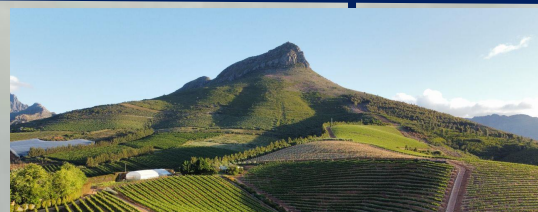


12ND INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE, ISMAR-12, POSTERS. STELLENBOSCH, SOUTH AFRICA



12º SIMPOSIO INTERNACIONAL DE GESTIÓN DE LA RECARGA DE ACUÍFEROS, ISMAR-12, PÓSTERES. STELLENBOSCH, REP. SUR AFRICANA

EDITORS: ENRIQUE FERNÁNDEZ ESCALANTE, FANUS FOURIE, KES MURRAY & NICOLETTE VERMAAK (IAH-MAR)



P-ISMAR 12. POSTERS OF THE 12th INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE, STELLENBOSCH, SOUTH AFRICA

INTRODUCTION

From 2025 April 28th to May 2nd has taken place in Stellenbosch, Protea Hotel and Conference Center, the 12nd International Symposium on Managed Aquifer Recharge (ISMAR 12), hosted by IAH-SA; under the auspices of the International Association of Hydrogeologists, Managing Aquifer Recharge Commission (IAH-MAR), UNESCO and ASCE, among others, under the title: **“Managed aquifer recharge: From theory to implementation and operation”**.

The symposium counted on 184 delegates from 30 countries (60% from outside South Africa), 11 exhibitors, 8 technical sessions, 108 oral presentations, 15 posters, 3 keynote presentations, side events, four first day short courses, five additional workshops, two panel discussions, three technical field trips, and plenty of knowledge. Detailed info is provided at <https://ismar12.org.za/> (last access 2025 May 23th).

A special Lifetime Achievement Award was presented to Dr Gideon Tredoux for his pioneering work on MAR in South Africa in the last 50 years. Four awards were presented to the Best Poster presentation by a student (T Mabula) and non-student (J. Myburgh) and Best Oral presentation by a student (E Derks) and non-student (D. Gonzalez and K Woolf).

Posters were specifically requested by the organizers, including a disclaimer for the exhibition and publication. All of them have been gathered in this collection called P-ISMAR 12 (mini-book).

Both, the classification and the editing tasks were carried out by IAH-MAR Commission co-chairs with the assistance of ISMAR 12's chairmen, Fanus Fourie and Kes Murray, and Nicolette Vermaak as scientific committee coordinator.

You can hereby enjoy the publication resulting from this cooperation, which consists of 15 posters, which allows us to share some information that, otherwise, could have been lost.

Further information on this event can be found at:

<http://recharge.iah.org/ismar>

<http://ismar12.org.za>



P-ISMAR 12. POSTERS DEL 12º SIMPOSIO INTERNACIONAL DE RECARGA GESTIONADA DE ACUÍFEROS, STELLENBOSCH, REPÚBLICA SURAFRICANA

INTRODUCCIÓN

Entre los días 28 de abril y 2 de mayo de 2025 ha tenido lugar en Stellenbosch, Protea Hotel and Centro de Conferencias, el 12º Congreso Internacional de Recarga Gestionada de Acuíferos (ISMAR 12), promovido por la Asociación Internacional de Hidrogeólogos, Comisión de Recarga Gestionada (IAH-MAR) y capítulo Surafricano (IAH-SA), UNESCO y ASCE, entre otros, con el lema: **“Recarga Gestionada de Acuíferos: de la teoría a la implementación y funcionamiento”**.

El simposio ha contado con 184 delegados de 30 países (60% no surafricanos), 11 expositores, 8 sesiones técnicas, 108 presentaciones orales, 15 posters, 3 conferencias clave, eventos colaterales, cuatro cursos de primer día, cinco cursos adicionales, dos panels de discusión, tras excursiones técnicas, y abundante conocimiento. Más información detallada se puede encontrar en <https://ismar12.org.za/> (ultimo acceso el 23 de mayo de 2025).

Se concedió un premio especial al Dr. Gideon Tredoux por su trabajo pionero sobre la técnica MAR en Sudáfrica durante los últimos 50 años. Se concedieron cuatro premios al mejor póster presentado por un estudiante (T. Mabula) y un no estudiante (J. Myburgh) y a la mejor presentación oral presentada por un estudiante (E. Derks) y un no estudiante (D. Gonzalez y K. Woolf, compartido).

