precipitation is likely to occur if the dissolved oxygen of the source water is considerably higher than modelled. A key consideration during the trial will be the management of dissolved oxygen levels and pH in the source water. Iron bacteria are a known problem in wells constructed along the River Murray to support operation of salt interception schemes and therefore may also cause clogging. Appropriate treatment will be required as part of the injection trial infrastructure to control the risk of clogging that may result from microbiological activity.

SONDE profiling (Figure 1) of observation wells close to the proposed trial site have identified increasing salinity with depth and decreasing pH with depth. Both these conditions in the target aquifer influence the well design. To avoid potential geochemical reactions that may arise by changing the pH and greatly increasing the salinity of the injected water the production and associated monitoring wells will target only the upper two to three metres of the aquifer.

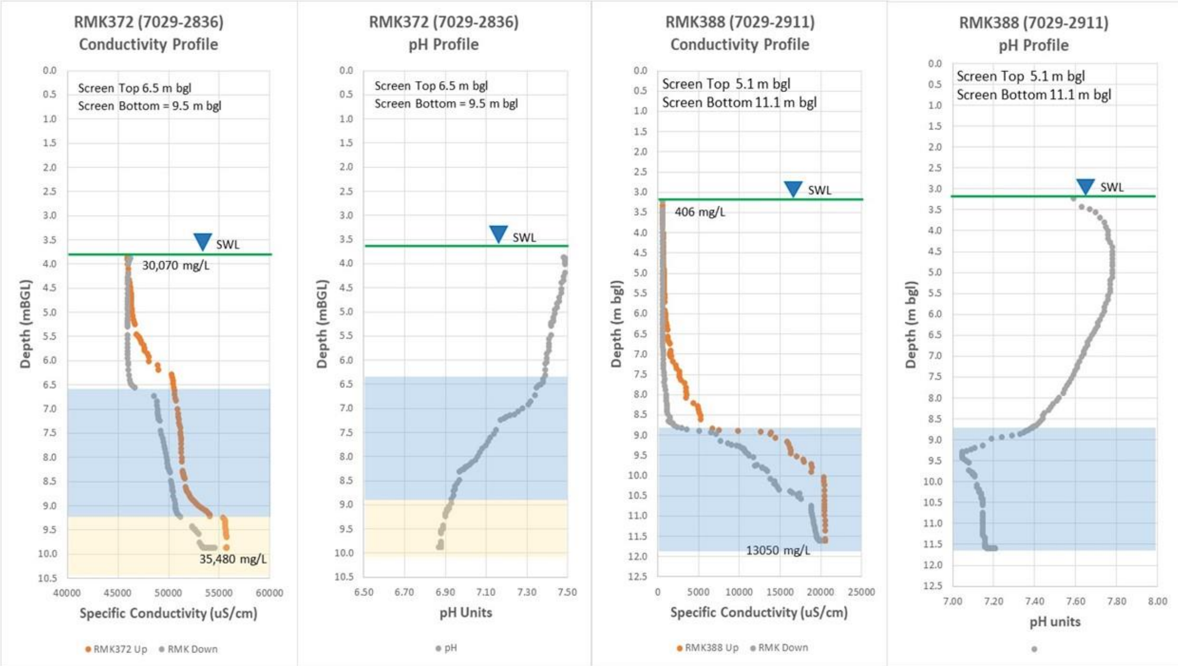

Figure 1. Vertical down hole SONDE profiles for wells 7029-2836 and 7029-2911, Conductivity and pH.

An approximation of the expected impress heads during injection and the effective influence of the injected envelope was undertaken using an analytical model. The modelling used average values of transmissivity for the floodplain and a low recharge rate to ensure that the water levels during injection (impress head) remain sub-artesian. The modelling demonstrated that even at a low rate of injection (1 L/s) for an average transmissivity of 18 m^2/d, and assuming no clogging, up to 16 ML could be recharged over the proposed six-month trial period. For the average aquifer properties, an assumed aquifer thickness of 4 m and radial flow at the end of the six-month injection period the envelope would extended radially around the injection well of approximately 100 m.

The analytical model is a simplistic approximation and ignores any aquifer heterogeneity but confirms that even at low injection rates most of the trial objectives can be reasonably achieved within the planned six months operation. Some uncertainty exists around evaluating the impacts on vegetation which may require the trial to be extended. The analytical model has assisted in determining the appropriate distance to install the associated monitoring wells and inform the monitoring regime throughout the trial.

The final component of the desktop study involved an assessment of the infrastructure that would be required for the trial together with a preliminary estimate of the capital costs. Importantly the desired water quality for injection can be achieved using simple filtration rather than having to move to a treatment train that would require flocculation to remove suspended solids. The infrastructure includes:

- Battery storage for the solar panels
- Submersible pump
- Backflush line
- Bag filter
- Chemical dosing to control Bacteria
- Non-return valve
- Inline water quality parameter monitoring probes (pH, EC, turbidity and Redox)
- Pressure and flow volumes
- Pipework as required

The estimated capital cost of the infrastructure only is between AUD$95,000 and AUD$120,000.

5. Conclusions and recommendations

The desktop evaluation has not identified any fatal flaws in the proposal to complete an injection trial on the floodplain to support aquifer freshening to meet vegetation requirements.

The potential for clogging was evaluated using a Membrane Filtration Index (MFI) test which confirmed that without pre-filtering clogging in the injection bore would be inevitable. Filtering of the raw water samples through an 11, 8 and 2.4-micron filter indicated that a 25-micron bag filter should remove up to 90% of the filterable solids. However, these results are for a one-off sample event and the temporal variability in suspended solids loading is not known therefore, for the trial a 10-micron bag filter will be used to ensure turbidity levels of the source water are maintained below 5 NTU. Importantly, the desired water quality for injection can be achieved using simple filtration rather than having to move to a more complex and costly treatment train that involves flocculation to remove suspended solids.

Hydrogeochemical modelling of the mixing between the source and receiving groundwater has identified iron precipitation may occur if the dissolved oxygen of the source water is considerably higher than modelled. A key consideration during the trial will be the management of dissolved oxygen levels and pH in the source water to minimise the risk of iron precipitation.

An analytical model was used to evaluate the expected outcomes of a trial using averaged data for aquifer hydraulic properties. The modelling demonstrated that even at a low rate of injection (1 L/s) for an average transmissivity of 18 m^2/d, and assuming no clogging, up to 16 ML could be recharged within the six- month trial period. For the average aquifer properties, an assumed aquifer thickness of 4 m and radial flow at the end of the six-month injection period the envelope extended radially from the injection well some 100 m.

The recommendation from the outcomes of the desktop feasibility study is for the program to progress to the trial with the first stage being construction and testing of the injection well and associated monitoring wells at the selected site. The steps for stage 2 include:

- Installation of one production well for injection and six monitoring wells to a total depth of between 10 to 12 m below ground level targeting the upper portion of the Monoman Formation.
- Geophysical logging of the production well and pumping tests to confirm the aquifer hydraulic properties at the site.
- Revisit the analytical model using the actual site aquifer properties and confirm the predictions regarding the extent of the injection envelope have not significantly altered.
- Report on the results of the above field program and confirm the viability of proceeding to the injection trial.

There are still some potential risks of clogging especially iron precipitation, but it is considered these can be adequately managed through design and operation. Use of the bag filters provides enough operational flexibility to improve filter capacity if suspended solids prove problematic.

If the drilling and testing program is successful, the injection trial is planned to be delivered over three steps:

1. Step 1 involves mobilisation and setup of equipment on-site and preliminary testing over 24 hours.
2. Step 2 involves a three-week commissioning phase to check that the aquifer is responding as predicted and the infrastructure is operating within the design parameters. This step allows for any minor adjustments e.g. changing the filter or adjusting flow rates and confirming the frequency of backwashing the injection well (if required) and mechanical filter.
3. Step 3 is the trial operation for six months which is inclusive of the two steps above.

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Paper for ISMAR10 symposium. ***Topic No: 15 (251#)***

PVC-O pipes and fittings, the most environmentally friendly solution for water transportation

Dolores Herran[1] and Yolanda Martínez[2]

[1] Molecor Tecnología, S.L. ; dolores.herran@molecor.com
[2] Molecor Tecnología, S.L. ; yolanda.martinez@molecor.com
* Correspondence: dolores.herran@molecor.com; Tel.: +34 675 592 352

Abstract: The installed pipe is one of the most important elements of the network, therefore, the importance in the choice of the material to be used. At this point it is very important to take into account the quality of the material, its durability and of course, its contribution to the environment. The environmental impact of a pipe system depends on its composition and on the application to which it is intended, being the type of raw material used, the production process, the finish of the product, and its useful life the main factors that determine the efficiency and sustainability throughout its life cycle. The European Commission has compiled all methods at European level and launched the Common Recommendation for Environmental Footprint Calculation 179/2013/EC in 2013, in order to establish the principles for communicating the environmental performance of a product or organization, which should include: transparency, reliability, integrity, comparability and clarity. Environmental Footprint Study of an Oriented PVC Pipe System (PVC-O) according to the European Commission's recommendation for calculation in order to show its environmental performance and its best contribution to the sustainable development of the planet. Along this paper we will evaluate the environmental footprint of PVC-O pipes networks.

Keywords: PVC-O, pipes, sustainability, water, transportation, energy, footprint, network.

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1. Introduction

Among environmental management actions, water management should be based on the guarantee of its availability and quality, its efficient management, the enhancement of regeneration and reuse formulas, in the creation of new resources, in the modernization of water networks, and in the incorporation of new technologies into productive processes. Targets should be set to promote savings and improve efficiency in water use, and technology transfer to the pipeline sector and the use of alternative water resources is necessary,- In short, sustainable and environmentally friendly water networks must be built.

The preservation of the scarce natural water resources available requires, among other actions, the avoidance of losses of the piped water, and the optimization of the hydraulic networks is necessary. Both their modernization and the choice of the material to be used in such pipelines are key factors in ensuring these challenges. Molecular Oriented pipes (Figure 1), are increasingly used in pressure water pipeline works, being the current solution of greater efficiency in the management of the hydraulic resources that demand the modern infrastructures and those that the best environmental performance present.

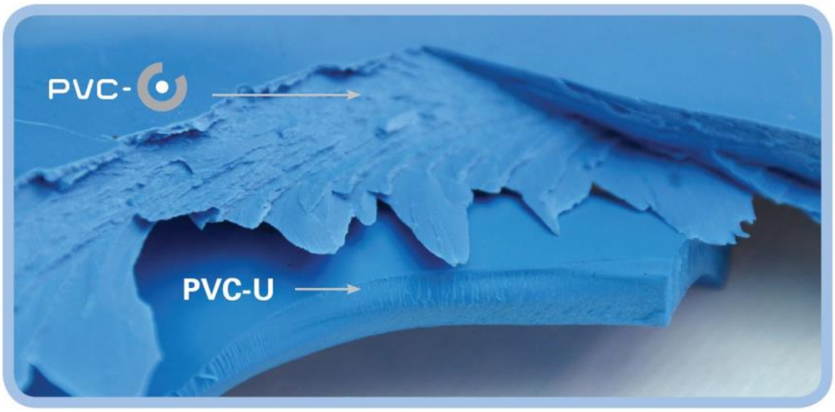

Figure 1. Laminar structure of PVC-O vs amorphous structure of conventional PVC.

2. Environmental Impact of Oriented PVC pipes

The environmental impact of a piping system depends on its composition and application thereof. The factors determining the efficiency over the entire life cycle of a pipe (Figure 2) are mainly: the type of raw material used, the production process, the product finish and its useful life.

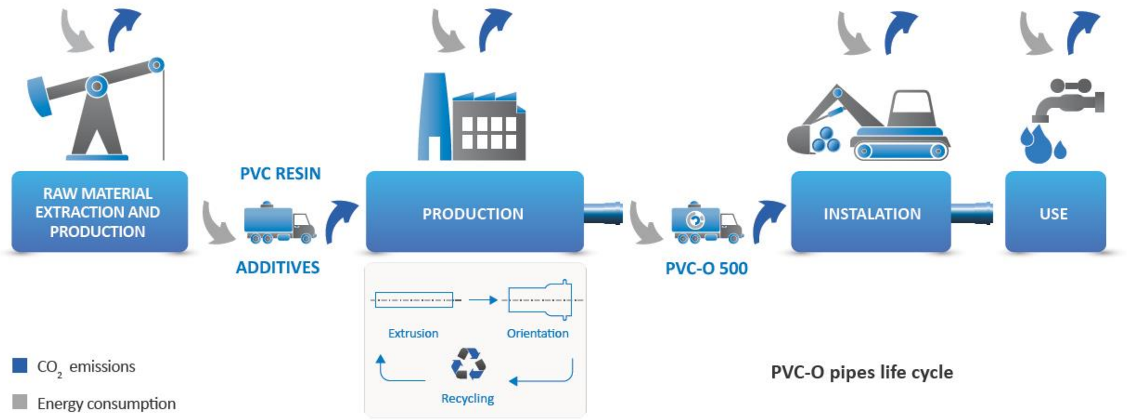

Figure 2. PVC-O lifecycle of pipes.

PVC-O pipes are presented as the most ecological solution due to their better contribution to the correct sustainable development of the planet, as it has been demonstrated by different worldwide studies, among which we can highlight: *Estimación del consumo energético y de la emisión de CO2 asociado a la producción, uso y disposición final de tuberías de PVC, PEHD, PP, Fundición y Hormigón (Univeristy Politectnic of Catalunya) and the studie PVC-O Environmental Product Declaration TEPPFA (The European Plastics Pipes and Fittings Association).*

The Oriented PVC present environmental advantages in all phases of their life cycle.

2.1 Natural Resources Efficency

Oil: Only 43% of PVC composition depends on oil, so high efficiency is obtained against polyolefin pipes that derive 100% from it.

Raw material: Orientated PVC (PVC-O) pipes are manufactured by a conventional extrusion process and subsequent molecular orientation, which significantly improves the mechanical properties of the product while keeping its chemical properties intact. Thus, with less raw material, pipes with better performance are obtained.

Energy: less consumption in:

1. Extraction raw material.

2. The manufacture of the pipe. The innovative manufacturing process requires much less energy than is necessary for the production of pipelines from other materials, and even than other PVC-O production processes. Only electrical energy is consumed in the production process under study.

3. Use on the networks. In the service life of a pipe system, the parameter that most contributes to energy consumption is the energy needed to carry out pumping. Considering a period of 50 years of life, according to various international studies, PVC-O pipes have a lower consumption.

2.2 Efficiency in Waste Management

PVC is a 100% recyclable material that can be reused for the manufacture of other plastic applications with lower technical requirements, where required for the raw material are lower. In this way, reduce the consumption of virgin raw materials and also the volume of waste generated

2.3 Optimization of the Hydrological Resources

The current networks show a high rate of leakage of the piped water, due both to the lack of sealing of the joints and to the breaks caused by the deterioration of the pipes. In many cases, this leads to channelings having to be replaced a few years after installation.

PVC-O is chemically inert against products present in nature and remains unchanged. This, together with the effective design of its socket, prevents leakage of the piped water and contaminations of the fluid circulating inside, thus maintaining the total quality of the water, while maintaining the complete flow of the pipeline without loss.

2.4 Long Useful Life

Thanks to these excellent mechanical properties, the pipe is very resistant, thus significantly minimizing breakages during handling and installation on site, and also remaining unchanged for years, reducing the substitution of damaged or deteriorated pipes in the network, thereby saving economic resources. This resistance is particularly noticeable at low temperatures, where other materials are very fragile.

2.5 Better Contribution to the Sustainability

Less carbon footprint. Due to the lower emissions of CO_2 into the atmosphere, various international studies show that throughout their long lifespan they have lower energy consumption, minimizing the impact on the planet’s climate change.

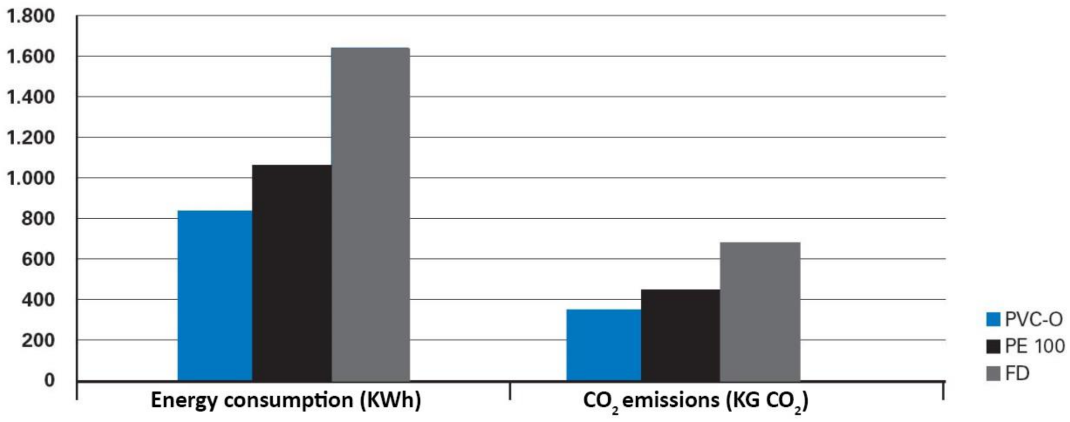

Figure 3. Chart of energy consumed and CO2 emissions throughout the life cycle of a pipe system.

Source: Estimation of energy consumption and CO2 emission associated with the production, use and final disposal of PVC, PEHD, PP, Foundry and Concrete pipes (University Politecnic Catalunya)

Lees environmental footprint. As shown by Teppfa's Environmental Product Statement (EPD), PVC-O pipes have a lower environmental impact than pipes manufactured in other materials, not just in the impact on global warming, but in other environmental parameters such as acidification or destruction of the ozone layer.

2.6 Oher environmental contributions.

Optimization of the transport. Thanks to the lower weight of the pipe, we can transport more material, so we will save fuel and minimize CO2 emissions.

Installation cost efficiency. Due to its lower weight, it is lighter and can be handled easier than pipes made from other materials. Thus, the handling and connection of the pipes can be done manual up to 250 mm diameters, thus reducing the use of machinery, with less fuel consumption and CO_2 emissions into the atmosphere.

3. European Guidelines on the environment

In recent years, the European Union has been promoting the proper preservation of the environment in all its regulations. For example, the Construction Products Regulations, as basic requirements in construction works, require in several points of Annex I the following concepts: energy saving, sustainable use of natural resources, reuse, durability of works and respect for the environment of raw materials and materials used.

There are various methodologies both in Europe and globally for the study of the environmental impact of a product that give results that are not comparable to each other, and sometimes even unreliable, so that the European Commission, gathering all this information at European level, it has published Recommendation 179/2013/EC on the calculation of Environmental Footprint (HAP- Product Environmental Footprint, PEF), in order to establish common calculation rules for all Member States.

This calculation is based on the study of the product life cycle (Life Cycle Analysis ACV - Life Cycle Assessment LCA) according to ISO 14040 and ISO 14044, and in the evaluation of their environmental impact on different environmental parameters.

PVC-O pipes are ahead of the rest of the pipelines in the market with the study of the environmental impact according to this latest recommendation of the European Commission. This analysis is not limited to calculating the impact on climate change due to greenhouse gas emissions (Carbon Footprint), but analyzes its behavior against 14 environmental impacts that are grouped according to the condition of the different means:

Affection on air and atmosphere:

- Climate change
- Acidification
- Depletion of the ozone layer
- Formation of photochemical ozone

Affection on water:

- Resource depletion (water)
- Fresh water eco toxicity
- Water eutrophication

Affection on soil:

- Resource depletion (minerals)
- Land eutrophication
- The use of the ground

Affection on human health:

- respiratory inorganic elements
- ionizing radiation
- effects on human health (carcinogenics)
- effects on the human health (no carcinogenics)

4. Results study environmental footprint

The calculation has been carried out through a thorough study of all the processes of the product life cycle over all the phases of the product, from the extraction of raw materials to the final disposal of pipes, through manufacturing, distribution and use.

The calculation has been done with the professional software Air.e LCA integrated with Ecoinvent and ELCD databases, also taking into account applicable product life cycle and environmental declarations (Environmental Product Declaration - EPD) regulations such as the 2007 IPCC and ILCD methodologies.

The results obtained are shown in the Table 1.

Table 1. Results environmental footprint PVC-O pipes class 500.

Environmental impacts	**Absoluts**	
Climate change (carbon footprint)	8.3E+01	kg CO2e
Ozone depletion	5.3E-06	kg CFC-11e
Ecotoxicity – aquatic, fresh water	1.8E+02	CTUe
Effects on human health – (cancer effects)	4.8E-06	CTUe
Effects on human health – (non cancer effects)	8.6E-06	CTUh
Respiratory Inorganics elements	1.3E-02 kg	PM2.5e
Ionising radiation – human health effects	5.3E+00	kg U235e
Photochemical ozone formation	4.1E-01	kg NMVOC
Acidification	4.1E-01	mol H+e
Eutrophication – terrestrial	1.0E+00	mol Ne
Eutrophication – aquatic, fresh water	1.6E-03	kg Pe
Eutrophication – aquatic, sea water	9.5E-02	kg Ne
Resource depletion – water	1.9E-01	m^3 SWU
Resource depletion – mineral, fossil	3.8E-03	kg Sbe
Land transformation	1.6E+02	kg Cdef

5. Conclusions

Thanks to the molecular orientation, PVC-O pipes present advantages applicable to both the quality of the product and its mechanical properties, as well as increased installation performance and the minimization of energy costs during operation, thus achieving very high cost efficiency in the implementation of water networks.

It should also be noted that PVC-O pipes are the most environmentally friendly solution, presenting a significantly lower environmental footprint than other alternative products. This is due both to the energy efficiency achieved during manufacture and use, and to the reduced emission of CO_2 into the atmosphere throughout its life cycle (Figure 2), thus making a smaller contribution to the global greenhouse effect and climate change.

They offer a better behavior of respect for the environment, presenting an environmental footprint inferior to other materials (Figure 4), improving the contribution to the correct sustainable development of the planet, and optimizing the consumption of natural resources.

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Topic 16. MAR WATER QUALITY…

Paper for ISMAR10 symposium. **Topic No: 16 (053#)**

The role of organic matter in the release of iron and manganese during bank filtration

Ahmed Abdelrady[1,2*]; Saroj Sharma[2]; Ahmed Sefelnasr[3] and Maria Kennedy[1,2]

[1]Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands, A.R.A.Mahmoud@tudelft.nl.
[2]IHE Delft Institute for Water Education, P.O. Box 3015, 2601 DA, Delft, The Netherlands, s.sharma@un-ihe.org, m.kennedy@un-ihe.org
[3] Geology Department, Faculty of Science, Assiut University, 71516 Assiut, Egypt, ahmed.sefelnasr@yahoo.com.
[*] Corresponding author: A.R.A.Mahmoud@tudelft.nl, Tel: 00201100260416.

Abstract: Bank filtration (BF) was used for many years as an economic technique for providing high-grade drinking water quality. However, turning the filtration environment into anaerobic and the releasing of undesirable metals such as iron (Fe), and manganese (Mn) reduces the bank filtrate quality and thus restrict the application of this technique. The main objective of this study is to gain insight into the role of the organic composition of the raw water on the releasing of Fe and Mn during the Bf process. Laboratory-scale column studies simulating BF were conducted at controlled room temperature (30°C) to assess the impact of dissolved organic matter (DOM) composition of the feed water on the Fe and Mn release in the bank filtrate. Fluorescence excitation-emission matrix spectroscopy coupled with parallel factor analysis (PARAFAC) was used to characterize the organic fractions of the feed water. Four fluorescence components were identified, three of which matched to humic-like compounds and the last one was linked to protein-like component. The results highlight the vital role of DOM constituents in releasing Fe and Mn from the sediment during the BF process. A positive relationship (r=0.91, $p<0.001$) was observed between the effluent iron concentration and terrestrial humic content in the feed water. This indicates the role of these electron-rich compounds containing reduced quinone-like moieties in releasing iron from the sediment via shuttle electron to enhance the iron microbial reduction as well as to complex with iron minerals and thus changing its redox state. Likewise, manganese release was found to be associated with both processed humic (r=0.8, $p<0.001$) and terrestrial-derived humic (r =0.77, $p<0.001$) content of the feed water. In contrast, protein-like component was found to be highly removed during the BF process and thus plays a moderate role in the release of iron sediment into the filtrate water, however, it highly impacts the Mn mobilization during the filtration process. In general, this research revealed that humic components (terrestrial and processed) play a major role in the release of iron and manganese during the BF process which should be considered during the BF well site-selection process.

Keywords: Bank filtration, iron and manganese release, anaerobic conditions, organic matter, PARAFAC-EEM.

1. Introduction

Bank filtration proved its effectiveness to produce high drinking water quality. This technique has been experienced in many developed countries for hundreds years, however, its application in developing countries is still limited [1]. Many cities around the Rhine, Elbe, and Danube Rivers were primarily supplied with bank filtrate water for hundreds of years [2, 3]. Recently, the utilization of this technique was extended for many countries (e.g., Egypt, Jordan and India) with different climate and hydrological conditions [4-6]. Bank filtration is a natural treatment technique in which water infiltrates from a surface water system into an adjacent production well. The infiltration area acts as a natural filter to remove the river water pollutants [2].

The quality of the pumped water is largely dependent on the biochemical and physical processes (e.g., sorption, biodegradation, precipitation and redox reactions) taking place during the infiltration process. The redox process was considered the main mechanism of contaminating the bank filtrate water with undesirable and toxic metal(loids) such as iron (Fe), manganese (Mn) and arsenic [7]. Turning the environment of the infiltration area into anaerobic condition provokes the microorganism to use insoluble Fe and Mn as an electron acceptor and release them into the filtrate water [8]. This process is almost accompanied by desorption of heavy metals such as cadmium and cobalt into the filtrate water [9]. This is dependent largely on the environmental conditions of the infiltration area such as temperature, pH, redox potential and the organic content of the raw water [10].

The impact of dissolved organic matter (DOM) on the releasing of Fe and Mn during the filtration process has been investigated in different previous studies [7, 9, 10]. DOM can play multiple roles during the mobilization process based on its structure [9]. Biodegradable organic compounds can serve as a source of energy for the microbial reduction of Fe and Mn. However, humic compounds have high shuttle capacity and thus they may bind with the metals and form soluble compounds. Recently, different analytical techniques such as fluorescence spectroscopy and size exclusion chromatography were used to probe the behaviour of DOM and define its role on the biochemical processes taking place during the subsurface flow [11]. In this research, fluorescence excitation-emission matrix spectroscopy coupled with parallel factor analysis (PARAFAC-EEM) was used to elucidate the organic characteristics of the raw water and assesses its impact on the releasing of Fe and Mn during the anaerobic column infiltration process.

2. Materials and Methods

Column Experiment

Column experiment was conducted to assess the effect of different organic composition raw water on the mobilization of Fe and Mn during the BF process. Four PVC columns with an internal diameter of 4.2 cm and a total height of 50 cm were used. The columns were filled up with a support layer of graded gravel and then filled with iron coated sand with a grain size ranged between 1-3 mm. All columns were fed with Oude Delft canal water" The Netherlands" (DC) in upward flow mode (saturated flow) and ripened for more than 70 days. The feed water tank was degassed with nitrogen stream to dissipate the oxygen (until the dissolved oxygen was less than 0.2 mg/L) and to develop anaerobic condition inside the columns. After the ripening process ended up, the columns were fed with different organic composition water types. The first column was continued feeding with DC and the second was fed with non-chlorinated tap water (NCTW) representing low organic matter content raw water. The other two columns were fed with DC mixed with: (1) secondary treated wastewater effluent from Hoek van Holland, The Netherlands simulating raw water with high concentration of biodegradable organic matter. (2) Water extractable organic matter (WEOM) represents raw water with high concentration of humic compounds. WEOM was prepared following the method of Guigue, Mathieu [12]. All the feed water tanks were filtered by 38 μm sieve to avoid the column clogging process and then degassed with nitrogen and introduced into the columns through a variable speed peristaltic pump at a constant hydraulic loading rate of 0.5 m/day.

Characteristics of the sand media

The iron-coated sand used during the experiment was brought from the groundwater water treatment plant Brucht (Netherlands). The sand was sieved through a 3 mm mesh screen and then cleaned with non-chlorinated tap water to remove the debris, and eventually dried at 70 °C. The bulk density and porosity of the sand were (1.2±0.1 g/cm^3), and (0.42), respectively. The organic content of the sand was measured following the method described in and estimated to be 10.8±5.4 µg-C/g. The Fe and Mn content of the sand was 32.8±1.2 mg/g and 12.1±0.8 mg/g, respectively.

Analytical methods

Samples were collected from the influents and effluents to characterize the organic characteristics of the feed water and measure the released Fe and Mn. The collected samples were filtered using 0.45 µm filtration (Whatman, Dassel, Germany) and preserved by adding 1 ml HCl. Inductively coupled plasma with a mass spectrometry detector (ICP-MS) instrument (Xseries II Thermo Scientific, Bremen, Germany) was used to determine the concentrations of Fe and Mn in the effluent water.

The dissolved organic carbon (DOC) of the feed water was measured in (mg-C/L) through the combustion technique. The measurements were conducted using a total organic carbon analyzer (TOC-VCPN (TN), Shimadzu, Japan). Specific ultraviolet absorbance SUVA254 (L/mg-m) is used as an indicator for the aromaticity degree of the DOM. It is estimated as a ratio between UV-Absorbance at 254 nm UV254 [L^{-1}] and its corresponding DOC value. The UV254 was measured in cm^{-1} using a UV/Vis spectrophotometer (UV-2501PC Shimadzu).

The organic characteristics of the feed water were elucidated using fluorescence excitation-emission (F-EEM)spectrophotometry (Fluoromax-3 spectrofluorometer, HORIBA Jobin Yvon, Edison, NJ, USA). The fluorescence intensity in Raman unit (RU) measurements were conducted at excitation wavelengths(λex) ranged between 240 and 452 nm with interval 4 nm and emission wavelengths (λem) from 290 to 500 nm with an increment 2 nm.

PARAFAC modelling

Parallel factor analysis technique (PARAFAC) is a multi-way statistical technique that uses an alternating least squares model to decompose the fluorescence signals into trilinear terms and a residual array. This technique was used to decompose the F-EEM dataset into the independent fluorescent components represent different fluorescent organic groups as stipulated by Murphy, Stedmon [13] (equation 1):

$$X_{ijk} = \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} + \varepsilon_{ijk},\ i = 1,\ldots\ldots,I;\ j = 1,\ldots\ldots,J;\ k = 1,\ldots\ldots..,k;\ f = 1,\ldots\ldots,F \quad (1)$$

where X_{ijk} is the fluorescence intensity of the I^{th} sample at the k^{th} excitation and j^{th} emission wavelength; f represents the number of fluorescence components; a_{if} represents the score for the f^{th} component; b_{jf} is the scaled estimates of the emission spectrum for the f^{th} component; c_{kf} is linearly related to the specific absorption coefficient at excitation wavelength k^{th}; and $\varepsilon_{ijk}$is the residual term.

A total of 80 F-EEMs of water samples collected from the inlets and outlets of the columns was used to develop and validate the PARAFAC model. PARAFAC models with three to seven components were developed, the right number of components were determined using different diagnostic tools such as split validation and residual error [13]. The maximum fluorescence intensity (F_{max}) was used to express the contribution of each PARAFAC components to the full fluorescence spectrum of each sample.

The redox index (RI) was used as an indicator for the DOM reduction capacity of the feed water [14]. It is estimated by dividing the F_{max} of the PARAFAC components contain reduced quinone-like moieties to the sum of the F_{max} of the PARFAC components contain oxidized and reduced quinone-like moieties. The DOM higher reducing capacity when its RI value is closer to one [15].

Statistical analysis

Pearson correlation (r) analysis was used to explore the relationship between the Fe and Mn concentrations of the effluent water and the F_{max} of the PARAFAC components of the raw water. The correlation strength was considered high when the *r*-value is higher than 0.7, moderate (*r=0.7-0.5*) and low (*r <0.5*) following the assumptions of [16].

3. Results and discussion

PARAFAC components

A PARAFAC model with four components was successfully developed and validated using the F-EEM dataset of the influents and effluents water. Four fluorescent components (PC1-PC4) were identified during this research that explained 99.7% of the data variability. The footprint of the identified fluorescence components can be shown in Figure 1. Three components were recognized as humics. The first component (PC1) was observed at an excitation wavelength of 240 and 340, and an emission wavelength of 480 nm and it is comprised of humic compounds of terrestrial origin that have reduced quinone-like moieties. These compounds are characterized by a high molecular weight (>10,000 Da) and low biodegradability [17]. The second component (PC2) appeared at an excitation wavelength of 240,308, and an emission wavelength of 402 nm. This component assigned as microbial humic and it encompasses recent biologically produced humic compounds that characterized with oxidized quinone-like moieties and intermediate molecular weight (650<C3<1000 Da) [18]. The third component (PC3) was observed at an excitation wavelength of 240,268, and an emission wavelength of 308 nm and it was allocated as a protein-like fluorophore (tyrosine and tryptophan compounds) that have high biodegradability character [19]. The fourth component (PC4) was detected at an excitation wavelength of 240,296, and an emission wavelength of 408 nm and assigned as marine humic fluorophore and it is mainly composed of organic matter contain oxidized quinone-like moieties. Therefore, the RI was estimated as the ratio between the F_{max} of the terrestrial humic and the sum of the three humic components.

Organic characteristics of the feed water

The experiment was conducted using four different feed water types with different organic composition. The results refer that WEOM feed water possesses the highest concentration of recalcitrant organic compounds; its average DOC and $SUVA_{254}$ were 18.23±1.6 mg/L and 4.85±0.51 L/mg-m, respectively. However, the average DOC of the DCW and DCWW influents were 11.64±3.51 mg/L and 11.73±1.06 mg/L, whereas their $SUVA_{254}$ values were 3.52±0.34 L/mg-m and 3.29±0.28 L/mg-m, respectively, this indicates that the DCW and DCWW influents had a moderate aromaticity character. In contrast, NCTW was retained with the lowest concentration of organic compounds, its average DOC was 3.98±0.73 mg/L, whereas its $SUVA_{254}$ value was 1.51±0.18 L/mg-m, this indicates that NCTW organic composition is mainly composed of aliphatic compounds.

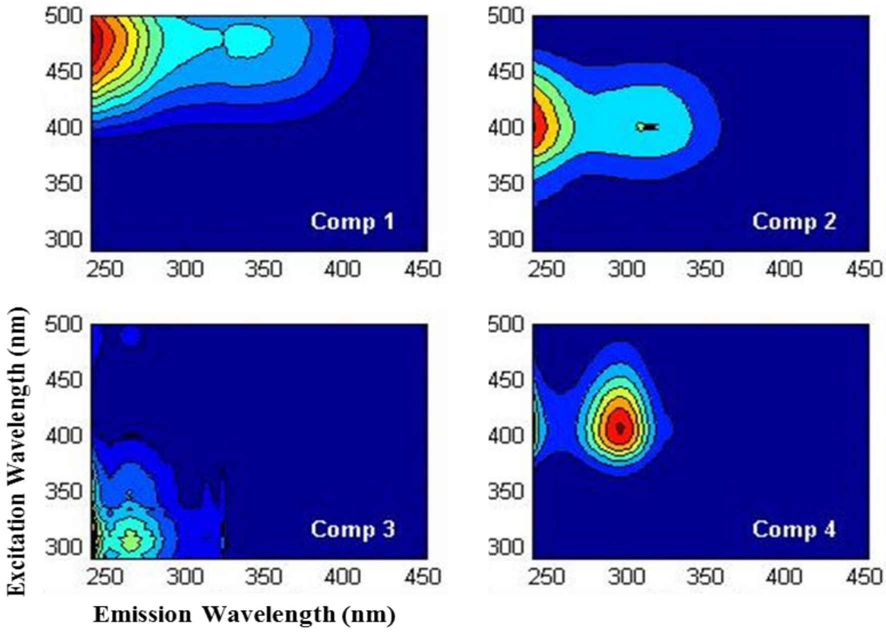

Figure 1. Footprints of the four components identified from the complete measured F-EEMs of the influents water of the column experiment.

PARAFAC-EEM technique was used to depict the organic characteristics of the feed waters. The fluorescence results revealed that the humic compounds were the dominated components of the WEOM feed water. The average F_{max} of the terrestrial (PC1), microbial (PC2), and marine (PC4) humic components were 3.65±0.72 RU, 2.41±0.75 RU and 0.66±0.09 RU, while the F_{max} of the protein-like (PC3) component was 0.76±0.11 RU. By Contrast, NCTW possessed the lowest F_{max} of the four PARAFAC components, the average F_{max} of PC1-PC4 components were 0.23±0.1, 0.21±0.1, 0.19±0.11 and 0.08±0.03, respectively. DCWW and DCW showed approximately the same organic fluorescent characteristics. The F_{max} of PC1-PC4 were recorded as 1.61±0.12, 1.23±0.21, 0.63±0.11 and 0.28±0.06 RU for DCW and 1.67±0.31, 1.33±0.26, 0.75±0.17 and 0.33±0.07 RU for DCWW, respectively.

Impact of DOM composition on Fe and Mn mobilization

The experimental results demonstrated that the mobilization of Mn is much higher than Fe during the infiltration process, the effluent Mn was ranged between (1500-3900 μg/L) while the effluent Fe was varied between (10-20 μg/L), The higher mobilization rate of Mn compared to Fe mobilization was also observed in many bank filtration and alluvial aquifer fields [20-22], and indicates that the infiltration area is mainly dominated by Mn-reducing environment. The environmental conditions (e.g., temperature and redox potential) primarily regulate the redox reactions taking place during the infiltration process. The column experiment was conducted at high temperature (30°C) and low hydraulic rate (0.5 m/ day) that favourably enhances the releasing of Mn into the filtrate water. This is in agreement with Paufler, Grischek [7] study which reported that increasing the temperature from 20 to 30°C will accelerate the releasing rate (K_{Mn}) of Mn by 10-15 times.

The feed water source and organic composition impact the mobilization of Fe and Mn during the infiltration process. WEOM exhibited the highest capacity to mobilize the former metals than the other influents. The average concentrations of the effluent Fe and Mn for the column fed with WEOM were 18.28±0.94 μg/L, 3590±185 μg/L. However, the average effluent Fe was 13.67±0.97 μg/L, 12.72±0.55 μg/L and 10.98±0.94 μg/L and the average effluent Mn was 3330±142 μg/L, 3126±103 μg/L and 1990±384 μg/L for the columns fed with DCW, DCWW and NCTW, respectively. In the same regard, strong correlations were determined between the organic content of the feed water and the effluents concentrations of Fe (*r= 0.83*, *p<0.001*) and Mn (*r=0.87*, *p<0.001*), this refers to the role of DOM concentration on the mobilization of metals (Fe and Mn) during the filtration process. Mladenov, Zheng [9] demonstrated that the DOM impacts the mobilization of metals during the filtration process through different mechanisms including redox process, complexation and competitive adsorption processes, the reaction of DOM towards the metals is mainly dependent on the composition and structure of the organics.

The fluorescence results (Figures 2 and 3) revealed that the mobilization of Fe and Mn during the filtration process was controlled by the organic composition of the feed water. Strong correlations were detected between the effluents Fe and Mn concentrations and the three humic PARAFAC components. The humic compounds characterize with high electron- shuttle capacity. Therefore, they are able to bind to the metals and whereby enhancing their solubility [23]. Moreover, humic compounds might act as a mediator for the microbial reduction process by

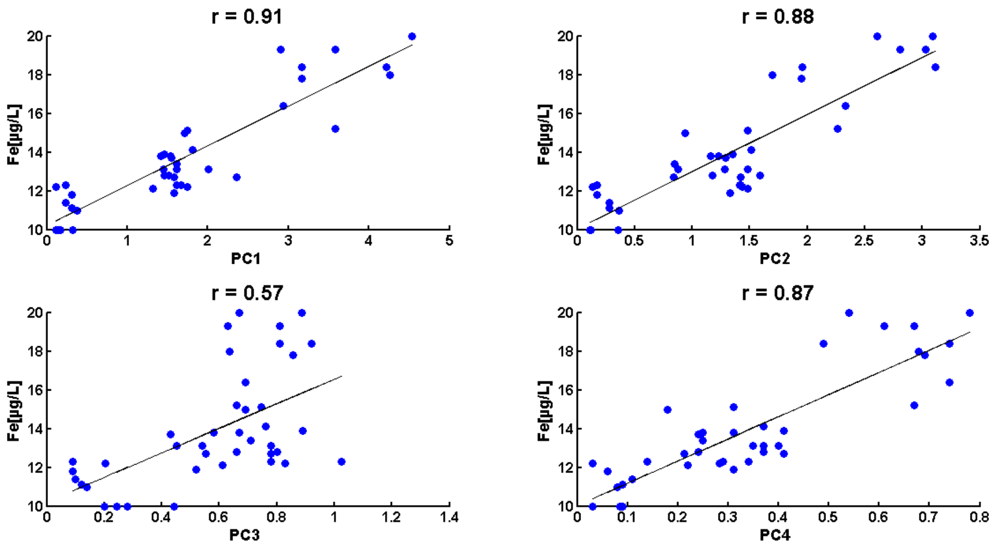

Figure 2. Correlation between the F_{max} of the PARAFAC components fluorescence intensity and effluent Fe concentration (column study, 30°C, anaerobic).

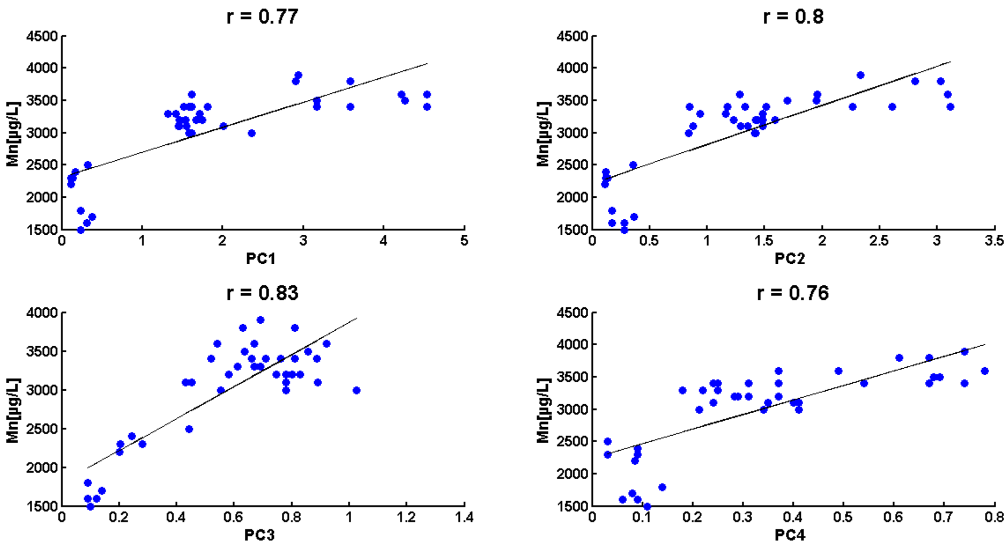

Figure 3. Correlation between the F_{max} of the PARAFAC components and effluent Fe concentration (column study, 30°C, anaerobic).

transferring the electron between the insoluble Fe- and Mn-oxides and the reducing microorganisms [24]. This research revealed that the low and high molecular weight humic compounds are both able to mobilize the Fe and Mn during the filtration process. However, a moderate correlation was detected between RI and effluent Fe (*r=0.6, p<0.001*), which refers to the higher capability of terrestrial humic compounds to mobilize Fe than processed humic compounds. In contrast, Mn was found to have a higher affinity with both processed humic and terrestrial humic compounds, where a weak correlation (*r=0.39, p<0.05*) was detected between effluent Mn and RI.

Biodegradable matter, on the other hand, exhibited higher potentiality to mobilize Mn than Fe during the soil passage process. A strong correlation was observed between F_{max} of protein-like compounds (PC3) and effluent Mn (*r=0.83, p<0.001*), whereas a moderate correlation was detected between PC3 and effluent Fe concentration (*r=0.55, p<0.001*). However, Mladenov, Zheng [9] pointed out that enhanced concentration of biodegradable matter might stimulate the microbial activity associated to the soil and reduce the redox potential into the level that allows for microorganisms to use Fe as a primary electron acceptor and thereby increasing its concentration in the pumped water.

Conclusion

A laboratory-scale column study was conducted at a controlled temperature 30°C room using different water types with different organic composition to assess the impact of organic matter composition of the raw water on the mobilization of Fe and Mn during the filtration process. A four PARAFAC model was developed and validated to elucidate the organic characteristics of the influents. The experimental results demonstrated that the mobilization of Fe and Mn is highly dependent on the organic concentration and composition of the feed water, as raw water with higher organic content has a higher capacity to release Fe and Mn during the infiltration process. The fluorescence results indicate that the humic compounds with higher shuttle-electron capacity and contain reduced quinone-like moieties (i.e., terrestrial humic compounds) are relatively more favourable to mobilize Fe into the filtrate water. However, both high and low molecular weight humic compounds exhibited comparatively the same capacity to release Mn into the filtrate water. Furthermore, labile organic compounds were found to be more effective on the Mn mobilization process than Fe mobilization. These findings should be considered during the bank filtration design and installing process.

Acknowledgments: We would like to acknowledge the support of Mr. Abdullahi Mohamed (IHE Delft Institute for Water Education, Delft, The Netherlands) for his assistance in laboratory measurements.