Los organizadores solicitaron expresamente la presentación de pósters, que han sido recopilados en esta colección llamada P-ISMAR 12 (minilibro).

La clasificación y edición la han llevado a cabo uno de los co-coordinadores de la comisión IAH-MAR, Enrique Fdez. Escalante, los coordinadores del simposio, Fanus Fourie y Kes Murray, y Nicolette Vermaak, coordinadora del comité científico.

El resultado es la presente publicación, que consta de 15 pósters de los ficheros digitales facilitados por los autores, que permiten compartir una información que, de otro modo, se podría haber perdido.

Información adicional sobre este evento se encuentra en:

<http://recharge.iah.org/ismar>

<http://ismar12.org.za>



Thank you, sponsors and exhibitors







ISMAR12 SYMPOSIUM PRELIMINARY POSTER PROGRAMME
28 April to 2 May 2025



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**IMPLEMENTATION OF MANAGED AQUIFER RECHARGE
FOR SUSTAINABLE MUNICIPAL WATER SUPPLY.
PRINCE ALBERT, SOUTH AFRICA.**

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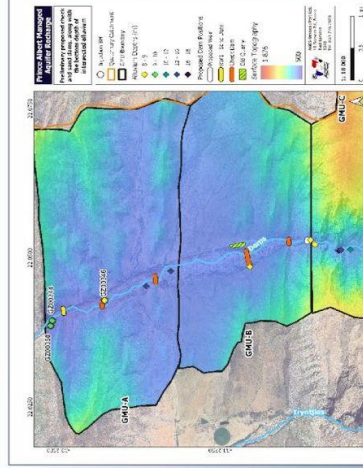
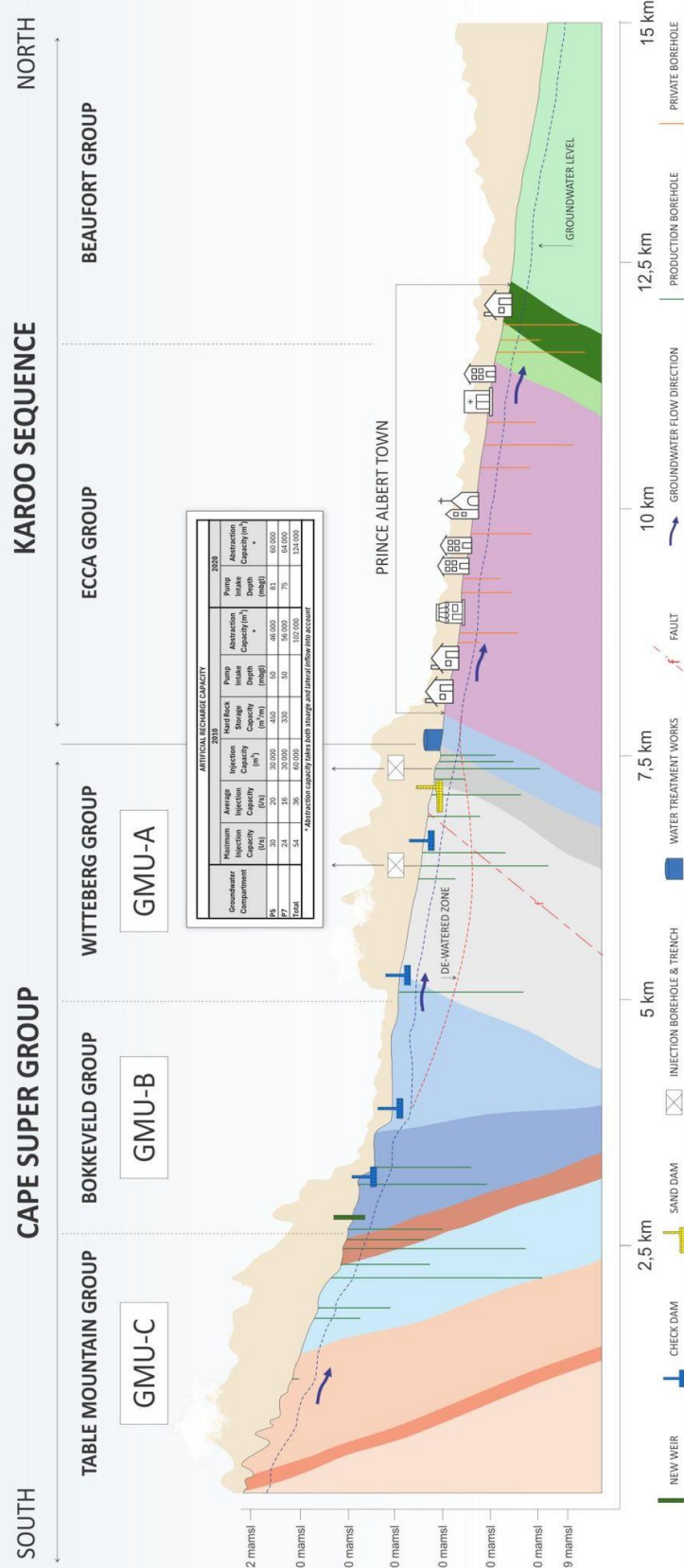
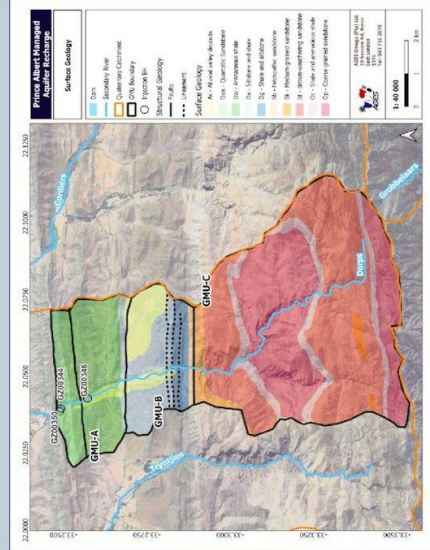
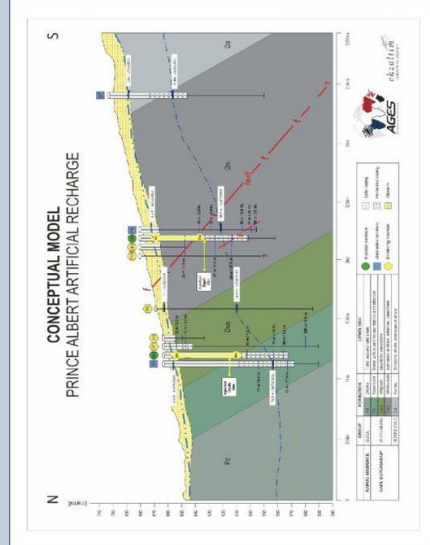
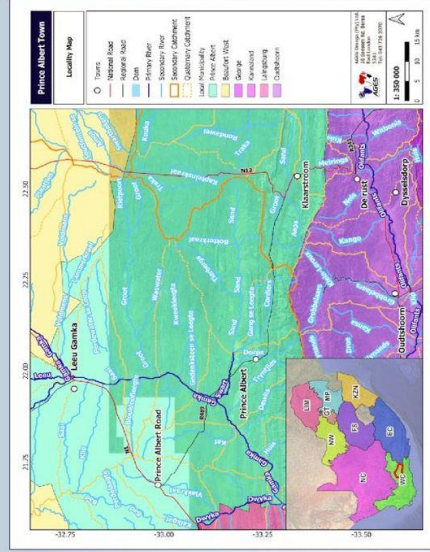
³Maluti GSM Consulting Engineers, Stellenbosch, South Africa; email philip@malutiwater.co.za | SMEC South Africa (Pty) Ltd, George, South Africa; James.Hought@smec.com; Theo.Kleythans@smec.com.

ABSTRACT - Prepared for the 12th International Symposium on Managed Aquifer Recharge, Stellenbosch, South Africa - 28 April to 02 May 2025.

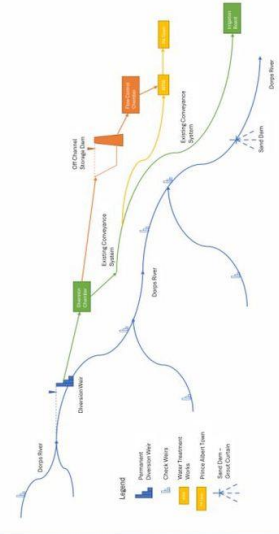
The picturesque Karoo town of Prince Albert, known for its harsh, dry conditions with limited rainfall and high summer temperatures, uniquely benefits from access to both groundwater and surface water. Managed Aquifer Recharge (MAR) studies conducted over fifteen years ago highlighted MAR's potential to sustain the town's water supply by using surplus surface water to replenish aquifers during dry seasons when groundwater is heavily relied upon. With funding from the Western Cape Department of Local Government, the Prince Albert Municipality has initiated the implementation of MAR in 2012, based on historical feasibility studies done by Groundwater Africa and the Department of Water and Sanitation between 2007 and 2010. The current project's first phase involved the rehabilitational and re-estab-