Author Contributions: Conceptualization, A.A and S.S.; methodology, A.A. and S.S. and M.K.; software, A.A. and A.S.; validation, A.A.; formal analysis, A.A.; investigation, A.A.; resources, S.S. and M.K.; data curation, A.A.; writing—original draft preparation, A.A.; review and editing, S.S., A.S., and M.K.; visualization, A.A.; supervision, S.S., A.S., and M.K.; project administration, M.K.; funding acquisition, A.A.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PARAFAC: parallel factor analysis
BF: Bank filtration
FEEM: Fluorescence Excitation-Emission Matrix
DOC: Dissolved Organic Carbon
DOM: Dissolved Organic Matter
RI: Redox Index
PC: PARAFAC Component
F_{max}: Maximum Fluorescence intensity

RU: Raman Unit
λex: Excitation wavelength
λem: Emission wavelength
WEOM: water extractable organic matter
DCW: Delft Canal Water
DCWW: Delft Canal Water mixed with secondary treated Wastewater
NCTW: Non-Chlorinated Tap Water

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Extended abstract for ISMAR10 symposium. **Topic No: 16 (081#)**

Migration of pharmaceuticals from the Warta River to the aquifer at a riverbank filtration site in Krajkowo (Poland)

Roksana Kruć[1]*, Krzysztof Dragon[1] and Józef Górski[1]

[1] Adam Mickiewicz University in Poznan, Institute of Geology, Department of Hydrogeology and Water Protection, ul. Bogumiła Krygowskiego 12, 61-680 Poznań; POLAND ;

* Correspondence: Roksana Kruć e-mail: roksana.kruc@amu.edu.pl

EXTENDED ABSTRACT

Riverbank filtration (RBF) systems are widely used for drinking water supplies. The infiltration of surface water to groundwater systems and water passage through the aquifer media cause improvements in water quality by a set of processes including: sorption, redox processes, and biodegradation [1, 2]. The mixing of bank filtrates with ambient, usually unpolluted groundwater, also takes place [3, 4]. Nevertheless, the quality of bank filtrate is strongly dependent on surface water quality. Currently, it is extremely important due to emerging contaminant (e.g., pharmaceuticals) detection in river (source) water. The occurrence of pharmaceuticals (such as antibiotics, analgesics, blood lipid regulators, contrast agents) has been studied all over the world in surface and also in bank filtrate [5, 6, 7]. RBF system can be used as a natural water treatment method [8]. This can be achieved if the travel time (i.e., time of water passage from surface water to wells) is long enough to remove or considerably reduce the contaminants from the bank filtrates [2,8,9].

The goals of the research presented are determination of the pharmaceuticals in both river water and bank filtrates and investigation of pharmaceutical removal rates.

For investigation of pharmaceuticals in river and bank filtrate water, the Krajkowo (Poland) well field was selected. The well field is located in a region of favourable hydrogeological conditions. The total thickness of the aquifer is up to 40 m. For investigation of pharmaceuticals, 6 sampling points were selected, source water – the Warta River and wells located at different distance from the river (HW, 177b/1, 1AL, 19L and 78b/1s). Three productive wells were selected for the research – HW, 19L and 1AL. The closest sampling point is HW with drains located 5 m below the river bottom. Observation well 177b/1 is located between the river and well 19L. Observation well 78b/1s is the furthest away sampling point.

Based on previous research relating to investigations of natural organic matter and organic micropollutants [10, 11], for preliminary investigation of pharmaceuticals, 3 sampling points were selected (surface water, 1AL and 78b/1s). Three sampling sessions were performed in September 2017, May 2018 and June 2018. The laboratory measurements addressing 13 constituents were performed in the ALS Laboratory in Prague, Czech Republik. Based on this investigation, consecutive sampling campaigns have been planned. The next investigations were performed in June, August and October 2018. The measurements of 75 constituents were performed in the Laboratory of Povodí Vltavy VHL Plzeň, Czech Republik. The analysis was carried out using liquid chromatography (LC-MS/MS) and ultra-high-performance liquid chromatography (UHPLC MS/MS).

Preliminary investigations performed in September, 2017 and May and June 2018 at three sampling points allowed to determine occurrences of pharmaceuticals in surface and bank filtrate water. The highest pharmaceutical concentrations (the sum of detected substances concentrations) and the largest variety of substances were detected in the Warta River (max. 485 ng/L). This investigation shows that the concentrations in bank filtration wells are considerably lower (max. 184 ng/L). On the basis of preliminary research, extended analyses were performed in July, August and October 2018. In general, the highest concentration of pharmaceuticals was detected in the river water. However, the concentrations decrease along the flow path from the river to the wells. The distance and travel time have an impact on the decrease in concentrations. Some of substances occur only in the river water (iopromide (max. 149 ng/L), diclofenac (max. 37.4 ng/L), metoprolol (max. 19.6 ng/L), penicillin G (max. 17.1 ng/L), saccharine (max. 360 ng/L), iohexol (max. 120 ng/L), cotinine (max. 50.8 ng/L), clindamycin (max. 12.7 ng/L), fexofenadine (max. 40.7 ng/L), valsartan) others also in the closest wells – HW and 177b/1 (caffeine, paraxanthine, sulfapyridine, sotalol, telmisartan) or just there (primidone). Carbamazepine, sulfamethoxazole, gabapentin, tramadol, oxypurinol, fluconazole and lamotrigine are the most common compounds from all sampling sessions and sampling points, being episodically detected also in the farthest productive wells – 19L and 1AL.

The concentration of some pharmaceuticals in the Warta River and in the nearest well HW, are similar (e.g. carbamazepine, sulfamethoxazole, tramadol, fluconazole, lamotrigine). This result is due to the short distance (5 m) and short travel time (1d) between the river and this well. Most of the substances found in the HW well are also observed in well 177b/1, but at lower concentrations Significant decreases in concentrations occur in productive wells 19L and 1AL, where most of the parameters were below LOQ. This finding is due to the longer distances (64-82 m) and travel times (40-50 days) for these wells. In well 78b/1s, which is located 250 m away from the Warta River with a travel time of 150 days, only two parameters, carbamazepine and gabapentin, were detected and were at relatively low concentrations.

The detected parameter concentrations in river water range from 10.8 ng/L (sulfapyridine) to 1470 ng/L (paraxanthine). The highest concentrations in river water occurred in the August 2018 sampling session. Oxypurinol presented high concentrations in river water that persisted (even at higher values) in nearby wells (HW) and also in more distant ones (1AL). Carbamazepine also persists at high concentrations (135 ng/L in river water and 179 ng/L in HW).

Detected parameters were divided into groups. Groups have been established based on the use of the substances. 9 groups were separated: antibiotics; X-ray contrasts; psychotropic, anticonvulsant and antiepileptic; beta-blockers and cardiac drugs; drugs like caffeine; analgesics and antiinflammatory; antifungal and antibacterial; antihistamine; and xanthine oxidase inhibitors. The highest concentrations show xanthine oxidase inhibitors, although there is only one substance in this group (oxypurinol). High concentrations also reach psychotropic, anticonvulsant and antiepileptic drugs and drugs like caffeine. On the similar – lower level antibiotics; X-ray contrasts; beta-blockers and cardiac drugs; analgesic and anti-inflammatory; as well as antifungal and antibacterial are formed.

The removal rate of pharmaceuticals was calculated. The lowest values occur in the HW (drains are located 5 m below the river bottom). In the HW, some of the parameters increase, which occurs because there were higher concentrations in the Warta River before the sampling periods. In observation well 177b/1, removal rates vary over a range of -29.6-100%. The removal rates in two productive wells, 19L and 1AL, show similar values. At the furthest sampling point, 78b/1s, most parameters are reduced by 100%. The removal rates depend on the location of the sampling point (distance and travel time from the river) but are also different for specific parameters. Evaluation of the lowest removal rates shows that carbamazepine (a psychotropic drug) is found at the farthest points (78b/1s - 250 m from the river) and decreases by 36.1- 51.8%, whereas sulfamethoxazole (an antibiotic), gabapentin (an anti-epileptic drug) and tramadol (an analgesic drug) reach similar values at a distance 38 m (177b/1s). Carbamazepine is a difficult compound to remove in spite of long distances and travel times. Gabapentin attains the highest removal rates but is not completely removed, even at the farthest point. Total reductions of same pharmaceuticals (sulfamethoxazole, tramadol, oxypurinol, fluconazole, lamotrigine) are achieved in wells 19L, 1AL and in observation well 78b/1s, while this did not occur in HW and 177b/1.

The degree of pharmaceuticals removal at sampling points depends not only on the travel time in ground environment, but also on the diverse impact of factors as temperature, sorption, redox reaction and biodegradation. The assessment of the impact of these factors was not analyzed in this article. On the basis of oxygen and nitrates volatility, it can be assumed that in wells located close to the river, the dominant factor can be biodegradation and redox processes. In the well located further away from the river (78b/1s), there is no oxygen or nitrates, and it can be assumed that the main factor is sorption. It can also be added that the redox processes and biodegradation are also favored by higher temperatures in summer in closer wells (up to 15 – 17^{o}C) and further away from the river, temperatures are leveled in the range of (8 – 12^{o}C).

This research shows the significant role of bank filtration in the removal of pharmaceuticals. Under existing hydrogeological conditions, wells should be located at least 60 m from river. Higher removal rates can be achieved at distances of 250 m from the source water. However, the results obtained emphasise the need for further monitoring studies to recognise the factors that determine the variability of micropollutants in the river, as well as in the production wells (hydrological conditions and seasons of the year). It is also necessary to identify processes that condition migration and removal rate of micropollutants. Future research should be focus on fewer compounds and their metabolites.

Acknowledgments: The authors would like to thank Aquanet SA (Poznań Waterworks operator).

Funding: This research was completed with support from the AquaNES project. This project has received funding from the European Union's Horizon 2020 Research and Innovation Program under GA no. 689450.

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Paper for ISMAR10 symposium. ***Topic No: 16 (095#)***

Seasonal Variations in Water Quality and NOM Removal in Natural Bank Infiltration of Boreal Lake Water

Maija Jylhä-Ollila[1*]; Hanne Laine-Kaulio[1]; Paula Niinikoski-Fusswinkel[2] and Harri Koivusalo[1]

[1] Aalto University School of Engineering, Department of Built Environment; maija.jylha-ollila@aalto.fi
[2] RWTH Aachen University, Institute of Applied Mineralogy and Economic Geology, paula.niinikoski-fusswinkel@emr.rwth-aachen.de
*Correspondence: maija.jylha-ollila@aalto.fi Tel.: +358-50-3838158

Abstract: Managed aquifer recharge (MAR) provides a means to improve water quality in drinking water production by natural organic matter (NOM) removal. We chose a natural bank infiltration site to investigate aquifer recharge over a much longer time scale than can be achieved by studying existing MAR sites or by column tests. The objective was to assess the long-term sustainability of MAR. Here we focus on the seasonal variation of NOM reduction and redox conditions during infiltration. To examine the NOM removal and its seasonal variability, lake and groundwater samples were collected, and total organic carbon, dissolved organic carbon, chemical oxygen demand, dissolved inorganic carbon, pH, dissolved oxygen, iron, manganese, conductivity, and stable isotopes of oxygen and hydrogen were measured. The lake infiltrate fraction was estimated at each sampling location in the aquifer by the isotope tracers. NOM along the groundwater flow pathway was found to be removed by 80-90 %, which is higher than reported at Finnish MAR plants. Seasonal temperature dependent changes in oxygen and iron levels at the lake shoreline were observed, but the removal of NOM was constant during all seasons. The main conclusion was that an aquifer can sustainably remove NOM from infiltrating water, without losing its efficiency. However, the northern seasons trigger variations in the redox conditions.

Keywords: Natural organic matter, managed aquifer recharge, bank infiltration, dissolved organic carbon, groundwater.

1. Introduction

In Finland, managed aquifer recharge (MAR) is mainly used in drinking water production to improve water quality by removing natural organic matter (NOM) from surface waters. The objective of this study was to assess seasonal variations in NOM removal in a natural lake-aquifer system, to support assessments of long-term sustainability of MAR. The natural bank infiltration was selected to investigate aquifer recharge over a greatly longer time scale than can be achieved by studying existing MAR sites or by column tests, on which the research on MAR has mainly focused so far, e.g. [1-12].

In MAR, the main processes of NOM removal are mechanical filtration, biodegradation, and sorption. Long-term sustainability of using MAR to remove NOM from surface water depends to a large extent on the mechanisms of NOM removal. If NOM is filtered or sorbed, organic material is accumulated in the aquifer over the long-term, which would reduce the filtering capacity. But if organic material is biodegraded to carbon dioxide, the process could be considered sustainable. Some studies suggest that 50 % [11] or 30-80 % [12] of NOM is removed by biodegradation. Based on these values, NOM accumulation in aquifers is possible.

In order to quantify NOM removal, related redox reactions, and the seasonal variations in the process, aquifer, lake and ground water samples were collected, and total organic carbon (TOC), dissolved organic carbon (DOC), chemical oxygen demand (COD_{Mn}), stable isotopes of hydrogen and oxygen, iron, manganese, pH, dissolved oxygen (DO) and conductivity (EC) were analyzed.

2. Materials and Methods

2.1. Site description

Lake Iso Tiilijärvi (Lat 61° 0' 28.064" Lon 25° 30' 10.982") is located in Southern Finland on a glaciofluvial end-moraine, consisting mainly of sand and gravel [13]. As the lake has no stream outlet, outflow occurs through bank infiltration into an aquifer (Figure 1). From the aquifer, groundwater is discharged to the Rätäksuo bog from several springs. The aquifer also receives groundwater formed from precipitation. The age of the studied natural bank infiltration system equals the age of the moraine that was formed during the deglaciation of the Scandinavian Ice Sheet, around 12 500 years ago [14,15].

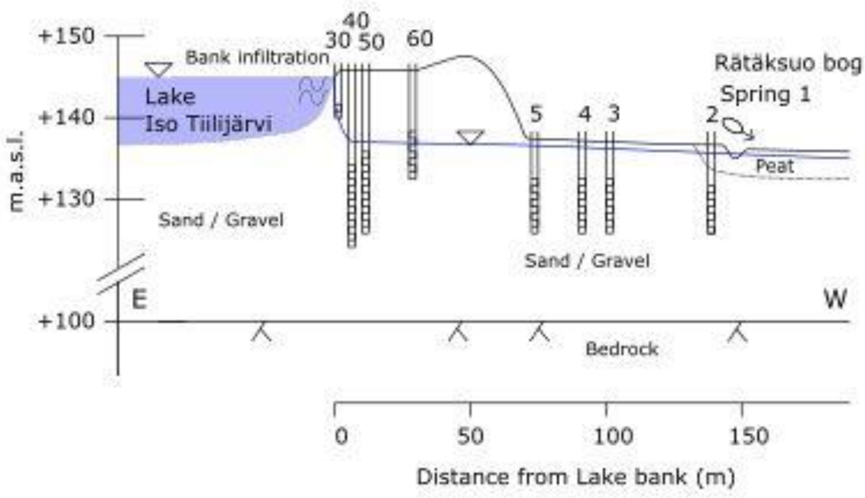

Figure 1. A cross-section of the studied aquifer with bank infiltration from Lake Iso Tiilijärvi and groundwater discharge to the Rätäksuo bog.

2.1. Sampling and Analyses

Stable isotopes of hydrogen and oxygen were used to estimate the fractions of groundwater originating from bank infiltration and from precipitation at each sampling well. Sampling was performed between August 2016 and November 2017 from the lake, groundwater well 30, and Spring 1 (Figure 1.). Additionally, a well located 6 km southeast from the research area (coordinates Lat 60° 59' 10.115" Lon 25° 36' 23.277") was sampled to assess the background level of groundwater originating from precipitation. The analysis methods used are similar to [12]. The method of calculating the fractions is given in Table 1.

NOM removal was investigated by analyzing TOC, DOC and COD_{Mn} from water samples collected from the lake and from the groundwater wells shown in Figure 1. Samples were collected every second month between December 2017 and November 2018. Temporal variations in water quality during infiltration were investigated by analyzing temperature, DO, EC, pH, Fe and Mn from the lake samples and from well 30, located at a 3 m distance from the lake bank. Well 30 was sampled irregularly between April 2017 and November 2017 and every month from November 2017 to December 2018.

Dependency of water quality on temperature was determined by calculating Spearman correlations between DO, EC, pH, Fe, Mn, TOC and water temperature in well 30.

3. Results

The average fraction of lake water in the aquifer, based on the composition of stable oxygen and hydrogen isotopes in water samples, was 0.96 near the lake bank at site 30, and 0.75 in Spring 1 (Figure 1) representing the aquifer outflow. H and O -isotope measurements are summarized in Table S1.

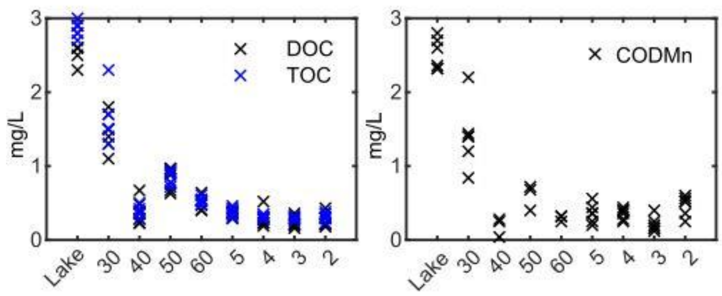

Figure 2. Concentration profiles of TOC, DOC and COD_{Mn} during natural bank infiltration at Lake Iso Tiilijärvi.

TOC concentration decreased from 2.9 ± 0.10 mg/L (average and standard deviation) in lake water to 0.3 ± 0.05 mg/L in well 2. Accordingly, the decrease of DOC was from 2.6 ± 0.19 mg/L in lake water to 0.3 ± 0.09 in well 2. This corresponds to a reduction of 89 % of TOC and 90 % of DOC during infiltration. The results of COD_{Mn} analyses were in accordance with the TOC and DOC results (Figure 2).

Table 1. Water quality of lake Iso Tiilijärvi and in well 30.

	Lake	Well 30
TOC (mg/L)	2.9 ± 0.10	1.5 ± 0.3
DOC (mg/L)	2.6 ± 0.19	1.4 ± 0.3
DO (mg/L)	11.1 ± 1.3	3.3 ± 4.0
Fe (µg/L)	12 ± 6	550 ± 660
Mn (µg/L)	7 ± 0.4	12 ± 3.4
EC (mS/m)	1.8 ± 0.1	2.1 ± 0.2
pH	6.0 ± 0.6	5.6 ± 0.5

During infiltration from the lake to well 30, oxygen levels decreased from 11.1 ± 1.3 mg/L (average and standard deviation) to 3.34 ± 4.02 mg/L in well 30 (Table 1), and Fe concentrations increased from 12 ± 6 mg/L to 550 ± 660 mg/L. Changes in Mn concentrations, EC and pH were small.

Groundwater temperature in well 30 varied between 0 °C (31.1.2018) and +18.4 °C (6.9.2018). DO (r = -0.69, p = 0.001) and Fe (r = 0.88, p < 0.001) levels strongly correlated with temperature. Mn (r = 0.60, p = 0.017) and EC (r = 0.41, p = 0.13) showed weak correlation. No correlation was observed between TOC and temperature (r = 0.24, p = 0.35), and pH and temperature (r = 0.22, p = 0.42).

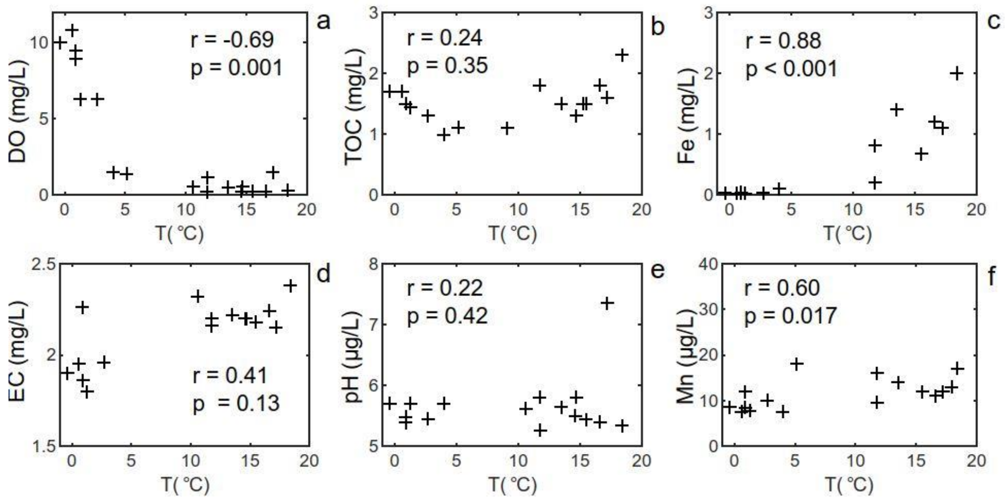

Figure 3. Scatter plots between a) DO, b) TOC, c) iron, d) EC, e) pH f) manganese and temperature in well 30. r is the Spearman correlation coefficient between the variables. p is the probability of the variables being uncorrelated.

4. Discussion

The composition of O and H isotopes showed that 75 – 95 % of the groundwater in the studied aquifer was infiltrated from Lake Iso Tiilijärvi. With the high percentage of groundwater originating from surface water, the area served as an analogy to MAR.

The measured 90 % reduction of total organic carbon during infiltration was higher than reported at constructed MAR plants: 30-50 % [12], 78 % [7], 70 – 85 % [9], 81 % [10] and 79-83% [11]. If dilution with local groundwater formed from precipitation was taken into account, and if the local groundwater was assumed not to contain organic carbon, organic matter reduction in infiltrated surface water would still be 80 %. Compared to constructed MAR plants, the studied long-term natural bank infiltration system did not show any sign of losing its capacity of reducing organic matter from the infiltrating surface water.

The natural bank infiltration system showed a similar, temperature dependent behavior in redox conditions that has been reported in numerous studies, performed at constructed MAR sites and column tests, e.g. [3-5]. Groundwater temperature in well 30 showed strong correlation with temporal variations of DO (r = -0.69, p = 0.001) and Fe (r = 0.88, p < 0.001). The variation is best explained by changes in microbiological activity that is retarded in cold temperatures. Anyhow, TOC concentrations remained stable in the infiltrating water and were not correlated with temperature. Similar behavior was observed at a bank infiltration site in Switzerland, and possible reasons are discussed in [13]. The correlation between Fe and temperature is a consequence of oxygen depletion in warm temperatures, which leads to Fe solution.

Compared with typical NOM levels in boreal lakes [16 - 17], the level of TOC in the infiltrating surface water at our research site was low. The seasonally observed oxygen depletion in the infiltrating water revealed that the degradation process of organic material at the lake bottom sediment [13] has a significant impact on the quality of the infiltrating water. The results suggest that, in particular, small scale bank infiltration sites with slow infiltration velocities are vulnerable to water quality problems arising from dissolution of iron and manganese in anoxic conditions. Better water quality could be achieved by well or pond infiltration because with these methods the effect of the lake bottom sediments can be avoided. Also, constantly cool surface water, pumped from the bottom-water (hypolimnion) of a lake, can be used in infiltration to avoid peaks in oxygen consumption during warm seasons.

The main conclusion was that an aquifer sustainably removed NOM from infiltrating water, without losing its efficiency. However, temporal variations in the bank infiltration were evident, affecting especially the redox conditions. Variations were triggered by the contrasting northern seasons, which have a clear impact on the biological processes during infiltration. Oxygen consumption and iron and manganese release in bank infiltration could probably be avoided by well or pond infiltration using constantly cool bottom-water from Boreal lakes.

Supplementary Materials: *The following are available online at www.mdpi.com/link, Table S1: Analysis Results of Stable Isotopes of Hydrogen and Oxygen.*

Acknowledgments: The study was funded by the K.H.Renlund Foundation, the Finnish Cultural Foundation Päijät-Häme regional Fund, and the Ramboll Foundation. The authors thank the land owners of the studied area and workers of Ramboll Ltd and Lahti Aqua Ltd for help with the field work.

Author Contributions: Maija Jylhä-Ollila designed the research, analyzed the data, and did the field work, assisted by Hanne Laine-Kaulio. Paula Niinikoski-Fußwinkel made the laboratory analyses of stable oxygen and hydrogen, and commented on the text. Maija Jylhä-Ollila, Hanne Laine-Kaulio, and Harri Koivusalo wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
DIC: Dissolved inorganic carbon
DO: Dissolved oxygen
DOC: Dissolved organic carbon
EC: Electric conductivity
MAR: Managed aquifer recharge
NOM: Natural organic matter
TOC: Total organic carbon

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APPENDIX 1

Table S1. Analyze results of stable isotopes of oxygen and hydrogen.

Date	Site	δ18O[1] ‰	δ2H[1] ‰	Fraction of lake water[2]
30.11.2017	Lake	-6.8	-59.75	
31.1.2017	Lake	-6.5	-57.79	
31.5.2017	Lake	-6.38	-57.53	
31.3.2017	Lake	-6.46	-58.14	
23.12.2016	Lake	-6.5	-58.02	
24.8.2016	Lake	-6.29	-55.6	
28.01.2016	Lake	-6.4	-57.4	
24.8.2016	GW from precipitation	-12.57	-89.6	
30.11.2017	GW from precipitation	-12.63	-90.88	
29.01.2016	30	-6.56	-58.2	0.99
3.2.2017	30	-6.9	-59.84	0.93
28.01.2016	Spring 1	-7.4	-63.1	0.85
26.4.2017	Spring 1	-8.58	-68.49	0.66
28.6.2017	Spring 1	-8.00	-65.31	0.75

[1] δ-values are calculated from Vienna Standard Mean Ocean Water (VSMOW)

[2] The fraction of the lake infiltrate in each groundwater sample was estimated from

$$\delta\ ^{18}O_{sample} = a\ \delta\ ^{18}O_{Lake} + (1-a)\ \delta\ ^{18}O_{GW\ from\ precipitation}$$

where a is the lake infiltrate fraction in the sample, $\delta\ ^{18}O_{sample}$ is the isotopic composition of the groundwater sample, $\delta\ ^{18}O_{Lake}$ is the average of the isotopic composition of the lake water samples and $\delta\ ^{18}O_{GW\ from\ precipitation}$ is the average of the isotopic composition of the background samples, representing the isotopic composition of groundwater originating from precipitation. $^{18}O_{Lake}$ and $\delta\ ^{18}O_{GW\ from\ precipitation}$ were the average value of the samples.

Extended abstract for ISMAR10 symposium. **Topic No: 16 (150#)**

Combined natural and engineered systems (cNES) for Managed aquifer recharge (MAR) & soil aquifer treatment (SAT) system with water storage and quality improvement

Pettenati, Marie[1]; Picot, Géraldine[1]; Thomas, Loic[2]; Aurouet, Axel[2]; Baïsset, Matthieu[3]; Appels, Joep[4]; Wünsch, Robin[5] Hochstrat, Rita[5]; Aharoni, Avi[6]; Raanan, Hadas[6]; Ried, Achim[7]; Gebhardt, Jens[7]; Gafri, Riki[8]; Paalman, Marcel[9]; Smet, Davey[10] and Wintgens, Thomas[5].

[1]BRGM, Orléans, France m.pettenati@brgm.fr
[2]GeoHYD (Anteagroup), Olivet France loic.thomas@anteagroup.com
[3]Imageau (SAUR), Montpellier, France matthieu.baisset @imageau.eu
[4]MicroLan, Waalwijk, Netherlands joep.appels@microlan.nl
[5]FHNW School of Life Sciences, Muttenz, Switzerland thomas.wintgens@fhnw.ch;
[6]Mekorot, Tel Aviv, Israël Aaharoni@MEKOROT.CO.IL
[7]Xylem, Herford, Achim.Ried@Xyleminc.com
[8]Wadis, Tel Aviv, Israël rikig@wadis-co.com
[9]KWR, Nieuwegein, Netherlands Marcel.Paalman@kwrwater.nl
[10]Hydrobusiness, Breda, Netherlands davey.smet@hydrobusiness.nl
* Correspondence: m.pettenati@brgm.fr; Tel.: +33-238-64-47-03

Abstract: MAR systems have numerous functions and advantages in water management. They are used to mitigate floodwater, control saltwater intrusion, store water to reduce pumping and piping costs, temporarily regulate groundwater abstraction or treat wastewater for water reuse. To maintain system performance and to enhance its efficiency, pre-treatment of the source water before infiltration or injection is necessary. This may encompasses the removal of critical contaminants (pathogens, ammonia, trace metals…) and a variety of chemical compounds, both endogenous and anthropogenic. Depending of the uses and in view of new target uses such as indirect potable reuse (InPR), sustained long term operation and compliance with regulatory requirements are key factors. Four MAR demonstrations sites representing multiple combinations of natural and engineered treatment systems (cNES) located in Europe and Israel are reviewed in this paper to cope with issues such as water scarcity, excess water in cities and micro-pollutants in the water cycle. Results from demonstrating these innovations highlight the benefits of combinations of natural and engineered components for improved or adapted design, operation and management of MAR systems using different kind of water sources (river water, wastewater and stormwater) for various hydroclimatic conditions.

Keywords: Natural and engineered water treatment, reuse, SAT, MAR.

1. Introduction

In a context of growing water scarcity caused by climate change, demographic and urbanization increase as well as groundwater overexploitation by industrial and agricultural high water demand (Hartog and Stuyfzand, 2017), adaptive solutions for sustainable water supply are required. Developing water treatment technologies these last decades leads to multiply the possibility of intentional water replenishment (Oller et al., 2011) called managed aquifer recharge (MAR) for a large range of hydroclimatic context, type of MAR, type of replenishment water quality, and uses (Dillon et al., 2018; Dillon et al., 2009). MAR is a method to enhance groundwater quantity and, particularly when combined with Soil-Aquifer-Treatment (SAT), groundwater quality, through the implementation of different types of structures. Some of the advantages of MAR include floodwater mitigation, control of saltwater intrusion, storage of water to reduce pumping and piping costs, temporary regulation of groundwater abstraction, and water quality improvements (Asano, 1985). The technology has also gained increasing attention as natural water treatment and water reuse application, for irrigation (Lazarova et al., 2011, Kazner et al., 2012) and, increasingly for indirect potable reuse (Grützmacher et al., 2013). Potential drawbacks and obstacles to large-scale implementation are i) decrease of system performance due to clogging of the infiltration system (Pavelic et al., 2007) ii) unforeseeable long-term behaviour due to low-kinetics geochemical processes, e.g. manganese release (Goren et al., 2012), iii) residual micropollutants, pathogens and antibiotic-resistant bacteria and genes (Pal et al., 2010) after treatment, iv) regulatory constraints related to potential impact of the qualitative status of groundwater bodies. In the view of new target uses, in particular indirect potable use, high regulatory standards have to be met and optimised approaches are required to reduce associated risks and allow wider implementation for MAR systems in the EU regulatory framework.

2. Materials and Methods

Four sites are presented in this paper to demonstrate the ability of real-size hybrid SAT/MAR and Aquifer Storage and Recovery (ASR) systems combined respectively with appropriate engineered i) Advanced Oxidation Processes (AOP) pre-treatment (Zucker et al., 2015) and ii) high velocity filters before infiltration (Vries et al., 2017): 1) The Lange Erlen case study (CH) uses conventional water sources (filtrated river waters) and deploys an AOP, UV-based oxidation process (UV/H_2O_2) to produce drinking water; 2) at the Shafdan case study (IL), secondary effluent from a municipal waste water treatment plant is treated with ozone, O_3/H_2O_2 or electro-pulse oxidation to treat water for ultimate use of reclaimed water irrigation purposes or even for Indirect Potable Reuse (IPR) scheme; 3) The Ovezand site (NL) where is tested and optimised a mobile high-rate filtration system (Galileo filter) combined to Aquifer Storage and Recovery (ASR) to better cope with and utilize storm water. The use of subsoil natural systems (soil and aquifer) for water treatment also requires a stringent monitoring and modelling to detect and foresee any adverse effects and risks for the concerned water bodies (e.g. contaminant flow beyond the confined injection-pumping perimeter) : 4) the Agon-Coutainville site (FR) where is developed a site specific Information & communication Technology (ICT) tool to assess and control the long-term performance of combined engineered-MAR solutions assisted by advanced monitoring and modelling.

3. Results

In Lange Erlen, combined system (UV/H_2O_2+soil treatment) shows a better performance in removal of Trace Organic Compounds (TrOCs) than single unit operations. No significant synergistic effects in their removal during subsequent soil passage are detected. A strong primary disinfection effect of UV/H_2O_2 is detectable along the subsequent biological treatment columns (Figure 1).

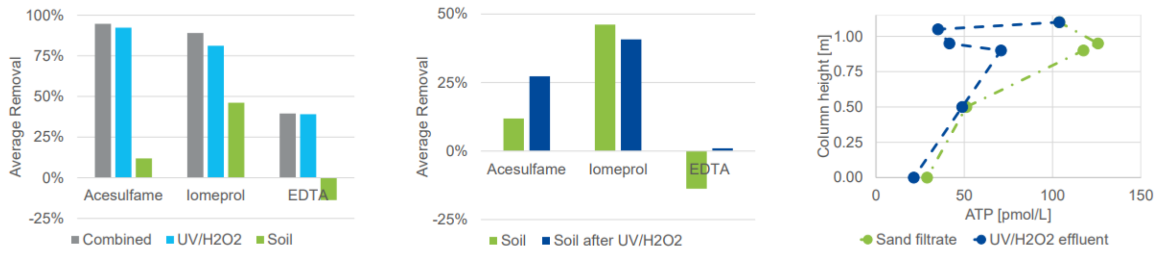

Figure 1. Performance of Lange Erlen UV/H_2O_2 treatment trains.

In Shafdan, TrOCs concentration is very low after the sSAT (Figure 2). For instance, CBZ was below 300 ng/L when continuously infiltrating ozonated water. DOC, TrOCs and bacterial counts were higher after the fully engineered O_3-BAC-cUF treatment train.

Water type	n	TrOCs									Ozonation by-products	
		IPDL ng/L	IHX ng/L	IPRM ng/L	Ibuprofen ng/L	Naproxen ng/L	BZF ng/L	CBZ ng/L	DCF ng/L	SMX ng/L	NDMA ng/L	BrO_3^- mg/L
Secondary effluents*	5	59	32,600	9,900	176	568	223	698	1,180	202	5	<DL
After ozonation*	5	31	13,920	5,120	66	<DL	26	<11	<23	<DL	56	11
After BAC**	3	30	12,000	2,433	<DL	<DL	23	26	<12	20	20	11
After sSAT	**5**	**<14**	**<DL**	**<11**	**<DL**	**<DL**	**<DL**	**238**	**<DL**	**80**	**<2**	**7**
Target max. concentration* **		1000			1000			300	300		10	10****

* For NDMA n=3; **BrO_3^- measured after BAC; ***List of substances assessed according to GOW 2276-90-6 - German Federal Environmental Agency; ****Israeli Regulations for Drinking Water Quality (2013)

Figure 2. Average TrOCs and ozonation by products along the ozonation treatment trains and related target maximum concentrations based on available IPR regulations.

Figure 3 shows the capacity of infiltration in ASR well in Ovezand regarding various treatment chains. Results show that Galileo L with a 5 micron filter was able to lower turbidity, but it was insufficient to prevent clogging. Removal of particles > 1 µm was enhanced by adding 1 micron (nominal) cartridge filters, but rapid clogging was still observed due to penetration of particles through the filters and biological growth. Desinfecting the water using UV did not improve the pre-treatment, but adding a disinfectant (Na-hypochlorite) did and suggested prevention of well clogging by preventing biological growth.

In Agon-Coutainville, one of the older seaside resort of the Manche department, a cNES (activated sludge & reed bed filtration) was provided both for golf irrigation reuse and avoiding direct discharge to the sea (health issues). A unified platform is dedicated to optimize the management of water reuse through the performance of innovative water quality real time monitoring and modelling technology linked to data management and communication (Figure 4). In this coastal area, groundwater quality and quantity are spatially and temporally linked with the natural environment (tides, natural recharge, rivers…). A set of groundwater online monitoring probes (water level, salinity, temperature…) was implemented at various distances from the sea and a transient hydrosystem model was built integrating the SAT/MAR system and saline intrusion hydrodynamics. This WWTP-SAT/MAR ICT system which is a site-specific decision support system (DSS) is able to drive a modelling and to provide services through web to address operational, tactical, strategic and executive management for a better integration of the decision making.

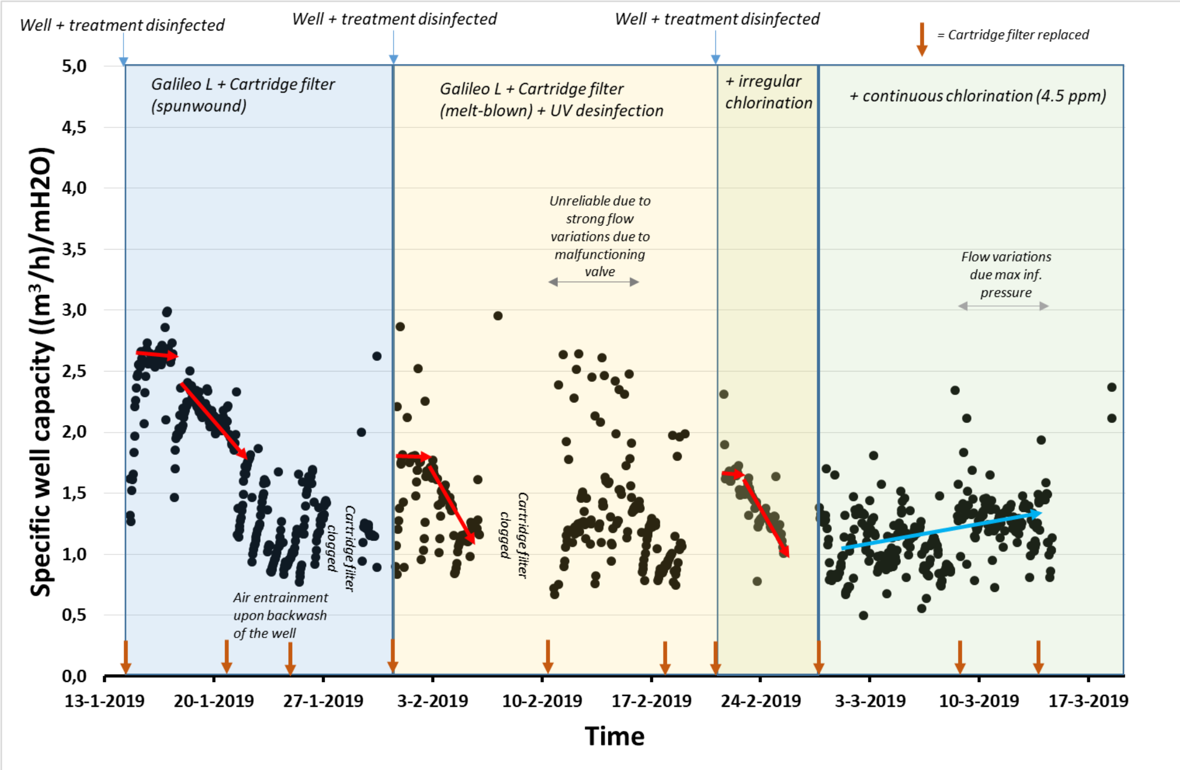

Figure 3. Specific capacity of the infiltration well of Ovezand ASR system in 2019.

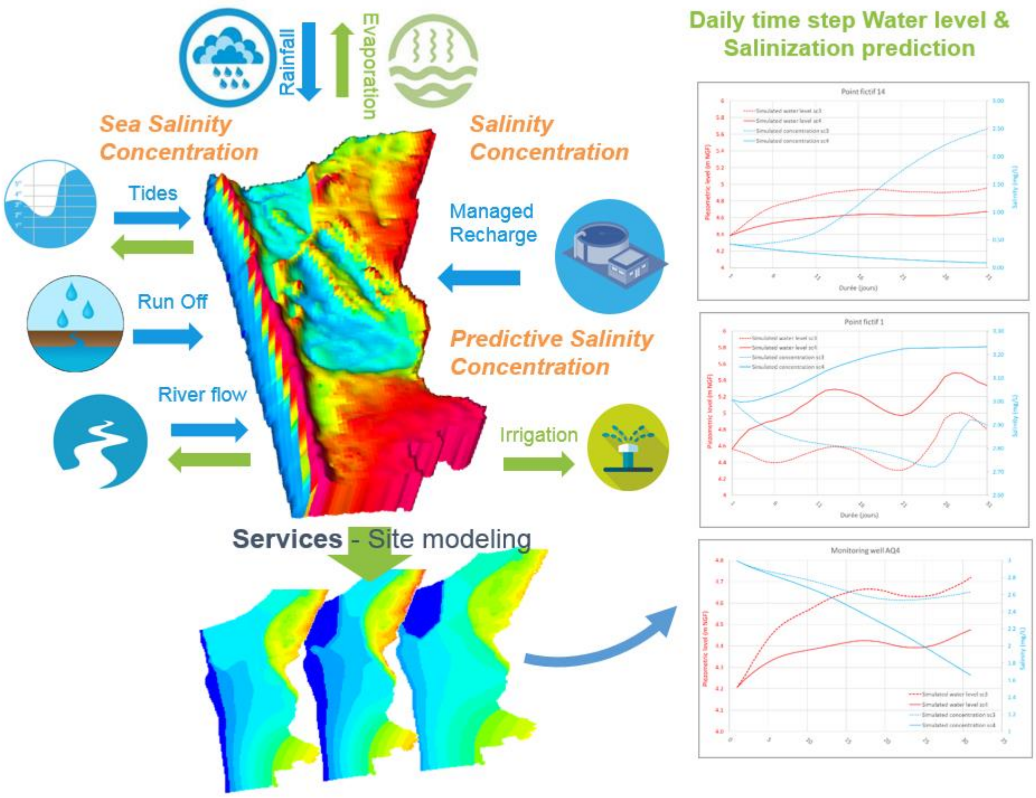

Figure 4. Conceptual scheme of SAT/MAR innovating on line/off line monitoring and ICT short water cycle management for water reuse in saline intrusion area.

4. Discussion

Feasibility of natural and engineered processes combination was demonstrated based on monitoring of 4 demonstration sites. In Lange Erlen, demonstration shows that UV/H_2O_2 is an easiliy scalable, well controllable and quickly adoptable processes for an additional barrier against TrOC parent substances with absent bromate formation problems (potential carcinogenic substance, threshold: 10 μg/L) for an additional costs for the implementation of the AOP treatment in full-scale: 0.03 €/m3 – 0.04 €/m3. In Shafdan, pre-treatment and ozonation were operated using 25% less H_2O_2 and 27% less O3 (based on the ratio of O_3/DOC) as compared to a similar system used before (Demoware, FP7, Lakretz et al., 2017). sSATwater quality after only 22 days is similar to cSAT after typically 6-12 months, and has lower CBZ concentrations compared to cSAT. The O_3-sSAT system complies with existing IPR criteria with respect to bacterial, TrOCs, ozonation by products, and DOC requirements (assuming the fraction of recycled water in the reclaimed water is ≤50%). Demonstration activities in Ovezand show performance of Galileo L filter in case of sudden peaks in particle load, preventing rapid clogging of the down-stream system. To perform as robust pre-treatment step prior to storm water infiltration, a second, finer filtration step is required. In case of a high nutrient and organic carbon content in the storm water, additional step are also required to prevent biological clogging. In Agon, results show that the MAR system provides a freshwater barrier in the aquifer which is seasonally affected by saline intrusion. A part of the aquifer is assessed for freshwater potential production, regardless of the natural and anthropogenic recharge. This novel subsurface monitoring and modelling provides a better understanding of the SAT capacity to enhance the quantity of freshwater and improve its quality.

Acknowledgments: The AquaNES project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 689450.

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Paper for ISMAR10 symposium. ***Topic No: 16 (256#)***

Three-in-one uses of a managed aquifer recharge system: the triplets in Los Arenales (Spain)

San Sebastián Sauto, J.[1*] and Fernández Escalante, E.[2]

[1] Department of Building & Engineering, Tragsatec, Julián Camarillo 6, Madrid, Spain
[2] Department of R&D Integrated Water Management, Tragsa, Maldonado 58, Madrid, Spain
* Correspondence: jsss@tragsa.es. Tel.: +34-91 3226661

Abstract: Los Arenales aquifer is a broad groundwater body that occupies 2,400 km^2 and lodges 96 villages with 46,000 inhabitants in Castilla y León, Spain. Managed Aquifer Recharge (MAR) activities began in 2002 in Santiuste area (12.2 Mm^3 per year). Later, two more areas on the same aquifer developed their own recharging facilities: El Carracillo (5.6 Mm^3/year) from 2003 and Alcazarén (3 Mm^3/year) from 2011. Core water usage is irrigation. Within Santiuste and Carracillo, two stretches of their canal networks have been designed to perform three functions in a row: decantation, biofiltration and restoration. This article is only focused on the first one. In 2005 a WWTP by lagooning began to spill its effluent into the junction with the near East infiltration canal of Santiuste. Therefore, the recharging volume from Voltoya River, with high-water quality (95%), began to be mixed up with the sewage (5%) into the immediate ditch. Hydrophilic plants in the canal bed help micronutrients absorption from water flow as their roots prevent clogging and increase infiltration. At the same time, the green cover is used as a fauna shelter. In a branch parallel to the canal the water may enter a three-pond-group artificial wetland, where purification, minimal infiltration and environmental functions follow. Water quality analysis and groundwater level monitoring have been carried out in a series of sample points to test processes in the triplet. Some chemical measurements show dissimilar behaviour in canal and ponds, indicating water content reduction that improves latter infiltration. The checked balance between water infiltrated and used by the plants in the ditches is still positive for the aquifer. The presence of artificial wetlands in MAR facilities plays a very complementary role into local biodiversity.

Keywords: Managed Aquifer Recharge, MAR, artificial recharge, groundwater quality, triplet scheme, SAT-MAR, TDO reduction, green-biofilter, artificial wetlands.

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1. Introduction

In 2002 the activities of Managed Aquifer Recharge began in Los Arenales aquifer [1], a project branded as "for National Common Good" and promoted by end-users through an appeal to their parliament member for Segovia province.

Building works were developed by the Ministry of Agriculture & public enterprise Tragsa, as a pilot-scale experience under two premises [2]: avoiding pumping costs (passive system) and using winter water surpluses for MAR (intermittent system). After the MAR activity started, the management and maintenance of the facilities were transferred to the irrigation communities, with two conditions: In the future these farmer associations are obliged to the maintenance and cleaning of the devices and to allow the Ministry of Agriculture and their in-house service suppliers (as Tragsa Group) to perform R&D activities in order to test if this scheme (if successful) might be extrapolated to analogous circumstances.

MAR water pre-treatment is still considered the most effective measure to enlarge the life-span of the facilities and to avoid clogging processes [3]. The most applied technical solution during MARSOL project at Los Arenales has been the device called "a triplet", composed by an assemblage of a stagnation structure-a green bio-filter and an artificial wetland.

This article exposes the achievements in these lines of action and how the scheme is improving the MAR water efficiency in these living labs. It is worth to describe the area were these activities are being performed, Los Arenales aquifer, prior the description of the "triplets", the results already obtained in them and the representativeness to extrapolate this mock-up to analogous scenarios.

1.1. The MAR demo sites in Los Arenales

Los Arenales aquifer is located in the southern sector of Duero Basin. Its surface spreads over 7.754 km^2 and includes some parts of the provinces of Salamanca, Valladolid, Segovia and Ávila. The main rivers that run across this aquifer are Duero, Zapardiel, Adaja, Eresma and Voltoya (**Figure** 1**a**). Its origin is polygenic with a predominance of Arevalo facies, i.e. Quaternary dune system sands, filling a complex substrate from the Miocene epoch, notably argillaceous (Cuestas) or arenaceous and argillaceous (Puente Runnel), with thickness up to 56 m. A detailed description can be found in the hydrogeological literature [4].

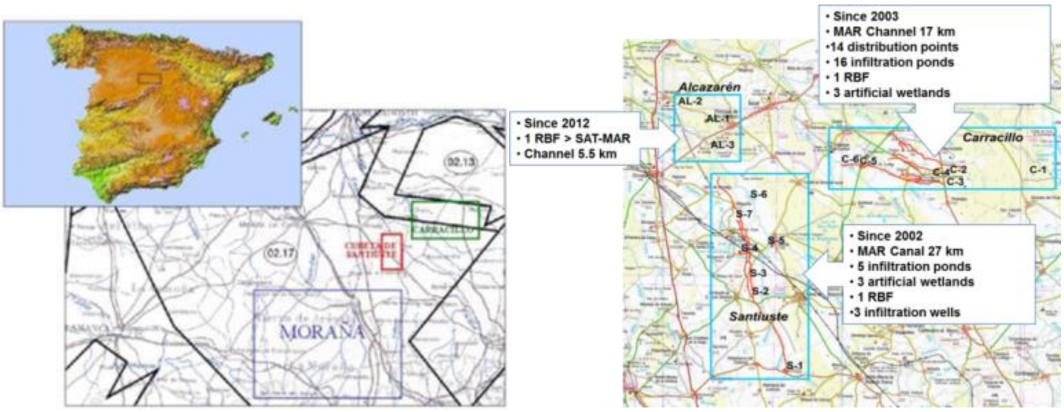

Figure 1. Los Arenales aquifer and its location in Spain. Scheme not to scale (a) Los Arenales aquifer MAR systems position and devise of the facilities on the topographic map with a list of the main MAR components. Approximate scale: 1:150.000 (b).

The intensive exploitation of groundwater in some areas of "Los Arenales aquifer" caused an outstanding decline of phreatic levels, and the subsequent reaction from the Spanish Ministry of Agriculture (MAPA) of the Spanish government, who planned to carry out several experiences of Managed Aquifer Recharge in this groundwater body, in order to minimize environmental alterations. The studied areas are located at Santiuste basin, Carracillo district, in Segovia province, and Alcazarén area, in Valladolid, (Figura 1b), with water surpluses from the Voltoya, Cega and Eresma rivers, respectively, also including a little volume taken from some Waste Water Treatment Plants (WWTP) in the first and third cases. The existing MAR elements in these demo-sites of Los Arenales aquifer are listed in It is important to note that almost 100% of the water is used for irrigation and that each MAR cycle or period when water is diverted from the rivers to the recharge facilities begins about November 1st and ends on April 30th, with eventual exceptions and depending on weather conditions: in case of water shortage in rivers the enhanced recharge is banned by the Basin Authority (CHD).

Table 1).

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Table 1: Main components at Los Arenales aquifer MAR systems.

DEMO SITE	Operability (years)	MAR transport pipe (km)	MAR infiltration canal (km)	Infiltration ponds	Infiltration wells	Artificial wetlands	RBF	WWTP for SAT-MAR
Santiuste	14	9.8	27	5	3	3	1	1
El Carracillo	13	46	17	17	1	1	1	0
Alcazarén	4	19	7	1	0	3	1	1

1.2. Description of the triplet system in Santiuste

It is a 2.7-km-long-structure within a MAR canal which starts at the point where the reclaimed water coming from a lagooning Waste Water Treatment Plant (WWTP) connects to the main MAR East canal, which is transporting and infiltrating MAR water initially from fluvial origin.

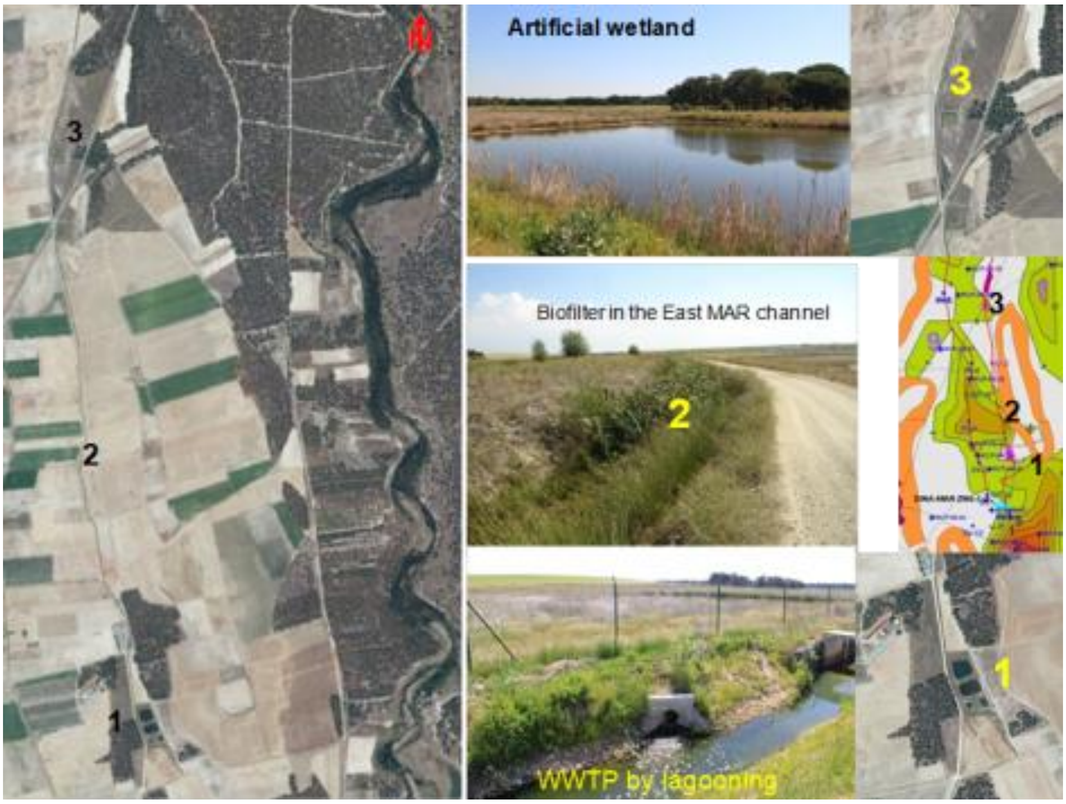

Figure 2: "Triplet" at Santiuste basin, a combination of elements to play a purification process on reclaimed water from a lagooning WWTP: spill of reclaimed water in the MAR canal (1), natural treatment along a green biofilter (2) and final treatment along two artificial wetlands (3).

This SAT-MAR structure is integrated by three consecutive elements (Figure): the "SAT-MAR" device (1), a green biofilter (2) and two consecutive artificial wetlands (3) to finish the purification process. Later the water returns to the MAR canal and continues advancing northwards.

In short, for the Santiuste case the lagooning WWTP pours reclaimed water into the canal, which conserves the natural vegetation in this stretch, working as a green bio-filter, until it can be derived to two artificial wetlands where it can also be sent back to canal again. Water is treated "in itinere" as it flows through the infiltration canal.

WWTP by lagooning

It begins in the junction of the WWTP spill with the MAR canal coming from the initial decantation pond. It is formed by four ponds where treatment occurs by lagooning.

The volume of reclaimed water in comparison to the MAR water in the canal is always below 5% during recharge season. Then, there is an important initial dilution of the vectors which might be insufficiently purified within the MAR water volume, which fulfils all the required standards and requisites.

Green biofilter

A stretch of 1,129 m of infiltration canal followed by another 1,577-meter-length section of semi-impermeable ditch connect the WWTP outflow with the artificial wetlands. The whole infiltration canal net occupies more than 25 km on the sandy aquifer and only 30 m slope.

It plays a double role: on the one hand the wild plants perform an important purifying activity on the potential pollutants which could have remained after the irregular water treatment process, even by single absorption of nutrients. On the other hand, roots pierce and break the clogging in the bottom of the canal, where complex clogging processes are combined, increasing the infiltration rate despite their direct consumption of water through evapotranspiration and photosynthesis.

The second line of action was initiated in 2005 [4, 5]. Considering the convenience of the green biofilter and the most appropriate plants to be induced to settle in this section, some species have been inventoried which are prone to penetrate the clogging layer, increasing the subsequent passage of water, and decreasing the amount of nutrients in the soil. Most listed species are those hydrophilic herbaceous with an annual cycle, rapid growth, high root expansion and ease of extraction with roots. The plants must be specific to each area of action, depending on the climate conditions, the substrate, etc. Some species that can meet these requirements in the demo site are [modified from 4]:

- *Dactylis glomerata*
- *Agrimonia eupatoria*
- *Althaea officinalis*
- *Althaea hirsuta*
- *Carum verticillatum*
- *Elymus hispidus susp. hispidus*
- *Galium palustre*
- *Iris pseudacorus*
- *Lolium rigidum subsp. rigidum*
- *Sparganium erectum*
- *Tetragonolobus maritimus var. hirsutus*
- *Triglochin palustris*
- *Ranunculus repens*

Artificial wetlands

This three-pond-group (Sanchón 1: 2,361 m^2, Sanchón 2a: 2,916 m^2 and Sanchón 2b: 13,000 m^2) is laterally placed near this infiltration canal and reconnected in the northern extreme back to the main East infiltration canal when fulfilled. They were built in 2008.

As the third element of the triplet they also play a double function: the purification of the water stored in the vessel, and an environmental function, as an ecologic spot of interest: shelter for wild fauna and restored temporal ponds.

As the bottom of the wetland stays slightly higher than that of the parallel canal, water does run all through the ditch (Sanchón 1 and 2a stay flooded) avoiding usually the whole cover of the wetland though a high flow enters the infiltration canal further the south spillway. For that reason, the biggest wetland (Sanchón 2b) is randomly covered by water.

The importance of this site as a purification enhancer and a habitat for aquatic species is very relevant. It occupies the functionality of many old temporary ponds that have been desiccated by years of ploughing because of an old farm tradition to decrease the run-off and thus the water table level.

2. Materials and Methods

Water quality analysis has been carried out in a series of sample points (Figure and Table 2) to test processes in the triplet.

The measures of unstable parameters have been conducted with a multiparameter HANNA HI 9829 [24]. The measures accomplished after fixing and georeferencing the stations have been pH, ORP (mV), TDO (ppm), EC (uS/cm), TDS (ppm), salinity (PSU), turbidity (NTU), T (ºC), pressure and time of collection. In 2009 were collected two data-sets in two campaigns (DINA-MAR project) in 2009 January 22th and February 18th. In the last MAR cycle have been measured the unstable parameters monthly (MARSOL project) in dates 2015 Feb 17th, March 16th and April 15th.

At Santiuste basin four water samples (last rows in table 2) have also been analyzed in the KWR laboratory in Germany (MARSOL partner) for the initial characterization of the system with determination of 111 parameters (see Annex A) in. The date of collection: was 2015 Feb 17th by standardized procedures.

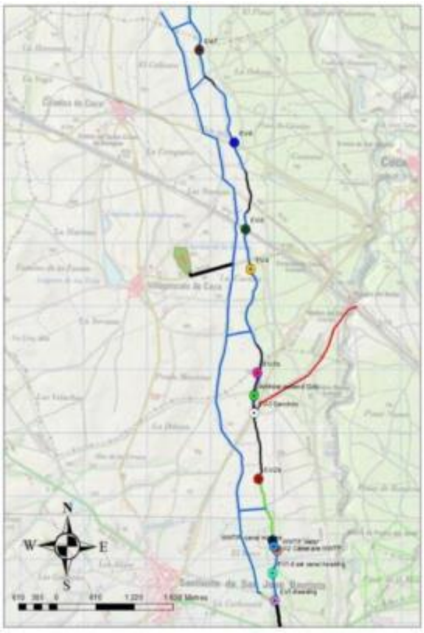

Table 2. Sample points location maps in Santiuste

STATION	X	Y	Unstable parameters 2009	Unstable parameters 2015	Unstable parameters 2016	Biochemical analysis 2015
EV1-Heading	370033	4557315	X	X		
EV1-East canal heading	369945	4557786		X		
EV-2 Canal pre WWTP	369972	4558275	X	X		X
WWTP water	369983	4558153		X		X
WWTP-canal mixture	369985	4558184		X		
EV-2b	369750	4559248		X		
EV-3	369674	4560291	X	X		
EV-3b (Canal)	369733	4560915		X		
EV3b (AW 2A)	369733	4560915		X		X
EV-4	369624	4562556	X	X		X
EV-5	369541	4563188	X	X		
EV-6	369361	4564552	X	X		
EV-7	368809	4566014	X			

Figure3. Sample points location maps in Santiuste.

3. Results

Seven water samples have been collected for detailed analysis along the “triplet” mock-up, and the unstable parameters have been determined too.

3.1. Santiuste unstable parameters

Regarding the conditions during sampling campaign and measurements, it is worth to remark for the lagooning WWTP the following conditions:

- Low/medium flow rate in surface water (reducing dilution of organics).
- Constant mixing ratio Treated Waste Water (TWW) /Surface Water (SW) during sampling. Optimum: portion of TWW <<< SW.

Table 3. Santiuste Basin 2009 water samples analysis. In situ water unstable parameters mean values from two campaigns (Multiparameter HANNA HI 9829).

STATION	pH	ORP (mV)	DO (ppm)	EC (ms/cm)	TDS [ppm]	Salinity (PSU)	Turbidity (NTU)	Temp (ºC)
EV-1 Heading	6.33	22.4	10.2	253	134	N/A	-	7.2
EV-2 East canal pre WWTP	7.1	-16.1	9.7	232	116	0.11	-	7.85
EV-3 Sanchón	6.01	-17.7	6.5	271	137	0.13	-	6.73
EV-4	6.9	-20.9	7.7	280	144	0.14	-	6.13
EV-5	7.02	-21.3	7.1	344	177	0.17	-	6.76
EV-6	7.04	-12.7	8.8	178	141	0.14	-	7.56
EV-7	7.01	-8.9	4.8	438	223	0.22	-	7.54

Dissolved oxygen (DO) notably falls in the canal after the WWTP inlet (60%) and recovers a little within the wetland but finally falls down to 40%. Salinity and conductivity show similar down-up-down profiles. Redox potential (ORP) fluctuates in canal though it shows a general decreasing trend.

Temperature hardly changes in the infiltration canal once water gets out of the pipe. pH decreases after WWTP (EV3) but later it gets back to the EV2 level. This couple of parameters gets numbers within the +/-15% band so they are not considered very pertinent.

The data that were obtained through 2015 campaign can be commented in a similar way though in this year the number of sample points was conspicuously increased from 5 to 12 (Table).

Table 4. Santiuste Basin 2015 water samples analysis. In situ water unstable parameters mean values from three campaigns (Multiparameter HANNA HI 9829).

STATION	pH	ORP [mV]	DO [ppm]	EC [µS/cm]	TDS [ppm]	Salinity [PSU]	Turbidity (NTU)	T [°C]
EV1-Heading	6.99	90.60	10.57	323.00	170.00	0.19	8.33	9.04
EV1-East canal heading	7.68	163.67	9.10	318.33	161.33	0.18	6.47	9.08
EV-2 Canal pre WWTP	7.96	173.80	6.56	286.67	143.33	0.15	8.87	9.34
WWTP water	7.85	76.23	5.83	809.33	377.67	0.49	7.23	9.59
WWTP -canal mixture	7.66	110.80	4.68	534.33	264.00	0.31	5.28	9.65
EV-2b	7.95	116.07	4.73	274.33	151.67	0.16	10.03	9.43
EV-3 Sanchón	7.98	152.40	3.98	291.00	150.67	0.18	10.90	9.58
EV-3b	8.38	126.70	4.73	388.00	183.50	0.21	38.85	11.34
Artificial Wetland (2A)	8.13	134.40	4.70	845.00	397.00	0.50	13.20	12.72
EV-4	8.22	154.23	4.44	332.33	165.67	0.16	5.00	10.14
EV-5	8.23	143.23	4.71	321.00	163.67	0.17	6.14	10.11
EV-6	8.24	159.63	4.61	324.33	168.00	0.17	10.29	10.26

The parameter DO falls again in the canal (40%) independently of WWTP inflow. Temperature only changes particularly in artificial wetland where water becomes stagnant. ORP concentration drops after WWTP mixture but then follows a clearly rising slope until it achieves a 1.5-fold balance. Turbidity goes up and down with a surprising out of range figure in canal (EV3b) at the same height than the artificial wetlands.

The parameters EC, TDS and salinity display a similar drift, as the high peaks in WWTP and artificial wetland are clearly restored to the baseline within the infiltration canal. The slender change of pH cannot be considered as related considering it stays in the relevance border.

The effect of the WWTP dilution and the performance of artificial wetland can be observed in some parameters. Winter illustrates the rapid effect of treated water on recharging flow and how it gets subsequently neutralized on the canal. Spring shows some changes in the lower WWTP influence and the EC, TDS, salinity, turbidity and temperature changes in the wetland. Parameters with values in Santiuste in winter and spring are graphically illustrated in Annex B.

3.2. Santiuste biochemical parameters

The effect of lagooning seems to be too limited as the WWTP analysis results of the main 19 parameters. These 19 values (see Annex C) were selected from the 111 in the aforementioned list. This lagooning plant has been annually spilling around 0.5 Mm^3 into the recharge canal since 2005 from the near little village of Santiuste de San Juan Bautista. Considering the concentrations that have been found in the WWTP water, some changes must be remarked: sulphates, Ca, DOC, Cl, alkalinity, hardness and As are increased between 200 and 400%, conductivity, Mg, Na, turbidity and nitrates in a range of 500-700%, K, P and phosphates in almost 2,000%. Caffeine and Ammonia content are respectively 5,600% and 14,211% higher in sewage. Only Fe and Cu concentration is lower in the effluent (63 and 74%).

Main chemical parameters suffer a quick recovery that sometimes is obviously a consequence of plain dilution as soon as WWTP spillway gets mixed with the huge volume of river water in the infiltration canal. Nevertheless, seven parameters (see Table) show a different behavior in their decrease depending if they follow the canal (Cu, turbidity and Dissolved Organic Carbon) or they enter the artificial wetland (Fe, P, PO_4 and NH_4). Changes below 12% have been considered irrelevant.

Table 5. Parameter comparison with significant differences in canal (3 negative figures) and artificial wetlands (4 positive figures) 17/02/2015.

STATION	Cu mg/l	Turbidity NTU	DOC mg/l	Fe mg/l	P mg/l	PO_4^{3-} mg/l	NH_4^+ mg/l
EV-2 Canal pre WWTP	100%	100%	100%	100%	100%	100%	100%
WWTP water	74%	546%	273%	63%	1902%	1910%	14211%
Artificial Wetland (2A)	84%	94%	125%	92%	130%	130%	263%
EV-4	32%	66%	97%	104%	149%	149%	289%
Difference EV4-AW2a	-53%	-28%	-27%	12%	19%	20%	26%
	Lower in canal			Lower in wetland			

4. Discussion

According to the Triplet results, some general conclusions can be obtained:

1. The water flowing along a vegetated infiltration canal helps to decrease the Dissolved Oxygen, diminishing the risk of clogging in the canal bed and the subsequent decrease in recharging rate.
2. There are some hints about the evolution of parameters along the triplet as well as some seasonal trends:
   - pH, in general increases along the triplets.
   - ORP tends to stay balanced along the canal.
   - TDO gets the highest values in winter time. In spring it decreases with the purification process and the presence of blooms. After the artificial wetland it registers a slight upward trend along the canal. In Santiuste Triplet TDO has a downward trend up to 5.2 ppm. All through the infiltration canals DO tends to fall.

- EC, salinity and TDS show their highest peaks in the vicinity of the WWTP and in the artificial wetland in spring. In the canal they stay balanced
- Temperature rise at the top of the column in the artificial wetland in spring.

3. The effect of the plants in the MAR canal breaks the clogging layer with a direct positive effect on the infiltration rate.

The analysis of 19 biochemical parameters in Santiuste has also shown some preliminary data about:

- Improvement in water quality: Decrease of NO3 (29%), Cu (68%) and turbidity (34%) in canal (EV-4) related to the inflow from Voltoya River (EV-2).
- Passive biological purification by dilution, sedimentation and biological activity in every single parameter (EV-4) in comparison to WWTP and according to data in some elements as Fe, P, phosphates and Ammonia in artificial wetlands (AW2a) in contrast to the canal (EV-4).

5. Conclusions

"Triplet" has been the name adopted to define a SAT-MAR structure for surface MAR facilities integrated by three elements to help purifying MAR water during the recharge process: a WWTP which effluent is used as a source for recharge, a green biofilter and at least one artificial pond to finish the purification process. Hence volume receives a treatment at the very same time the recharge process is accomplished in-treatment). In the demo-sites the triplet structure length has only 200 m in El Carracillo but 2.7 km long in Santiuste.

It starts at the junction WWTP-MAR canal with water from fluvial origin. After the purification process, the water returns to the MAR canal.

The lagooning WWTP presents a volume of reclaimed water / fluvial water below 5%, posing a high concentration of biological processes at the bottom.

The green biofilter has a double function: on the one hand has a purifying activity on the potential pollutants by plants; and on the other the roots pierce and break the clogging in the canal, increasing the infiltration rate.

Most of the inventoried species are hydrophilic herbaceous with an annual cycle, rapid growth, high root expansion and ease of extraction with roots. According to the currently obtained datasets [6], the balance between the water infiltrated and the amount consumed by the biofilter plants is still positive for the aquifer storage.

The artificial wetlands cover a double function as well: the purification of the water stored in the vessel and a complementary environmental function, as a shelter for flora and fauna.

Water proceeding from a WWTP is scarce in these examples (<5%). Unfortunately, the effects with a bigger volume cannot be tested in these facilities in Los Arenales aquifer.

The advantages of water quality improvements permit to obtain new volumes from increasing sources as WWTP and SWTP in order to balance the decrease or instability of natural origin (as more exceptional winter surpluses) in a Mediterranean area.

By means of appropriate SATs techniques such as water pretreatment, "in itinere" filtering, and the "in-treatment", the efficiency of the system has increased considerably regarding not only water quality but also the groundwater quantity storage.

SAT-MAR facilities might be included in the current operative schemes and each "triplet" mock-up must be "tailor made" according to each aquifer´s characteristics.

This experience throws excellent opportunities for a bigger presence of MAR facilities in IWRM schemes, especially for those involving SAT-MAT elements.

Acknowledgements: This article have been developed and written within the framework of MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and

Drought FP7, www.marsol.eu, GA 119120), financed by the European Commission and Tragsa Group.

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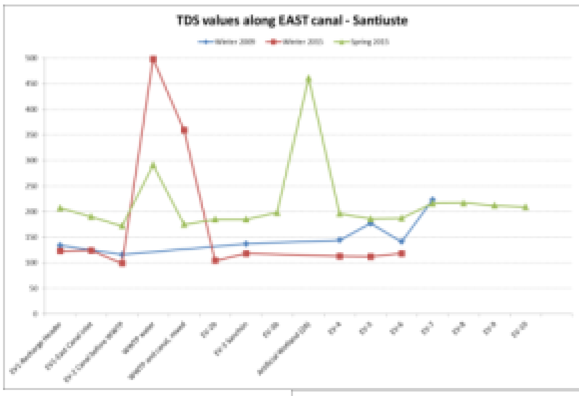
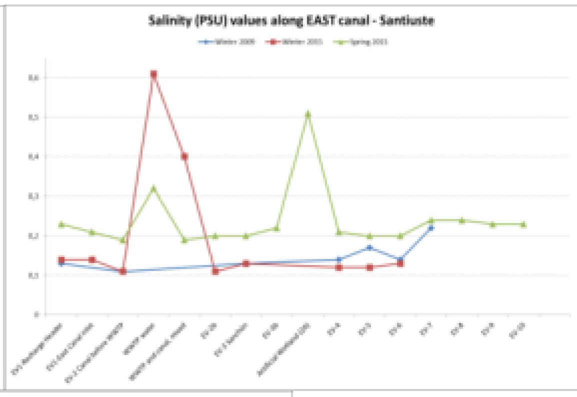
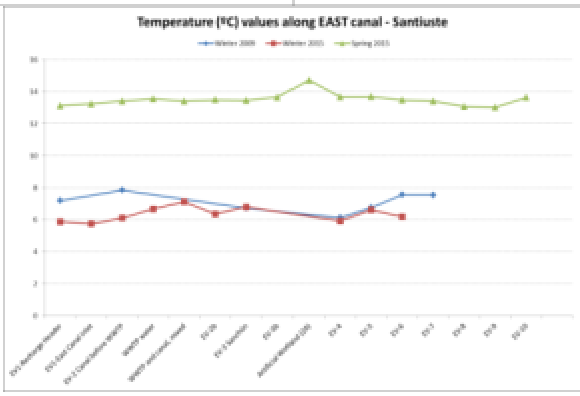
ANNEX A: List of analyzed parameters.

Conductivity
Turbidity
Ammonia
Nitrite
Chloride
Nitrate
Sulfate
DOC
Iron, dissolved
Potassium
Cupper
Magnesium
Manganese
Sodium
Nickel
Phosphate. total
Phosphor. gesamt
Cadmium
Calcium
Total Hardness
Sum earth alkali elements
Arsenic, dissolved
Lead, dissolved
Zinc, dissolved
Chemical Oxygen Demand
Biological Oxygen Demand
Filterable Solids
2-Bromo-biPh
2.2´.4.4´.6.6´-Hexabromo-biPh
2.2´.4´.5-Tetrabromo-biPh
2.2´.4.5.5´-Pentabromo-biPh
2.3´.5-Tribromo-biPh
2.4-Dibromo-biPh
BDE 100
BDE 153
BDE 183
BDE 28
BDE 47
BDE 77
BDE 99
BDE-Sum
BDE154
Bisphenol A
4-Nonylphenol. Isomer mixture
4-tert.-Octylphenol
Atrazine
Caffeine
DEET
Hexachlorbutadiene (HCBd)
Parathion-methyl
Chloramphenicol
Chlortetracyclin
Clarithromycine
Dehydrato-Erythromycin
Doxicycline
Erythromycin
Oxytetracycline
Roxithromycine
Sulfadiazine
Sulfadimidine
Sulfamethoxazole
Tetracycline
Trimethoprim
Atenolol
Betaxolol
Bisoprolol
Metoprolol
Pindolol
Propanolol
Sotalol
Acetylsalicyl acid
Bezafibrate
Clofibric acid
Diclofenac
Fenoprofen
Gemfibrozil
Ibuprofen
Indometacine
Ketoprofen
Naproxen
Carbamazepine
Diazepam
Etofibrate
Fenofibrate
Pentoxifylline
Phenacetin
Phenazone
beta-Sitosterol
Estradiol
Estriol
Estrone
Mestranol
16a-Hydroxyestrone
17a-Ethinylestradiol
Amidotrizoic acid
Iodipamide
Iohexol
Iomeprol
Iopamidol
Iopromide
Iothalamic acid
Ioxaglinic acid
Ioxithalamic acid
EDTA
Tris(2-chloroethyl) phosphate
Tris(1-chlor-2-propyl) phosphate
Tris (1.3-dichlor-2-propyl) phosphate
TMDD
Acesulfame
Cyclamate
Saccharine

ANNEX B: Winter (2009, 2015) and spring (2015) data from 7 main unstable parameters.







Annex C1: Analysis results of 19 main Biochemical parameters.

STATION	Turbidity NTU	NO_3^- mg/l	K mg/l	Cl- mg/l	SO_4^{2-}mg/l	COD mg/l	Na mg/l
EV-2 Canal before WWTP	9.12	1.6	1.59	21.5	5.68	7.7	14
EV-2 WWTP	49.8	11.3	29	58.7	12.7	21	69.5
EV-3 Artificial Wetland	8.55	1.18	2.69	23.2	6.34	9.6	16.1
EV-4 canal after AW	6.02	1.13	2.8	24	6.61	7.5	16.5

STATION	Mg mg/l	Ca mg/l	PO_4^{3-} mg/l	P mg/l	Alcalinity mmol/l	Caffeine µg/l
EV-2 Canal before WWTP	3.59	14.2	0.174	0.057	0.503	0.15
EV-2 WWTP	14.9	32.9	3.324	1.084	1.43	8.4
EV-3 Artificial Wetland	4.13	15.6	0.226	0.074	0.558	0.25
EV-4 canal after AW	4.34	16.2	0.26	0.085	0.581	0.24

STATION	pH	NH_4^+ mg/l	Fe mg/l	Cu mg/l	As mg/l	Conductivity mS/cm
EV-2 Canal before WWTP	2.82	0.038	0.089	0.019	0.0017	0.18
EV-2 WWTP	8.02	5.4	0.056	0.014	0.0066	0.734
EV-3 Artificial Wetland	3.13	0.1	0.082	0.016	0.0022	0.206
EV-4 canal after AW	3.26	0.11	0.093	0.006	0.0023	0.212

Annex C2: Analysis results of 19 main Biochemical parameters (Change in % related to canal with fluvial recharge as a 100%).

STATION	EV-2 Canal before WWTP	EV-2 WWTP	EV-3 Artificial Wetland	EV-4 canal after AW	EV4-EV3 difference
Fe mg/l	100%	63%	84%	32%	-53%
Cu mg/l	100%	74%	94%	66%	-28%
SO4 2-mg/l	100%	224%	125%	97%	-27%
Ca mg/l	100%	232%	167%	160%	-7%
COD mg/l	100%	273%	74%	71%	-3%
Cl- mg/l	100%	273%	115%	118%	3%
Total alkalinity mmol/l	100%	284%	114%	118%	3%
°dH	100%	284%	110%	114%	4%
As mg/l	100%	388%	108%	112%	4%
Conductivity mS/cm	100%	408%	112%	116%	5%
Mg mg/l	100%	415%	111%	116%	5%
Na mg/l	100%	496%	111%	116%	5%
Turbidity NTU	100%	546%	115%	121%	6%
NO3- mg/l	100%	706%	129%	135%	6%
K mg/l	100%	1824%	169%	176%	7%
P mg/l	100%	1902%	92%	104%	12%
PO4 3- mg/l	100%	1910%	130%	149%	19%
Caffeine µg/l	100%	5600%	130%	149%	20%
NH4+ mg/l	100%	14211%	263%	289%	26%

Topic 17. MAR HEALTH ASPECTS

Paper for ISMAR10 symposium. **Topic No: 17 (106#)**

Combined removal of organic micropollutants and ammonium in a column study with reactive barriers simulating MAR

Jakub J. Modrzyński[1], Christian N. Albers[1], Arnau Canelles[2], Nora Badawi[1] and Jens Aamand[1*]

[1] Department of Geochemistry, Geological Survey of Denmark & Greenland (GEUS), Copenhagen, Denmark
[2] Department of Civil and Environmental Engineering. Universitat Politècnica de Catalunya, Barcelona, Spain
*Correspondence: jeaa@geus.dk; Tel.: +45 9133 3565

Abstract: Due to challenges of ground- and drinking water deficits in many countries, the development of sustainable methods ensuring safe drinking water is urgent. Managed aquifer recharge (MAR) holds the potential to be an attractive solution to this problem, yet, despite being a decades-old technology, it is often operated as a black box technology. Our focus was on removal of organic micropollutants, classified as emerging organic contaminants (EOCs). Using laboratory columns, we simulated operation of reactive MAR barriers, composed of sand or sand-compost mixtures. During nine weeks of operation, the columns were fed with synthetic wastewater containing EOCs (1 µg/L each) and ammonium (2 mg/L). The EOCs included sulfamethoxazole sulfadiazine, paracetamol, carbamazepine, and diuron. Paracetamol removal occurred in all columns while sulfamethoxazole showed significant removal only in columns with 50% compost. In contrast, no pronounced removal was observed for carbamazepine and diuron, except for a transient removal, which was attributed sorption. Oxygen was depleted within the top few cm of the columns where also complete nitrification occurred. Overall, ammonium and some EOCs were degradable, while others were more recalcitrant; the latter potentially threatening groundwater resources following MAR.

Keywords: Emerging organic contaminants, degradation, sorption, nitrification.

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1. Introduction

Today's world is challenged by drinking water scarcity in many regions. The problem being accelerated due to climate changes with extended drought periods, water pollution, and increased water consumption. Thus, there is an urgent demand for the development of sustainable methods ensuring safe drinking water [1]. Managed aquifer recharge (MAR) has the potential to be an attractive solution to this problem, as it is an environmentally and economical sustainable technology, requiring little maintenance [2,3]. Importantly, it allows reuse of discharged water to replenish groundwater reservoirs – being a source for drinking water extraction [4]. Yet, despite being a decades-old technology, MAR is often operated as a black box, with only superficial understanding of processes and factors governing removal of contaminants.

Effluents from wastewater-treatment plants are potential sources of water that may be recycled by MAR. Such water, however, usually contains trace amounts of organic pollutants, collectively named emerging organic contaminants (EOCs) [4–8]. EOCs cover pharmaceuticals, personal care products (e.g. antiseptics, veterinary and illicit drugs, fragrances, sunscreens), pesticides (e.g. herbicides), and industrial chemicals, and their metabolites. Although EOCs are often present at very low concentrations (ng-µg/L), their presence in groundwater and subsequently in drinking water is undesired and raises considerable concerns for human health, especially when present in complex mixtures and for prolonged exposure periods [1,4,9]. Ammonium may also be present in high concentrations in wastewater, which is also undesired in groundwater to be used for drinking water. It is therefore important to know whether EOCs and ammonium are removed by MAR to secure that they are not leaching to groundwater resources.

The efficiency of EOC removal by MAR depends on their physical- and chemical characteristics and their reactivity towards different treatment processes. Their attenuation is dependent on environmental conditions such as temperature, pH or abundance of organic matter, and often relies on biological processes; hence efficiencies may vary seasonally and between different MAR facilities [10].

EOC and ammonium removal may be stimulated by the establishment of reactive barriers on the top of MAR facilities. For instance, compost was recently shown to enhance removal of some EOCs (sulfamethoxazole, caffeine, benzoylecgonine, trimethoprim, atenolol, gemfibrozil and cetirizine), while others (carbamazepine, 1H-benzotriazole and tolyltriazole) remained unaffected [11,12]. The compost probably acted both as a source of sorption sites, degrading microorganisms, and nutrients stimulating microbial activity. Furthermore, the compost was assumed to create a broad range of redox conditions also expected to increase EOCs removal [11–13].

Our aim was to estimate the impact of compost amendment on simultaneous removal of ammonium and EOCs, and to assess the potential of MAR systems to prevent leaching of these pollutants to groundwater resources. Using laboratory columns, we simulated the operation of reactive-MAR barriers composed of sand and compost in different proportions and fed with synthetic wastewater effluent containing EOCs and ammonium. The studied EOCs were sulfonamide antibiotics: sulfamethoxazole and sulfadiazine, pharmaceuticals: paracetamol and carbamazepine, and a pesticide/biocide: diuron (Table 1). These model EOCs represent chemicals with varying physio-chemical characteristics and shown previously to be present in wastewater and groundwater [4–7]. The removal of the model EOCs was assessed by SPE-LC-MS/MS following passage through the MAR-columns.

2. Materials and Methods

2.1. Emerging organic contaminants

The model EOCs (Table 1) were all of analytical purity (≥98%), purchased from Sigma-Aldrich, Germany. Synthetic wastewater containing 1 µg/L of each EOC and 2 mg/L ammonium was used as inlet for the columns (Table 2). The composition was designed to chemically reflect effluent from wastewater treatment plants with reproducible quality. The final composition is presented in Table 2. The solutions – except EOC solutions – were sterilized by filtering (humic acids, $FeCl_3$) or autoclaving (all the rest).

2.2. Columns setup and operation

The setup consisted of six laboratory columns made of Plexiglas (Figure 1). The columns were equipped with oxygen sensors at depths of 4, 8, 13 and 20 cm from the barrier top. The bottom of the columns was protected with a metal net and a 3-cm layer of coarse quartz sand

(1.2-2.0 mm diameter) to prevent barrier material to clog the outlet. The barrier material was composed of either pure sand, or sand amended with compost (Figure 1). The sand and mature vegetable compost used as barrier material had organic matter contents of 0.6% and 25.5%, and pH of 8.4 and 7.8 respectively. For the sand-compost mixture, sand and compost were weighed and mixed homogenously resulting in 10% or 50% compost by volume. The columns were filled with the barrier material using 'wet packing' technique, with water table sequentially raised above subsequent, small portions of the barrier material. This was done order to avoid stratification of compost and sand and to avoid having air trapped in the sediment and preferential flow paths. A 2-cm layer of pure sand was placed on top of the barrier material to prevent any components of the barrier to float. Duplicate columns were prepared for each treatment. All the six columns were then inoculated by using fresh activated sludge from a local wastewater treatment plant by passing 1 L through each column over 10 h.

The columns operated for 9 weeks at 22°C, in the dark, with a flow of 0.5 mL/min. The influent was a mixture of two stock solutions; one with EOCs, ammonium, yeast extract, and humic acids, all kept at 1 °C and replaced weekly, and another being a buffer solution with inorganic nutrients and trace elements kept at 22°C (Table 2). The two solutions were mixed in a ratio of 1:10 at the column inlet to reach the final concentrations (Table 2).

2.3. Analyses

The EOCs were up-concentrated by solid-phase extraction and quantified using ultra-high pressure liquid chromatography tandem mass spectrometry (UPLC-MS/MS) with quantification limits of 0.01 μg/L. Ammonium was quantified spectrophotometriacally.

Table 1. List of EOCs used in the study.

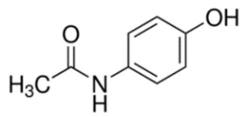
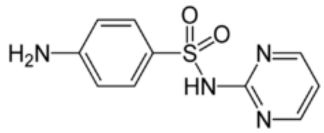
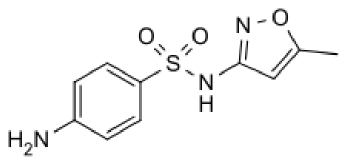
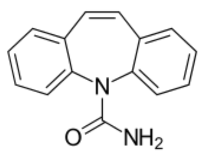
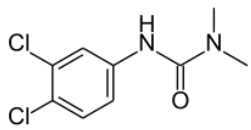
Name	Abbreviation	CAS number	Structure	Category
Paracetamol (Acetaminophen)	PAR (APAP)	103-90-2		analgesic
Sulfadiazine	SDZ	68-35-9		antibiotic, sulfonamide
Sulfamethoxazole	SMX	723-46-6		antibiotic, sulfonamide
Carbamazepine	CBZ	298-46-4		psychiatric drug
Diuron	DCMU	330-54-1		Pesticide and biocide

Table 2. Chemical composition of the synthetic wastewater effluent, used as influent for the columns mimicking a MAR system.

Chemical	Concentration (mM)	Concentration (mg/L)
Buffer:		
NaH_2PO_4	0.04	4.8
$NaHCO_3$	3	250
Nutrients:		
$CaCl_2$	2	222
KCl	0.6	45
$MgSO_4{\cdot}7H_2O$	1.5	370
NaCl	7	400
Trace elements:		
NaBr	0.013	1.3
NaF	0.016	0.7
$FeCl_3{\cdot}6H_2O$	0.0002	0.05
H_3BO_3	0.002	0.12
$MnSO_4{\cdot}H_2O$	0.002	0.34
$CuSO_4{\cdot}5H_2O$	0.0002	0.05
$ZnCl_2$	0.0009	0.13
$CoCl_2{\cdot}6H_2O$	0.0002	0.05
$Na_2MoO_4{\cdot}2H_2O$	0.001	0.05
Ammonium:		
NH_4Cl	0.11	5.9
Organic carbon:		
Yeast extract		1.6
Humic acids		2.0
Methanol*		1.1
EOCs:		
Sulfadiazine, Sulfamethoxazole, Paracetamol, Carbamazepine, Diuron		0.001

*Methanol used as solvent for EOC stock solutions, introduced at EOC spiking.

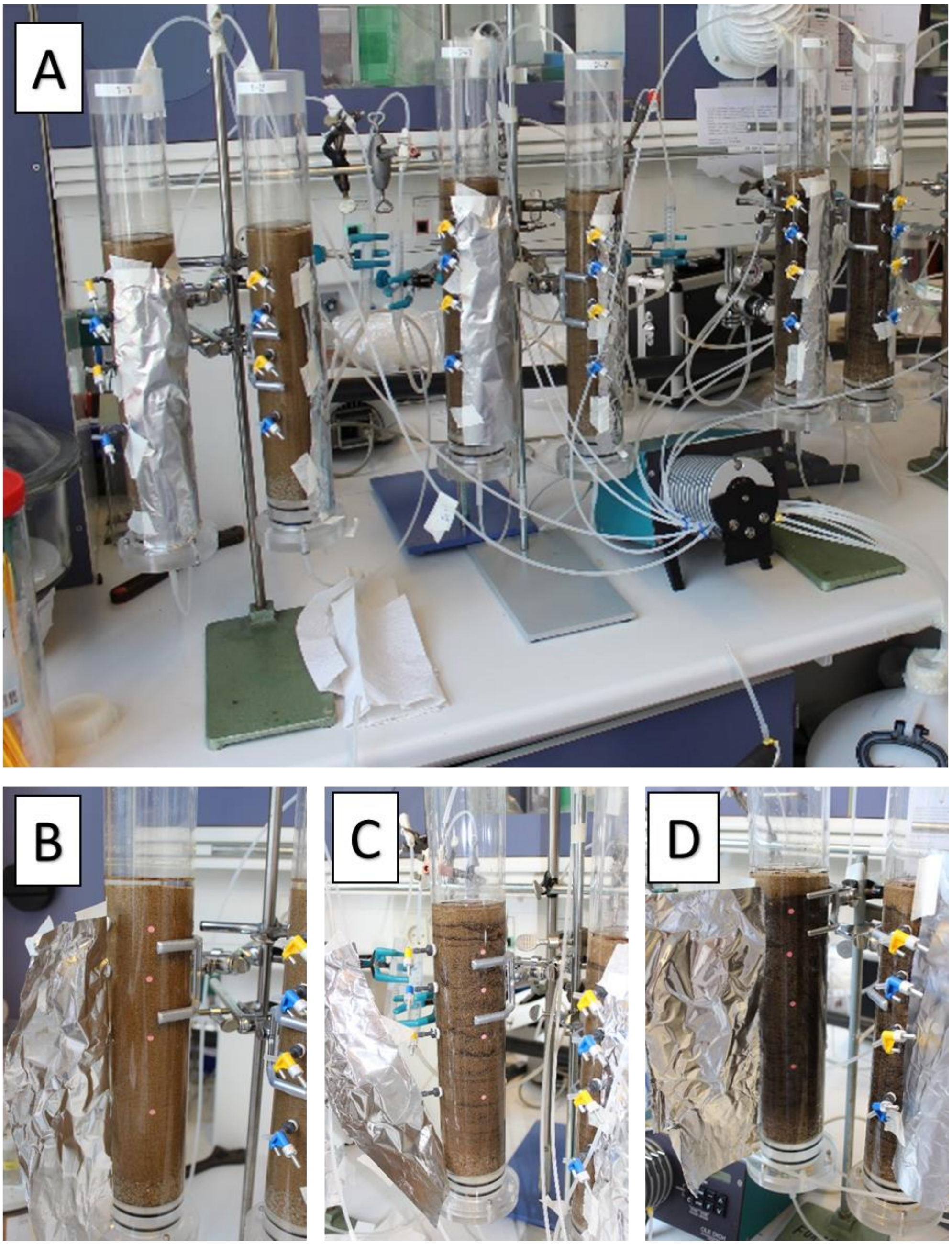


Figure 1. The columns setup. A – columns operating; B – column filled with pure sand; C – with 10% compost; D – 50 % compost. Visible foil for protection from light to avoid algal growth and oxygen sensors.

3. Results

3.1. Redox conditions

At most cases, oxygen was completely depleted within the top 4 cm of the columns. The only exceptions were the columns with pure sand where small amounts of oxygen (1-3 mg/L) were measured at week 5-9 decreasing with depth. The oxygen was arguably consumed due to oxidation of organic carbon (yeast extract, humic acids, and constituents in the compost) and ammonium. As a consequence, aerobic degradation and nitrification was possible only in the top of the columns, whereas the barrier below would allow anaerobic processes including denitrification.

3.2. Removal of EOCs

The removal of EOCs, i.e. degradation and sorption, was assessed as the relative decrease in concentration measured in the column outlet compared to the inlet.