injection boreholes and installing the necessary injection infrastructure and monitoring equipment for the water injection trials. Due to above-average rainfall in the year preceding the planned trial, the aquifers were currently fully recharged leaving insufficient space for effective injection trials. A short injection test was conducted to calibrate equipment, with an extended trial being scheduled for the dry season when groundwater levels are expected to lower, allowing sufficient space in the aquifers for effective injection assessments. Additionally, a shallow injection trench was constructed in the overlying alluvium and connected to the injection infrastructure, enabling future injection into either the deeper fractured aquifer or the overlying alluvium. This will provide valuable data on the alluvium's capacity artificial recharge

The feasibility of in-channel modification and flood retention structures, to increase recharge to the underlying aquifer, was investigated in 2025 and preferred sites for such structures were identified in collaboration with the civil engineering team as part of a raw water security improvement study. This additional study investigated the feasibility of constructing of a permanent intake weir and off-channel raw water storage dam as well as several check-dams and possible sand dunes in the Dorps River floodplain. The final design and extent of the MAR project can be completed and implemented once the extended injection trial is completed, and applicable authorisations have been obtained.



PRINCE ALBERT RAW WATER SECURITY
OVERALL SCHEMATIC WITH VARIOUS OPTIONS



SUPPLY AND DEMAND

Since 2021, above-average precipitation has caused increased surface water storage, reducing the need for artificial recharge and limiting induced injection traps.

Excesses turn out from seasonally aligns with peak aquifer recharge during the wet season. However, in other years with below-normal precipitation, there is more storage capacity available gradually, leaving open storage for artificial recharge.

Additional storage capacity can be created by strategically managing groundwater extraction from boreholes. Once sufficient storage is available, excess extraction can be reduced or stopped for short periods.

The surface water authority can provide short notice updates on excess flow availability, which occurs when municipal and agricultural demands are fully met and less frequently, when remaining flow exceeds supply infrastructure capacity.

Excess storage capacity can be used to ensure that water is available in summer and winter crops.

CALIBRATION TRIAL INJECTION TESTS OUTCOME

The furrow water is of high quality, meeting most ideal drinking water standards with only aluminum and turbidity slightly exceeding operational limits. When mixed with groundwater, it is expected to enhance overall water quality by diluting any elevated concentrations. However, careful monitoring of oxidation reactions is necessary to prevent clogging and ensure sustainable recharge.

Injection Borehole Calibration Test (4.8 hours):
Short-duration injection tests were conducted on borehole GZ00346 and a nearby trench. The borehole and trench tests indicate that aquifer response varies significantly, with the borehole showing greater recovery compared to the trench.

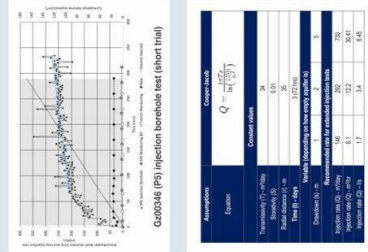
The injection rate was kept constant at 35.3 m³/hr (9.8 l/s) from 50 minutes onward.

The groundwater level rose 1.87 m in the first 50 minutes and an additional 1.2 m over the next 240 minutes, indicating steady-state behavior.

- **Future Extended Trial Recommendation:** Injection rates of 1.7 l/s, 3.4 l/s, and 8.45 l/s are recommended to raise groundwater levels by 1 m, 2 m, and 5 m, respectively, over 72 hours.

Injection Trench Calibration Test (2 hours)
The injection rate was kept constant at 12.15 m³/hr between 65–120 minutes. The groundwater level increased by 24.2 cm in the first 60 minutes, with a total rise of 45.6 cm by the end of the test.

- Future Extended Trial Recommendation: Injection rates of 1.4 l/s, 2.7 l/s, and 6.9 l/s are recommended to raise groundwater levels by 1 m, 2 m, and 5 m, respectively, over 72 hours.



FLOOD RETARDATION MAR

Managed aquifer recharge schemes often use in-channel modifications or artificial channels to enhance the recharge of underlying aquifers. Flood retardation refers to the deliberate slowing, detaining, or managing of floodwaters in a controlled manner to reduce its speed and volume. This process often involves using engineered structures or natural features to temporarily store floodwater, allowing it to infiltrate into the ground or be released downstream more slowly.

In regions with intermittent or seasonal surface water, floodwater retardation can be used for aquifer recharge – to make it available for use during drier periods, and potentially improve the groundwater quality. Structures like check dams, rechargeleaky dams, and channel spreading help capture and slow flows for more effective infiltration and aquifer recharge. Flood retardation techniques are most effective in areas with high soil and aquifer permeability (unconfined), where retained water can percolate rapidly into the groundwater system. Various in-channel modifications for MAR have been extensively researched and successfully implemented on a global scale.

WAY FORWARD

FEASIBILITY PHASE COMPLETION:

- Complete the current feasibility phase by carrying out extended injection trials.
- Injection trials to include water quality monitoring during extended injection at the borehole and infiltration trench when aquifer conditions are favourable, or sufficient injection capacity has been created by strategically managing groundwater extraction from production boreholes within the respective aquifer
- Implement a long term sustainable injection rates as well as storage and abstraction capacities.
- Develop preliminary infrastructure design and define project implementation phases and cost requirements.
- Identify funding sources
- Complete a detailed project implementation plan.

IMPLIMENTATION

- Obtain the necessary water use licence and environmental authorisation for the MAR scheme.
- Develop and test new injection and abstraction boreholes as well as injection trenches. Construct flood retardation infrastructure.
- Set up the groundwater and recharge water monitoring system
- Develop the detailed infrastructure design, carry out the tendering processes, and construct the project.
- Compile monitoring, operation & maintenance procedures

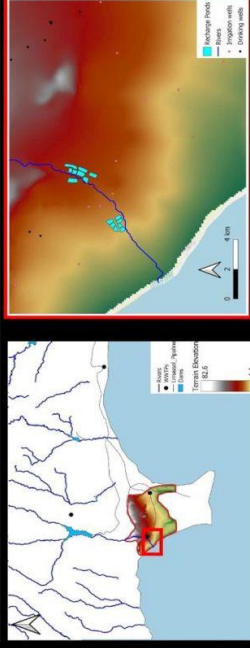
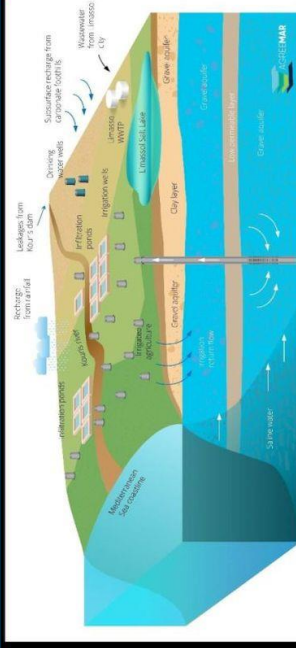
REFERENCES

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Study area and MAR concept

Akrotiri alluvial aquifer is situated in the south-central part of Cyprus island, with longitude and latitude around 34.65 °C and 32.9 °C respectively, and covers an area of approximately 5.1 km². Akrotiri peninsula is considered to be a semi-urban area since it is located very close to Limassol urban area, and extends within several semi-urban communities. The highest altitudes are observed at the northern part of the study area, approximately 82.6 meters above sea level (masl), progressively decreasing to 0 masl while approaching the coastline. During rainy periods, an ephemeral river passes from the north-western part of the study area and discharges into the sea, stemming from Kouris dam, which is the biggest dam in Cyprus with maximum capacity of 115 million cubic meters (Mm³).

A MAR facility is currently operating since 2016 at the western part of Akrotiri peninsula, very close to Kouris delta riverbed, and recharges the aquifer system between 1 and 4 Mm³ in an annual basis. Raw wastewater is collected from the nearby urban and semi-urban areas, which is subjected to tertiary treatment in the urban WWTP. The treated wastewater is then distributed to the end-users (mainly farmers) via a network of pipelines. Part of the treated wastewater is discharged into a complex of seventeen infiltration ponds comprising a total area of 56,000 m², from which it penetrates the unsaturated zone until it reaches the aquifer. Subsequently, a mixture of ambient groundwater and treated wastewater is abstracted from nearby wells, and distributed to the end-users.