Initially, sulfadiazine showed a moderate removal, highest in the pure sand (Figure 2) but decreasing with time. In contrast, the removal of sulfamethoxazole was right from the beginning significantly higher in the columns with compost, and increasing with time, especially at 50% compost (Figure 2).

Similarly, the removal of paracetamol at week 2 was clearly correlated with the presence of compost (Figure 2). Later in the experiment, however, all columns showed identical, efficiencies with virtually all the paracetamol being removed.

In contrast, there was remuval of neither carbamazepine nor diuron in the pure sand. At week 2, there was removal in the compost-amended columns, highest with 50% compost where both carbamazepine and diuron were completely removed. However, the period with efficient removal was short, suggesting that carbamazepine and diuron are recalcitrant, and only being retarded due to sorption to organic matter in the compost (Figure 2).

3.3. Removal of NH_4

In general, ammonium was effectively removed from the inlet water following passage through the columns. However, initially (week 2) elevated concentrations of NH_4 was found in the outlet of the columns with 50% compost probably due to leaching of ammonium from the compost material. Clearly, the ammonium removal efficiency increased over time although complete ammonium removal was not achieved in the columns with 50% compost (Table 3).

Table 3. Ammonia removal efficiency in weeks 5 and 9 of the columns in operation. The concentration measured in the column outlet relative to the inlet concentrations is given. Mean value for two replicate columns and standard deviation are exposed too.

	NH_4 (% of inlet concentration)			
	Week 5		**Week 9**	
	Mean	SD	Mean	SD
Pure sand	**1**	1	**1**	1
10% compost	**12**	8	**1**	0
50% compost	**53**	10	**8**	1

4. Discussion

4.1. Impact of compost on removal of EOCs

We observed a distinct increase in sulfamethoxazole removal efficiency with time in the columns with 50% compost probably due to adaptation of the microbial community to degrade this compound. Although sulfamethoxazole was significantly removed in the presence of compost, it cannot be excluded that the transformation was a reversible process. Previous studies have shown formation of sulfamethoxazole transformation products (e.g. with additions of acetyl- or glucuronide groups) that may be converted again to the parent compound [14]. Therefore, analysis of transformation products seems relevant for sulfonamides, although being hindered by limited access to analytical standards of the transformation products. Alternatively, studies of complete mineralization of sulfonamide antibiotics may provide new insights into the fate of these compounds.

Paracetamol was removed with high efficiency especially in the compost material and after adaptation of the microbial community to degradation. Our study has focused on compound removal without detailed investigations of possible degradation products. However, a degradation product of paracetamol, 4-aminophenol, has been detected in groundwater and is known for its high biological activity and thus higher toxicity as compared to the parent compound [5]. Therefore, standardized analyses of degradation products should be included to assess the environmental impact of paracetamol following MAR.

Effect of reactive barriers created by compost amendments was assessed in field-scale MAR experiments. In these experiments, most of the tested EOCs (e.g. sulfamethoxazole) showed improved removal as compared to performance prior to installation of the barrier, although others remained unaffected (e.g. carbamazepine) [11,12]. In contrast, the authors observed decreased removal rates of compounds that are easily degradable under aerobic conditions (e.g. paracetamol) [12]. These results are in good agreement with our findings for sulfamethoxazole (improved removal with compost) and carbamazepine (recalcitrance, unaffected by compost), but contrast with our observation of compost showing beneficiary or neutral effect on paracetamol removal.

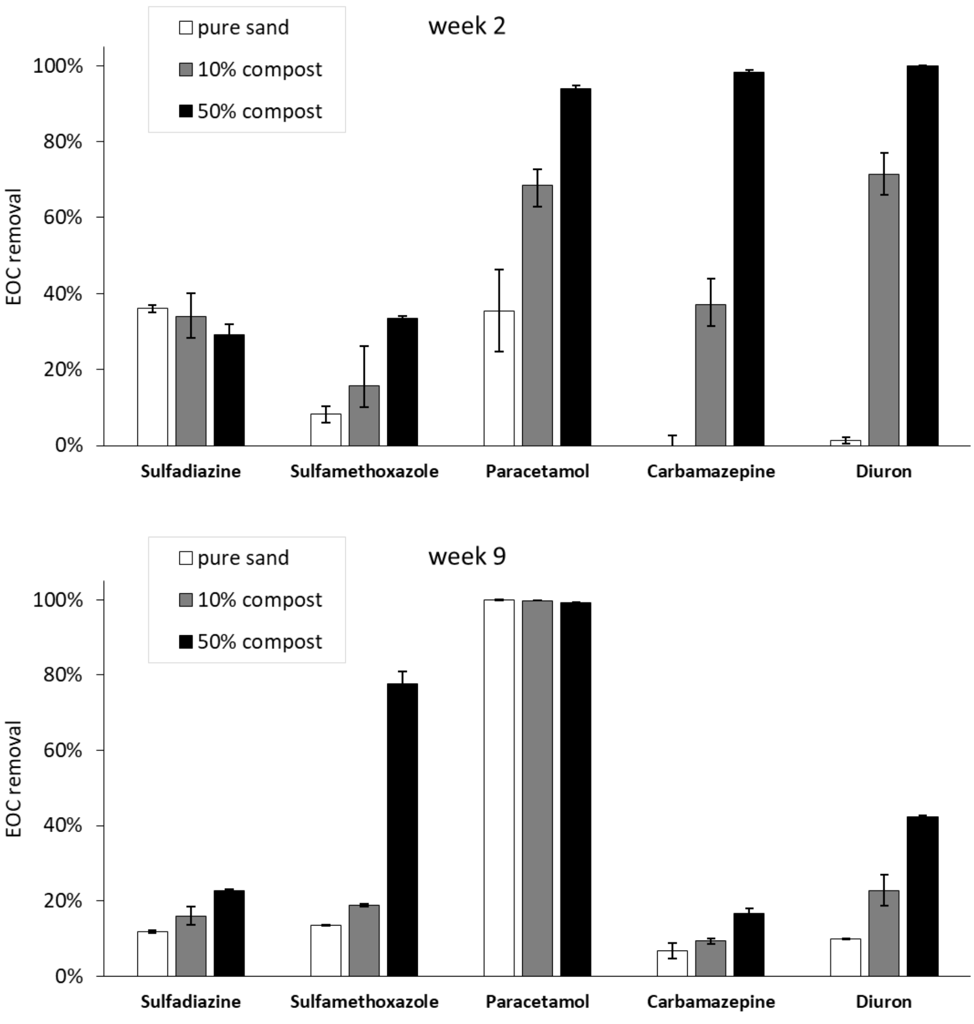


Figure 2. Removal of EOCs in barriers with varying compost content at week 2 and 9 of columns operation. Mean values of two replicate columns and standard deviations are given.

4.2. Impact of compost on removal of NH_4

Despite the generally effective removal of ammonium, especially in week 9, we observed elevated levels in leaching from the columns with 50% compost. This indicates either incomplete ammonium oxidation due to rapid depletion of oxygen in presence of compost, formation of ammonium from the compost material itself or dissimilatory nitrate or nitrite reduction to ammonium in the anoxic parts of the columns. More in-depth analysis of the concentration of nitrogen species at different levels in the columns as well as microbial molecular analyses will hopefully reveal which of these possibilities is the right one. As large concentrations of ammonium in ground- and drinking water are undesired the effect of compost on the nitrogen cycle should be taken into account when designing and operating large-scale MAR systems.

4.3. Applicability of MAR systems with compost-based reactive barriers for removal of EOCs and ammonium

It is apparent from this study that MAR barriers may not be efficient for removal of all EOCs. All the studied compounds except paracetamol, passed the columns almost intact as the majority of the chemicals entering the columns was detected in the outlet, although sometimes retarded due to sorption. This suggests that a substantial fraction of the micropollutants entering the MAR systems may leach to the groundwater, especially during the first weeks of operation. Construction of reactive barriers by e.g. amendment of compost on top of MAR system can in some cases mitigate the problem e.g. by enhanced degradation of EOCs as was shown for sulfamethoxazole and paracetamol. Yet, this seems to only be an incomplete solution, which will not prevent leaching of at least a fraction of various chemicals. Noteworthy, treated wastewaters usually contain a much more diverse set of EOCs.

Oxygen availability is crucial for efficient and rapid degradation of many EOCs. Degradation rates for oxic conditions are often higher than for anoxic environments. In our columns, oxygen was almost completely depleted in the top layer, which, arguably, could explain the limited removal of some of the compounds. Noteworthy, the C and N levels found in wastewater effluent or river waters – often used as influx to MAR systems – usually exceed those we applied in this experiment (Table 2) [15], and hence dominance of anoxic conditions seem inevitable. Putting more efforts into construction of MAR systems allowing for more oxygen penetration of the barriers may therefore be highly advantageous. Actually, recent experimental MAR system with two consecutive infiltration steps allowing intermediate exposure to oxygen resulted in higher EOC removal efficiencies [16–18].

Regarding ammonium removal, compost addition may limit nitrification during MAR, especially in the initial phase of operation. This can result in ammonium leaching to groundwater, and should be considered, especially for MAR systems recharging anoxic aquifers where ammonium will most likely remain until abstraction.

5. Conclusions

Overall, it seems that both ammonium and EOCs can be removed from water by passing a reactive barrier. Yet, apparently neither sand nor sand-compost mixtures applied as the MAR reactive layer can fully remove all EOCs from water. Therefore, substantial fractions of compounds like sulfadiazine, sulfamethoxazole, carbamazepine, diuron, and several other compounds of comparable bio-chemical properties, will probably leach and finally reach groundwater aquifers.

Acknowledgments: This work has been performed within the ACWAPUR project (acwapur.eu). The authors thank our project partners, especially Cristina Valhondo and Jesus Carrera (CSIC, Barcelona) for providing the barrier material from a MAR field site in Palamós, Spain. We are grateful for access to the facility and assistance in sampling at Lynetten wastewater treatment plant in Copenhagen, Denmark. We also thank Spire M. Kiersgaard and Pernille Stockmar for help in sampling and laboratory analyses.

Author Contributions: JJM, CNA and JEAA conceived and designed the experiments; JJM, CNA, NB and AC performed the experiments; JJM, CNA and JEAA analyzed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations. The following abbreviations are used in this manuscript:
EOCs – emerging organic contaminant
SPE – solid-phase extraction
LC-MS/MS – liquid chromatography-tandem mass spectrometry

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Extended abstract for ISMAR10 symposium. ***Topic No: 17 (179#)***

Anticipating pathways and timing for cyanobacteria breakthrough at a 2-lake bank filtration site via environmental tracers

Masse-Dufresne Janie[1*], Baudron Paul[1], Barbecot Florent[2], Pasquier Philippe[1], Barbeau Benoit[1], Patenaude Marc[1], Pontoreau Coralie[1] and Proteau-Bédard Francis[1]

[1]Polytechnique Montréal, Department of civil, geological and mining engineering, Montréal, Canada
[2]Geotop-UQAM, Department of Earth and Atmospheric Sciences, Montréal, Canada
*Correspondence: janie.masse-dufresne@polymtl.ca

Abstract. Cyclic presence of different types of phytoplankton, including cyanobacteria, in the lakes at various depths and eventually at some wells was observed at a 2-lake bank filtration site. Due to their potentially high toxicity, understanding the origin and pathways of cyanobacteria is crucial to maintain the security of the drinking water supply. Measurements of temperature were carried out at Lake B from February 2017 to May 2018 in order to better understand the lake's dynamics. We determined that complete mixing of the water column occurred from mid-October to mid-November. By anticipating the extent and the timing for the autumnal turnover, one can adjust management strategies. This work is the first step towards a better understanding of the controlling factors over cyanobacteria breakthrough.

Key words. Lake bank filtration; lake stratification; mixing ratios; pumping schemes; cyanobacteria.

EXTENDED ABSTRACT

Background

Bank filtration systems were proven to be effective for the removal of cyanobacteria and associated toxins when sufficiently long travel times prevail, allowing for biodegradation to occur [1]. There is no standard minimum travel ensuring adequate removal of cyanobacteria, because the efficiency depends on numerous site-specific factors such as the colmation layer (i.e. sediments at the surface water/aquifer interface) [2]. Pazouki, Prevost [3] demonstrated the passage of various phytoplankton, including cyanobacteria cells, at a 2-Lake BF system in Quebec and highlighted the importance of having an intensive monitoring program to detect future breakthroughs. They reported that cyanobacteria species observed at the pumping wells were similar to the species found in Lake B (compared to species observed at Lake A and in the lakes' sediments). Higher phycocyanin relative fluorescence units (PC RFU) were measured at 10m depth in Lake B (compared to 0.5m, 1m and 5m depth) and at all depths in October 2013. Increase in PC RFU in the lakes also coincides with higher counts in the pumped water. In sum, the results of the investigation conducted by Pazouki, Prevost [3] point out that the similitude between the observed cyanobacteria species at Lake B and at the pumping wells is due to insufficiently long travel times. In comparison, longer travel times prevail between Lake A and the pumping wells.

In this context, the BF more effectively removes cyanobacteria. Hence, it seems that this 2-Lake BF system could be more vulnerable to cyanobacteria contamination originating from Lake B. Understanding the dynamics of Lake B appears important to anticipate pathways and timing for cyanobacteria breakthrough. The aim of the present work was to assess the (1) extent and (2) timing of the autumnal turnover of the water column in Lake B.

Materials and methods

Physico-chemical parameters, including temperature, electrical conductivity (EC), pH and redox potential, of Lake B were measured using a multiparameter probe assembled with a 30-meter long cable (YSI Pro Plus multiparameter meter with Pro Series ph/ORP/ISE and Conductivity Field Cable). Measurements were performed with a depth interval of 1m in the middle of the lake from March 2017 to May 2018. During periods of limited access to the lake (i.e. ice-cover formation or removal periods), the same measurements were performed only at the surface of the lake from nearshore.

Continuous measurements of temperature were conducted in Lake B from September 11, 2017 to May 15, 2017. Three temperature sensors (iButton®; DS1922L; accuracy ± 0.5 °C; resolution 0.0625 °C) were installed at 7m, 9m and 13.5m from the surface of the lake (measured on September 11).

Results and discussion

Timing of the automnal turnover at Lake B

Evolution of temperature at various depths in Lake B is shown on Figure 1. The monitoring started on March 2, 2017. During wintertime, water temperatures are typically minimal and show an inverse thermal stratification, ranging from 3.6 °C (at 2m depth) to 5.1 °C (at 14m depth). A few weeks later, water temperature at the surface of Lake B started to rise and reached 9.2 °C on April 19, 2017. Warming of the entire water column continued throughout summertime, resulting in the development of a strong thermal stratification. Maximal temperature (23.3 °C) was observed at 2m depth on August 7, 2017. On October 26, 2017, the upper part of the lake (0-4m depth) showed a homogenous temperature (~ 14°C), indicating that the mixing of the water column was possibly already initiated. In the meantime, water temperatures in the bottom part of the lake (5-13m) ranged from 13.5°C to 6.6°C. From October 28 to November 7, 2017, water temperature at 7m rose from 9°C to 10.5°C, prior to going through a rapid cooling. The same trend, but with less intensity, was also observed at greater depths (9m and 13.5m) from mid-November to early December. Mixing of the water column occurred over a 1-month period from mid-October to mid-November. Then, water temperatures at 7m, 9m and 13.5m stabilized at ~4°C for few days on early December. During winter 2018, we observed a slow and gradual warming of the entire water column; except for the most surficial part (0.1-1m). In fact, the first centimeters showed cooler temperature due to water-air heat transfer (air temperatures being below 0°C).

Implications for water management

Studies showed that thermal stratification typically limits exchanges between the different layers of lakes. Nutrients and dissolved oxygen can thus go through a gradual depletion over summertime due to biological activity. However, autumnal turnover allows for the mixing of the water column. This vertical mobilization of water can drive nutrients and oxygen renewal at depths where low concentrations were potentially inhibiting development of microorganism prior to the autumnal mixing [4]. We demonstrated that the autumnal turnover occurred from mid-October to mid-November. We thus suggest that water managers adapt the pumping strategy according to the lake's dynamics.

The results of the present investigation highlighted that continuous measurements of temperature at various depths allow us to easily characterize the timing of the autumnal turnover. Other measurements, such as stable isotopes of water and electrical conductivity, would be helpful to track geochemical shift associated with the lake turnover in the bank filtrate. Such information could help with developing a precursor to anticipate for potential cyanobacteria breakthrough.

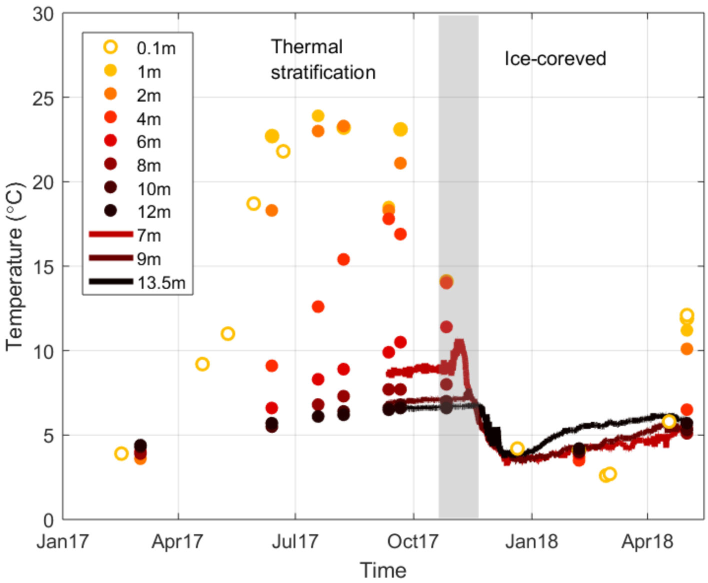

Figure 1. Temporal evolution of water temperature in Lake B at various depths. Discrete measurements (circles) were performed with a YSI multiparameter probe, whereas submerged iButtons allowed for continuous measurements (solid lines). The grey shaded area illustrates the period of the autumnal turnover.

Acknowledgements

The authors would like to thank the students who made the fieldworks. We emphasize their availability and enthusiasm when carrying out sampling campaigns. Also thanks to M. Leduc, J. Leroy, J.-F. Hélie and M. Tcaci for their laboratory support.

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Topic 18. URBAN MAR

Paper for ISMAR 10 symposium. **Topic No: 18 (014#)**

Recharge of aquifers through wells in urban areas of Mexico City

Andrés Benton

Affiliation: Asociación Geohidrológica Mexicana, México. andres_benton@yahoo.com
*Correspondence: byaso@prodigy.net.mx, Tel. + 052 (55) 5255-3642

Abstract: In 2004, the General Direction for the Construction of Hydraulic Works in Mexico City, carried out with great success a program for aquifers recharge at the southern zone on the valley, in an igneous rock formation with high permeability characteristics, which finally allows the recharge of up to 6.0 m3/sec during the rain, through the construction of 52 absorption wells in the unsaturated zone at shallow depth (between 10 and 15 meters).
Due to the difficulties of vehicular circulation that occur in that area during the rainy season, this program was developed with the dual purpose of recharging the aquifer existing there and else preventing flooding and vehicular clogging that take place as an urbanized area of hills and at the foot of the "Ajusco" mountain range.
For this program, it was necessary to consider the topography, the geology and define the small hydrological basins that would feed the structures designed for cleaning of papers, garbage, drag fines, grease and oils, going with the water through grids that cross the paved streets before discharging into the wells that finally allow the surface drainage and to recharge the aquifers.
These structures facilitate carrying out its maintenance periodically.
This program that allows the recharge during the rain, due to its effectiveness has already been duplicated.
The presentation details the procedures used to know the parameters of the igneous formations present in the area, in which the recharge capacity was calculated in each site of the wells, necessary data to design the capacity of the grids and structures that prevent the silting and plugging of the wells.
With the information obtained from the wells cuttings and the geohydrological interpretations carried out during the development of the works, the geology and geohydrology of the area obtained are integrated at the end of the presentation like it was defined.
An important part of these aquifer recharge systems is to carry out the maintenance work of the structures, cleaning these materials that have partially clogged, reducing the infiltration capacity, taking also the precaution of leaving the well completely clean and not damaging the slotted casing.

Keywords: Recharge Wells, geohydrology, rain.

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1. Background

When the Spaniards arrived in the valley of Mexico, they saw a city with great lakes communicated with each other and they settled in the same place as the islets of the Tenochtitlan city.

Due to the frequent floods that caused many misfortunes in the city, the great concern of its inhabitants was always to drain these lakes out of the Valley of Mexico. Finally, that was achieved by leaving only a few little lakes, reaching a condition in which now is lacking water to supply the inhabitants of the metropolitan area of the valley and it has been necessary to drill wells to partially solve the problem pumping groundwater from aquifers that once were large lakes.

Since the 1950s, the urban sprawl of the Valle of Mexico has been expanding, settling indiscriminately in agricultural areas that, on those times, supplied the food consumption for the inhabitants of the Valley and also had been areas provided of vegetation that favored the recharge of rainwater or with the water used in the agricultural irrigation.

As a result of those actions, a double problem has been presented increasing seriously. On one hand, the dramatic decrease in natural recharge of aquifers, and on the other; the gradual increase pumping groundwater to supply the population since the last century. And due to serious problems of flooding areas during the rainy season, the rainwater drains into the collector's systems, degrading its quality and leaving the Valley of Mexico, thus losing the most important source of recharge of the valley's aquifers.

These recharge programs that are carried out by the city government to partially reverse this serious situation, turn out to be very beneficial to some aquifers that supply the population of the Valley of Mexico. In the southern part of the Federal District, these areas are covered by Quaternary volcanic rocks, basalts, pyroclastics, boulders, and sands, all of them present a very high permeability.

2. General aspects

The rainwater that runs along the streets to a bottom of the valley, in addition to not infiltrating, causes water floods which hinder vehicular circulation.

Through the wells program, this problem was minimized and on the other hand, the recharge benefits the existing aquifers.

During 2004, the WATER SYSTEM OF MEXICO CITY carried out a construction program of 52 recharge wells and catchment structures, with capacity in these to infiltrate the aquifer up to a total of 4,500 lps (between 50 and 150 lps per well) of rainwater that drains into the rock formations towards the aquifers. The proven capacity of the recharge wells finally carried 6,000 lps.

It is important to bear in mind that until now there is no precedent in Mexico, of a Great Vision Program of Wells with capacity to recharge more than 4.5 m3 / sec to aquifers, with some wells that can be recharged up to 150 lps, like it was made by the Water System of Mexico City.

During these works, technical control was carried out that allowed obtaining detailed information on the geohydrology of the recharge zone.

Once the site was located, exploratory drilling was carried out at the depth of the project, which varied between 10.0 and 15.0 meters depending on the drilled formation.

During these explorations, samples of cuttings were taken for their classification, as well as data of lose circulation, and depth where rocks and sands fallen. All these related to the very high permeability of the geological formation traversed.

It is convenient to clarify, that these wells were drilled in the unsaturated area, and with an elevation above the level of saturation, as it´s considered in the existing normative in Mexico.

Once the explorations were completed, recharge tests were carried out by the controlled discharge of water, with volumes to reach flow rates between 80 to 170 lps.

3. Recharge tests

To define the permeable zones and values of each well, the abatement and recovery data were used, applying the Jacob approach.

With this data, it was possible to establish the correlation with the geological strata of the well.

3.1 WELL TL-A-136

This well has an area with average permeability of k=0.05 cm/sec, (average) between 2.33 and 9.78 m deep, with the capacity to recharge 100 lps, through materials corresponding to clastics with a thickness of 7.45 m, which is gradually reduced to 10.09 m depth, not reaching its initial level, due to the fallings in the bottom. As seen in the following two graphics:

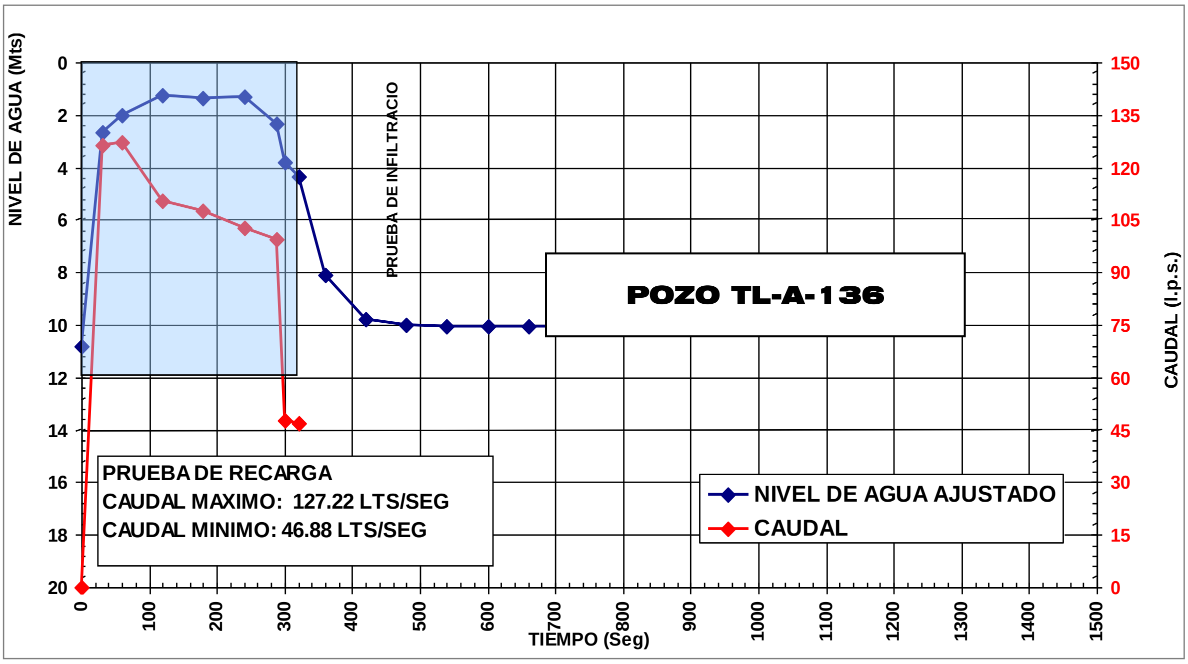


Figure 1. Recharge test in WELL TL-A-136.

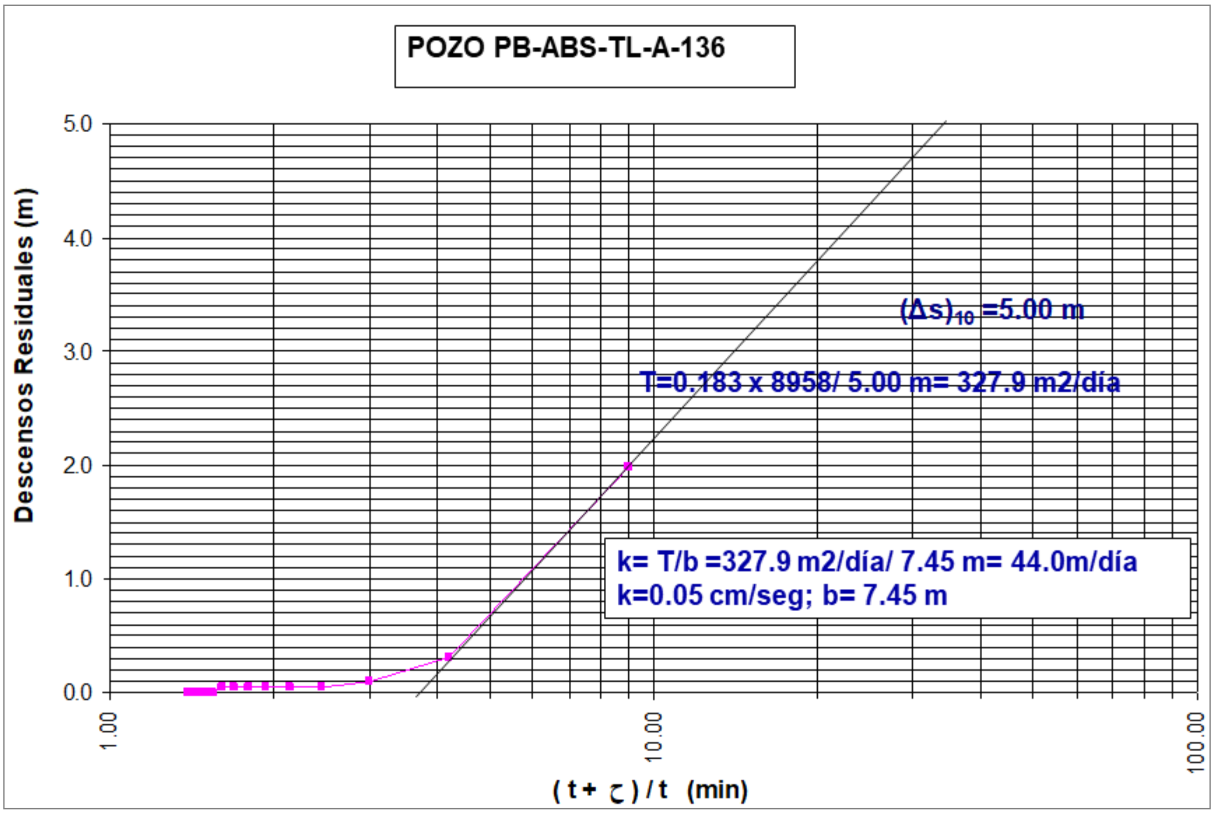


Figure 2. Recovery Interpretation.

Another example is the well TL-A-141, where it shows two aquifers.

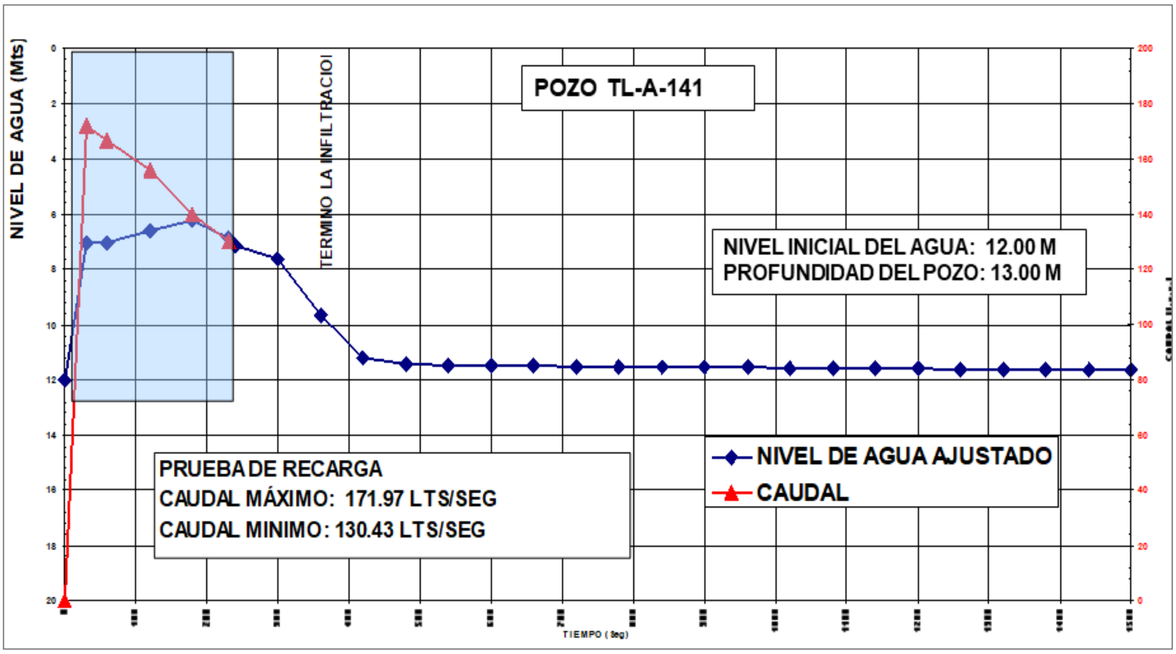


Figure 3. Recharge test in WELL TL-A-141.

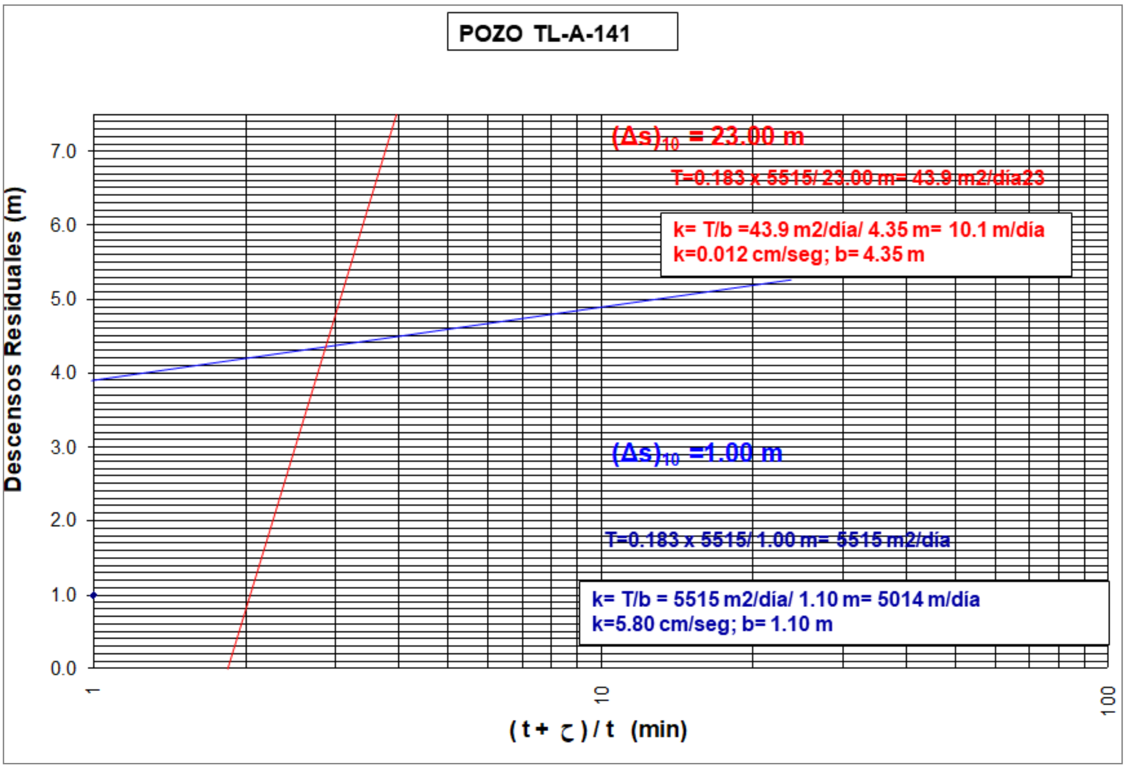
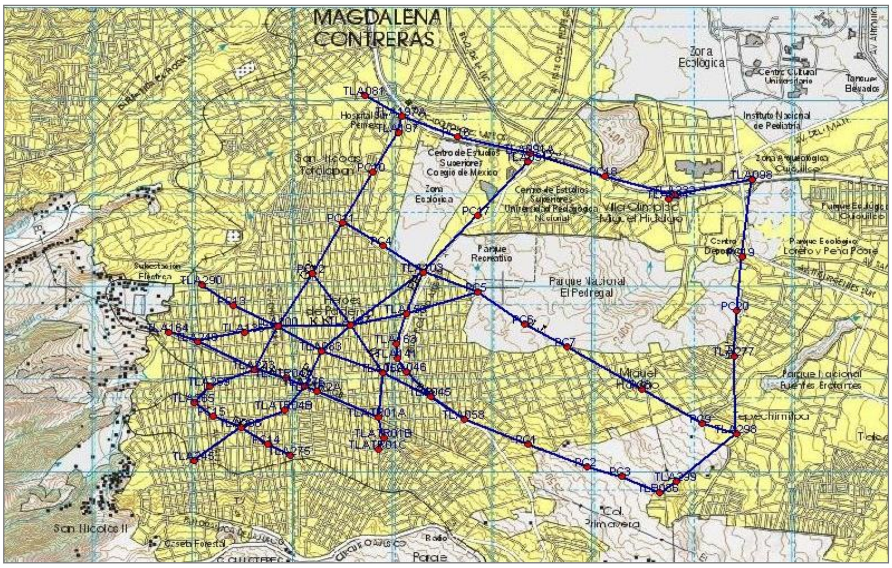
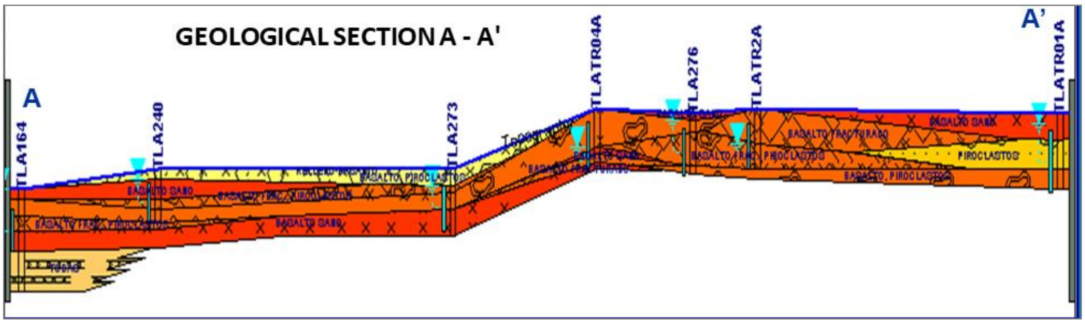


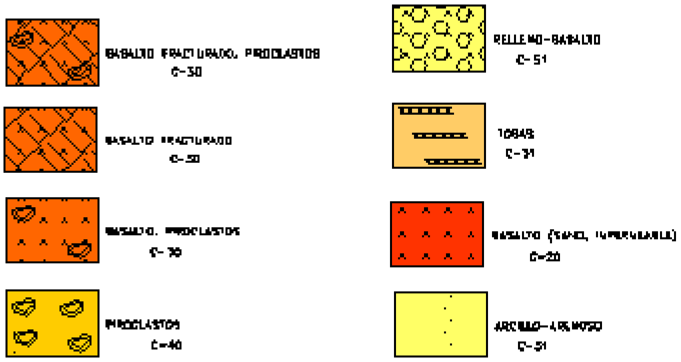
Figure 4. Recovery Interpretation.

This well TL-A-141, is located in an area with average high permeability of 5.80 cm/sec between 6.35 and 7.25 m deep, and a second zone of low permeability between 7.25 and 11.60 meters with k= 0.012 cm/sec. This well has the capacity to recharge 150 lps.





Symbology



With the geology were made cross sections and with these the model that is presented in the figure 6.

Figure 5. Recharge wells – cross sections and position map.

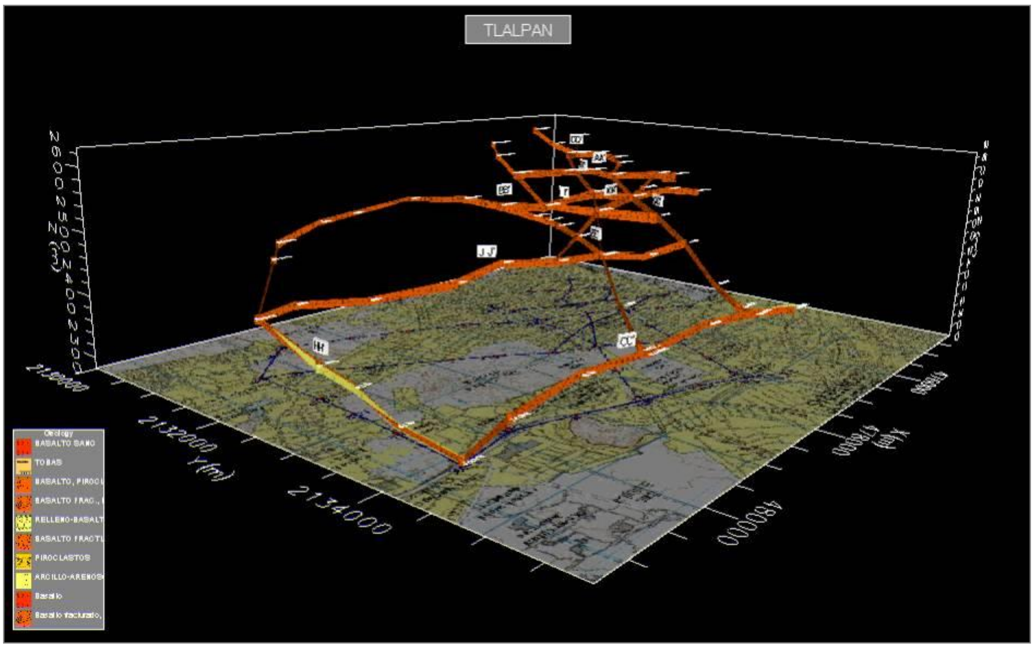


Figure 6. Geologic 3D Model.

This 3D model was made considering only the geology drilled at each site of the Wells.

4. Conclusions

This recharge program was very successful, first because it was located in a favorable geological formation with very high permeability and second by the extensive area covered.

These works were relatively low cost since the depth of the wells for the recharge were almost superficial, between 10 and 15 meters deep, having also solved serious problems of water clogging of the drainage and flooding in the streets that impaired a good circulation of vehicular traffic.

5. Recommendations

It is recommended to support these recharge programs.

We have to consider that their success will be based on the high permeability of the drilled geological formations.

It is essential to periodically establish the maintenance of the structures and wells, preferably before the rainy season.

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Paper for ISMAR10 symposium. ***Topic No: 18 (034#)***

Preventing pluvial flooding and water shortages by integrating local aquifer storage and recovery in urban areas

Koen Zuurbier[1,2*], Bert de Doelder[3], Wilrik Kok[4] and Boris van Breukelen[5]

[1] KWR Watercycle Research Institute ; koen.zuurbier@kwrwater.nl
[2] Allied Waters; koen.zuurbier@alliedwaters.com
[3] Municipality of Rotterdam; br.dedoelder@rotterdam.nl
[4] Field Factors; wk@fieldfactors.com
[5] TU Delft; b.m.vanBreukelen@tudelft.nl
* Correspondence: koen.zuurbier@kwrwater.nl; Tel.: +31 30 60 69 666

Abstract: Water management in urban areas forms an increasing challenge due to intense rainfall events and the increasing water demand for non-potable use. Rainwater harvesting and use can be successful in providing a high-quality additional water source. Due to its limited spatial footprint, large capacity, and potential disinfection, aquifer storage and recovery (ASR) can be an interesting MAR-technique in urban areas. The Urban Waterbuffer concept was developed and tested in the city of Rotterdam (The Netherlands). It aims to locally collect and retain rainwater from 4.5 hectares of different urban areas and pre-treat it with green infrastructure such that it can be used for infiltration by an ASR. It was found that a retention basin was needed to compensate for the low infiltrate rate of the ASR well. The biofilter was camouflaged in the urban space and provided sufficient treatment to meet legal water quality limits. DOC, suspended solids, and Fe concentrations were still higher than operationally desired, and can result in well clogging. A reduction in infiltration capacity at the ASR well was already observed during moments of high Fe concentrations in the infiltration water. A closer microbial risk assessment is required to ensure safe use of the recovered water, but could not be executed with the data collected so-far. The main disinfection is of the rainwater is expected in the aquifer, based on the operation and location of the biofilter and the first plate count results.

Keywords: aquifer storage and recovery; urban; water management; irrigation; water quality; groundwater

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1. Introduction

Water management in urban areas is becoming an increasing challenge. Extreme rainfall events require rapid discharge and retention. Prolonged droughts require external freshwater supply from the sometimes water-stressed surroundings [1]. Groundwater overdraft results in sinking cities like Mexico and Jakarta [2] and saltwater intrusion [3]. At the same time, the number of people living in cities in increasing rapidly [4], while climate change is increasing the need for dedicated water management [5].

Managed aquifer recharge (MAR) may provide an important water management technique for urban areas, for instance for water recycling [6]. This is because aquifers can retain vast volumes with limited spatial footprints aboveground and provide natural treatment, (filtration, sorption, and degradation). For those reasons, MAR can be a very strong combination with rainwater harvesting in urban areas. It can result in retention and discharge of rainwater, a source of high-quality of freshwater, and mitigation of groundwater overdraft and the resulting subsidence and saltwater intrusion. To date, MAR is however primarily used to discharge stormwater [e.g. 7] and in some good Australian examples to where also storage and recovery is involved to store and recovery large volumes of stormwater in a sandy carbonate aquifer [e.g. 8, 9, 10], generally upon treatment in a wetland.

For cities coastal and delta areas like The Netherlands, a specific aquifer storage and recovery (ASR) concept has been developed to cope with local urban water surpluses and non-potable water demand. It is constructed to elegantly fit even in very dense urban areas, without compromising on the required pre-treatment. By exploiting the multiple partially penetrating wells [11], the recovery efficiency in brackish aquifers and the removal of pathogens is to be enhanced, such that the water can be better used upon recovery. A first pilot is realized in the Spangen neighborhood of Rotterdam (The Netherlands). The aim of this paper is to discuss the concept and results of the injection and recovery cycle.

2. Materials and Methods

2.1. Field site

The site is located in the Spangen neighborhood in the city of Rotterdam (The Netherlands). This neighborhood (9500 inhabitants) was built in the early twentieth century for the workers in the rapidly growing harbor. It is situated in the polders close to the river "Nieuwe Maas" (1,500 m to the south) and has a surface level of 1.3 m below sea level (mBSL). The distance from the coastline (tot the northwest) is 22 km. The estimated area connected to the Urban Waterbuffer field pilot is around 46,000 m^2 and consists of squares, parking lots, parks, roofs, and a football stadium. In 1998, a rainwater collection system discharging the local rainwater to the surface water system was constructed in order to relieve the sewage system. After realization of the Urban Waterbuffer, it was found that the drainage of the park east of the area was also connected to the rainwater system.