Conceptualization of the groundwater model in Akrotiri peninsula

A numerical steady-state model has been developed at INOWAS platform using MODFLOW, and calibrated for January 2019 (Base Scenario, BS), that considers both the hydrological complexity of the study area and the plethora of recharges/extractions from the local aquifer due to different processes. In close consultation with the national water authorities, two additional steady-state simulations were conducted for the following hypothetical scenarios: a) 50 % reduction in recharge amounts in the infiltration basins (Scenario 1, S1) and b) 50 % increase in recharge amounts in the infiltration basins (Scenario 2, S2).

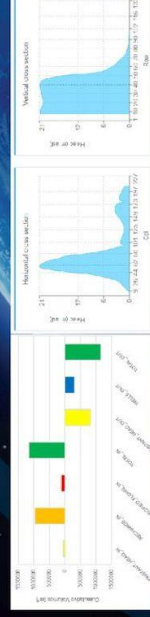
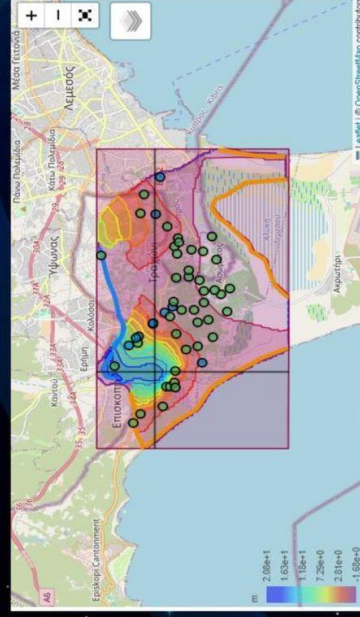


Description	Type
Natural recharge due to rainfall that reaches the ground surface of the study area (surplus of monthly precipitation and actual evapotranspiration data)	Source
Subsurface recharge from carbonate hills (upstream of study area, covering 100 km ²), applied along the northern border.	Source
Aquifer recharge via recharge ponds, located at the western border of the study area (delta of Kouris River)	Source
Irrigation return flow (15 %* of the total amount of irrigated water which is allocated within the study area)	Source
Surface run-off stemming from Kouris dam losses/linkages	Source
Groundwater extraction from drinking wells	Sink
Groundwater extraction from irrigation wells	Sink
Times series of groundwater levels measured from wells located near the northern part of Akrotiri salt-lake (southern border)	BC
Northwestern part of the study area	BC
Eastern part of the study area: zero gradient (no flow)**	BC
Western coast of the study area: sea barrier	BC

Preliminary results, conclusions, and main remaining question according to the water authorities

According to the BS, the highest head levels are observed around the infiltration ponds and the Kouris delta, whereas the maximum values is 24 masl. The head levels are decreasing towards the coast and the Salt Lake, dropping to -2 masl. Those areas are especially prone to saltwater intrusion and abstraction needs to be managed carefully. S1 comprises the reduction of recharge rates in the infiltration basins by 50 % due to less water availability. As a result, the groundwater mound around the infiltration basins in the Kouris delta is increasing by 7.6 m, causing a decrease in head levels around the drinking wells. The results show the evolution of a depression cone which reaches -4.3 m compared to 0.2 m in the BS. Hence, a higher risk of seawater intrusion occurs for this scenario. For S2, the groundwater mound around the infiltration basins in the Kouris delta is further increasing by 7.4 m. Also, the depression cones in some drinking water wells are rising to 4.6 m above sea level compared to 0.2 m in the BS, indicating that the drinking wells are protected from seawater intrusion and treated wastewater when the extraction rates are kept constant. Regarding the water budgets, keeping the extraction rates constant, the outflow through the constant head boundaries towards the sea fluctuates because of the direction of the head gradients in the study area. The leakage to the sea is reduced by 27 % for S1, compared to the BS (50 % decrease of infiltration rates), whereas the leakage to the sea is increasing by 27% for S2 (50% increase of infiltration rates) compared to the BS.

As part of ongoing work, the effect of SAT-MAR at the drinking wells, located upstream of Akrotiri site, will be evaluated using MODPATH.



Investigating groundwater hydrodynamics of the managed aquifer recharge system for improved sustainable groundwater supply, Limpopo,



South Africa

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Introduction

The present study was conducted to investigate groundwater hydrodynamics focusing on the geometric properties of subsurface, flow and transport properties. Polokwane Urban Aquifer is more susceptible to pressure due to rapid increase in human population, industrial growth and extreme climate events like drought. Polokwane's urban aquifer system's hydrogeological characteristics, particularly the hydrodynamics, remain poorly understood. Thus this background necessitated understanding groundwater flux and its exchange processes which crucial for improving management practices aimed at contaminant remediation and assessing how the aquifer system contributes to the overall water balance across seasonal changes in semi arid regions.

Aim & Objectives

The focal point of the study is enhance knowledge of the hydrogeological characteristics of Managed Aquifer Recharge (MAR) systems ,which is vital for sustaining groundwater supplies.

- Characterize the urban aquifer system to understand its hydrogeological conditions and groundwater flow dynamics.
- To determine aquifer hydraulic parameters: Transmissivity and Storativity .
- To develop the site specific hydrogeological conceptual model for urban hydrogeology.

Data Collection methods

The data was collected using geophysics and two types of hydraulic test namely Step down test and the constant rate test.



Data analysis methods

The data set collected from hydraulic tests was analyzed using Flow Characteristic Method (FCM) for parameter estimation and aquifer hydraulic conditions. Hydro-geophysics data was analyzed using Magneto telluric method (MT) method for aquifer characterization.

$$T = \frac{2.3Q}{4\pi\Delta S}$$

T-transmissivity(m^2/d)

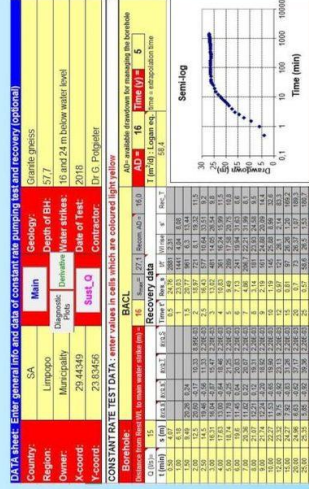
Q- discharge rate (m^3/d)
 Δs -hydraulic gradient (m)

$$S = \frac{2.25Tt_0}{r^2}$$

S- storativity(-)

 t_o - intercept (min)

r- distance between the pumping and the observation well (m)



Output and expected outcome

- The detailed delineated geometry of the aquifer system and its boundaries.
- Characterized hydraulic properties of urban aquifer system for groundwater sustainable management .
- Detailed aquifer conditions (diagnostic, flow regimes and derivative) and fluid movement associated with Polokwane Urban hydrogeology.
- Produced comprehensive HCM to inform and guide the development of numerical model, within a Managed Aquifer Recharge (MAR) scheme

Study area

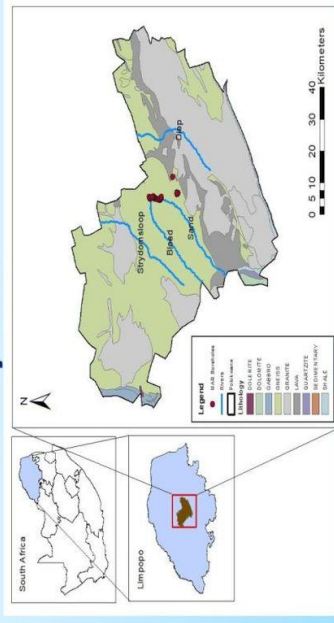


Figure 1: Shows study area map

Preliminary Results

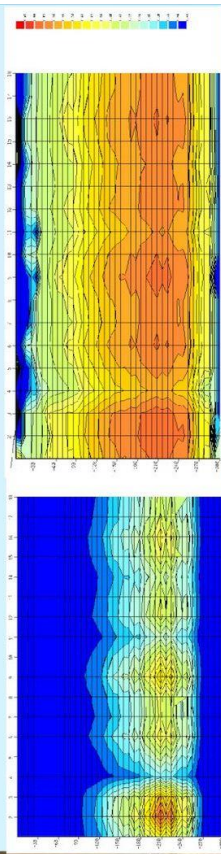


Figure 2: Shows geophysics profiles with varying resistivity of geological depths