2.2. Set-up of the Urban Waterbuffer Spangen

The Urban Waterbuffer concept was added to the existing rainwater collection system. A threshold was created at the discharge point towards the surface water to create an overflow. A 1400 m^3 large retention basin ('buffer') was constructed using the Rigofill system (Fraenkische, Germany) wrapped in EPDM foil to create a closed basin, without interaction with the local groundwater. The function of this basin was to retain the rainwater (30 mm maximum) during rainfall events, in order to distribute it to the target aquifer for ASR with a lower rate than the rainfall intensity. This retention is crucial as infiltration rates via ASR are generally too low to rapidly discharge intense rainfall. The first treatment step is removal of coarse material and light non-aqueous phases with a Sedipoint system (Fraenkische, Germany) in the pipeline leaving the retention basin. From there, the water is pumped towards a so-called *Bluebloqs* biofiltration system (Field Factors, The Netherlands). The system is based on a combination of slow sand filtration and vertical reedbed filters and is constructed to spatially fit in public space. The surface area of the filter is 90 m^2 and the maximum discharge on the filter is 30 m^3/h, resulting in a designed maximum velocity of 0.3 m/h through this 1 m thick filter with a top layer of sieved 0.4 - 0.8 mm of fluvial sand. Reeds and sedges were planted in the top layer, which was then covered with woodchips. Upon filtration, the water is transported to a standpipe (Ø = 400 mm), 3.0 m high above surface level. From this standpipe, the water flows to the ASR well. The ASR well consist of two partially wells in a single borehole (Ø = 500 mm). The well screening in target fluvial sand aquifer (16.75 to 26.5 m below surface level) is 17-19 m below surface level (W1) and 20 – 26.5 m below surface level (W2). W2 is used for infiltration, W1 is used for recovery. This way, more water is to be recovered with a low salinity [11] and a higher rate of disinfection via aquifer passage may be achieved [12]. Upon aquifer storage, the water is supplied to the nearby football stadium, back to the biofiltration system (as irrigation for the plants), and a water feature. Both infiltration wells perform back-flushes every upon a defined volume of infiltration.

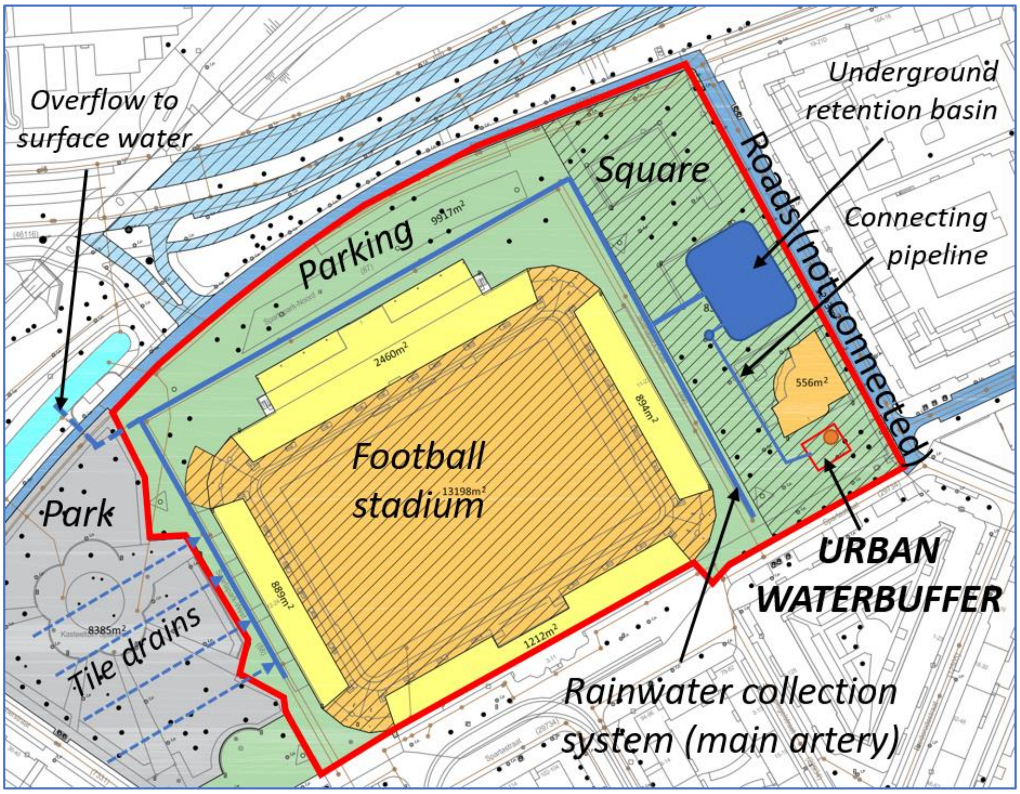

Figure 1. Top view of the Urban Waterbuffer field site in Spangen, Rotterdam. The rainwater collection system collects the water within the red line.

Table 1. Type of urban area discharging towards the Urban Waterbuffer Spangen

Type	Area (m²)	Remark
Roof	6,000	Bitumen, Zinc
Paved	18,300	Bricks
Pitch + surrounding	13,200	Artifical gras and pavement
Park	8,400	Green, pavement
Total	**45,900**	**Mixed**

2.3 Monitoring of the Urban Waterbuffer

In order to understand the functioning of the Urban Waterbuffer, a broad monitoring program was set up. The monitoring consists of:

- Electronic water meters (type: Woltman; recorded every 30 minutes):
  - Water pumped to the biofiltration system
  - Water pumped to the standpipe
  - Water infiltrated in W1 and W2 (separately)

- Water recovered from W1 and W2 (separately)
- Water levels using pressure, EC, and temperature sensors:
    - Retention basin (pressure, every 30 minutes)
    - Biofiltration system (pressure, every 30 minutes)
    - Standpipe (pressure, every 30 minutes)
    - Water from retention basin (EC, every 30 minutes)
    - Water from W1 and W2 (EC, every 30 minutes)
    - Monitoring well (MW) 1: conductivity, pressure, and temperature via CTD Divers (Van Essen, The Netherlands), every 15 minutes
- Water sampling and analysis (see Table 2) on the following parameters:
    - Macrochemistry: EC, pH, Temp, Dissolved Oxygen, Turbidity, Na, Cl, Ca, K, Mg, Fe, Mn, HCO_3, NH_4, NO_3, PO_4, SO_4, trace elements
    - Full scan: Macrochemistry, DOC, suspended solids, heavy metals, oil, BTEXN, PAH (EPA), glyphosate and AMPA, E.Coli, Enterococci, plate count (37 °C).

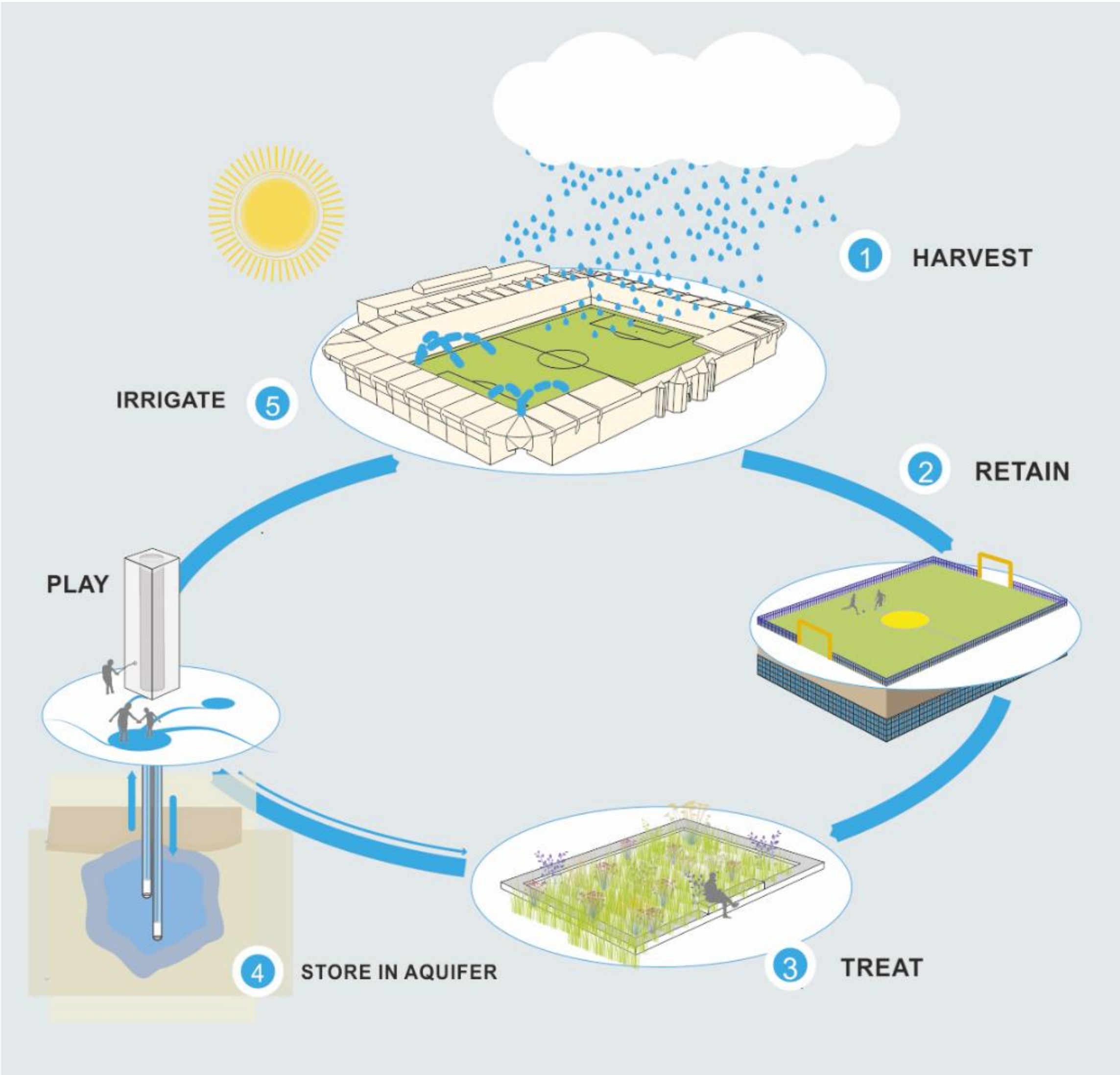

Figure 2. Outline of the Urban Waterbuffer in Spangen, Rotterdam.

Table 2. Water sampling at the Urban Waterbuffer Spangen.

Date: (dd-mm-yyyy)	15-5-2018	10-9-2018	24-9-2018	22-10-2018	12-11-2018	18-12-2018	14-1-2019	28-1-2019	26-2-2019	29-3-2019	22-4-2019	20-5-2019	
week #:	*37*	*38*	*40*	*44*	*47*	*51*	*2*	*4*	*8*	*9*	*16*	*20*	
Location													*Analyses:*
Groundwater at MW1	■				■		■	■	■	▒	▒	▒	Macrochemistry
Rainwater		■	■	■	■	■		■	■	Pro	jec	ted	Full scan
Infiltration water		■	■	■	■	■		■	■	▒	▒	▒	Full scan
Recovered water								■	■	▒	▒	▒	Full scan

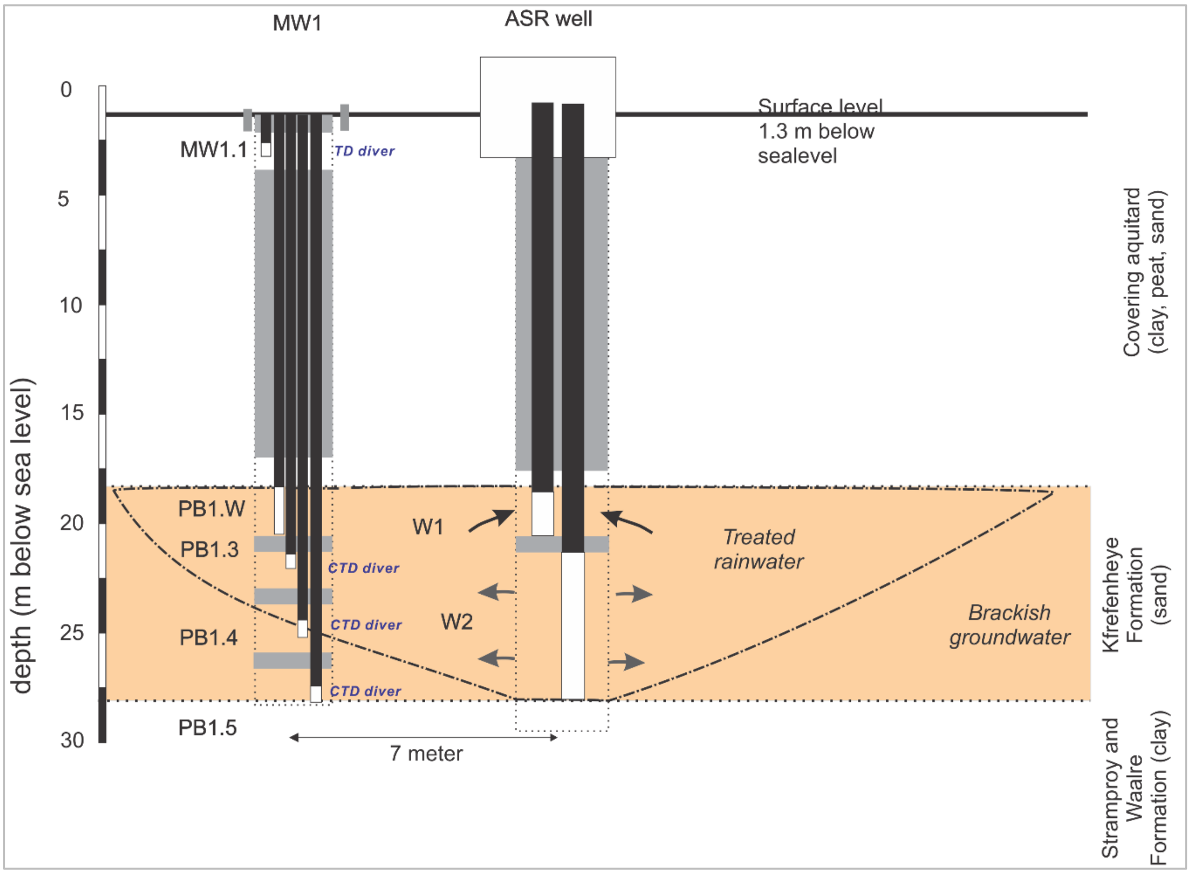

Figure 3. Cross-section of the ASR well and the monitoring well at the Urban Waterbuffer Spangen (Rotterdam).

3. Results

3.1. First operation of the Urban Waterbuffer Spangen

The operation of the Urban Waterbuffer started with a test phase of the biofilter. In this phase, the treated water (2390 m³) was disposed of on the Rotterdam sewerage system. Four grab samples were taken to assess its quality, before starting the infiltration. The water quality analysis results showed no concentrations above background levels (measured in May, 2018) or were below target concentration, leaving no objections to infiltrate the water. This infiltration started early November (Figure 3b), using W1 only. After a stable infiltration rate in November, followed a decrease in December. In January, both W1 and W2 were used, while from February onward, only W2 was used for infiltration, as planned. In these periods, the infiltration rate remained relatively stable. During the first 4 months of operation, almost 4000 m³ of rainwater was infiltrated and around 500 m³ was recovered during back-flushes and irrigation of the football pitch. The Urban Waterbuffer was able to lower the basin level rapidly upon rainfall events (Figure 4a). The EC of the infiltration water was found to be remarkably high for rainwater, especially in periods with a low level in the retention basin. During moment with significant rainfall (like December 2018), a clear dilution was observed.

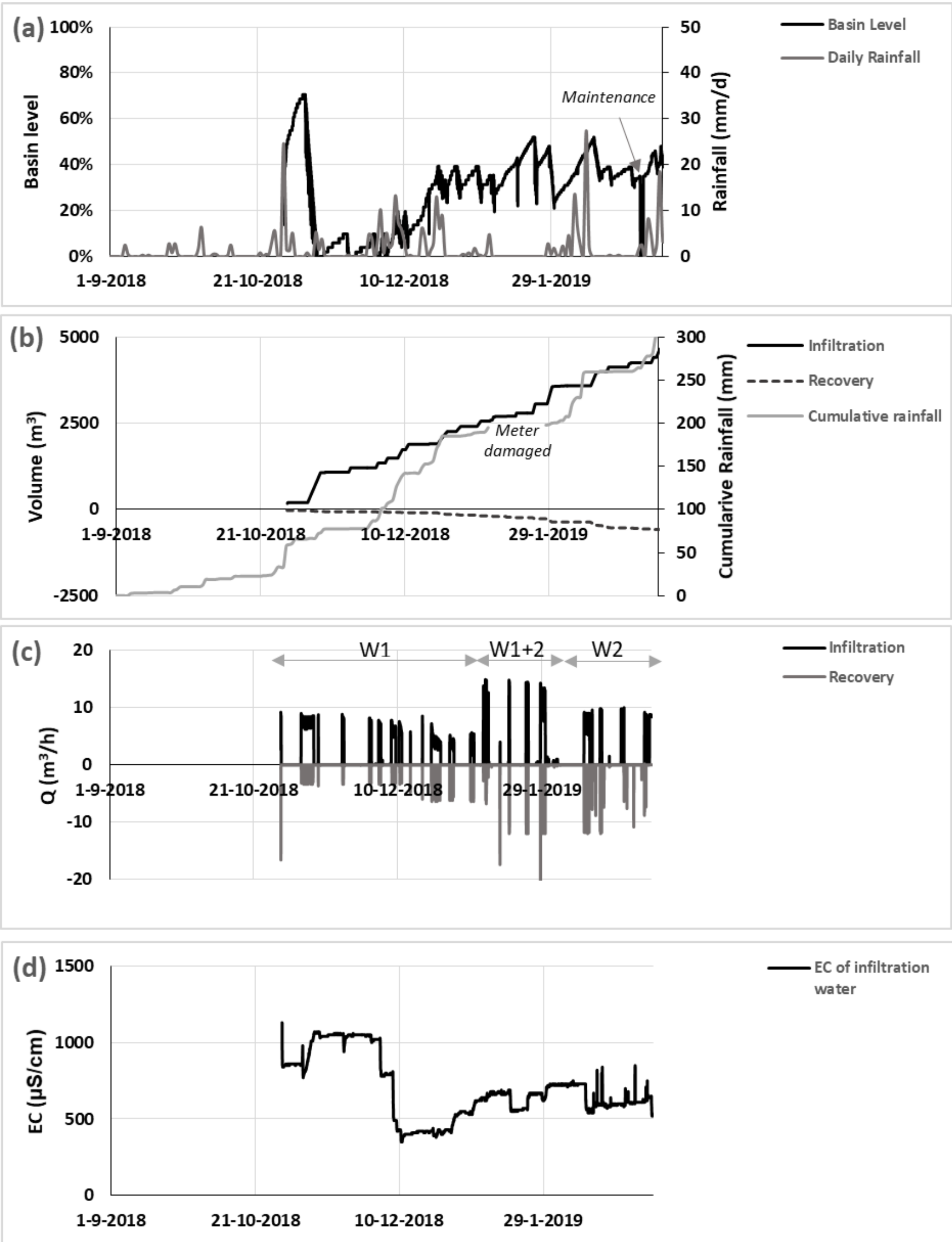

Figure 4. Electronically recorded data of rainfall and basin level (a), pumping (b, c), and EC (d) of the infiltration water.

3.2. Water quality analyses

The first rounds of water quality measurements show that the collected rainwater is already relatively clean, with only turbidity, suspended solids, total-Fe, DOC, and Zn exceeding the targeted concentrations. Thanks to a 73% decrease in Zn concentration, there were no chemical legal exceedances in the infiltration water. The high removal may be explained by the fact that more than half of the Zn in Dutch rainwater is bound to particles [13], which will be largely removed in the biofilter.

The remaining parameters of concern relate to increased risk of physical, chemical, and biological well clogging. Especially the high incoming concentrations of iron (merely dissolved, as shown by additional analysis in October 2018) can have strong negative impact on well clogging, despite a 35% removal by the biofilter. The 40% reduction in infiltration capacity observed at W1 in December 2018 (Figure) coincided with a firm peak in the Fe concentration in the infiltration water (up to 1.8 mg/l). Its source was found to be shallow groundwater intruding the rainwater collection system via tile drains and leakages, as was later found by mapping the Fe concentrations in the rainwater system. This source was confirmed by the composition of the shallow groundwater, which was sampled in a shallow piezometer installed centrally at the square and showed high Cl, Na, NH_4, and Fe concentrations.

Based on the plate count results, the biofilter did not perform any disinfection. On the contrary, there was even a slight increase observed, which might be due to the fact that the biofilter is accessible for public and animals (pets). The results suggest that the main disinfection step is provided by the aquifer only. Analysis on E.Coli and enterococci were unfortunately performed with a too high detection limit. Therefore, they could not provide any useful information.

The water quality arriving at MW1.2 does not show distinct changes with respect to the infiltration water: the observed concentrations are within the ranges observed during infiltration and the lower Na, Cl, and NH_4 concentrations in combination with the higher Fe concentrations suggest that the observed water was infiltrated in December 2018.

4. Discussion

In this paper, the concept of the Urban Waterbuffer and the first results during operation are presented. Based on the realization and the first monitoring results, it appears that a viable concept of urban ASR has come available, but also that certain critical issues require further attention.

The main issue relates to the clogging potential created by the infiltration water. High concentrations of Fe were observed in the incoming rainwater and were insufficiently removed by the biofilter. The implication is that stimulated aeration is required before or while the water enters the biofilter to enhance iron precipitation and enable removal by the sand filtration in the biofilter. Also removal of suspended solids and DOC were found to be too low to ensure stable infiltration without clogging. Further research must focus on the performance of the biofilter during prolonged operation with further build-up of a Schutzdecke on top to increase removal of particles [14] and the growth of the vegetation in the next summer season, which may positively impact the DOC removal [15].

Another critical issue is the safe reuse of the stored water upon recovery. In the concept, aquifer passage is essential for disinfection and subsequent safe use of the rainwater, since the biofilter will presumably not perform sufficient disinfection. Although the water is injected deeper in the aquifer with respect to the zones of recovery, short flow paths between W2 and W1 and therefore short residence times may exist when recovery follows quickly after injection, which may result in insufficient removal of bacteria and viruses. This needs careful evaluation via for instance a QMRA [16] and if needed: a modification in the control system to prevent recovery for a certain time after infiltration.

To be demonstrated is the final recovery efficiency of the chosen set-up, with a long well screen for injection in the lower ~2/3 of the aquifer and a very short well screen for recovery at the top, a concept that can significantly enhance freshwater recovery [11]. In that context, the experienced, relatively elevated EC of the stormwater at the UWB in Spangen due to the intrusion of shallow groundwater, Rotterdam can be beneficial by limiting the density difference ratio [17].

5. Conclusions

A local urban ASR set-up using collected rainwater was developed and tested in the city of Rotterdam to prevent pluvial flooding and provide non-potable water. The pre-treatment was based on biofiltration system at street level. It was found technically viable to realize and operate this ASR scheme and supply water with an apparently acceptable quality. The risk of groundwater contamination was found to be limited after the removal of zinc by the biofilter. The main operational risk was found to be the high concentration of Fe passing the biofilter and potentially DOC and suspended solids, which may induce clogging of the ASR well. A clear decrease in infiltration capacity was found to coincide with high concentrations of Fe in the infiltration water, underlining that a higher degree of Fe removal is required. A closer assessment of microbial risks is required, in which the disinfection provided by the target aquifer will be a crucial aspect.

Table 3. Water sampling at the Urban Waterbuffer Spangen

	EC	pH	Turbidity	DO	Susp. solids	Cl	Na	Ca	K	Mg	Fe-tot	Mn-tot	HCO3	NH4	NO3	P-Phosphate	SO4	DOC	As
	mS/m	-	NTU	mg/L	mg/L	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	µg/l	mg/l	mg/l	mg NO3/l	mg P/l	mg/l	mg C/L	µg/l
Legal limits infiltration					0.5	100	120	-	-	-	-	-	-	3.2	50	6.9			18.7
Operational limits infiltration [18]			1.0		0.2						10							2	
Limits recovery						500	350				500		150						
Native groundwater (4)	4135	6.8				1110	558	180	16	75	11875	1073	738	27.0	0	0.18	0.6		
Rainwater (7)	800	7.5	7.7	3.1	5.6	113	68	60	5.7	14.2	1251	407	189	1.0	0.7	0.06	42	12.0	<4
Infiltration (7)	810	7.5	3.1	2.3	2.1	123	72	60	6.1	13.7	817	254	184	0.7	0.3	0.05	47	6.6	<4
MW1.2 (Feb 26)	639	7.8	2.2	0		70	44	72	5.1	12	1800	210	210	0.55	0.0	0.05	37		
Recovered (2)	673	7.5	3.3	1.4	5.3	59	39	76	4.8	9.7	570	122	235	1.0	0.0	0.12	38	9.8	6.2

	Ba	Cd	Co	Cu	Hg	Pb	Mo	Ni	Zn	Naftalene	SUM PAH (EPA)	Benzene	Ethylbenzene	Toluene	SUM xylenes	Mineral oil	AMPA	Glyphosate	Plate count
	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	kve/mL
Legal limits infiltration	500	0.35	0.7	1.3	0.01	7.4	3.6	20	65	0.01	-	0,2	4	7	0,2	50	<0.1	<0.1	
Operational limits infiltration [18]																			
Limits recovery																			
Native groundwater (4)																			
Rainwater (7)	42	<4	<2	<5	<0.02	<5	<2	<5	155	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.03	<0.01	440
Infiltration (7)	36	<4	<2	<5	<0.02	<5	12[a]	11	42	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.04	<0.01	470
Recovered (2)	37	<4	<2	<5	<0.02	<5	2.2	9.3	37	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.08	<0.01	65

[a] *Only 1 of 7 samples had a concentration of 63 µg/l, the other 6 were <2 µg/l .*

Acknowledgments: The project is co-financed by the premium scheme of the Top Sector Alliances for Knowledge and Innovation (TKIs) of the Ministry of Economic Affairs and Climate Policy.

Author Contributions: Koen Zuurbier is the main researcher in this project. Evaluation of the biofilter is supported by Wilrik Kok. Bert de Doelder is coordinating the UWB realization and operation. Boris van Breukelen contributed to the set-up of the monitoring and the water quality analyses and interpretation.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper for ISMAR10 symposium. ***Topic No: 18 (195#)***

Participatory Aquifer Management an Alternative Approach to Sustain Urban Water Supply – a case study of Bhuj City – Gujarat, India

Jadeja Yogendrasinh[1]*, Parmar Gaurav [1], Jadeja Manisha [1], GorasiyaJayantilal[1] and Reel Gopal[2]

[1] Arid Communities and Technologies; act,pgwm@gmail.com
[2] Jalsathi – A Bhujal Jankar's Institute; jalsathi.bj@gmail.com
* Correspondence:yogeshjadeja@gmail.com; Tel.: +91-997-985-0931.

Abstract: The present abstract is a case study of Bhuj city of Gujarat state, explains how urban water management planning to be adopted against dynamic urbanization development. The paper is a classic example of advance growth of urban area based on centralized water supply facilities gradually de-linked local, traditional and decentralize in nature water management practices. Present status of city of Bhuj has evolved through three stages with and the same stages are evidences of ignorance of traditional water management systems. In this scenario Arid Communities and Technologies – A Bhuj Based not for profit organization, has demonstrated Participatory aquifer management activities to make a self-reliance city by evolving strategies such as Decentralized people centric watershed management plans for urban – peri urban areas, preparing integrated groundwater recharge plan by using storm water recharge structure and revival of water harvesting structure in watershed inflow areas, development of land use specific techniques for recharge and water harvesting and most importantly and by constituting recognized and knowledge equipped citizens' forum and Bhujal Jankars. Success of this experience can be judged through incorporation of recharge techniques in urban development program, town planning process and recognition of citizen's forum as urban water managers.

Keywords: Urban Groundwater; Participatory; Bhujal Jankars.

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1. Introduction

Bhuj City, the capital of the Kachchh district in western India, has a rich history deeply intertwined with-and dependent upon-water. The biggest and most successful city in an arid region, Bhuj owes much to its strategic water reserves, which have allowed the city to thrive and grow for more than 500 years despite minimal rainfall and frequent drought. The total urban area spreads over about 56 sq km. The city has total about 11 administrative wards. ([Figure. 1) The city's traditional water management system has been abused by rapid population growth and urbanization through three phases. Arid Communities and Technologies (ACT) – not for profit organization has evaluated Bhuj City's traditional water management system geo-hydrologically to assess feasibility to provide domestic water supply even after such changes.

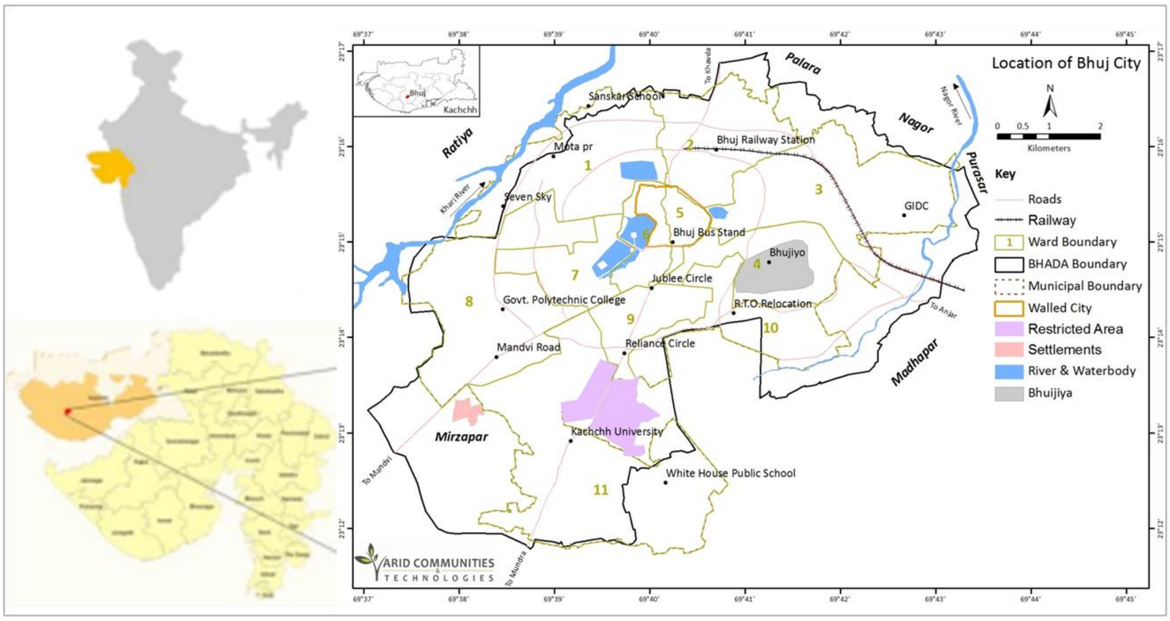


Figure 1. Location of Bhuj City.

2. Materials and Methods

An integrated approach has been adopted and accordingly techno-social-institutional devices have been worked out for inclusion of participatory groundwater management considering its urban-peri-urban linkages. As far as technological aspects are concerned, the geo-hydrological assessment of entire project area has held through mapping of aquifer, study of water levels and groundwater quality, estimation of overland flow, aquifer properties and water budget. To quantify groundwater related problems groundwater monitoring network has established since year 2008 that successively periodically revised to study the impact. The findings of this investigation have been utilized for urban – peri – urban water management planning and to design demonstrations of specific activities those can help community and administration to allocate resources for execution.

In case of social aspects, intensive and series of social mobilization activities have organized to sensitize, educate and aware the community regarding importance of local resources from their protection, potential and their interlinked urban-peri-urban dynamics. As community involvement was most crucial part each activity has planned with specific objective and specific output. Social processes includes activities such as exposures, workshops and seminars, rallies, slideshows, competitions, drama, traditional celebrations on specific religious days. Another way of social mobilization and advocacy processes that adopted was demonstration of appropriate techniques for groundwater recharge and water supply management for various units of urban and per urban areas.

As far as institutional aspects are concerned the methods adopted were capacity building, setting up of small institutions and group for focused objectives. As the aim of this institute is to maintain momentum of knowledge generation and to transfer to next generation an aquifer level forum has been set up by identifying a sensitive and community accepted distinguished representatives from urban and surrounding rural areas. Under the forum tank watershed level committees are being set up for some of the tanks of area. Both these kind of institutions have aim to keep watch on protection of water resources to manage supply part. While at demand side management setting up of drinking water committee in slums, campus water management committees RRWHs committee have constituted by the aquifer wide forum. Besides setting up of committees and forum, a youth team of 07 persons whom known as Bhujal Jankars (BJs) has trained for regular assessment of groundwater by collecting and analysing data from observation network, to facilitate technical designs and planning of water supply, recharge, rain water harvesting activities by stakeholders including gram panchayats (Village secretariat) and municipality.

3. Results

The results of the study is discussed under various sub heads such as historical expansion and change in water management practices, terrain and geo-hydrological characteristics, groundwater potential of the city and action research activities carried out to develop participatory groundwater management approach.

3.1. Historical Expansion and Change in Water Management

Expansion process of Bhuj city has passed through three important events i.e. first, after independence during 1947 (nation-wide change in ruling system) second, when Municipal system came in existence and third post-earthquake where urban development authority has established. All these three development stages reveal how Bhuj city's local geo-hydrological characteristics based traditional water management system has ignored and fetching water from peri urban areas have affected land and water resources of both the areas and finally influenced life. Changes in land scape and land use has decrease land resources results into scarcity of agriculture and grazing lands for traditional livelihoods of peri urban areas. The same has also increased flood threat and over land flow. Water supply from groundwater resources from adjoining villages have resulted into depletion in water levels that again increased water scarcity for agriculture productivity as well drinking water supply for rural areas. Water level depletion led deterioration in groundwater quality has resulted into health issues. In addition, infrastructures like sewage disposal again polluted existing water bodies, groundwater and land resources again urban peri urban areas. The development and expansion city has placed several challenges and changes as mentioned in table 1

Table 1. Phase wise Urban Developmental Process and Emerging Trends in Bhuj City.

Phase	Pre Independence Before 1947	Pre Earth quake of 2001 (1947 – 2001)	Post-Earthquake After 2001
Process	Establishment of Bhuj City as Capital of Kachchh	Expansion of Bhuj city in some part, Change in land use in surrounding of city, Development of Semi - Centralized water supply	New Development and expansion plans, New Infrastructures like road network, drainage network, water supply and distribution plans, Change in Land uses
Water Sources	Interlinked Water Bodies	Local open wells and some bore wells from adjoining rural areas	Tube well in peripheral villages and Narmada Supply, Private borewell, Bottled supply, Tanker Supply
Manageme nt by	King and community	Municipality	Municipality GWSSB, GWIL, Private enterprises
Major Issues	Drought	Irregular supply, Encroachments in water ways and water bodies, Increase dependency on Municipality. Breakdown of traditional management system	Complete dependency on outside sources, Irresponsible citizens, Disappearing of water bodies and water channels, Floods and water logging, Decrease in Recharge, Local GW quality issue, Leakage and poor management of water and sewage infrastructure and discharge in downstream rural areas
Copping Mechanis m	Interlinked Catchments and Water body, Wells	New Bore well exploration, Bring water from distance source, Tanker supply	Disaster response Draining out of Strom water, Lack of long term copping mechanism

3.2 Physiogrpahy – Drainage and Watersheds

Physiographically the Bhuj city area has two important divisions i.e. southern dissected ridges resulted due to upliftment due to Katrol fault rocky and gravelly pediment zones. (Biswas, 1982) Both are regional nature division and have various local level landforms. Important landforms of the area are southern dissected hills, Bhujiya hill within city, Khari river gorge at western boarder of Bhuj city. [1] Besides these there are various rivers and ridges of local scale define micro watersheds. It is important to mention that majority of landform in the project area are results of tectonic processes like faulting and ingenious activities [2].

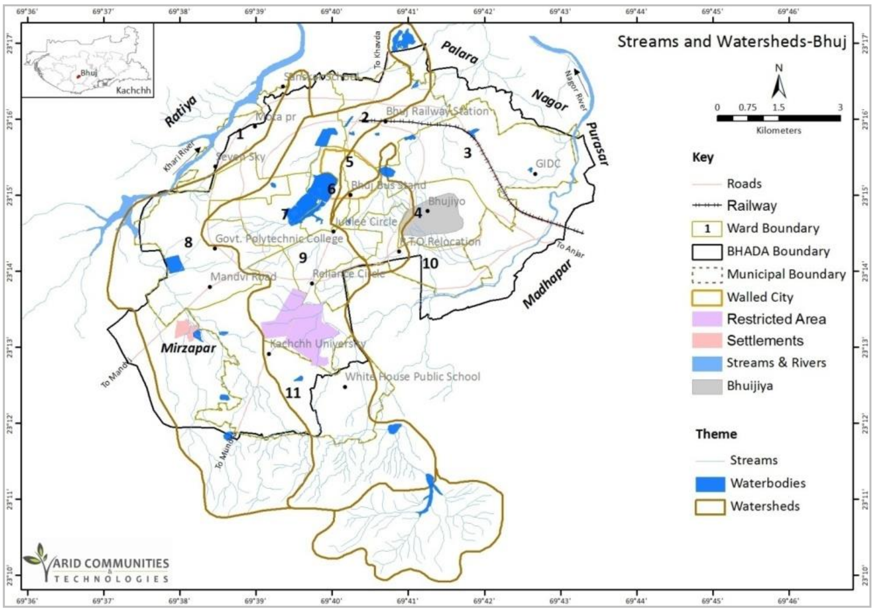


Figure 2. Drainage Pattern and Watershed of the Bhuj City.

Drainage and watershed wise the Bhuj city represents part of Rudramata basin that originates from Kachchh mainland ridge portion in south to merges into Banni in North. To manage city water requirement historically people have developed three lakes and their relevant watershed management. These lakes systems are (01) Hamirsar Lake System (02) Umasar lake system and (03) Deshalsar lake system. All three lake system and their watershed are inter linked with each other by developing canals and tunnels with an area of 40 km2. (Figure. 2)

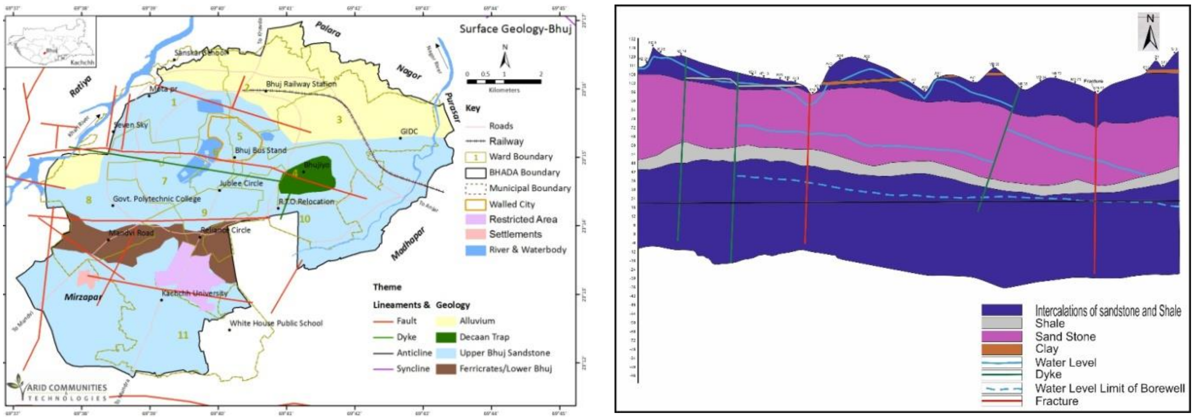
3.3. Geo-hydrological Characteristics

3.3.1 Geology

The rock formations of the area show their age ranging from Middle Jurassic to the recent age. The main rock formations of the area are sandstone and shale with a few basaltic intrusions. The oldest rock formations in the area are shale and fine grain sandstone of the Chhari and Katrol series of the Middle and Upper Jurassic. (Biswas, 1082 and Merh 1995)There is frequent intercalation between the shale and sandstone, as well as with limited limestone deposits in the region. On average, the formation shows gentle dip towards south, ranging from 5° to 13°; at its shallowest the sandstone is only 18m deep, and deepens to 123 m at its southern tip.

3.3.2Aquifer Complexity

The belt of cretaceous sandstone is the region's only good aquifer, but has a risk of high salinity due to the naturally saline nature of the sandstone and proximity to iron and shale deposits. Due to Kachchh region's peculiar tectonic framework had divided Bhuj sandstone into various pieces and each piece has its own dynamic geo-hydrological characteristics. Figure 3 shows various types of lineaments mapped within the Bhuj city. [3, 8] Due to dyke network the Bhuj formation as aquifer can divide into two zones north zone and south zone while stratigraphically sequence the same formation can divide into upper and lower Bhuj or shallow and deep aquifer respectively. Hence considering litho-tectonic set up the aquifer system of Bhuj can further categorize into four as north south shallow aquifers and north south deeper aquifers.



(a) (b)

Figure 3. This is a figure, shows (a) Surface Geology and Lineament Fabrics and (b) how these lineament are functioning as subsurface barriers and fracture systems within Bhuj City and Peri Urban areas, figure also portraying control of lineaments on groundwater levels.

3.3.3 Groundwater Levels and Quality

It is well known that Kachchh region has very peculiar tectonic framework represented by various major fault, folds, fractures and volcanic structures. Bhuj city area also reveals lineament fabric that divides Bhuj sandstone into various compartments as modifies its hydraulic properties in term of secondary properties. Fig. 7 shows various types of lineaments mapped within the Bhuj city. Due to dyke network the Bhuj formation as aquifer can divide into two zones north zone and south zone while considering stratigraphic sequence the same formation can divide into upper and lower Bhuj or shallow and deep aquifer respectively divided by red colored lateritic zone exposed in middle of the city area. Hence considering litho-tectonic set up the aquifer system of Bhuj can further categorize into four as north south shallow aquifers and north south deeper aquifers [1,2].

There is a high concentration of pollutants in the groundwater that make it non-potable in many areas. The Total Dissolved Solids (TDS) concentration ranges from 750 mg/l in shallower areas to over 7000 mg/l in the deeper bores. This is an indication that, as the water table lowers, the concentration of dangerous pollutants increases. Additionally, and wells are dug deeper (beyond 125m), they draw water from intercalation of sandstone with shale, yielding a very high saline content. It is crucial to improve surface water collection and percolation across the catchment to raise the water table to facilitate access to potable water across the region.

3.3 Water Balance

The quantitative estimation of total water resource of the Bhuj city has been attempted on annually replenishable components of recharge or discharge. There exists two such approaches viz. (01) Water Balance Approach and (02) Water Table Fluctuation/ Specific Yield Approach.

Estimation of water balance is useful tool to determine the groundwater recharge. It is accepted concept that a balance exists between the quantity of water supplied to the aquifer and the quantity of water stored in a aquifer over a specific period. In general, for balance all in-flowing and out-flowing parameters are considered. Based on this fact equation for groundwater recharge can be expressed as:

Change in Storage = (Inflow into basin - Outflow from basin).

In a normal hydrologic cycle distribution of rainfall takes place into various parts when it reaches to the land surface, quantum of rainwater reaches to groundwater regime through percolation; water return to atmosphere through evapo-transpiration; traps into soil as soil moisture; some part is stored into water impounding reservoirs; whereas remaining part flow out from the catchment as overland as well as sub-surface flow. During this cycle aquifer gains the water and this balance can be expressed as water balance (Schicht and Walton, 1996) and the equation to this effect can be derived as

$$Rr + \mathrm{Re} + Ri + I + Si = Se + O + Et + Dp + \Delta S$$

Where:

Rr = Recharge due to rainfall
Re = Recharge due to canal seepage
Ri = Recharge due to return flow of applied irrigation waters
Se= Groundwater flow due to effluent seepage
I = Inflow from areas outside the basin
Si = Recharge due to inflow seepage from rivers, streams, reservoirs, lakes and ponds etc.
O = Outflow to the areas outside basin
Et = Evapo-transpiration lossess
Dp= Groundwater draft (pumpage)
ΔS = Change in groundwater storage.

Based on input and output parameters water resources have budgeted for Bhuj city shown in Table 6.12. this very clearly shows that during year pre monsoon season of year 2014 to pre monsoon season of year 2015 there is net available water resources are 10.15 MCM that is more than the city's estimated annual water requirement i.e. 9.85 MCM considering about 2 Lakh population and 135 lit/day.

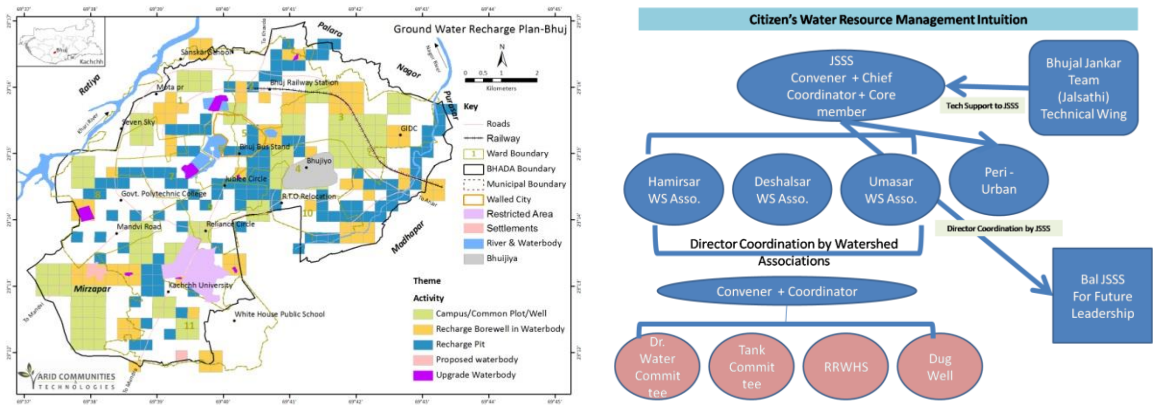
Table 2. Overall Water Resource Budget of Bhuj City.

Net Watershed Area (A) = 72.6 sq. km and Average Annual Rainfall (R) = 0.430 m			
Sr. No	**Parameter**	**Inflow (MCM)**	**Outflow (MCM)**
1	Rainfall (R×A)	31.218	
2	Recharge from rainfall (Rr)	4.005	
3	Recharge from Canal Seepage (Re)	0.000	
4	Recharge from return irrigation seepage (Ri)	0.460	
5	Recharge from surface storage (Si)	0.843	
6	Surface runoff (O)		15.448
7	Evapo-transpiration (Et)		8.849
8	Ground water draft (Dp)		8.400
9	Change in ground water storage (ΔS)		-6.318
	Total	36.526	26.379
Balance : (Inflow – Outflow)			10.147

4. Discussion

As groundwater management is not only technical solution it also requires aware society and administration. Keeping this in mind the Bhuj city groundwater management plan has been prepared with strong consideration of local geo-hydrological conditions and with systematic social awareness process aimed with competent citizen's institution. The management plan includes both the aspects i.e. resource strengthening with efficient supply management and competent citizen's institution. As far as resource strengthening is concerned, recharge plan has been proposed considering aquifer potential and its hydraulic characteristics for Bhuj city (Fig. 4) and to maintain recharge in to aquifer water ways and water bodies requires special attentions. Therefore, for water channels specific width of each channel has calculated and recommended to urban development authority to carry sufficient and guided rain water volume towards recharge structure.

During the project each aquifer has considered for specific recharge plan. The techniques suggested for recharge area (01) Providing recharge bed and percolation well in common plot in societal areas; (02) each campus should have rainwater harvesting and recharge bore well; (03) each rivulet should have percolation structure at regular 300 m interval; (04) each water channels should have specific width to transfer storm water load based on run off from respective micro catchment. (06) all not registered water bodies should be registered as municipally or gram panchayat's property; (07) identified water body must have recharge borewell. With all these techniques Bhuj city recharge plan has developed as shown in Fig. 3. It is important to mention that all techniques suggested for this planning have properly demonstrated through community participation and proven their successes based on regular monitoring of groundwater levels and quality with respective rainfall condition.



(a) (b)

Figure 4. This is a figure, shows (a) Groundwater Recharge Planning for Bhuj City and (b) Aimed Institutional Structure for Urban-Peri-Urban Water Resource Management (JSSS)

It is proven that without participation of stakeholder resource management in any area may not provide sustainable solution therefore, ACT has began to educate citizens of Bhuj city to fulfil the aim of establishment of citizen's empowered institution. Fig. 4 explains the institutional structures that evolved after citizen's awareness actions and emerging institution in the name of "Jal Srot Sneh Samvardhan Samiti" (JSSS).

5. Conclusions

The Participatory Groundwater Management (PGWM) experiences of Bhuj City have provided the directions how one can though about management of water resources for rural as well as urban areas during rapid urbanization phase of development. To prevent local water resources especially in adjoining rural areas and to sustain urban water resources in decentralized but people centric manner following conclusions can be made.

Detail geo-hydrological characterization of each city is an important decision making tools that need to be consider as one of parameter for developing urban area development plan. Involvement of all level of stakeholders with proper education through awareness is non-negotiable condition especially for increasing ownership of citizen's on local water resources. Municipality and NOGs should jointly made efforts to establish empowered and technically strengthened citizen's forum along with Bhujal Jankar as bridge between community and government. While supplying urban water priority must be given to local sources and therefore, while designing centralized supply form distance sources its allocation should be based on availability of local water. Experiences like Bhuj city need to be given attention at state level.

Acknowledgments: Authors are highly thank full to Bhuj Municipality, Bhuj Urban Development Authority, citizens of Bhuj, and various partners such as Sahjeevan, Bhuj Setu, KMVS, CEPT, GWSSB, Prof. K. C. Tiwari, ACT members and Arghyam Trust for providing all kinds of support to achieved results so far. Authors also acknowledge organizers of Peri Urban Conference, 2017 for providing opportunity to present their experiences in the seminar.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest." Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Any role of the funding sponsors in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results must be declared in this section. If there is no role, please state "The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results".

Abbreviations

The following abbreviations are used in this manuscript:

ACT: Arid Communities and Technologies
BJs: Bhujal Jankars
CEPT: Center for Environment Planning and Technology
GWIL: Gujarat Water Infrastructure Limited
GWSSB: Gujarat Water Supply and Sewage Board
JSSS: Jal Srot Sneh Samvardhan Samiti
KMVS: Kachchh Mahila Vikas Sangathan
PGWM: Participatory Groundwater Management

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Extended abstract for ISMAR10 symposium. ***Topic No: 18 (240#)***

Building resilience to climate change: synergies between SUDS and MAR

Prieto Leache, Ignacio; García Ruiz, Luisa María and Ferreiro Gómez, Pablo

Tragsatec, Madrid, Spain
*Correspondence: iprl@tragsa.es, lgarci39.ext@tragsa.es, pferreir@tragsa.es

Key words. Sustainable Urban Drain Systems, Managed Aquifer Recharge cycle of water, rain, climate change.

EXTENDED ABSTRACT

Climate change implies an increase of global temperature, with negative consequences to every scope. Referring to current urban areas, the progressive deterioration of environmental conditions, material damages and human losses reveal the need to adapt to a new situation.

These circumstances put cities in an emergency situation to become resilient. To face that challenge, a global strategy that confronts an urban change is necessary, in particular in rain management in built environments, in addition to mobility and consumption changes.

The implantation of Sustainable Urban Drain Systems (SUDS) is an effective tool related with this objective of resilience. Its aim is to recover the natural water cycle and mitigate the climate change by links of dispersed systems, according to the principle of local action with global thought.

The advantages of these systems are the reduction of the rain overflow, the improvement of air quality, the decrease of "heat-island" effect by evapotranspiration, and the optimization of the water resource. Some examples are permeable pavements, vegetal building roofs, infiltration trenches, infiltration stores or straining belts. The linked implantation of different typologies strengthens the effectiveness of the SUDS and mitigates the climate change effects in urban environments.

Based on the principle "stop, slow, store and infiltrate", SUDS have also an important role in aquifer recharge, increasing the stored and infiltrated water into the soil, which reduces consume, increases soil retention ability by permeability recovering and restores natural water cycle.

Urbanization has significant effects on groundwater resources. Despite ground surface waterproofing generally reduce infiltration, cities are complex systems where a multiplicity of new recharge channels emerge. Nevertheless, aquifers are extremely vulnerable to urban pollution.

SUDS propose a direct, decentralized collection of rainwater, taking advantage of soil and vegetation to recover the natural hydrological cycle. They bring new soft engineering solutions based on nature which synthetize pollution on site, in an easy and inexpensive way, instead of transferring it to another location.

Permeable pavements allow the direct infiltration of uncontaminated water, and retention areas can accumulate water, bring recreational landscapes to underused urban areas and treat water before the aquifer recharge through direct infiltration into the soil.

SUDS are starting to be successfully implemented in many Spanish cities, and their hydrological impacts and benefits have been already measured. The analysis of rainwater infiltration into permeable pavements, with concrete blocks and porous mixtures, for the source control of flooding has been evaluated quantitatively, and some tests have been developed to understand their hydraulic behaviour (Universidad de Cantabria). Moreover, urban green infrastructures for storing and infiltrating rainwater have shown both in quantitative and qualitative terms that SUDS contribute to creating more sustainable cities. Benaguasil and Xàtiva in the Mediterranean area, or Vitoria-Gasteiz in Basque Country are some successful examples.

This creates a new scenario of comprehensive strategies and synergies between SUDS and aquifer recharge in urban environments, which would be particularly attractive in groundwater-dependent cities.

Climate change is a global problem with a vague origin that represents a real and present threat to ecosystems, economy and human lives. In the urban field, transforming cities in resilient ones by planned connected strategies is urgent.

SUDS represent one of the ways of addressing this challenge. Despite its effectiveness, they are a partial response, and must be part of a coordinated global strategy. To overtake their profits, they must be implemented in any urban intervention and linked to all the rest, generating a territorial sustainable drainage network. Making public all of these strategies, as SUDS, to citizens, enterprises, industries and institutions that could act in the process of urban design is necessary; spreading the message that adaptation and mitigation by chained dispersed strategies is possible and achievable through knowledge and consciousness-raising.

Topic 19. R&D PROJECTS ON MAR

Paper for ISMAR10 symposium. **Topic No: 19 (050#)**

Evaluation of Operation and Performance of the Everglades C-111 MAR Project

Christopher Brown [1]*and June Mirecki[2]

[1] School of Engineering, University of North Florida, Jacksonville, Florida, USA; christopher.j.brown@unf.edu
[2] U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, Florida, USA; June.E.Mirecki@usace.army.mil
* Correspondence: christopher.j.brown@unf.edu; Tel.:01-904-742-0191.

Abstract: The C-111 project, which includes a large managed aquifer recharge component, has been operating since before 2000. The project includes a series of giant infiltration basins constructed along the eastern edge of Everglades National Park in Florida, USA. The C-111 project was conceived as a means to improve the hydrology of Everglades National Park and to decrease high-flow, pulse releases of freshwater into Barnes Sound and Florida Bay, both ecologically sensitive areas. The C-111 project typically infiltrates billions of liters of water per year into the shallow Biscayne aquifer and probably represents one of the largest MAR projects in the world located in a sub-tropical climate. An initial evaluation of the project operation and performance from 1998 to 2010 was previously completed by one of the authors herein. This study undertakes an additional performance evaluation of the project through 2018. The overall operation and performance of the project is assessed using a variety of metrics ranging from improvement in wetland hydroperiod to reductions in pulse discharges to Barnes Sound. The research team organized the assessment into quantity, quality, timing, and distribution (e.g. QQTD) metrics consistent with the overall restoration objectives of the Everglades system in general. The results show that the project continues to operate similar to the 2000 to 2010 period. Quantity, quality, timing, and distribution metrics remain fairly consistent.

Keywords: Everglades; C111; Water Budget; Restoration Planning; Hydrology; Water Control; MAR.

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1. Introduction

Hydrologic and environmental restoration of the Everglades ecosystem has been underway since 1999 [1]. A particular challenge is to assess the success of a particular project [2]. The C-111 project located along the eastern edge of Everglades National Park (ENP), USA, is an example of a project that has been operating for a considerable period. The C-111 project is a multi-purpose project balancing restoration of wetland hydroperiods in ENP while reducing flooding to the east of ENP. The project includes a series of managed artificial recharge (MAR) basins located just east of the ENP boundary. The basins, designated B-North, B-West, C, and D percolate massive quantities of stormwater into the porous Biscayne aquifer. The infiltration basins are bounded on the east by the L-31N/C-111 Canal system which provides water supply and flood control capability to Miami and Homestead, Florida USA. The canal system is dominated by large water control structures including both gravity weir structures and active pumping stations. The project study area is shown on Figure 1.

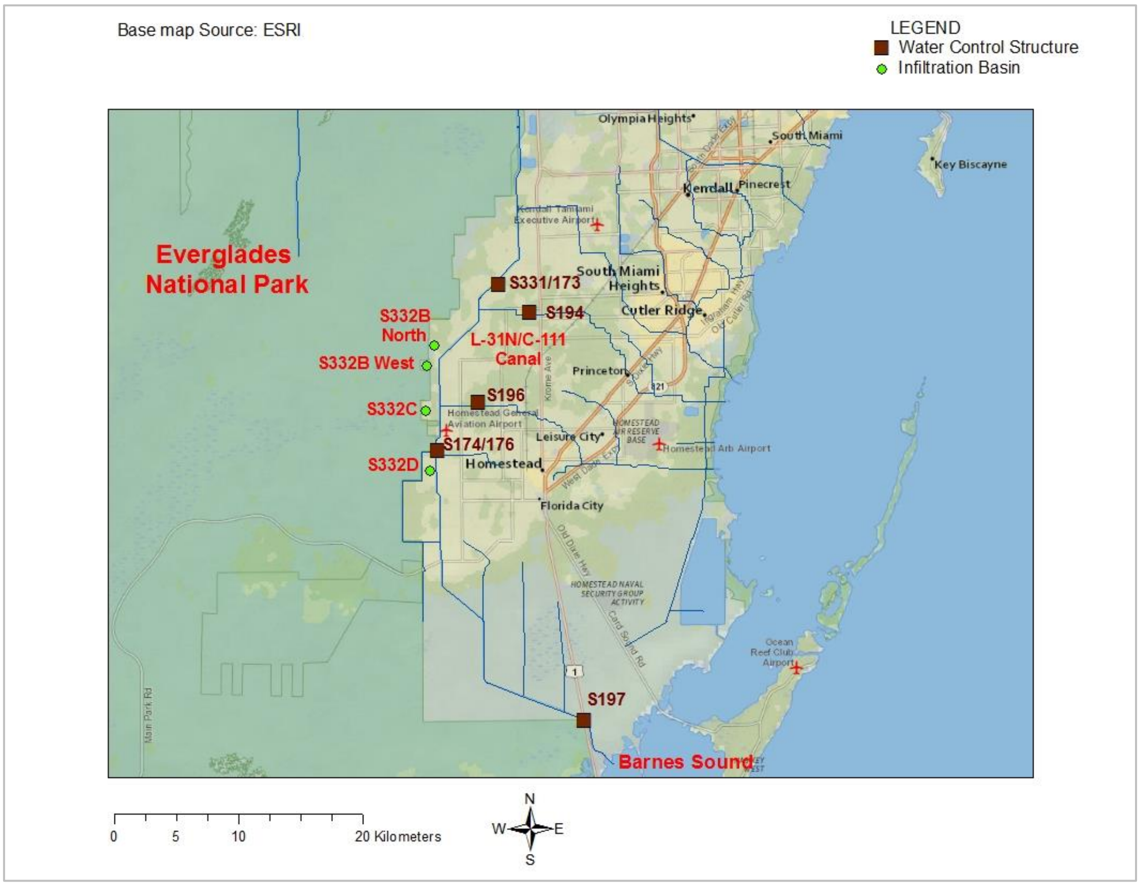

Figure 1. C-111 project study area.

The area is categorized by low lying topography with a wide mosaic of natural wetlands, novel wetlands, agricultural lands, and urban development. ENP, a World Heritage Site, is a giant sub-tropical, freshwater wetland system. ENP is heavily influenced by the area water control structures and drainage canals [3]. The canal system was developed by the U.S. Army Corps of Engineers (USACE) in partnership with the South Florida Water Management District (SFWMD). Identifying the changing nature of the basin and effects of water management on wetlands in the basin, the SFWMD advanced a water resources improvement plan in 1983 [4]. The proposed improvement plan included a multitude of components:

- Land purchase of major portions of the basin for floodwater retention and environmental preservation;
- Partial backfilling and elimination of certain canals;
- New pumping facilities;
- Dispersion of freshwater across marshlands; and,
- Redistribution of flow away from Manatee Bay/Barnes Sound into Florida Bay.

The C-111 project has been constructed in phases between 2000 and 2008. Parts of the project have now been in operation for 18 years. The project was comprehensively assessed by Brown et al. in 2014 [5]. That first assessment effort focused on the pre-project period from 1982 to 2000, and later during the initial project operation from 2000 to 2010. This assessment evaluates the 2000 to 2018 period to determine if the project is still operating as we intended. The assessment focuses upon water quantity, quality, timing and distribution (QQTD). The C-111 project is considered a foundation project for full Everglades restoration [6].

2. Materials and Methods

The C-111 assessment was split into four broad assessment categories consistent with the Central and Southern Florida Project Comprehensive Review Study, also known as the "Restudy" [1]. The four categories are:

- Quantity;
- Quality;
- Timing; and,
- Distribution.

This study assessed each category using different assessment metrics. The overall quantity of water was assessed using a comprehensive water budget of the L-31N/C-111 Canal system. The timing of the flows into Barnes Sound was assessed by reviewing positives flows out from water control structure S-197. The timing of hydroperiods, water quality of stormwater, and distribution of stormwater was assessed using published annual reports from the SFWMD and new studies completed for this research effort. Since publication of the first C-111 assessment studies, a complementary project called the "C-111 Spreader Canal" has also been constructed south of the primary C-111 study area. So, as part of its annual reporting to the Federal Government for the project, the SFWMD evaluates the entire C-111 and C-111 Spreader Canal study areas annually including metrics related to stormwater quality, wetland hydroperiod, and water levels in the agricultural areas to the east of the canals [7]. The metrics used are identical or very similar to those first used by Brown et al. [5] as part of the initial assessment for the C-111 project area. These data were adopted for this study as a complement to the new evaluations that were completed. Therefore, the primary novel efforts completed for this study were the determination of an updated project water budget and analysis of hydroperiod in the project area. Equation (1) lists the overall water budget equation used herein.

$$+/-DS = P + RO + SWin - ET - SWout +/- GWseep +/- Error, \quad (1)$$

Where DS is the change in storage; P is precipitation directly into the canal system; RO is runoff into the canal system from areas along and east of the canal system; SWin is surface water flow in through S-331 and S-173 water control structures; ET is evapotranspiration directly out of the canal system; SWout is surface water flow out of the system through S-176, S-174, S-194, S-196, S-332B, S-332C, and S-332D water control structures (water flows into MAR areas B North, B West, C, and D); GWseep is the seepage in or out of the canal system; and Error is the cumulative errors of all terms. For this study, equation 1 was rearranged to solve for the GWseep in or out of the canal system. Negative values of GWseep mean that groundwater seepage is into the canal while positive values indicate recharge from the canal system to the aquifer system. Negative values indicate that the canal system is "mining" groundwater from the Biscayne aquifer.

The canal section evaluated for this water budget from S-331 in the north to S-176 in the south was approximately 16,500 meters long with a weighted-mean channel width of 14.61 meters and a weighted-mean channel bottom elevation of -2.77 meters NGVD 1929. The water budget was calculated on a daily time step and then integrated on an annual basis. The change in storage, DS, was calculated using the daily change in water level in the canal multiplied by canal mean width. The precipitation was the daily rainfall recorded at the S-331 West structure weather station. The daily precipitation was multiplied by the average canal top width to estimate the direct P input into the canal system. Runoff, RO, from lands along and to the east of the canal system slopes, toward the canal and can provide water inputs into the system. The RO was calculated using the Soil Conservation Service (SCS) Curve Number methodology using a mean curve number of 80 and assuming a contributing watershed of about 26 km^2. At this curve number value, RO was only generated when daily precipitation exceeded about 1.27 cm. SWin and SWout were estimated using observed mean daily flow data at the relevant structures using published data from the SFWMD DBHYDRO database (https://www.sfwmd.gov/science-data/dbhydro).

Daily ET from the canal system was estimated using published monthly evaporation data from south Florida [8]. The daily ET rate was multiplied by the average canal top width to estimate the ET flux out of the canal. Due to the small relative contribution of DS, P and ET to the water budget, the most important elements of the water budget are the water control structure surface water flows and runoff.

3. Results

3.1. Water Quantity

The results of the water budget study are depicted in Table 1. Table 1 displays the total inflows into the four primary MAR percolation basins and the net seepage into or out of the canal system. The GWseep term is negative eight out of nine years indicating net seepage into the canal system. In 2015, the analysis indicates that the canal system likely provided net recharge to the Biscayne aquifer. The mean annual net seepage value for the assessment period is about -145,000,000 m^3.

Table 1. Water budget summary 2010 to 2019.

Year	Total annual flow volumes into MAR basins (m^3) [1]	GWseep - Net annual seepage into or out of canal system (m^3)
2010	525,077,846	-152,821,351
2011	256,908,701	-27,152,472
2012	646,513,766	-216,843,447
2013	576,926,348	-172,860,123
2014	393,196,509	-56,526,067
2015	206,896,547	27,294,699
2016	881,182,472	-378,015,559
2017	430,824,339	-126,660,662
2018	379,507,110	-204,819,627

[1] Combined flows into B-North, B-West, C, and D Ponds.

3.2. Water Quality

The water quality assessment for the project has always been focused upon nutrients including total nitrogen and total phosphorus. Recent nutrient data suggest that total mean phosphorus concentrations in the canal stormwater being recharged in the MAR basins in 2017 remains at about 6 μg/l [7] which is generally the same as reported previously for the period 2000 to 2010 [5]. Mean total nitrogen inflows recorded at the S-200 structure located just east of S-332D measured 600 ug/l in 2017 [7].

3.3. Water Timing and Distribution

The timing and distribution assessment utilized both existing published data and new evaluations developed as part of this study. Flows out the S-197 water control structure were used to assess impacts of large freshwater pulse discharges into Barnes Sound, a sensitive ecological area in southern Florida. Unfortunately the flow data was only available for 2010, 2011, and part of 2012. Mean outflow from S-197 during 2010 and 2011 was about 23,000,000 m^3/year. Hydroperiod, or percent of the time that wetland areas are inundated above ground, was used to assess timing of the MAR flows into areas along ENP as well as areas east of the canal system that are used for agriculture. Inundation of the wetland areas is considered a positive while worsened inundation of the agricultural areas is considered a negative. Figure 2 depicts the key observation wells used to assess hydroperiod in the study area previously [5]. Unfortunately, the monitoring at well G3622 was discontinued during the assessment period in mid-2011 while Frogp_g monitoring was discontinued in March 2010. Therefore, for this study, hydroperiod for the entire period of record from 2010 through 2018 was calculated for wells G3437, G789, and Rutzke.

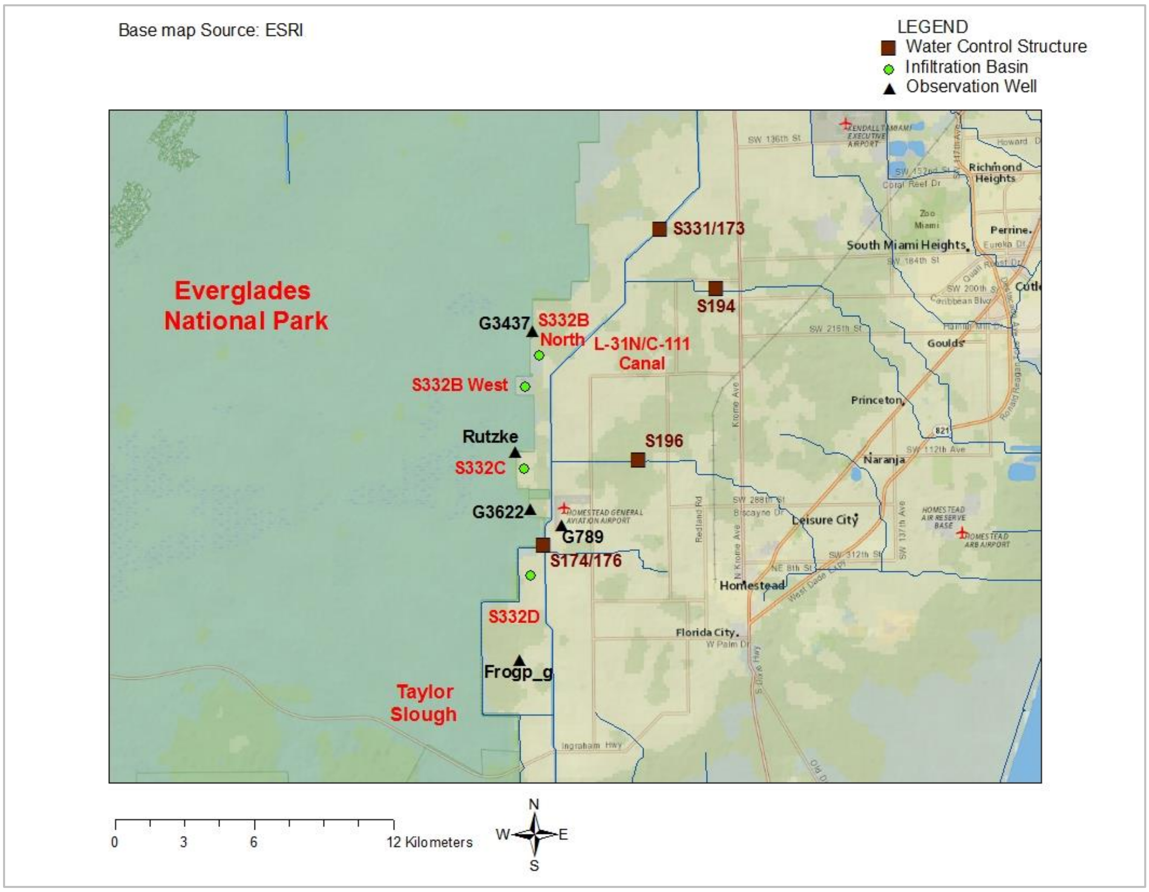

Figure 2. C-111 project study area assessment wells.

The analysis indicated that the hydroperiod was as follows for 2010 through 2018:

- G3437 – Inundated 26% of the time;
- G789 – Inundated 0% of the time; and,
- Rutzke – Inundated 50% of the time.

Hydroperiod was also estimated recently for the 2017 water year for the project areas of C-111 and C-111 Spreader Canals [7]. Their estimates indicate the hydroperiods for each area as follows:

- G3437 area – 30 to 60 days out of 365 or about 8% to 16% of the time;
- G789 area – No inundation during the period;
- Rutzke area – 180 to 210 days out of 365 or about 50% to 57% of the time;
- G3622 area – 0 to 30 days out of 365 or about 0% to 8% of the time; and,
- Frogp_g area – 0 to 30 days out of 365 or about 0% to 8% of the time.

4. Discussion

Overall this study has evaluated the performance of the C-111 project from 2010 through 2018, a period of nine years. The assessment was focused on water resources metrics including water quantity, quality, timing, and distribution. The evaluation was based upon existing SFWMD published annual reports and new research completed for this study. The analysis of water quantity indicates that over the analysis period from 2010 through 2018, the canal system had about 145,000,000 m^3 of seepage inflows on average annually. Brown et al. reported a value of about 151,000,000 m^3 annually for the 2000 to 2010 period [5]. Therefore, it appears the overall project water budget has remained about the same. The inflow concentrations of total phosphorus also remained stable at about 6 ug/l as compared to the 2000 to 2010 period. The outflows from water control structure S-197 provide an incomplete picture of the detrimental pulse freshwater flows into Barnes Sound. Only data from 2010 and 2011 was fully available. Of these data, the annual outflow into Barnes Sound was about 23,000,000 m^3 as compared to 25,000,000 m^3 annually during the 2000 to 2010 period which is about the same.

When comparing hydroperiod for wetland areas and agricultural areas the results appear to be mixed. The hydroperiod at wells G3437, G789, and Rutzke have improved with the inundation percentages increasing in the wetlands while decreasing in the agricultural areas. The inundation in the G3622 area could only be estimated using published data from 2018 for the 2017 water year. Using these data, it appears that the inundation in this part of the study area has remained stable from the 2000 to 2010 period. Similarly, only published data was available in the Frog Pond area. The published data from 2018 indicates that the hydroperiod in this portion of the study area has decreased considerably from the 2000 to 2010 period.

So in summary, for the 2010 to 2019 assessment period, it appears that the C-111 project continues to function generally as originally planned. A performance assessment completed as part of this study indicates that overall the project performance metrics are mostly stable as compared to the previous assessment period from 2000 to 2010.

Supplementary Materials: The following are available online at www.mdpi.com/link: None.

Acknowledgments: This work was completed as unfunded research by the authors. The authors would like to thank the SFWMD for the use of its data downloaded from the DBHYDRO database.

Author Contributions: Dr. Chris Brown led the research efforts for this article as part of his research program. The conceptualization of the work was performed by Dr. Chris Brown. The formal analysis was completed by Drs. Brown. This article was written by Drs. Brown and Mirecki. Dr. Brown provided project administration and final article editing.

Conflicts of Interest: The authors declare no conflict of interest. No one other than the authors had a role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
MDPI: Multidisciplinary Digital Publishing Institute
DOAJ: Directory of open access journals
ENP: Everglades National Park
SFWMD: South Florida Water Management District
USACE: U.S. Army Corps of Engineers.

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Paper for ISMAR10 symposium. ***Topic No: 19 (093#)***

Optimal Trenches for MAR by Tertirary Treated Water: HYDRUS2D Versus Vedernikov's Seepage Theory Revisited

A. Al-Shukaili[1] and A.R. Kacimov[2*]

[1,2*]Department of Soils, Water and Agricultural Engineering, Sultan Qaboos University, Oman
*Correspondence: anvar@squ.edu.om, akacimov@gmail.com ; Tel.: (968) 24141-201

Abstract: Coupled surface-subsurface flow is studied in application to MAR through a lattice of small-size channels constructed on the pedestals of sand dunes or in the interdunal valleys. Longitudinal flow downslope (in the *X*-direction) is gradually varying and MAR takes place at the trench segment $0<X<XM$ [A_0, K_s, n, s_t] where X_M is the "extinction length" (front) of the MAR "jet". Surface flow is 1-D, quasi-normal, of an area $A(X)$ obeying an ODE which is integrated by computer algebra routines. Conjugation of steady surface and subsurface flows is a special limit of transient regimes in furrow irrigation or flash floods in ephemeral streams. By HYDRUS2D, triangular trenches of different bank slopes, λ, were simulated. The Morel-Seytoux shape factor $\mu=q_i/(K_sA_0^{1/2})$ as a function of λ is plotted. If $q_i \ll Q$, then at a given A_0 there is a unique minimum of $\mu(\lambda)$. If q_i is not small, we determine the trench shape of a given A_0, which maximizes the total volume of water infiltrated from the trench. For Vedernikov's steady seepage from solitary trenches we evaluated $\beta=V/(K_s A_0)$. The function $\beta(\lambda)$ for a given dimensionless parameter $e=K_s n/(s_t^{1/2} A_0^{1/3})$ has a maximum (an optimal shape of a MAR-trench).

Keywords: Normal surface flow in channel (Manning's equation) conjugated with 2-D flow in porous bed (Richards' and Laplace's equations); Recharge through trenches; Optimal MAR-maximizing shapes.

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1. Introduction

Haya Company in Oman is the main producer of treated wastewater (TWW, currently 150,000 m^3/day) and feasibility of using this resource for MAR is currently studied [17]. So far, TTW is used for filling surface lagoons in the capital, Muscat [7] and for injection through a gallery of wells in the Salalah coastal plain (South of Oman, see [11]). Large areas of desert dunes across Oman can be explored for MAR if natural *wadis* or small-size constructed trenches are involved as channels, which both convey and seep TTW into the vadose zone. Mini-treatment plants managed by desert touristic camps and remote villages can use small-scale infiltration trenches. The infiltrated TTW can be recovered by wells adjacent to trenches.

Key design question are: What should be the length of a MAR section of the channel to infiltrate all water released at the commanding reach? What is the optimal size and shape of a channel for a MAR site of a certain topographic slope, roughness of the bed, hydraulic conductivity of the sand, provided a designed quantity of TTW to be infiltrated?

Natural or artificial recharge of unconfined aquifers from wadis (or other ephemeral and intermittent streams) in arid environments calls for adequate modelling of conjugation between relatively, rapid horizontal surface flows and relatively slow vertical water motion in the vadose zone and aquifer. Several models study interaction of a coupled dynamics of these two water bodies in application to furrow irrigation and hydrology of flash floods in wadis. For example, [1] and [16] used HYDRUS for evaluation of seepage from a channel. They considered a hybrid of a subsurface Darcian flow modelled by the 2D Richards' equation with a surface flow. Simpler models of 1D infiltration from a channel have been also used (see e.g. [2], [8], [9] and [14]).

In this paper, we consider a steady flow of surface water in an array of identical and equidistant triangular soil channels, downslope in the horizontal direction OX oriented along an axis of one channel (Fig.1a). This axis is parallel to a rough bed of the channel, the bottom of which is a straight line D_uDD_d (Fig.1b). The period *L* of the channel lattice is the distance between two neighboring channels. Due to symmetry, we consider just one channel of the lattice. The channel is triangular in each vertical cross-section (Fig.1c) with the bank slope $\lambda=\gamma\pi$, where $0<\gamma<1/2$.

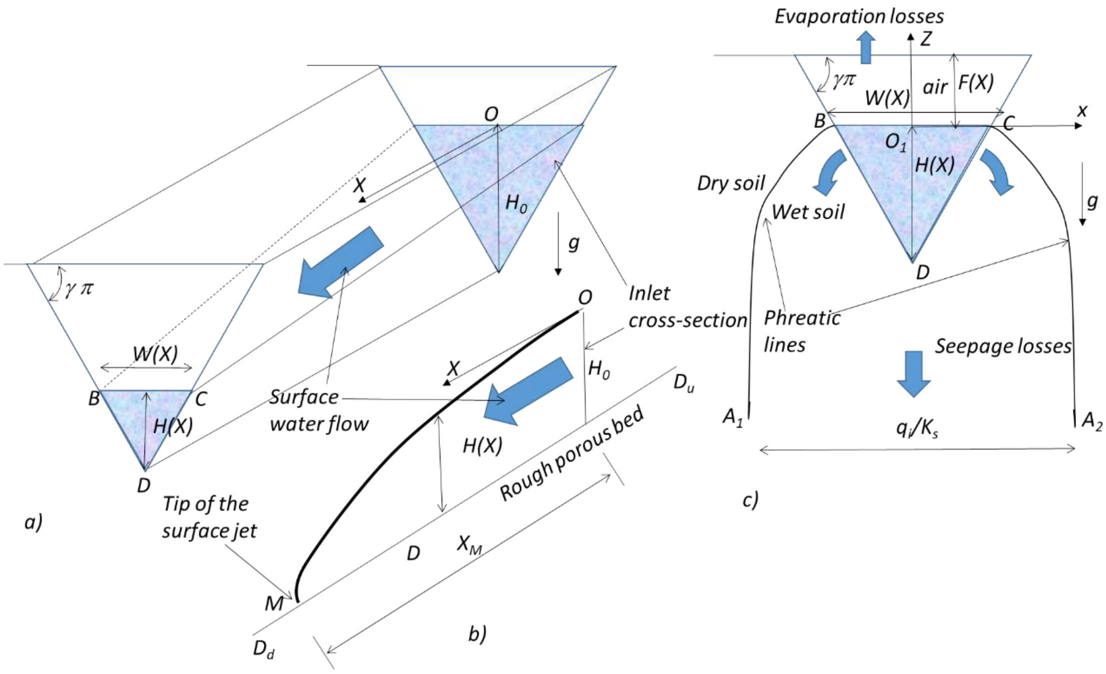

Figure 1. a) 3-D sketch of surface flow through a triangular trench, b) "free jet" of surface flow in a cross-section along the trench axis, c) seepage flow in a vertical cross-section perpendicular to the channel axis.

2. Analytical Conjugation of 1-D Surface Flow with 2-D Seepage

In this Section, we use purely analytical solutions and consider a solitary channel ($L=\infty$). At the commanding inlet *X=0* (Fig.1a,c), the depth of water in the channel is $H=H_0$ (m), free surface width $W=W_0$ (m), free board $F=F_0$ (m), area of a wet cross-section $A=A_0=H_0^2 \cot \lambda$ (m[2]), wetted perimeter $P=P_0= 2H_0/\sin \lambda$ (m), hydraulic radius $R=R_0=0.5H \cos \lambda$ (m) and the volumetric discharge $Q=Q_0$ (m[3]/s). Gravity and roughness of the bed facilitate and resist, correspondingly, the surface flow.

Water is lost to evaporation from the open surface and to seepage into a permeable bed of hydraulic conductivity K_s and effective porosity $m_e= \theta_s - \theta_r$, where θ_s and θ_r are soil's volumetric moisture content at saturation and residual saturation, respectively [10] . Due to these losses, the septad of geometric and hydraulic quantities (*H, W, F, A, P, R, Q*) decreases with *X*, while γ remains constant. At $X=X_M$ the "free jet" gets extinct (Fig.1b shows a vertical cross-section passing through the OX axis). We assume that the topographic slope is $\omega\,\pi$, where ω is a small constant. On scales of drainage basins the relief ω is found from Google Earth; for short furrows, this parameter is measured by a theodolite. Manning's roughness n_M is a dimensional (s/m$^{1/3}$) constant, which we retrieve from handbooks on hydraulics.

In a vertical cross-section perpendicular to OX $(0<X<X_M)$, a system of Cartesian coordinates is xZO_1 (Fig.1c). The wetted contour of the channel is a triangle BDC and free water surface is a segment BC. We assume that seepage is 2D in the plane xZO_1. The rate of seepage (per unit length in the OX direction) is q_i (m^2/s). Evaporation losses (also per unit length in the OX direction), are $q_e=e*B=e*2\,H \cot\lambda$ (m^2/s), where the evaporation rate e (m/s) is a constant measured by an A-pan (a typical value in Oman is e=0.7 cm/day) or calculated by the Penman-Monteith (FAO) formula.

From the conservation of mass, we have an ODE:

$$\frac{dQ(X)}{dX}=-q_i(X)-q_e(X), \qquad Q(0)=Q_0,\ \ Q(X_M)=0 \tag{1}$$

where the position of the tip M (Fig.1b), XM, is to be found. It is noteworthy that in applications to furrow irrigation and flash flood hydrology the surface flow is essentially transient while in MAR applications a steady release of a stable quantity of TTW is not uncommon.

The second equation for shallow flow in the channel is retrieved from the Saint-Venant theory [3]. Below we select the simplest model of the so-called "kinematic waves" (eqn. 3 of Furman [3]):

$$S_0 = \mathrm{S}_f \tag{2}$$

where (Fig.1b). Manning's friction slope is

$$\mathrm{S}_f = {n_M}^2\frac{Q^2(X)}{A^2(X)R^{4/3}(X)} \tag{3}$$

Usually, in analytical models $qi\ (X)$ in Eqn.(1) is assumed to be an empiric function of the geometry of the wetted contour in Fig.1c or is obtained from models, which postulate that a transient but 1D (or quasi-1D) infiltration. Vedernikov [13] (see also [12]) assumed that seepage q_i does not depend on X but the Darcian flow is essentially 2-D and depends on the shape and size of the channel. Vedernikov used a potential theory and exactly solved the problem of steady 2D flow in the xZO_1 plane. He used complex variables and the hodograph method based on conformal mappings. He analyzed seepage from arbitrary trapezoidal channels, in particular, triangular contours BDC in Fig.1c. Vedernikov ignored capillarity and assumed the piezometric (total) head $h(x,Z)=p+Z$ (where p is the pressure head) constant along BDC. Two phreatic lines A_1B and A_2C (Fig.1c) demarcate a positive pore pressure "plume" which extends to infinity. These curves have vertical asymptotes such that the width of the fully saturated zone at is q_i/K_s. Seepage takes place only in the "plume" bounded by A_1B and A_2C. Vedernikov [13], eqn. (208) , found that seepage losses are:

$$q_i = K_s\left[W(X)+A_V(\gamma)H(X)\right] \tag{4}$$

$$A_V(\gamma)=\frac{2}{\tan\alpha\pi}\left[\frac{1}{1-\dfrac{f(\gamma)}{0.5\pi I(\gamma)}}-1\right],$$ (5)

$$f(\gamma)=\int_0^1\frac{\arcsin u}{u^{1-2\gamma}(1-u^2)^{1-2\gamma}}du,\quad I(\gamma)=0.5\mathrm{Be}[\gamma,1/2-\gamma]$$

where B_e is the Euler Beta-function.

We evaluate the integral in eqn.(5) by Wolfram's Mathematica [15] as:

$$f(\gamma)=0.25\sqrt{\pi}\Gamma(\gamma)\Gamma(3/2+\gamma)\frac{2}{\tan\gamma\pi}*$$
$$\left[\frac{\sqrt{\pi}}{\Gamma(3/2+2\gamma)}-\frac{2\ \mathrm{HypergeometricPFQRegularized}[\{-(1/2)-\gamma,\gamma,1/2+\gamma\},\{1+\gamma,1+\gamma\},1}{1+2\gamma}\right],$$

where Γ is the Gamma-function and HypergeometricPFQRequilarized is the regularized generalized hypergeometric function (a *Mathematica routine*).

In eqns. (1), (3), and (4) we express *W, H, R* and *Q* via *A*. Then we put *Q* from eqns. (2) and (3) into eqn.(1) and get an ODE:

$$\frac{dA(\mathrm{X})}{dX}=-U_d A(X)^{1/6},\qquad A(0)=A_0,\ \ A(X_M)=0$$ (6)

$$U_d=\frac{K_s n_M}{\sqrt{S_0}}\frac{3}{2^{4/3}}\frac{(\sin\gamma\pi)^{1/6}}{(\cos\gamma\pi)^{5/6}}\left[(2+e/K_s)\cot\gamma\pi+A_v(\gamma)\right]$$

We define a dimensionless Darcy-Manning friction coefficient, which juxtaposes three physical factors controlling the coupled dynamics of surface and subsurface flows, viz. a Darcian resistance of the porous medium (K_s), a viscous shear which the surface current experiences from a rough channel bed (n_M), and gravity (S_0). We introduce other dimensionless quantities (*Q*, A*, X*, W*, H*, e**, Q_i*, *V**)=($Q/(K_sA_0)$, A/A_0, $X/A_0^{1/2}$, $W/A_0^{1/2}$, $H/A_0^{1/2}$, e/K_s, $Q_i^*/(K_sA_0)$, $V/A_0^{3/2}$). Then eqn. (6), re-written in a dimensionless form, becomes

$$\frac{dA^*(X^*)}{dX^*}=-U\ A^{*\,1/6},\qquad A^*(0)=1,\ \ A^*(X_M^*)=0$$

$$U=r\frac{3}{2^{4/3}}\frac{\sin^{1/6}\gamma\pi}{\cos^{5/6}\gamma\pi}\left[(2+e^*)\cot\gamma\pi+A_v(\gamma)\right]$$ (7)

It is noteworthy that in the ODE (7) U does not depend on *A** and *X**. Consequently, the BVP (7) is explicitly integrated as:

$$A^*=\left(1-\frac{5}{6}U\ X^*\right)^{6/5},\quad X_M^*=\frac{6}{5U}$$ (8)

For other channel shapes analyzed by Vedernikov [13] (in particular, for trapezoidal channels) such simple integration, as done in eqn.(8), is not possible. Therefore, the triangle is unique in delivering a rigorous but elegant final solution to the problem of a 1D surface flow conjugated with a 2D Darcian flow.

Example: Let a triangular channel of a slope γ=1/4 discharge with the inlet wetted section sizes of W_0=10 cm and H_0 =5 cm (A_0=0.0025 m^2); a free surface BC (Fig1a,c) evaporates into the atmosphere at the rate e=0.5 cm/day. The channel is laid with a topographic slope S_0=0.01 in sand having Manning's roughness n_M =0.02 s/$m^{1/3}$ and conductivity K_s =2*10^{-4} m/s. Therefore, Q_0= 0.00085 m^3/s, r=0.000295, U= 0.00096. Then from eqn.(8) we evaluate $X_M^* = 1251.4$, or returning to dimensional quantities, X_M=62.6 m. For the selected triad $(\gamma = 1/4, e^* = 2.9*10^{-4}, r = 0.000295)$, Fig.2 shows the dimensionless area, channel's water depth and 10^{-3} Q^* as functions of X^* (curves 1-3, correspondingly).

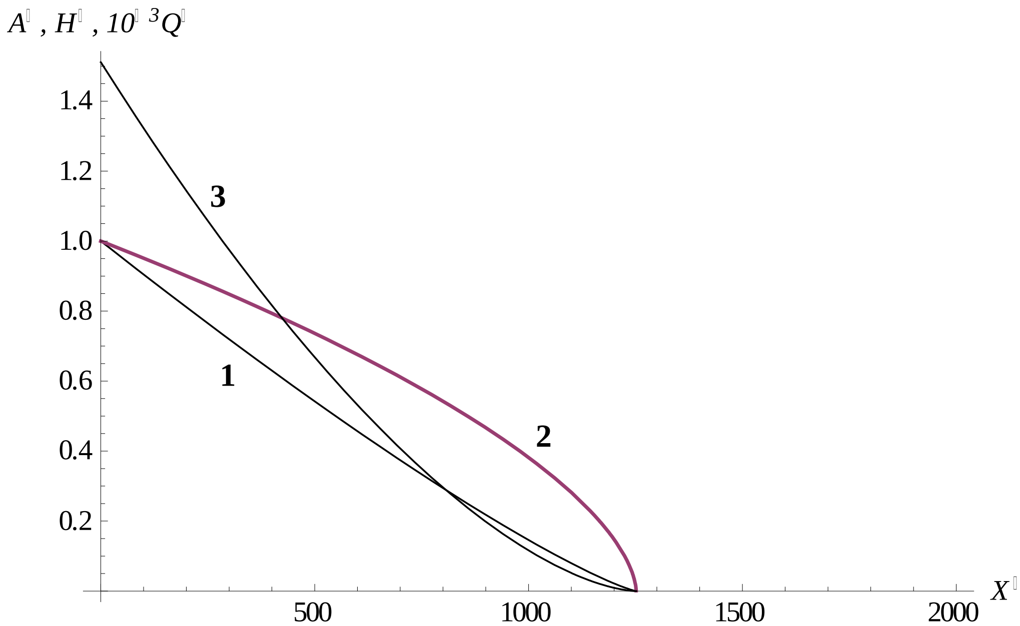

Figure 2. Dimensionless wetted cross-sectional area A*, depth H* and Q* as functions of dimensionless longitudinal coordinate X* (curves 1-3) for a channel with a triad of parameters. $(\gamma = 1/4, e^* = 2.9*10^{-4}, r = 0.000295)$

Practically, evaporation losses from BC in Fig.1 can be neglected. Then the total seepage losses from the whole channel are:

$$Q_i = \int_0^{X_M} q_i(X)dX \qquad (9)$$

We integrate eqn.(9) and get dimensionless losses:

$$Q_i^* = \frac{(\sin 2\gamma\pi)^{1/3}}{2r} \qquad (10)$$

From eqn.(10), we get an obvious result: for a given soil (i.e. a given bed roughness and Darcian permeability), topography and A_0 the maximum of $Q_i^*(\gamma)$ is attained at $\gamma = 1/4$. This maximum is $Q_i^*(1/4) = 1/(2r)$. It can be used as an upper bound for assessing efficiency of MAR through arbitrary triangular trenches.

For irrigation applications, the volume V of free water in the channel can be of interest. From our solution, this volume is explicitly evaluated as:

$$V = \int_0^{X_M} A(X)dX, \quad (11)$$

upon integration gives in dimensionless quantities:

$$V^* = \frac{6}{11\,U} \quad (12)$$

We note that Vedernikov's solution is valid for the case of seepage into an infinite layer of an initially dry homogeneous soil with no groundwater beneath. If the channel bed is clogged, the vadose zone is subtended by a low-permeable stratum, or bounded by "backwater" of a shallow aquifer (see e.g. [4]), then q_i in each cross section X=const of Fig.1a is reduced as compared with what eqns.(4)-(5) give. On another hand, soil's capillarity increases q_i.

3. HYDRUS2D Simulations

In this Section, we simulated 2-D saturated-unsaturated water flow in soil by considering a cross-section in Fig.1c for triangular trenches of different λ, placed in a lattice of a finite period L. The base geometry of a HYDRUS2D model was a right half of one period, viz. a rectangle of sizes (x, z) = (100, 150) cm with its left upper corner "chopped" by a half-channel. Thus, the flow domain is a pentagon shown in Fig.3. We modelled two scenarios:

a) Uncoupled subsurface flow at a constant normal depth i.e. when the septad (H, W, F, A, P, R, Q) does not vary with X (Fig.1a)

b) Coupled surface-subsurface flow with triangle sizes and seepage losses decreasing in the X-direction of Fig.1b.

3.1 Relatively small seepage losses

If channel's W and H are large and water is conveyed at a large Q, the seepage losses are relatively minor for relatively short distances X in Fig.1a i.e. the surface flow is "normal" (scenario modelled in this subsection).

Unlike Section 2, seepage takes place in the whole pentagon of Fig.3, i.e. there are no free surfaces. This pentagon was discretized into finite elements of a size of 1.0 cm that made 494 and 45010 of 1D and 2D elements, correspondingly. We assumed that soil is a homogeneous sand from the HYDRUS soil catalogue (K_s=713 cm/day and the Van Genuchten parameters α =0.145 1/cm, n=2.68).

Initially *(t<0)* the soil is dry with a pressure head assumed to be p_0 = -1000 cm everywhere in the pentagon. At *t=0* the whole channel is instantaneously filled with surface water and 2-D seepage starts. The water board F (Fig.1b) is assumed to be zero at any *t>0* for all simulated channels.

A constant (hydrostatic) head h is maintained at *t>0* along a wetted perimeter of the channel (segment DC in Fig.3). This is an inlet HYDRUS boundary condition along DC. A HYDRUS free drainage condition is imposed along the outlet segment GJ. Other sides of the pentagon, CE, DG and EJ in Fig.3 are impervious. The maximum number of HYDRUS iterations was 10 and the water content tolerance was 0.0001. A t=1 day, seepage from the channel stabilized (checked by comparison of velocity magnitudes along GJ at several time instances close to t=1). The corresponding values of steady seepage losses q_i are shown in Table.1.

We formulate the following: Optimal Shape Design Problem. For a given cross-sectional area A=A_0 of a triangular channel, given the soil properties and L, determine the bank slope λ which minimizes HYDRUS-computed q_i.

In order to solve this optimization problem, we varied H but kept constant W=20 cm, see Table.1. For each H (and, correspondingly, λ) we calculated the vertical velocity v along GJ and the Morel-Seytoux shape factor $\mu=q_i/(K_s \cdot A^{1/2})$. The minimum μ ($\lambda$) solves the shape optimization problem (see [5],[6] for more details). Table 1, shows that for the HYDRUS sand and L=200 cm the minimum of μ is attained at H = 10 cm, i.e. λ = 45°.

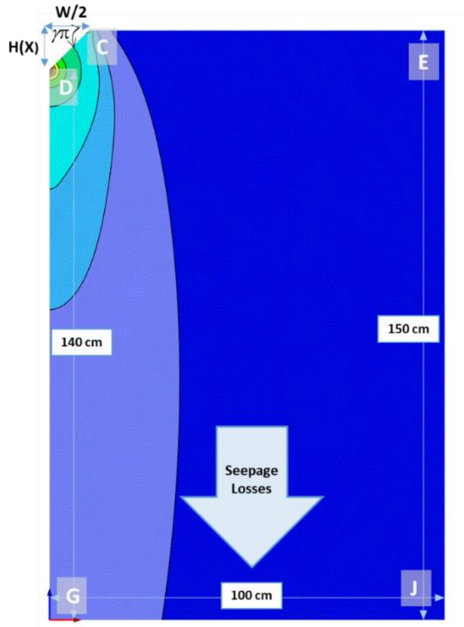

Figure 3. Pentagon as seepage domain in HYDRUS2D, contours indicate colored zones from relatively low (blue) to large (red) pressure heads.

Table 1. variation of H (similarly, λ), v and μ were calculated along GJ. The minimum of μ is attained at H = 10cm, i.e. λ= 45°

H(cm)	λ(°)	v (cm/day)	q_i (cm²/day)	μ(-)
3	16.70	119.93	11992.79	4.31
5	26.57	133.89	13389.37	3.80
6	30.96	141.40	14139.55	3.62
8	38.66	157.10	15710.15	3.48
10	45.00	173.84	17383.66	3.42
13	52.43	200.00	19999.65	3.47
15	56.31	218.07	21807.12	3.52
20	63.43	264.00	26400.33	3.70
25	68.20	310.72	31071.75	3.90
30	71.57	357.94	35793.83	4.10
35	74.05	404.51	40450.71	4.30
40	75.96	452.61	45260.87	4.50

3.2 Coupled HYDRUS2D seepage and kinematic wave surface flow

If the channel is relatively small, then q_i is relatively large as compared with Q. Then the impact of seepage on surface flow has to be taken into account [3]. In this section, we couple surface flow and seepage in the same manner as in Section 2: we solve the BVP (1) but with q_i computed numerically by HYDRUS2D, rather than analytically by the Vedernikov theory. We ignore evaporation. We illustrate coupling of surface-subsurface flows for a particular case of a triangular channel having λ=45°, which we showed above to have extreme properties of interest in MAR applications. For this angle, we kept W=20 cm and varied the channel depths of H=2, 3, 4, 6, 7, 8, and 10 cm. The corresponding seven values of q_i (computed as in Subsection 3.1 for steady state seepage) were retrieved from HYDRUS. Next, an interpolation function and interpolation polynomial q_i [H] has been obtained by *Wolfram's Mathematica*:

$q_i[H]$= -163871□+202262□ H - 96917□1 H^2 + 23936□ H^3 - 3192□48 H^4 + 218.515 H^5 – 6.01235 H^6 (13)

This approximation is poor at the end points H=2 cm and 10 cm. We put the polynomial (13) into the right hand side of the ODE (1):

$$\frac{\sqrt{2s}}{4n_M}\frac{dH^{8/3}(X)}{dX} = -q_i[H(X)], \qquad H(0) = H_0, \;\; H(X_M) = 0 \tag{14}$$

We introduce dimensionless quantities (X^*, H^*, q^*,c)=(X/W , H/W, $q_i/(K_s W)$, $\frac{\sqrt{2s_t}}{4n_M}\frac{W^{2/3}}{K_s}$) and get the Cauchy problem for a non-linear ODE:

$$c\frac{dH^{*8/3}(X^*)}{dX^*} = -q_i^*[H^*(X^*)], \qquad H^*(0) = H_0^*, \tag{15}$$

This equation cannot be explicitly integrated as we succeeded with integration of eqn.(7). Therefore, we numerically integrated eqn.(15) (which involves eqn.(13)) by the **NDSolve** routine of *Mathematica* for the same soil and topography as in Section 2. We also selected the commanding depth of water $H_0^* = 0.4$ that is the Cauchy condition in eqn.(15). The results are shown in Fig. 4.

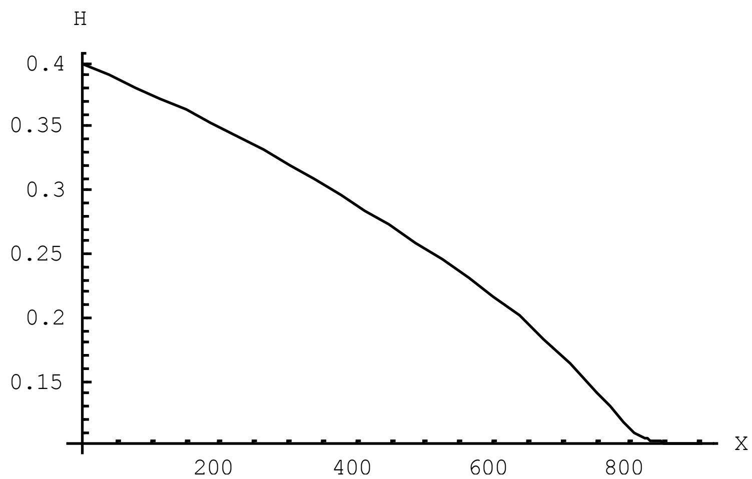

Figure 4. Numerically integrated profile of the "free jet" of surface flow with HYDRUS computed seepage losses.

For X* >800 the model is not reliable because at small H^*, the selected HYDRUS mesh is too coarse to model the infiltrating channel which becomes geometrically too small.

4. Concluding remarks

Analytical and numerical coupling of a steady-state 1-D surface flow of water (Manning's equation) in a triangular channel with 2-D seepage (Vedernikov's theory of capillarity-free flow in the positive pressure "plume" between two free boundaries and Richards' equation for saturated-unsaturated flow in a pentagon made of the Van Genuchten soil as a fixed domain) allows evaluation of the length of propagation of a "free jet" downslope from the inlet where a given quantity of water in MAR is released. This also allows optimal shape design problems to be solved, with selection of the seepage losses and channel's cross-sectional area (or volumetric flow rate) as criterion and a major integral constraint imposed (soil properties, topographic slope and roughness of the channel bed are other constraints).

Acknowledgments: This research was accomplished as part of SQU-funded projects IG/CAMS/SWAE/18/01

Conflicts of Interest: The authors declare no conflict of interest.

List of notations and Abbreviations

Symbol	Discerption	Unit
θ_v	Volumetric water content	[-]
θ_r	Residual water content	[-]
θ_s	Saturated water content (porosity)	[-]
K_s	Saturated hydraulic conductivity	cm/day
n	VG parameter in the soil water retention function	[-]
α	VG parameter in the soil water retention function of the matrix	cm-1
p	Capillary pressure head	cm
h	Total pressure head	cm
t	Time	day
x	Horizontal Cartesian coordinate in the vertical cross-section, used in HYDRUS and analytical model	cm
y	Vertical Cartesian coordinate in analytical model	cm
z	Vertical Cartesian coordinate in HYDRUS	cm
v	Vertical component of Darcian velocity	cm/day
λ	Slope of the channel bank	degree
q_i	Seepage losses per unit length	cm^2 /day

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Paper for ISMAR10 symposium. ***Topic No: 19 (112#)***

An integrated system based on MAR and reclaimed water reuse for sustainable agriculture irrigation under climate change conditions in Mediterranean countries

Vurro, Michele[1*]; Portoghese, Ivan[1]; Al-Raggad, Marwan[2]; Bouden, Sarra[3]; Doveri, Marco[4]; El-Mansouri, Bouabid[5];Fernández-Escalante, Enrique[6]; Giordano, Raffaele[1]; Lobo-Ferreira, João Paulo[7]; Mahjoub, Olfa[8]; Michiel, Caroline[9]; Monacelli Giuseppina[10]; Rossetto Rudy[11]; Santoro, Oronzo[12]; Sapiano, Manuel[13] & Tuccinardi, Francesco P.[14]

1. Consiglio Nazionale delle Ricerche, Istituto di Ricerca Sulle Acque, Bari, Italy
2. Water, Energy and Environment Center, University of Jordan, Amman, Jordan
3. DSA Technologies, Semoy, France
4. Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, Pisa, Italy
5. Lab_Geosciences/Natural Resources Hydroinformatic Section, IbnTofail, Kenitra, Morocco
6. Tragsa Group, Madrid, Spain
7. Laboratório Nacional de Engenharia Civil, Lisboa, Portugal
8. National Research Institute for Rural Engineering, Water, and Forestry, Ariana, Tunisia
9. Bureau de Recherches Géologiques et Minières, Orléans, France
10. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, Italy
11. Scuola Superiore Sant'Anna, Pisa, Italy
12. Aquasoil S.R.L., Fasano (BR), Italy
13. Ministry for Energy and Water management, WSC, Luqa, Malta
14 Promete S.R.L., Napoli, Italy

*Correspondence: michele.vurro@cnr.it; Tel.: +30-0805820549.

Abstract: The exploitation of groundwater has challenged to sustainability of water resources, even more in dry areas. Managed Aquifer Recharge (MAR) is a method useful to reduce the stress conditions, and secure groundwater systems. Our purpose is to develop an integrated system for sustainable management of non-conventional water resources through the smart integration of direct and indirect reuse practices, for increasing water availability via soil and aquifer treatment (SAT) and MAR, using both treated waste water (TWW) and rainwater harvesting (RH) techniques. The system aims to recognize, characterize, and offer solutions for overcoming the persisting barriers to the large scale implementation of SAT-MAR techniques. The conceptual scheme will analyze relevant barriers such as regulatory frameworks, safety risks, economic concerns and social acceptance by adopting an innovative approach involving local communities and experts. Different capacities (isotopy, chemistry, microbiology, etc.) will be pooled together to develop knowledge and common innovative solutions/technologies to effectively integrate SAT-MAR techniques with reuse of TWW. The system will contribute towards addressing water scarcity, environmental status by supporting countries in a comprehensive capacity building process. This key transversal objective of this system will also be achieved through capitalization activities for young and mid-career water researchers and practitioners.

Keywords: MAR, ASR, SAT, SAT-MAR, irrigated agriculture, water governance, monitoring system**,** ICT.

1. Introduction

Groundwater represents a considerable part of total water supplies worldwide: more than 60% of groundwater use is allocated to agriculture in semi-arid and arid regions which produce 40% of the world's food [1], while about 60% of total drinking water is from groundwater. The annual estimation of groundwater withdrawals in 2010 is, globally, about 982 km^3/year [2]. In the USA, groundwater contributes 65% to the total water supply [3]; this contribution reaches around 60% in the Netherlands [4], and about 85% in Switzerland [5], while in Germany 90% of the daily water supply comes from aquifers [6]. Groundwater exploitation has grown very fast with water scarcity affecting more than 40% of the global population. Over 1.7 billion people are currently living in river basins where water use exceeds recharge [7], therefore different measures have been defined in order to increase the resilience of water resources. MAR (Managed Aquifer Recharge) is one the measures useful to reduce water stress; therefore the International Association of Hydrogeologists (IAH) established a specific commission on Managing Aquifer Recharge (IAH-MAR) to tackle most relevant issues on MAR practices and to share and disseminate knowledge advances in global MAR applications over the last 60 years [8]. Efforts have been addressed also to create a global inventory of MAR plans [9,10].

The purpose of this paper is to create a conceptual scheme for the sustainable management of non-conventional water resources through the smart integration of direct and indirect reuse practices, thus increasing water availability via Soil and Aquifer Treatment (SAT) and-MAR supplied by TWW and RH. This integrated system aims to recognize, characterize, and offer solutions for overcoming the persisting barriers to the large scale implementation of SAT-MAR techniques.

This approach is innovative considering that only few countries provide guidance for health and environmental protection concerning MAR operations, while minimum quality requirements for water reuse regulation are still under discussion at European level [11].

2. Materials and Methods

Direct TWW reuse for crop irrigation and SAT-MAR techniques have been used successfully in several countries, as example in USA [12], Israel and Australia [13], to alleviate water scarcity in agriculture and improve groundwater quality through the storage and treatment of water by infiltration. Moreover, several cases have amply demonstrated the clear advantages that can be obtained from the implementation of SAT practices, which are considered among the Natural-Based Solutions (NBS) [14], because of the low energy required for chemical and biological processes occurring through the soil and the unsaturated zone, compared to the traditional advanced wastewater treatment. Moreover storage of surplus water in aquifers can help minimize evaporative losses and help farmers adjust to surface water variability during droughts, provided that MAR is technically feasible and cost effective. Experimental studies have also investigated the feasibility of aquifer storage and recovery (ASR) of winter surplus derived from surface reservoirs designed for flood protection and the pathogen decay in MAR applications under different geochemical characteristics [15]. The feasibility and reliability of SAT-MAR solutions and their comparative cost analysis with other alternative solutions, as example discharge in river or into the sea, depend on a number of physical, enabling and financial factors which have to be thoroughly investigated with regard to the local conditions of suitable sites.

Innovative technologies, including those based on bioengineering and NBS, are being developed to increase energy efficiency and reduce pollutant loads including pathogens and contaminants of emerging concern (such as pharmaceutical residues, and pesticides), in order to produce water of appropriate quality for specific uses. Such sustainable, cost-effective and scalable solutions may be particularly relevant in developing countries where the vulnerability to water-related disasters and impacts of climate change remains high. Specifically for irrigation purposes, good practices and techniques should be promoted to ensure enabling water reuse applications conditions at the field level in order to avoid clogging of drip irrigation systems, soil degradation and nutrient leaching to the groundwater and surface water. It is therefore advisable to adopt specific wastewater treatment techniques to support indirect reuse, considering hybrid approaches including aquifer storage and recovery (ASR) techniques. In this regard, the recharge of reclaimed water into the subsoil can be considered as an additional treatment, thus reducing the operation cost and energy consumption. Moreover, MAR practices applied to coastal aquifers may be effectively considered to create hydraulic barriers against sea water intrusion hence enabling the use of inland water resources for more productive uses [16].

The general objectives of this integrated system for the management of non-conventional water resources are:

a) improving technical performances and optimizing socio-economic impacts related to the development of non-conventional water resources through:

- feasible, reliable, and cost-effective water management technologies that can improve the quality and increase the quantity of TWW available for reuse;

- development of optimization schemes for non-conventional water, combining direct reuse for irrigation and nutrient recovery with indirect reuse for MAR;

- application of innovative soil and water monitoring techniques to enable the enhancement of natural purification processes, SAT, and the minimization of water-related risks [17];

b) exploring the effectiveness of direct-indirect reuse schemes under several scenario in countries characterized by different environmental, technological and socio-institutional peculiarities through a program of activities for i) demonstrating the value of the proposed technological and methodological solutions, and ii) enabling their replication in other similar contexts;

c) increasing the future use of similar solutions, by enhancing their social acceptability through stakeholders' involvement and experience sharing processes, accounting for the understanding of related benefits - and co-benefits - and costs;

d) overcoming the main institutional, legal and regulatory bottlenecks, thus ensuring the development of a coherent water reuse implementation framework through the active involvement of water, health and environment authorities;

e) capacity building and innovation sharing through innovative knowledge and experiences exchange tools, for helping water stressed regions in planning and managing water reuse facilities [18]. Innovative methodologies for measuring environmental benefits will also facilitate a transition to a circular economy in the Mediterranean region with the creation of new jobs.

3. Results

The previous sections highlighted the multi-disciplinary and integrated approach to be tackled in order to successfully implement MAR techniques. In particular, the proposed integrated framework stems from the importance of institutional (regulatory and legislative) aspects in the implementation of non-conventional water resources and water reuse. The accurate analysis of the institutional regulatory and legislative barriers will be the starting block of a stakeholders-driven processes aiming at co-developing of MAR measures. The engagement of stakeholders and local communities will help overcoming barriers by establishing local "Water Tables" for group discussion and decision.

Through the interaction with technical experts, the local Water Tables will enhance the feasibility of MAR applications by creating a positive environment for:

- increasing knowledge about social and cultural factors influencing the decision capacity of water managers and farmer to reuse water. To this aim, the structure of the system shall continuously and bi-directionally interact with the other items focused on more scientific aspects;

- increasing groundwater availability using river or lake water or reclaimed domestic water; these situations aim to increase domestic purposes or agricultural, industrial and ecological purposes, and/or, in some regions where groundwater extraction rates exceed the natural groundwater recharge, aquifer management is mostly used to prevent saltwater intrusion [9];
- achieving an evaluation framework for water reuse practices (e.g. Benchmarking, Life Cycle Cost analysis, Cost-Effectiveness Analysis, Multi-Criteria Analysis) involving local stakeholders in the definition of the expected benefits and co-benefits [19] for a given environmental and socio-economic context;
- defining the ability of the territory to be subject to MAR, including water availability for MAR, soil infiltration capacity, vulnerability of the territory to MAR unexpected impacts;
- sharing knowledge concerning the behavior, the fate and the removal of (micro-)-pollutants in MAR systems using TWW or non-conventional sources such as excess winter flows in rivers. In particular, attention shall be devoted to advance the state of the art in the use of SAT systems to enhance (micro-) pollutants removal [20]. To date, while several tests have been undertaken at lab scale, by means of soil-column experiments – few tests document what is happening at field scale. It is important to run specific experiments on selected compounds (heavy metals, organics, pharmaceuticals and pathogens) at true scale demonstration sites;
- evaluating the influence on the reuse of treated agro-industrial wastewater in irrigation is still scarce and more studies are needed to evaluate the quality of the treated effluent under different conditions, in terms of both industrial processes and wastewater treatments, and the long-term effects on soil and plants. Some findings suggest that this practice is an effective option to have a useful alternative to conventional water resources in areas where intensive agriculture is present and the sustainability of agricultural sector strongly depends on water availability [21];
- evaluating landscape capability to MAR implementation, i.e. characterizing all phases of water reuse and SAT-MAR implementation processes, ranging from the regional, sub-regional and local survey of needs and constraints to the post-construction phases, dealing with operational burden, water and soil monitoring and system maintenance.

The second block of the integrated framework is addressed to the improvement of SAT-MAR plant design and is particularly focused on:

- innovative management of water reuse techniques to test and evaluate practices such as (i) application of integrated direct-indirect water reuse to protect groundwater from seawater intrusion, (ii) groundwater infiltration of winter surplus from dams, river beds and TWW, (iii) optimized design, operation and maintenance of MAR and TWW reuse schemes;
- solution to monitor water and soil quality for safer and more efficient SAT-MAR techniques and TWW reuse in agriculture. New techniques and protocols will be developed for monitoring efficiency and safety of TWW reuse techniques based on (i) bio-sensing platform for the detection of pathogens, (ii) microbial diagnostic with bio-indicators in soil and groundwater, (iii) detection of emerging compound in water, (iv) environmental sensor for metal trace, pharmaceutical residues, pesticides, (v) evaluation of impacts on crop quality, (vi) multi-isotopic analyses on TWW, groundwater and streamwater, and (vii) geophysical monitoring techniques able to assess water infiltration and salt concentration in soils [22].
- risk assessment of water reuse practices through different, complementary tools to be developed and tested on a wide range of hydrogeological and risk conditions: (i) setup of decision support tools (DST) for safe and reliable MAR sites development, (ii) specific MAR modelling tools (in porous and/or fractured aquifers) enabling to evaluate transport/decay of pathogens and reduction of seawater intrusion in coastal aquifer [23], (iii) use of emerging

compounds (such as conservative pharmaceuticals active compounds) as environmental tracers.

All the data and information collected and scenarios built using models and the risk analyses results will be validated though the evaluation web platform for water reuse planning and management in water stressed regions. This platform is developed from the analysis of water reuse practices for agriculture (and landscape) in the focus areas, by including perception and attitudes from farmers and the public to decision makers. Moreover, data collected from existing pilot sites will be harmonized and made readily accessible to end-users. This virtual meeting place between water demand and supply communities will support key data elaborations and analysis aiming to share scientific and technical knowledge as a basis for decision support in real cases. The experiences from the sites will deepen the benefits and co-benefits of the adopted solutions by focusing not only on water quality attributes but also on the socio-economic environment in which the solutions have to be applied. Among the outcomes of the web platform, the development of common guidelines and protocols will positively influence the acceptability of water reuse practices as well as the optimal design and management of water reuse facilities.

The third block of the framework, together with the research activities, includes a number of key Communication, dissemination and exploitation activities mainly directed towards end-users and stakeholders, including (i) Elaboration of dissemination materials (e-bulletin, project leaflets, technical visits to the pilot sites) presenting the project's results; (ii) Papers in peer-reviewed journals and articles in the general press, (iii) Organization of meetings with stakeholders and target groups, including officials from the EC, (iv) Training activities for young and mid-carrier water researchers and practitioners.

The proposed strategy has the ambition to progress to front-line of research on the application of TWW reuse and SAT-MAR schemes by using non-conventional water resources for aquifer replenishment, also providing technical support to EU initiatives on MAR and water reuse. From a scientific point of view, this approach will also impact the research community shifting from basic to more applied research related to the Water Sciences and Engineering sectors (Environmental and Agricultural ones in primis), with innovative outcomes in the fields of groundwater hydrology, transport of contaminants in the unsaturated zone and in aquifers, and irrigation, as well as ICT for water (hydro informatics and advanced monitoring systems).

The flowchart, reported in figure 1, represents the implementation strategy as an iterative process enhancing basic knowledge and improving design and management of MAR infrastructures. Institutional aspects will seek to regulate the implementation and to establish links with EU policy development processes such as the WFD Common Implementation Strategy (CIS) in view of (i) the proposal for water reuse regulation in agriculture adopted earlier this year by the Commission; and (ii) the development of common guidance for water reuse in MAR planned to be undertaken under the CIS.

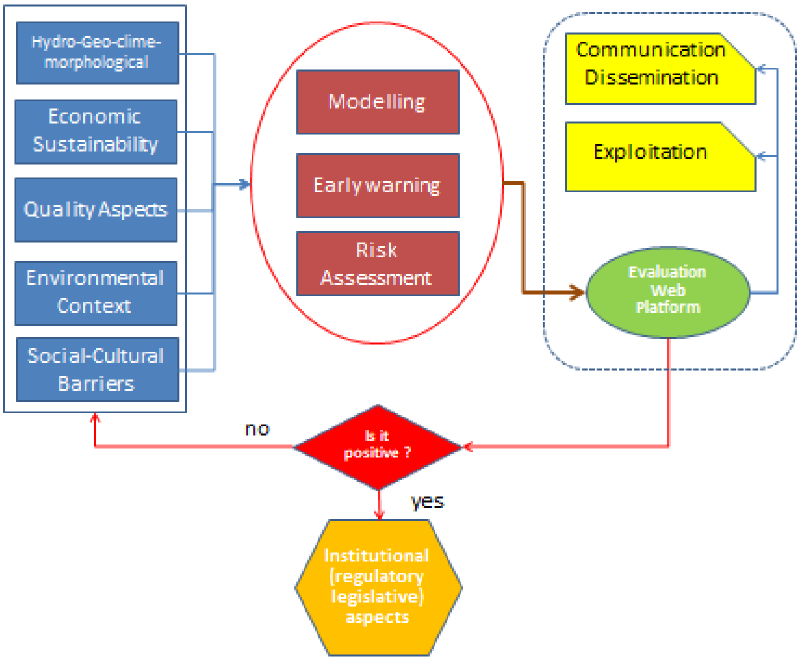

Figure 1. Flowchart representing the implementation process.

4. Discussion

The integrated system primarily impacts the water reuse sector and contributes to an increased technical knowledge on the application of water reuse and MARs techniques under the different climatic and environmental conditions. Specific focus is given to the identification of the potential impacts of these techniques on environmental matrices such as soil and groundwater, hence enabling the formulation of implementation frameworks which are not only innovative, but also safe to human health and the environment. This increased knowledge base will in-turn support the development of regulatory frameworks which will enable the application of water reuse and MAR as tools for the achievements of the WFD's environmental objectives. Hence, the system aims to demonstrate water reuse and MAR to water authorities and policy makers as a safe and sound tool which can be applied with a high level of confidence to support the future development of the agricultural sector in semi-arid and arid region. Particularly attention should be addressed to Mediterranean Region.

An impact of this integrated system is in the centrality of capacity building on SAT-MAR design and management. Possible barriers and obstacles to the smooth and plain implementation of MAR solutions and the achievement of the expected impacts may arise from the national regulation and standards which could negatively impact the experimental activities at possible demo sites. Similarly, a limited public acceptance of wastewater reuse may represent a bottleneck even for the experimental phases.

Acknowledgments: The authors gratefully acknowledge to researchers involved in the preparation of a PRIMA proposal dealing with MAR-SAT.

Conflicts of Interest: "The authors declare no conflict of interest."

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Topic 20. TRAINING ON MAR

Paper for ISMAR10 symposium. ***Topic No: 20 (052#)***

Building more collaborative approaches in contentious MAR projects - Findings from Finland

Vuokko Laukka[1]*, Tapio S. Katko[2], Lasse Peltonen[3] and Riikka Rajala[2]

[1] Kuuselankuja 6, 33900 Tampere, Finland; vuokko.laukka@gmail.com (N.B. the last name has changed from Kurki to Laukka)
[2] Tampere University, Tampere, Finland; tapio.katko@tuni.fi, riikka.rajala@tuni.fi
[3] University of Eastern Finland; lasse.peltonen@uef.fi
* Correspondence: vuokko.laukka@gmail.com; Tel.: +358 44 33 44 010.

Abstract: In Finland community water supply has increasingly relied on natural groundwater and artificially recharged groundwater as raw water source. Several managed aquifer recharge (MAR) projects have proceeded considerably well in co-creation between the involved parties, while there are some cases that have raised considerable resistance among the public. It seems that success or failure in MAR cooperation is related to management cultures and ways in which various interests are taken into account, from the very beginning throughout the process. Empirically, the paper builds on comparison between two conflictual case studies in Finland: one in the Tampere region and the other in the Turku region. The study analyses the major constraints of these projects through discourse analysis and negotiation theory, and reflects them with larger context of collaborative governance framework. The material is gathered through theme interviews, newspaper articles and a stakeholder workshop. The results indicate that conventional management approaches, drawing from expert-based instrumental rationality, were insufficient in both cases. Legitimacy for the groundwater projects should be gained through joint knowledge production and interaction for creating options for collaboration. The emerging paradigm emphasizes more collaborative approaches for natural resources management and urban planning. These issues should be taken more seriously in research, education, and practice, if the aim is to promote MAR systems with their huge potential.

Keywords: groundwater conflicts; complexity; collaborative governance; instrumental rationality; discourse analysis; negotiation; Finland.

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1. Introduction

While the circulation of water in the natural and built environment is rather understandable and can be easily explained through maps, diagrams, and tables, the flows of human affairs are more difficult to grasp. Indeed, community water systems, including managed aquifer recharge (MAR), can be classified as complex in nature. These systems involve interactions between natural, built and social environments as well as several networks and stakeholders, which are often competing for a limited and common resource [1]. In addition, actors operate at various levels (local, regional, national and international) and within various development sectors (e.g. agriculture, energy, industry, communication etc.) [2,3].

Management of modern water systems has emphasized technological matters, not acknowledging the complexity of the systems and importance of governance experimentations [4]. In environmental research it is common to assume that physical and ecological features of the problem can be separated from their social context [5]. These features do not exist, however, in a vacuum. Therefore, the conventional approach is not applicable to complex problems, such as water management problems that involve several unpredictable, unknowable, and uncontrollable interactions. Thus, water management problems are not lying on the tables of water professionals only but require interdisciplinary approaches [6]; on the other hand, the profession of water manager needs to be redefined as well.

As we are talking about MAR as a response to the global water crisis, this fundamental matter should be acknowledged. For example OECD [7] states that the current water crisis is not about water scarcity but about mismanagement, with strong public governance features [see also 8-10]. Indeed, several international organizations (FAO, UNESCO, IAH, WB and GEF) have addressed the groundwater issues through the governance framework. Groundwater governance can be seen as a complex and over-arching framework of water policies - searching the ways how strategies are executed and how actors from various fields interact [11].

As a hidden and often overexploited resource, groundwater forms a fruitful arena for debates and conflicts [12] especially in terms of land use and spatial planning [13-15], social development and equity [16, 17] as well as jurisdictional controversies [18, 19]. Although groundwater conflicts and governance have evoked research especially concerning arid and semi-arid countries, the research is still in its infancy [12, 20]. Therefore, it is interesting to analyze the case of Finland, where rather water-abundant conditions have not prevented groundwater conflicts. This context introduces an interesting perspective to the discussion about water issues being related to a problem of governance rather than water scarcity.

This paper is based on the doctoral dissertation published by Kurki in 2016[25] [21]. The purpose of the study is to find new perspectives for groundwater governance by analyzing two contentious cases of MAR in Finland. The study analyzes the major constraints of these projects and reflects them with larger context of collaborative governance framework [22-25], and finally outlines the lessons for future collaboration. The major research questions are: How collaborative were the processes in the case studies and how were the preconditions for collaboration identified and addressed?

2. Research Methodology, Materials and Methods

Twentieth century's policy literature and practice has followed the logic of instrumental rationality which assumes that through logical steps experts can gather objective data, analyze it and find the best alternatives to bring on the tables of decision-makers [1, 23]. However, the complex world does not follow the logic of linear model of the universe and the shift from vertical and hierarchical government to network-like and horizontal governance has emerged [25-27]. As a response to social complexity, planning and policy scholars and practitioners have developed the collaborative governance framework, which can be defined as the kind of public policy that brings multiple perspectives and interests to the same table in order to deliberate on the problems that various interest groups are facing together [see e.g. 22, 25].

Based on the collaborative governance framework this research analyses two case studies, two inter-municipal MAR projects, both of which may be classified as groundwater conflicts. Assessment is performed through collaborative governance framework and discourse and conflict analysis are used as analyzing methods.

Here discourse analysis explores how different stakeholders view the reality and how they participate in the construction of the problem through discursive practices. It analyses their perceptions and actions in and through a text and talk [28]. This research exploits two concepts;

[25] The last name has changed from Kurki to Laukka.

storyline and discourse coalition, introduced in Hajer's [29] discursive framework; and these concepts were complemented with the idea of knowledge coalition introduced by van Buuren and Edelenbos [30].

The concept of storyline can be described as a generative narrative which simplifies a phenomenon in order to construct a comprehensible picture of it. The storylines are like discursive cement that keeps a discourse coalition together, while the coalition participates in maintaining and transforming the storyline. [29] Since knowledge production is an important part of coalition-building, the idea of knowledge coalitions was used in order to complement the analysis of discourse coalition. The idea contributes to the discussion of the transgression of science and society [31-33], and moves the focus from between the policy and knowledge worlds themselves to between the coalitions that may include actors from both worlds: for example, citizens, authorities, private sector, and policy-makers [30].

While this study utilizes discourse analysis to explore the way different parties see the phenomenon, conflict analysis is used to describe the conflict, central issues and interests of each party. Here the negotiation theory is used in order to analyze the stakeholder interactions.

Negotiation theory involves two main models of negotiation: distributive and integrative bargaining [34]. The previous includes a strong emphasis in positions, through which parties define their goals and generally engage themselves to a zero-sum negotiation. The main purpose is to defend one's own goals with as minor concessions as possible and to maximize the share of the fixed amount of benefit [35, 36]. Strong positions overshadow the parties' interests and they are locked in narrow-minded thinking thus not acknowledging creative new solutions which could also satisfy the underlying interests.

While distributive bargaining concentrates on the visible tip of the iceberg, the integrative negotiation approach[26] emphasizes the underlying interests which can be seen as the 90% of an iceberg that lies below the surface. According to Susskind [37] the goals and positions hide the parties' true interests, the underlying reasons that explain why they take the positions they do. If these interests are revealed, alternative solutions and benefits for all parties can be searched for. Thus, this value creation process requires a shift from positional thinking to interest-based negotiation [1].

The two cases were studied simultaneously by using an overlapping approach: the observations from one case study were compared with the observations from the other during the whole research process. The case studies involved multiple materials, including newspaper articles (approx. 400 pcs), stakeholder interviews (n=45), and material gained from a workshop. The interviews included representatives from all the major stakeholder groups: environmental and municipal authorities, decision-makers, representatives of a water company, land-owners, representatives of an NGO, and other active citizens.

3. Results

The results of the study are summarized in these three sections. The first section outlines the basic characteristics of the two cases and how different parties interpreted the problem. While the second section introduces the circumstances that led into a conflict and the dynamics in the interaction between the parties, the third section presents possibilities for future groundwater governance.

3.1. What happened in the study cases?

Natural groundwater and artificially recharged groundwater are commonly used as raw water source in Finland. Although artificial recharge was tried in Vaasa, western coast in the late 1920s, wider use of artificial recharge did not start until 1970. In historical perspective, the selection of raw water between ground and surface sources has been an everlasting issue of

[26] Also known as principled negotiation or interest-based bargaining.

debate in the country [38]. Currently, the combined share of the natural groundwater and artificially recharged groundwater supplied is some 66 per cent, out of which 16 percent is artificially recharged and 50% natural groundwater.

Finland is part of the boreal region having rather abundant water resources. The major groundwater resources including MAR, which is mainly used as water treatment method [39], are located in inland eskers and ice-marginal delta formations [40]. The major part of the population is, however, situated in coastal areas. Thus, large city centers are often obliged to withdraw groundwater from afar. While crossing municipal borders, tensions between jurisdictional units may occur.

In addition, MAR projects have evoked contradictions related to spatial planning. MAR processes have indirect impacts on land use due to possible restrictions for other land use activities such as gravel mining, plant nursery, or agriculture. Furthermore, MAR processes involve physical land use requirements for different recharge methods, such as recharge basins, sprinkling, and recharge wells.

The two cases can be shortly described as follows. The first case is situated in the southwestern coastal Turku Region (later referred as case TRW), and the second in the inland Tampere Region (case Tavase) (Figure 1). They are often referred to as sister-projects: In both cases the growing urban area needs to secure its raw water supply in terms of quality and quantity. Good quality groundwater can be found from the rural area although not in sufficient quantity. The problem could be solved with MAR techniques, although the rural area in question does have adequate groundwater resources for the needs of the local community without using MAR. Thus, the local community does not necessarily have motivation for cooperation, which is a key problem in collective action. In both cases opposition emerged in the rural areas and led to long litigation processes.

Case TRW started already in the 1970s. Turku Region Water company (TRW Ltd) was established in order to withdraw raw water from Lake Pyhäjärvi. However, due to strong opposition the project was voted down in 1993 when new plans were directed towards the MAR project in the same rural region.

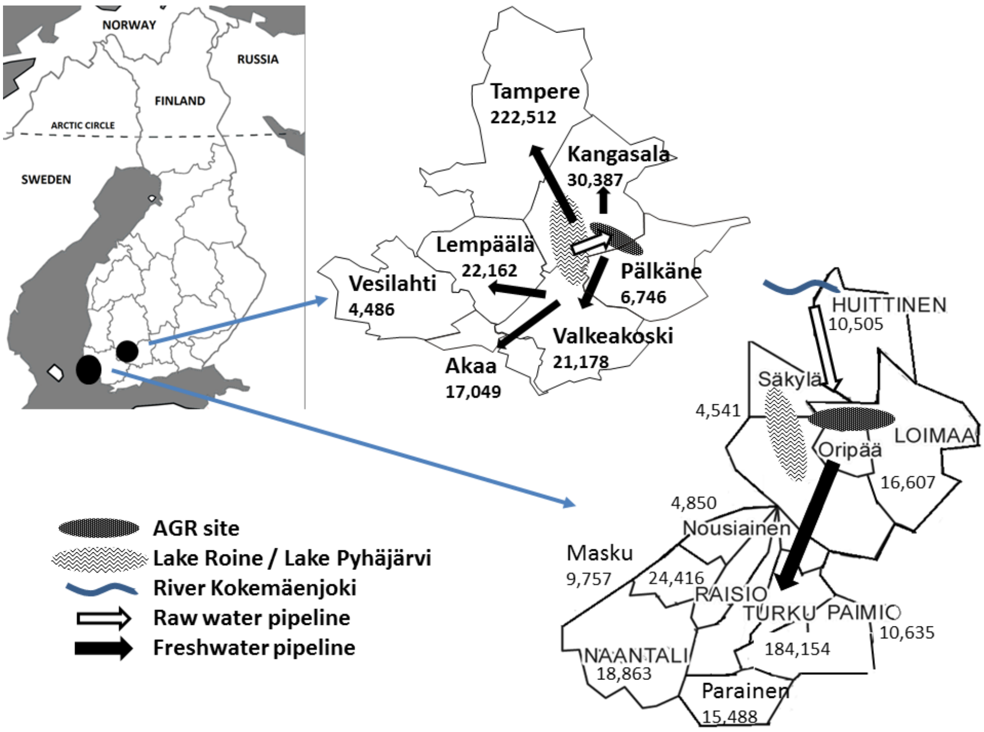

Figure 1. Geographical locations of the two case studies: Turku Region (case TRW below) and Tampere Region (case Tavase above) including the numbers of inhabitants of the municipalities [21].

The opposition continued but after several phases the project got the permission from the Supreme Administrative Court in 2008 and the MAR plant started to operate in 2010.

Case Tavase started in the end of the 1980s, as the municipalities together sought a proper solution for future water supply of the region. In consensus they decided to establish a MAR project, which would be implemented on an esker situated in the rural areas of the region, and managed by a water company called Tavase Ltd. The MAR plant would be constructed on the top of the esker situated in two municipalities, Pälkäne and Kangasala. In this case the opposition emerged gradually, starting from Pälkäne the only municipality that did not have nor need any shares in the project. The opposition was a surprise to the project planners, who were not prepared to respond to these changes in social orders. After years of litigation the project got a negative decision from the licensing authority in June 2015. However, in 2018 a decision came from the Supreme Court of Administration to continue the permit process with the submitted plans in Kangasala municipality. This comprises 70% of the planned drinking water production. According to the decision a change of plans is needed for the operations in Pälkäne municipality: it should be ensured that there will be no risks regarding the wellbeing of a nature conservation area. The permit process continues and further decisions from the authorities are expected in 2019.

While being sister-projects, they do have differences as well. First, while case TRW operates in water-scarce conditions (by Finnish standards), case Tavase region is water abundant. Second, according to geographical positioning, only case TRW may be regarded as a long-distance water transfer project, as it is managed and implemented in two separate areas. In case TRW, the municipalities where the MAR plant is situated are not shareholders of the water company, whereas with Tavase Ltd the municipality of Kangasala is one of its shareholders.

The discourse analysis of the two cases revealed various storylines related to the projects. However, two of them were interpreted as the most relevant ones: local economy and environmental changes storylines, which could both be clearly distinguished in both cases. The opponents were afraid that the MAR project would threaten the local economy e.g. in terms of tighter restrictions concerning other land use activities. However, the other storyline was much stronger and supported the hegemonic environmental discourse: the local residents in both cases saw the MAR project as an environmental threat, whereas the project planners saw it as an environmentally friendly solution to water management problem. There was a clear contradiction between the two discourses: the latent local economy discourse indicates economic competition between jurisdictions as well as tensions between rural and urban areas which should be acknowledged in concrete policy-making. However, the policy decisions were mostly colored by the environmental discourse, especially those aiming at the opposition of the projects.

Despite of this positioning, these conflicts were not formed between experts and lay people. Instead, in both cases, the project opponents also included highly educated actors, and they utilized expert-based factual arguments to support their cause. Furthermore, the local residents included only few local resources in their knowledge claims; instead, they used research results published by outside experts, and individual groundwater experts also gave their personal support to the opponents. Thus, the formed discourse coalitions can also be called knowledge coalitions [30] which move the focus from between the policy and knowledge worlds themselves to between the coalitions that include actors from both worlds.

3.2. Why did this happen?

From the perspective of collaborative governance the principal problem can be summarized as follows: the project planning and management has not been able to recognize the complexity of the problem and thus collaborative tools were not used. This conclusion is described in more detail below.

First, instrumental rationality, with an emphasis mainly on rational expert knowledge, still prevails in water management sector where socio-economic environment is not adequately acknowledged. In the case studies, the projects were managed merely from technical perspective and the influence of social orders to water management was underestimated. The base for conflicts which emerged around the two MAR projects was in the planning approaches based on instrumental rationality that could not successfully operate in the field of complex water management.

Second, collaborative governance includes dialogue and negotiation between parties, especially integrative bargaining which emphasizes the interests of the parties [1, 37]. However, in the case studies the actors concentrate on the positions of actors which can be seen as the tip of the iceberg, the visible part of the conflict, while the invisible interests were neglected. Thus, the argument here is that actors put most of their efforts and energy into a minor fraction of a problem while the major and most important part is left without attention. Accordingly, although in both cases the environmental argumentation acted as the main discursive cement inside the opposing coalitions, the latent local economy discourse revealed some profound concerns and interests of the local residents. Whereas protecting groundwater and the environment was of particular relevance to local actors, the local economy formed one of the main concerns related to the MAR projects. However, the interests and values are often hidden under the positions and here environmental argumentation overshadowed a latent but important local economy discourse. At this point, the planners' professional skills, which leaned on instrumental rationality, did not support a more comprehensive analysis of the case and acknowledging the interests of the opponents. Instead of acknowledging the interests of the other side, the parties aimed towards their own goals with a competitive mindset. The project planners were locked into their own positions defined by the water companies, and the opposing coalitions could not see any other way out than trying to stop the whole projects.

Third, as opposed to collaborative governance, the parties adopted a mental model of distributive bargaining. This refers to a tendency for zero-sum game [1] where the ground rule is that the amount of benefit is fixed and the parties need to compete for those benefits, since any concession for one would mean fewer benefits for the other. Thus, a competitive atmosphere was formed around the projects: the local residents feared economic losses and environmental impacts that the MAR projects would cause to their municipality and they were not willing to negotiate any concessions. In both cases, project planners tried to indicate some benefits that local residents would gain from the project and to offer compensation if some unintended effects would occur but they did not manage to build any collaborative negotiation process. Thus the compensations were not acknowledged in this competitive atmosphere and mutual trust was already lost: the opponents claimed that these concessions were false or inadequate. There was no place for alternative or creative solutions, which would satisfy the underlying interests of both parties. Distributive bargaining model easily ends up in a deadlock or only creates winners and losers; thus, it often destroys relationships and fosters mistrust and hostility [41].

Fourth, collaborative governance framework supports a knowledge production process where the expert knowledge is integrated to the negotiations through a collaborative process, for example joint fact-finding [42]. In the case studies, however, expert knowledge did not work as a tool for collaboration but as a fuel for even stronger counter-argumentation. Knowledge coalitions were formed between the opponents and project planners, and neither of them approved the arguments presented by the experts from the other coalition. The situation turned to a deadlock where the expert-based arguments did not calm down the opposition; instead, it became even stronger. Therefore, this research supports the argument presented, for example, by Nelkin [43], Pellizzoni [44], and van Buuren [45]: increasing the amount of expert knowledge does not necessarily solve the problem.

3.3. What could have been done otherwise?

Analyzing the challenges which the two MAR projects faced can offer some lessons for future complex groundwater projects. These lessons are presented in this chapter and complemented with literature on collaborative governance.

Whereas the goal of conventional groundwater management is to achieve outcomes that fulfill technical, legislative, and environmental requirements, in collaborative groundwater governance the basis should be in the legitimation process. In that process two major aspects needs to be considered: interaction and knowledge production. As the two case studies illustrated, failed interaction is one of the fundamental constraints for complex groundwater projects and can form an insurmountable barrier between parties. However, if the interaction is successful it can form a bridge even between contentious interests of various parties. In a collaborative process, acknowledging the concerns of the other side and clarifying the interests of each party would help them to see outside the box [36]. Thus, parties would start to realize that instead of having a fixed amount of benefits, they have several other options, and it is worth investigating those options before committing to particular solutions. The integrative negotiation model is used in order to produce an agreement between the parties. However, the aim is not that everyone wins (it would be unrealistic); instead, the aim is to enter into an agreement that meets the parties' interests better than if they could not reach an agreement at all [1].

As for knowledge production, conventional groundwater management is driven by an assumption of perfect and objective information that can be obtained by expert analysis. However, in complex cases this assumption leads to a deadlock. Disagreement on the facts prevails also among the experts themselves. In the case studies, also the opponents invoked authorities who were considered to be experts in the field. This was possible, since, among the experts, MAR was not unambiguously approved as the best water management solution to the areas in question. Here neither the opponents nor the project planners consider the knowledge produced by the other party as reliable. Thus, the main task is to create a legitimate knowledge base together with experts and stakeholders [see 1, 46]. In this joint knowledge production process, expertise is exploited as a fundamental source of knowledge but it is complemented with local, experiential, and other forms of non-scientific knowledge. However, the most important question is to find legitimate ways to gather this knowledge base, which then forms a cornerstone for the collectively produced truth about the problem.

In these settings, the role of a water manager should be redefined. Instead of being the holder of the only legitimate source of knowledge, she or he could be a facilitator or even a mediator who has the key to expert-based knowledge but could also acts as a conveyor, who constructs and maintains collaborative process and ensures that every relevant stakeholder is around the negotiation table. Especially in complex groundwater conflicts it is critical that a mediator has technical background and understanding of the substance [12]. Water managers should embrace the idea that in order to reach durable and feasible outcomes in processes, instead of just *allowing* stakeholders to participate, we really *need* them to participate. The stakeholders should be viewed as partners or allies who are an invaluable asset for dealing with current groundwater management problems that are inherently complex in nature.

4. Discussion

This research analysed two MAR conflicts using the framework of collaborative governance. Together with discourse and conflict analysis and negotiation theory this led to a comprehensive analysis of the iceberg: visible discourses, hidden interests as well as main constraints were revealed. These cases involved conventional way of thinking and management of groundwater, which was based more on instrumental than collaborative rationality. Tools and practices derived from the conventional management were not sufficient in governing complex MAR issues.

Evidently, implementing collaborative tools include several practical challenges. It might be, for example, challenging to persuade every party to the negotiation table, especially in the situations already escalated or blocked, as it was in both cases. If one of the parties assumes that it is already winning the case and it would be even harmful to start negotiations, they may use the power of not collaborating [47, 48]. Accordingly, the emphasis should be transferred from conflict resolution to anticipatory work. Early engagement is often emphasized as essential in order to achieve durable outcomes [e.g. 13, 41, 49, 50].

Furthermore, many water professionals as well as authorities may discard collaborative approaches because of their complexity. A collaborative process is likely to be more complex with multiple parties involved than the conventional linear process. In addition, some professionals may fear the loss of authority in informal problem-solving, whereas elected officials may view consensus-based process as giving up power. [1] Conventional way of thinking is rooted deep in practices and structures of water management sector as well as in the education of water professionals, thus setting the standard of acting for multiple parties [23]. These standards may be difficult to break in individual cases, unless a larger paradigm shift occurs.

The need for more holistic approaches in scientific inquiries and also in practice has been acknowledged for decades [23]. Conflicts can be seen as anomalies that challenge the prevailing paradigm. Since current ways of thinking and practices of operation no longer provide satisfactory results, the problems need to be redefined. Accordingly, conflicts around the two MAR projects can also be seen as challenges to the expert system and prevailing planning paradigm. It seems that the world of water planning and management is balancing between two paradigms: instrumental and collaborative rationality.

Accordingly, the new paradigm neither discards the old one totally nor offers direct solutions to old problems. Approaches framed by the old paradigm are still usable in some cases. For example, constructing a water pipeline network to a new residential area is not as complex nor as unpredictable management problem as is an inter-municipal MAR project. Thus, its construction would probably not require a collaborative planning and implementation process. Therefore it is crucial to identify the level of complexity of the problem and analyze the problem thoroughly. This would help choosing proper management tools and approach for the planning process.

The new paradigm can be seen as an addition to the coexisting theoretical sources and practices from the old paradigm [51]. Accordingly, the core of groundwater governance should be in collaborative rationality while some of the tools can be obtained from rationalistic expert-based planning, not vice versa. For example, expert-based knowledge production can be exploited as a crucial part of the joint knowledge production process in order to answer the question of what we are processing. Instead, collaborative approaches can answer the question of how we should proceed in terms of interaction and legitimation of the process.

Finally, the contextual framework of this study lies in the larger context of urban planning as well as natural resources management (NRM), and the findings echo the earlier research on collaborative governance in these fields. Although the specific context here is in groundwater management and MAR as well as geographical context in boreal regions, the results are most probably transferable to other settings as well. As the results indicate, context needs to be considered in every analyzing process but the most profound reasons for conflict do not necessarily depend on context. Thus, this research offers signposts for directions from which answers can be searched for but the journey for the search varies in different terrains.

Acknowledgments: We wish to acknowledge the VEPATUKI research cluster for the financial support.

Author Contributions: Vuokko Laukka has performed the research related to the doctoral dissertation and is the main writer of this article. Tapio Katko was the supervisor of the thesis and commented this paper. Lasse Peltonen and Riikka Rajala commented this paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:
MAR: Managed Aquifer Recharge
TRW: Case Turku Region
Tavase: Case Tampere Region

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Extended Abstract for Proceedings of ISMAR10 ***Topic No: 20 (096#)***

Evidence dispels commonly held views on streambed recharge structures in hardrock aquifers in Rajasthan, India

Peter Dillon [1], Yogita Dashora [2], Prahlad Soni [2], Basant Maheshwari [3], S. Davande [4]

[1] CSIRO Land & Water, and NCGRT, Flinders University, Adelaide, Australia; pdillon500@gmail.com
[2] Vidya Bhawan Krishi Vigyan Kendra, Udaipur, India; dashora.yogita@gmail.com; prahladsoni.baif@gmail.com;
[3] Western Sydney University, Penrith, New South Wales, Australia; b.maheshwari@westernsydney.edu.au
[4] Arid Communities and Technologies, Kutch, Gujarat, India, (currently at Foundation for Ecological Security, Anand, Gujarat, India)
*Correspondence: pdillon500@gmail.com; Tel.: +61 419820927

Abstract: Four commonly held views on the effectiveness of recharge structures in ephemeral stream beds to enhance recharge in hardrock aquifers of India have been have been objectively evaluated in the Dharta catchment of Udaipur district in southern Rajasthan. It has long been claimed that: (1) groundwater level rise demonstrates that recharge structures are effective; (2) the greater the rise in groundwater level, the more effective is the recharge structure; (3) recharge from streambed structures is greater when the water table is shallower; and (4) recharge structures only benefit farmers in very close proximity. Three years of monitoring of rainfall at four stations, water levels in four checkdams and groundwater levels in 250 wells, have conclusively disproved these views, and in two cases the reverse is in fact true. Importantly this shows that monitoring practices in current general use are incapable of demonstrating the effectiveness of streambed recharge structures, nor their maintenance requirements. However the work has also demonstrated simple methods that can be used by farmers to evaluate recharge rates from streambed recharge structures, and this can be used for scheduling desilting. Increased information generated in this way will be valuable in siting and sizing of any future structures in a catchment, taking account of local and downstream impacts.

Keywords: Streambed recharge structures; check dams; natural recharge; ephemeral streams; monsoon; semi-arid; hydraulic connection; stream-aquifer interaction; monitoring; irrigation.

EXTENDED ABSTRACT

1. Introduction

A well-monitored catchment provided the opportunity to assess the relative importance of recharge from check-dams with 'natural' recharge in the prevailing landscape. The Dharta catchment in south eastern Rajasthan was one of two hard rock catchments studied in the Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention project (MARVI) (Maheshwari *et al* 2014) [1] between 2012 and 2016, and is still being monitored in 2019. The project was aimed at (1) determining the hydrological balance of the catchment, to determine hydrological and economic impacts of recharge structures, (2) to assess demand-side measures to maximize the benefit of the groundwater resource, and, in an extension, (3) to implement and evaluate the effectiveness of village groundwater cooperatives to manage water resources. An important feature of the project was to train farmers to monitor rainfall, dug wells and check dams and use the observations to plan evidence-based solutions for water management (Jadeja et al 2018) [2].

2. Materials and Methods

The 4500ha Dharta catchment of Udaipur district in southern Rajasthan was studied in the MARVI project. Water levels of 4 checkdams on first and second order ephemeral streams were monitored daily over 3 years by farmers to determine recharge rate and water balances and recharge rates were calculated using area- and volume-elevation curves, as described by Dashora et al (2018) [3]. Groundwater levels were monitored over this period at nearby wells and the results reported by Dashora et al (in press)[4]. In addition direct recharge to 5 wells from filtered runoff from fields was monitored for one year and groundwater levels for 11 direct recharge wells for 2 years. Recharge wells and nearby wells and were monitored for at least two years before water was admitted to wells Direct well recharge results are reported separately by Soni et al (*ibid*). Groundwater levels were monitored weekly over 4 years at 250 wells dispersed in the same catchment. Electrical conductivity and fluoride concentrations were recorded in all wells before and after the monsoon in one year. Annual recharge volumes in each monsoon season for each check dam were related to groundwater level rise in nearby wells and in all wells. Semi-variograms of water level rises were produced in relation to distance of each well from its nearest checkdam and the distance from the nearest stream. Contour maps of monsoon season groundwater level rise were also krigged. Statistical analysis of groundwater levels provided answers and levels of confidence.

3. Results

Results for direct recharge wells are given in Soni et al (2019) ibid [5]. Detailed results for check dams, including tables and graphs from analyses will be given in the oral presentation at ISMAR10 and included in an expanded paper. Below is given just a brief summary of results for check dams.

3.1. Groundwater level rise demonstrates that MAR is effective

This statement was proven FALSE. Groundwater level rise was shown to be overwhelmingly dominated by natural recharge in this catchment. Over three years the 4 monitored checkdams contributed only 8% of the gross recharge Dashora et al (in press) [4] and Chinnasamy et al 2018 [6]. While effective MAR will result in groundwater level rise, the rise in level is mainly caused by natural recharge. So a check dam could be completely clogged and groundwater levels in the vicinity will rise due to natural recharge. Hence groundwater level rise does not demonstrate that MAR is effective. To demonstrate the effectiveness of MAR we need to monitor the decline in water level in the percolation tank and subtract the evaporation rate to give dry weather infiltration rate. From a volume and area-elevation curve for the structure, the volume of recharge from the recharge structure can be calculated. Additionally, if we observe change in groundwater salinity (chloride if possible) of percolation tank water from the end of the monsoon until before it dries, and making use of volume- elevation curve, the decline in storage can be partitioned between infiltration and evaporation, as a confirmatory measure. We would generally consider a recharge structure to be effective if dry weather infiltration rate exceeds 3 or 4 times the evaporation rate. In winter evaporation rate is estimated to be about

5mm/d. So dry weather infiltration rates larger than 15 to 20mm/day would indicate an effective recharge structure.

3.2. The greater the rise in groundwater level, the more effective is the MAR

This statement was proven FALSE. Rise in water level depends on the rate and volume of infiltration, and on the aquifer transmissivity, the specific yield and the rate of lateral flow in the aquifer, neglecting pumping over monsoon months. Among check dams there was no correlation between head rise in adjacent wells and the magnitude of recharge. Transmissive aquifers which are the most efficient to recharge will give a lower head rise than less transmissive aquifers under the same recharge rate. Hence, the same head rise can be indicative of both high recharge rates in a high transmissivity aquifer or of low recharge rates in a low transmissivity aquifer, and so they are not proof of high recharge rates. For proof of effectiveness of recharge structures we need to monitor water levels in the structure. Monitoring groundwater levels concurrently allows an assessment of whether hydraulic connection between the impounded surface water and groundwater has occurred. If this takes place when there is a large increase in groundwater levels the recharge rate will diminish significantly.

3.3. Recharge is greater when the water table is shallower

This statement was proven FALSE. This may be true for natural recharge where the water table is well below the ground surface, so that groundwater does not discharge to the surface. For deep water tables more water remains in the soil in the unsaturated zone so that recharge reaching the water table is less than the infiltration from the surface. With recharge structures, if water table rises to reach the floor of the impoundment, as is more likely when the initial water table is shallow, then hydraulic connection between the surface water and groundwater occurs, and infiltration rates reduce by an order of magnitude, because the hydraulic gradient has reduced. If water table continues to rise, remembering that this is also due to natural recharge, then if this exceeds the water level in the recharge structure, recharge stops and groundwater starts to discharge into the impoundment. This adds to the baseflow in the stream until rainfall stops and the groundwater level recedes. The processes are described in Dillon and Liggett (1983) [7] showing the transition through connection and disconnection of ephemeral streams and examples are given for Rajasthan check dams in Dashora et al (in press) [4]. For each check dam that became hydraulically connected in a 'wet' year, because of the high natural recharge, check dam recharge was less than in 'average' years Dashora et al (in press) [4] owing to higher water tables.

3.4. MAR only benefits farmers in very close proximity to recharge structures

This statement is considered to be FALSE for the hydraulic characteristics of the unconfined aquifer in the Dharta catchment. In aquifers with low transmissivity and high specific yield and low lateral hydraulic gradients, the benefits of recharge structures may be localized. However in the majority of cases water recharged through streambed structures contributes to the overall groundwater balance in an area and many farmers benefit from the increased storage. Very often there is underlying alluvium that helps to spread the recharged water down gradient into what has been termed the "command area". Using aquifer hydraulic parameters defined for this catchment (Chinnasamy et al 2018) [6] it is evident that lateral flow is extensive over the monsoon and rabi/winter seasons so many farmers beyond the immediate proximity of the recharge structure would benefit.

Acknowledgments: The MARVI Project (Managed Aquifer Recharge and Village scale Interventions project) was supported by the Australian Centre for International Research (ACIAR). Extensions are to be supported by ACIAR, Australian Water Partnership and the

Government of Rajasthan via the Rajasthan Centre for International Water Research and Management.

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Paper for ISMAR10 symposium. ***Special session adaptation*** *124#*

Implementing an energy-neutral ASR system in a complex setting in Lebanon

Lukas Rolf[1]*; Sieger Burger[1]; Arjen de Vries[1]and Ane Wiersma[2]

1 Acacia Water, Van Hogendorpplein 4, 2805 BM Gouda,The Netherlands; info@acaciawater.com
2 Deltares; Daltonlaan 600, 3584 BK Utrecht, The Netherlands; ane.wiersma@deltares.nl
* Correspondence: lukas.rolf@acaciawater.com. Tel.: +31 182-686424

Abstract: As part of the project "Strengthening the Lebanese Water and Agricultural Sector" a Managed Aquifer Recharge (MAR) pilot system was implemented in the western Bekaa Valley. This paper gives a project overview; 1) Background: The geological setting and challenges of implementing MAR systems in karstic aquifers; 2) Development of a site suitability framework for MAR in karstic aquifers; 3) Site selection process outlining the decision to implement the pilot project in an alluvial aquifer; 4) Design, installation and monitoring of the pilot system; 5) Evaluation of the course of the project; 6) Recommendations for future MAR projects in Lebanon. Major challenges during project implementation included the short project duration of 2 years without a possibility of extension and lacking support of local water authorities. Nevertheless, building a tangible pilot project based on sound scientific research and with state-of-the-art technology proved to be a suitable approach for showcasing the potential of MAR in helping to alleviate Lebanon's groundwater problems. The project can have a valuable contribution to advance the discussion and local knowledge development on technological aspects of ASR systems, ownership models and business cases, requirements for regulatory frameworks and governmental support in regards to recharging aquifers.

Keywords: Agricultural ASR; MAR siting; pilot system; project overview; Bekaa Valley, Lebanon.

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1. Introduction

Lebanon, on the eastern Mediterranean coast, has over the past decades struggled with decreasing groundwater reserves. It is not a dry country per se. It receives relatively large sums of precipitation and unlike most countries in the region is not dependent on inflow from other countries. An advantage is also that snow constitutes a considerable part of the precipitation, which prolongs the natural runoff into the dry summer. Lebanon has renewable water resources of around 900 m^3/cap/year, which places it slightly below the water scarcity threshold of 1,000 m^3/cap/year [1].

The country's challenge in water supply is that most water flows rapidly the short distance from the mountains into the Mediterranean Sea during the rainy and melting season without being harnessed or used, while many rivers run dry during the summer when demand for irrigation water is the highest. Of Lebanon's 40 streams more than half are seasonal. Thirteen rivers with an average length of less than 60 km flow from the high Lebanese coastal range directly into the ocean. Utilizing the winter discharge to recharge groundwater reservoirs is a promising method of improving the water supply during the dry summer.Managed Aquifer

Recharge (MAR) has been on the table in Lebanon for a long time, but was piloted only once in the 70's with insufficient monitoring[2].

As part of the project "Strengthening Lebanese Water and Agriculture Sector" a MAR system was implemented between 2017 and 2019, the first of its kind in Lebanon. The aim of this project was to construct a MAR scheme that could serve as a demonstration project and assess the potential to upscale such installations in Lebanon.

2. Background

MAR in karstic limestone

Lebanon has a geology that is typical for many countries around the Mediterranean. Most of the rocks are limestone, which are deeply weathered by the dissolution of the calcium carbonate making up the limestone. This dissolution results in bare rough rocks at the surface and a maze of underground caves and fractures. The features related to this limestone dissolution are called "karst".

Globally, there have been successful applications of MAR in karstic limestones [3]. However, due to the unpredictability of the underground fractures and caves, the performance is highly uncertain and therefore also many failures of MAR application are reported in similar settings. In these MAR systems, water can be successfully injected, but it is not always clear where the water is going to. The karst aquifers of Lebanon are large, complex systems and for large parts of them there is not sufficient geological data available. Especially in the mountainous regions injected water is unlikely to stay in the vicinity of the infiltration well, making a small-scale MAR system using a single infiltration and abstraction well not feasible. For this pilot project it was therefore decided to not continue to pursue a MAR installation in the limestone aquifers, as the chances of success are very uncertain.

MAR in Lebanon

Previous studies in Lebanon identified potential MAR sites in karstic limestones based on a GIS analysis of local conditions. MAR as a potential mitigation measure in Lebanon has been discussed by various authors theoretically. The Lebanese Ministry of Energy and Water (MoEW) provides a comprehensive assessment of Lebanon's groundwater resources and analyzes the potential of MAR [4]. The authors identify 30 potential locations for MAR schemes, 20 of which would use river or spring discharge for infiltration and 10 would use sewage treatment plant effluent. Feasibility studies of MAR facilities at four of the proposed sites were conducted [5 – 8]. The proposed projects are of rather large scale and require considerable investments (US$ 3 – 18 million).

Daher et al. [9] developed a conceptual methodology for assessing the rechargeability of karst and demonstrated it for a region in Lebanon. The method, referred to as ARAK, utilizes four physical parameters to develop a map of MAR potential.

Several studies propose MAR schemes of different kind in the Damour area, where public wells for Beirut's water supply cause an aquifer over-exploitation of 13.5 MCM/year. Daher et al. [9] for example, draft a MAR scheme of horizontal tunnels drilled into the side of the Damour River valley to recharge the karstic aquifers. Khadra et al. [10] propose "fresh-keeper wells" to protect inland groundwater from seawater intrusion and produce fresh water by desalinating brackish groundwater.

3. Site suitability framework for MAR in karstic aquifers

A comprehensive desk study was carried out at the beginning of the project to scan the potential for MAR on a national scale in Lebanon and to develop a framework for assessing site suitability for MAR in karst regions [11]. A thorough literature review and expert interviews were carried out which contributed to the compilation of criteria that can indicate the suitability of a location for a MAR system. In a multi-criteria analysis, a selection of eight potential MAR sites in Lebanon that were previously proposed by a MoEW study [4] were compared, and the sites' suitability regarding different aspects was analyzed.

The central part of the site suitability assessment framework is a multi-criteria analysis. Its core is a newly developed criteria catalogue which provides a wide range of aspects that the plausible MAR sites can be compared across. Depending on the objective of the MAR project and the focus of the decision-making process, criteria from different domains can be chosen. Data availability will also affect the selection of criteria from the catalogue. The criteria catalogue (Figure 1) is divided into eight themes which contain 52 categories which, in turn consist of 141 criteria. For example, criteria that can be evaluated to rate site suitability in the category "level of aquifer stress" include: Groundwater balance; decrease of groundwater levels; but also increase of salinity.

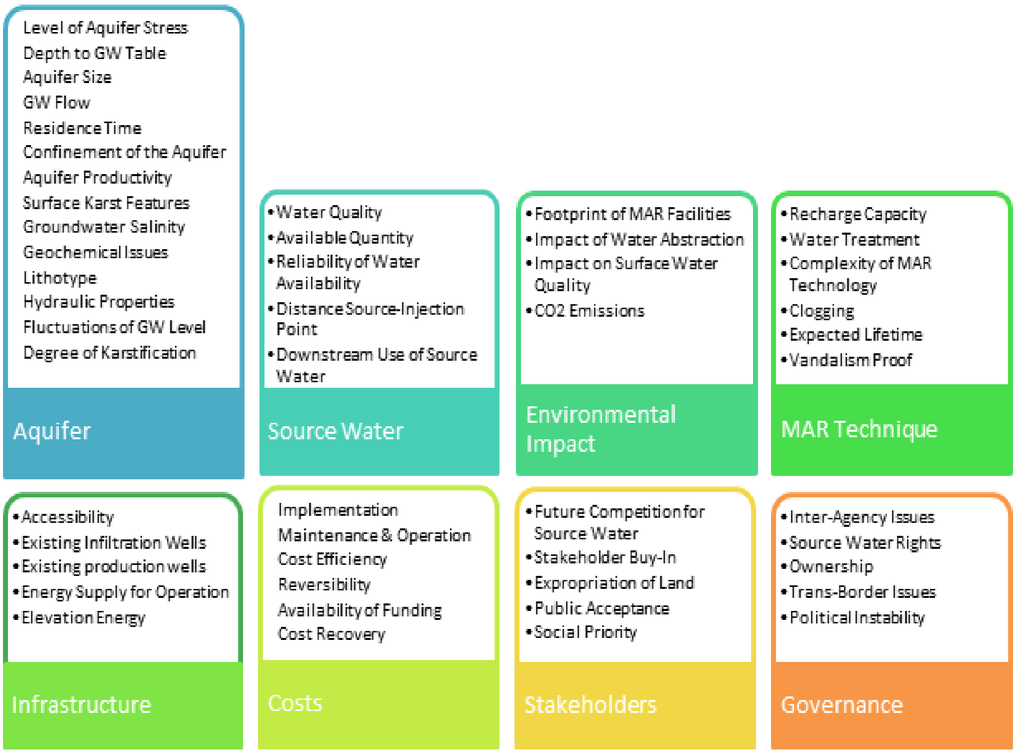

Figure 1. Themes and categories of the criteria catalogue for assessing the MAR site suitability in karst [11].

MAR in alluvial sediments

An important finding of this desk study was that the hydrogeological challenges of storing water in highly permeable karstic aquifers add an extra layer of uncertainty to a MAR pilot project. Determining the hydrological characteristics of a karst aquifer at a given point is very difficult because of the heterogeneity. Transmissivities and yields observed at one well might not be achievable at a well close by because fractures and conduits are not distributed uniformly. For a MAR system this implies that the karst aquifer must be thoroughly tested at the potential MAR well, especially with regards to the aquifer's ability to hold the water in the vicinity of the well for the entire recharge period. If not known, it is unclear where the infiltrated water flows to, which makes it hard to determine the impact.

Implementing a pilot MAR system seems therefore more promising in alluvial sediments of the Quaternary and Miocene than in the Cretaceous and Jurassic karstic limestones. A consequence is that the MAR system will have a smaller capacity. However, if the pilot proves successful the small scale systems can be implemented on a larger scale.

To achieve this, the developed framework can help in determining promising locations. This study also outlines what data is necessary to determine suitable sites and design the MAR scheme. The framework is not exclusively applicable in Lebanon but is a useful starting point for other projects that aim at implementing managed aquifer recharge systems in karst aquifers worldwide.

4. Selection of MAR pilot site

After the inception phase had revealed that implementing a MAR pilot system in karstic aquifers would be too risky the focus lay on locations with unconsolidated sediments, such as sand or gravel. In the Netherlands, the involved parties have an extensive track record with MAR in unconsolidated sediments. In Lebanon, there are three areas with unconsolidated formations that have been identified during the inception mission with field investigation and associated desk studies to have potential for the MAR pilot: The Akkar Plain, the Damour coastal strip, and the Bekaa Valley (see Figure 2).

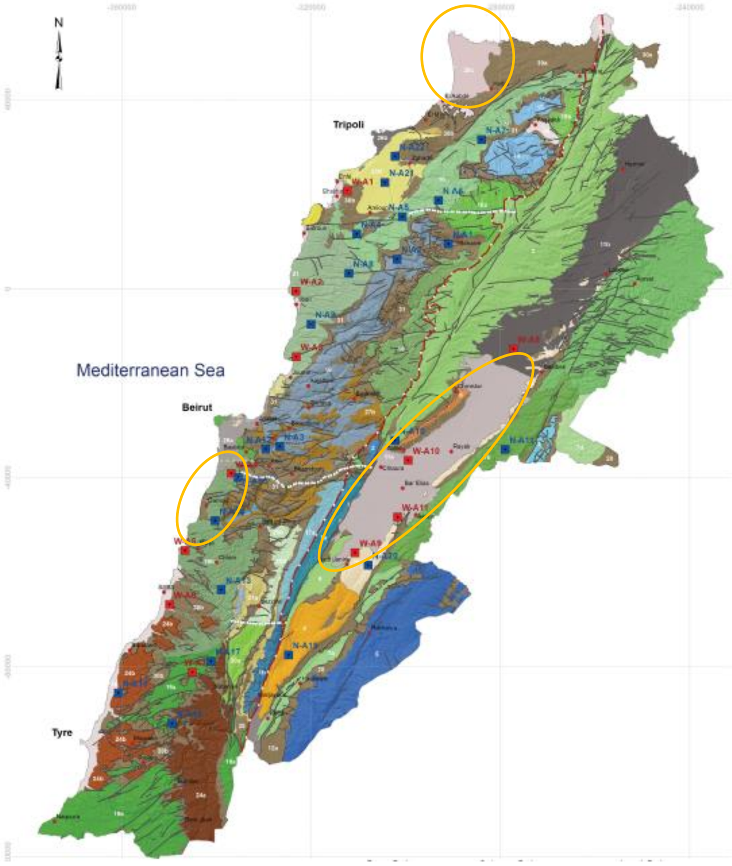

Figure 2. Suitable site for MAR in alluvial sediments: The Akkar Plain in the north of Lebanon, the Damour coastal strip south of Beirut and the Bekaa Valley [4].

First, a number of requirements were defined that the MAR pilot site should fulfil. The main requirements were:

- Geology: soil properties should be suitable for the application of MAR
- Water: a water source with clear unpolluted water needs to be available for infiltration. The project needs to have the approval to use this water

• Landowner: A cooperative and enthusiastic land owner is the most important prerequisite for ensuring long-term ownership, for supporting swift implementation by provide practical on-site support, and for being a strong ambassador of the technique.

Other requirements are power supply, telecommunication service, security, accessibility and water demand. After narrowing down the number of potential sites based on these criteria, extensive field investigations and electrical resistivity surveys, a site on a grape producing farm in the Bekaa valley proved to be the most favorable location.

The landowner and the executing manager of the selected site were very enthusiastic and cooperative. The farm promotes a sustainable approach to farming where MAR is seen as a technology that closely matches this approach. In addition, unpolluted water is available nearby in a ditch on the premises, which can serve as water source – another indispensable precondition for a pilot site.

Benefit of MAR in the Bekaa Valley

The Bekaa Valley is flanked by the Lebanon and Anti-Lebanon mountain ranges. It is drained to the south by the Litani river, that feeds the Lake Qaraoun reservoir. The river is fed by the many springs that flow from the foot of the limestone mountain ranges (Figure 3). The valley is underlain by a series of aquifers, which are alluvial unconsolidated sediments at the top, and older karstic limestones below. These aquifers are generally overexploited by the many, partly unlicensed, wells that withdraw water, mostly for irrigation purposes. Hence, the groundwater levels decline at an alarming rate – the situation is unsustainable.

A side effect of this overexploitation is that the springs coming from the mountains diminish. In addition, the river, that used to be naturally draining the Bekaa Valley, now is or will soon become a looser stream, infiltrating and losing water to the subsurface. This leads to a lower availability of surface water, and lowering of the water table of Lake Qaraoun.

Successful application and upscaling of underground water storage in the form of MAR could result in reduced extraction of the deeper aquifers. This results in partial recovery of the natural groundwater system and facilitates recovery of spring discharge and therefore the surface water availability.

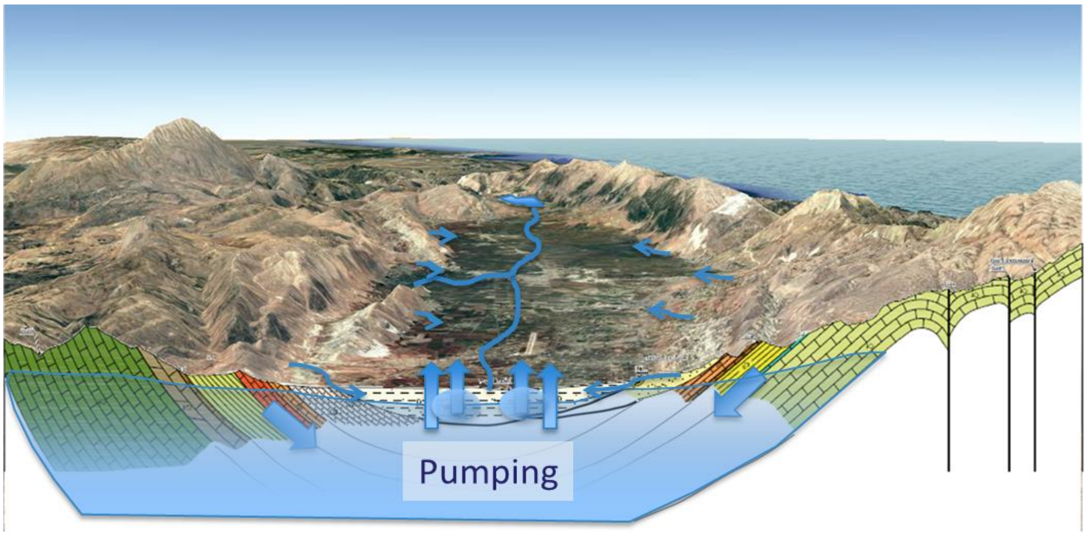

Figure 3. Schematization of the geology and (ground)water system in the Bekaa Valley, looking south. Recharging the groundwater in the unconsolidated sediments in the valley plain (white) would take pressure off the underlaying limestone aquifers, thereby benefitting spring discharge ([12], modified Google Earth image).

5. Design, installation and monitoring of the MAR system

The MAR system was designed as an off-grid solution with low operation and maintenance requirements. Its functioning can be schematized in three processes (Figure 4): During capturing surface runoff that is generated by the winter rains and by snow melt water is abstracted from a ditch. It is piped to the operation unit where it is filtered. The clean water then enters the storage phase during which it is infiltrated in the aquifer via MAR well. Due to the low permeability of the aquifer the infiltrated water stays close to the well. In the summer, when the surface water has dried up, the stored groundwater is pumped up for irrigating vineyards.

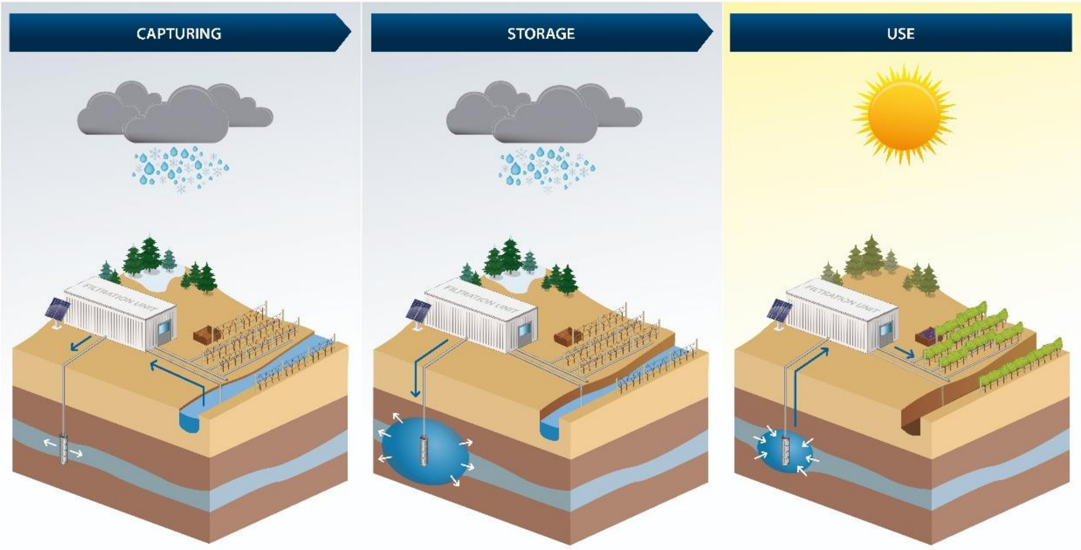

Figure 4: Schematization of the operation processes of the MAR system.

The outcome of the site selection led to the decision to install the MAR system on a vineyard and drill the MAR well in Miocene sediments (consolidated and unconsolidated). During the drilling down to 230 m no underlying hard rock was found, which gives important new insight into the geology of the area. The geophysical investigation and existing knowledge of the local geology had indicated that the thickness of the overlying sediments was in the order of 100 m. Suitable unconsolidated layers for storing water were found in the section of 156 – 198 m depth and correspondingly the filter was placed in this section.

The MAR scheme, which can be operated energy neutral and off-grid, consists of three main components:

1. Source water intake point: Consists of a small abstraction weir in a drainage ditch which gathers the surface runoff and return flow of a 3 km2 catchment area. From the abstraction point the source water flows through 800 m of pipeline to build up pressure for filtration using elevation difference of the landscape.

2. Operation and filtration unit: A container houses 8 filters to treat the source water before infiltration. It also contains the controls and water monitoring equipment which can be accessed online. A generator in the container acts as a backup in case the field of solar panels do not produce enough energy to power the abstraction pump.

3. Dual-purpose well: 200 m deep well with one filter column for infiltration during the winter and abstraction during the irrigation season using a submersible pump which is solar-powered. The borehole was drilled with a 15" diameter while the filter and casing have a diameter of 8". The well column is constructed of PVC in the filter and lower casing section and of corrugated steel in the upper casing section.

6. Course of the project

The project ran for about two years. As I t is often with projects that involve a field component in a challenging country, not everything went as planned. In the following an overview of the course of the project is provided, and some of the issues that that were faced are summarized.

Project approach

The objective of the project was to find solutions for small-scale groundwater storage with upscaling potential to bridge the gap of low water availability during the irrigation months. It was important to implement a tangible pilot system, rather than only producing a feasibility study.

To this end, a funneling approach was chosen: During the inception phase a scan of the entire country was carried out, and then the site selection was focused on a number of potential locations in sedimentary aquifers. The final MAR site was selected so as to make optimal use of the landscape to achieve minimal energy consumption. The MAR system was then designed according to the site conditions. The project was accompanied by an economic assessment to determine the agricultural sectors and preconditions for upscaling the technology. Throughout the project stakeholder involvement was ensured by frequent meetings and joined activities of the Dutch and Lebanese partners, and by close communication with all parties involved in the implementation process.

Project conclusion

At the point of writing the MAR system is functional, but with limitations regarding the infiltration capacity, clogging management, and monitoring. Despite a very tight time schedule and various geological, logistical, and engineering challenges it was possible to build a functional pilot system. However, in very recent developments the governmental support for the system was revoked. It remains unclear whether the MAR system will be able to operate or if the site will have to be cleared of all equipment.

However, MAR has a prominent position as "projected additional water resources" in the National Water Sector Strategy 2010 – 2035 developed by the Ministry of Energy and Water [1]. Accordingly, MoEW officially supported the project. In short, the benefits of MAR are:

- Storing water without contamination risk, as opposed to open reservoir which tend to be heavily polluted
- Storing water where it is needed, avoiding transportation via canals of irrigation schemes
- Storing water without evaporation losses
- Counteracting the deteriorating groundwater levels, thereby improving base-flow of the Litani River because less irrigation water has to be abstracted from springs.

The role of local water authorities

Next to the MoEW, overarching water authority and endorser of the project, the Litani River Authority (LRA) is a major stakeholder in the project. Responsibilities of the LRA include the management of Lake Qaraoun, Lebanon's only large-scale reservoir. The reservoir is used for hydropower production and to feed irrigation schemes in the south of the Bekaa Valley. In a normal year there is not enough inflow into the reservoir to fill it to full capacity. The constructed MAR project lies in the upstream catchment area of the Litani River which feeds Lake Qaraoun. LRA's concern is that an operational MAR system upstream of the reservoir will further diminish the inflow into the reservoir, thereby decreasing the capacity for energy production and irrigation.

Unfortunately, the LRA does not endorse the project, reasoning that MAR in the Bekaa Valley, once upscaled, would compete with the recharge of the prominent Quaroun reservoir. This view does not take into account the comparatively small capacity of MAR systems, even if 100 or 1,000 systems were constructed in the Bekaa Valley, nor does it consider the benefits of MAR for irrigation agriculture when compared to water storage in open reservoirs. The potential environmental benefits of MAR in counteracting the development of Litani River becoming a losing stream are equally disregarded.

Project duration

The project was scheduled to run for two years. The implementing partners faced many difficulties to achieve the ambitious goals within this timeframe and proposed a budget-neutral extension of the project duration. This would have allowed for a proper testing of the MAR system and optimization of the system during a full cycle of infiltration (winter) and irrigation (summer) – at no additional costs. Unfortunately, it was not possible to extent the project duration.

7. Recommendations and lessons learned

A number of important lessons were learned during the course of the project and future MAR projects in Lebanon might be able to profit from these recommendations:

- Source water: Source water measurements, both quality and quantity should be done at an early stage, so that the design of the MAR system can be adjusted accordingly (e.g. how much water is available for infiltration, what type of filtration is necessary).
- Stakeholder cooperation: One of the selection criteria for the site was good stakeholder cooperation; the enthusiasm of the land owner and farm manager have contributed to the successful construction of the pilot system.

- Drilling technique: Mud drilling is not a standard drilling technique in Lebanon. The only method available for drilling in sedimentary formations is straight flush rotary drilling. This method creates a mud cake on the borehole walls and artificially clogs the aquifer, which requires complex well cleaning after drilling. In order to have good infiltration wells in sedimentary formations, it is vital that improved drilling techniques (such as reverse flush rotary drilling or airlift drilling) are made available for Lebanon. This also makes sampling of cuttings easier.
- Well development: The local drilling industry in Lebanon is not yet familiar with more advanced well development techniques that are necessary after mud drilling. The use of biodegradable bentonite as drilling mud, and a professional bentonite remover chemical are not common. Also, suitable well development techniques, such as air plunging, intermitted pumping and section pumping are not common. Developing this expertise would significantly increase the well performance of deep boreholes drilled in sedimentary aquifers and benefit future MAR systems.
- Well lining material: Much of the material for the pilot MAR well was imported (e.g. PVC casings, filters, gravel). For efficient construction of new infiltration wells a supply chain of well lining material needs to be set up in Lebanon.
- MAR system: The applied Dutch MAR technology, delivered as a single operation and filtration unit, can be installed off-grid and in short time (plug and play). It should be investigated if similar solutions can be made locally.
- Time: In order to achieve good cooperation with local partners, to do all needed field investigations, to select the best site, and to do a full cycle (infiltration & abstraction) of operation and monitoring a timeframe of at least 3 years is needed.
- Economic feasibility: Most promising investors in MAR are the middle and large scale farmers, who grow high value crops such as table grapes, wine grapes and avocados. Further piloting of MAR is recommended to gain an improved understanding of the benefits and risks, and to eventually develop the most suitable MAR-system in relation to both cost-benefit and water use in the Lebanese context.
- Water governance: Groundwater should be governed as a common pool resource and water authorities need a strong mandate to manage them in a sustainable way. Public investments in MAR can help to recharge the deteriorating groundwater reserves. This can include implementing MAR in karst aquifers with the aim to benefit groundwater users at a regional level. At the same time, more efficient water well licensing mechanisms need to be in place and abstraction points need to be regulated and monitored.
- MAR expertise: To develop more understanding of the feasibility of MAR in Lebanon more pilot schemes should be implemented and monitored. Next to larger MAR schemes (possibly in karst) much potential lies in small-scale and low-cost systems that utilize existing (dry) wells. Subsidizing MAR systems for smallholders would help to improve the resilience of the rural population.
- Stakeholder mapping and involvement: The importance of stakeholder involvement cannot be overstated. To target the most important institutions, organizations, and individuals, stakeholder mapping should be carried out at an early stage of the project. It is important to understand the local political situation and the relationship between the stakeholders including official and unofficial power differences. Ideally, each stakeholder's interest in the project as well as its power to support or prevent the project are mapped.

8. Conclusion

To implement a pilot MAR project in Lebanon in two years, including an extensive site selection process and establishment of collaborations with different organizations, proved to be a challenge. Nevertheless, the project approach of building a tangible pilot project based on sound scientific research and with state-of-the-art technology was the right decision. In Lebanon, many projects of international cooperation to improve e.g. the water or agricultural sector are carried out, but too often the results remain concealed in reports or workshops. Implementing a tangible pilot project that can be operated, studied and monitored beyond the project duration was therefore much appreciated by most of the Lebanese project partners.

Needless to say, it is disappointing that the project has ended not according to plan; it remains unclear whether it will ever be possible to operate the MAR system. It is unfortunate that the pilot project does not receive support from the regional water authority and that, as a consequence of this, ministerial support of the project was also discontinued. A longer project duration would have probably helped to build a stronger relationship with the Lebanese institutions, in order to be more effective within the Lebanese context. Furthermore, a financial contribution by MoEW (e.g. 20% of the installation costs) could have ensured continued support and better engagement of the Lebanese water authorities.

One of the major successes of the project is the good cooperation between Dutch implementing organizations (namely Acacia Water and Deltares) and the Lebanese project partners Elard and American University of Beirut (AUB), resulting in mutual learning (e.g. capacity building during well drilling) and development of new scientific insight (e.g. site geology). It is important that AUB is able to continue the planned research beyond the duration of the project even if the project itself is discontinued.

The MAR pilot project will help in quantifying the upscaling potential of MAR in Lebanon. In addition, it acts as a great opportunity for capacity building in the Lebanese water sector and helps to shift the paradigm that only high-yielding but vulnerable karst aquifers are productive water reservoirs towards the possibility of actively managing the groundwater reserves in sedimentary aquifers with lower productivity.

Acknowledgments: This project is implemented within the program "Strengthening the Lebanese Water and Agricultural Sectors", funded by the Dutch Ministry of Foreign Affairs, represented by the Dutch embassy in Beirut. The project is implemented by the Dutch companies Acacia Water, Deltares, KWR, and Broere Hortitech together with the Lebanese partner Elard in cooperation with the American University of Beirut (AUB) and in coordination with the Ministry of Energy and Water (MoEW), the Bekaa Water Establishment (BWE) and the Litani River Authority (LRA).

Abbreviations

The following abbreviations are used in this manuscript:
ASR: Aquifer Storage and Recovery
AUB: American University of Beirut
BWE: Bekaa Water Establishment
LRA: Litani River Authority
MAR: Managed Aquifer Recharge
MoEW: Lebanese Ministry of Energy and Water
MoFA: Dutch Ministry of Foreign Affairs.

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Editor: E. Fernández Escalante. Tragsa Group.
2019 November