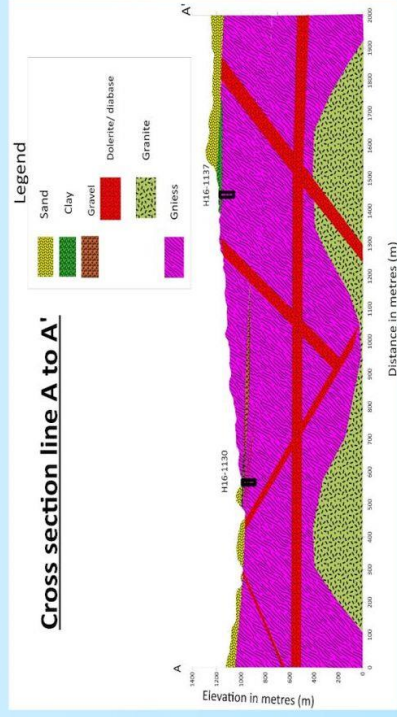


Figure 3: Showing geological cross-section A to A'

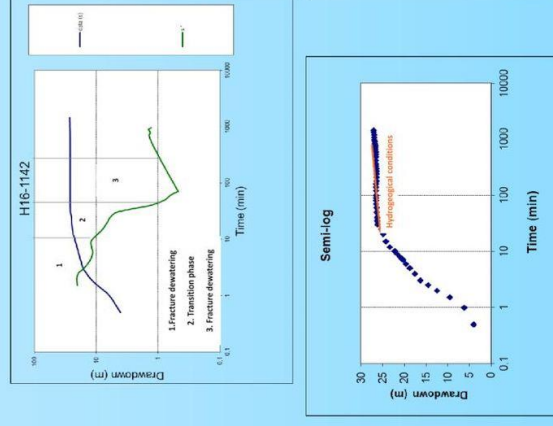


Figure 4: Shows Semi log, Log-log and derivative plots of H16-1142



Introduction

The need for a **reliable groundwater supply** was emphasized during the droughts experienced in South Africa from 2015 to 2017. **Groundwater modelling** has been proven to be an **effective groundwater management tool for MAR**. The aim of the current study was to **use numerical modelling results** to investigate the **feasibility of MAR** in the unconfined Langebaan Road Aquifer (LRA). **The LRA wellfield** situated in **Langebaanweg**, South Africa was used as a case study.

Study Objectives

- 1. Describe **groundwater dynamics** using a **site-specific conceptual model**
- 2. Develop a **numerical model** to evaluate **theoretical MAR scenarios**
- 3. Assess MAR scenarios to evaluate **MAR feasibility** using model results

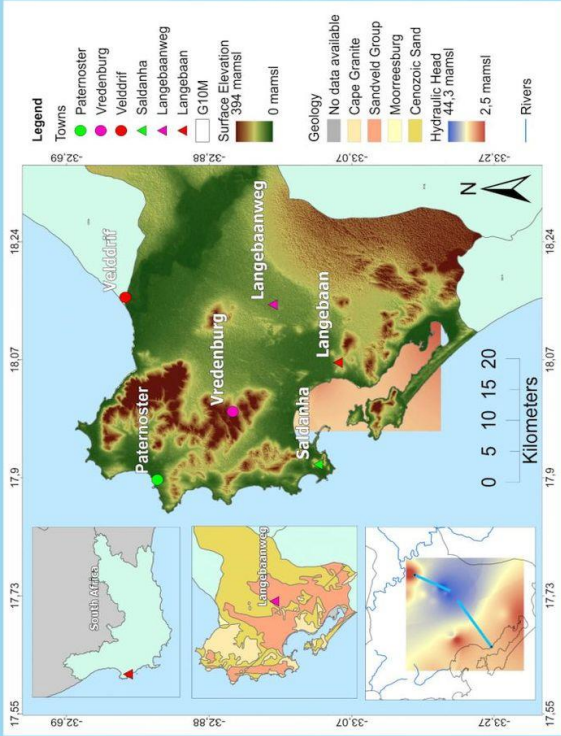


Figure 1: Topographic, lithological and hydrogeological mapping of the West Coast of South Africa

Methodology

Data collection: hydrodynamic properties such as **hydraulic conductivity** collected from **past studies**; historical groundwater levels collected from **NGA**

Data analysis: model was calibrated against historical water levels using the **root mean square error analysis**

Modelling software: **MODFLOW-6** code and **ModelMuse** was used; constant head, recharge, well and observation packages used, **ArcGIS** used for **data preprocessing**

Scenario development: S1: No injection, infiltration or abstraction; S2: Injection and abstraction via boreholes; S3: Infiltration ponds and abstraction via boreholes

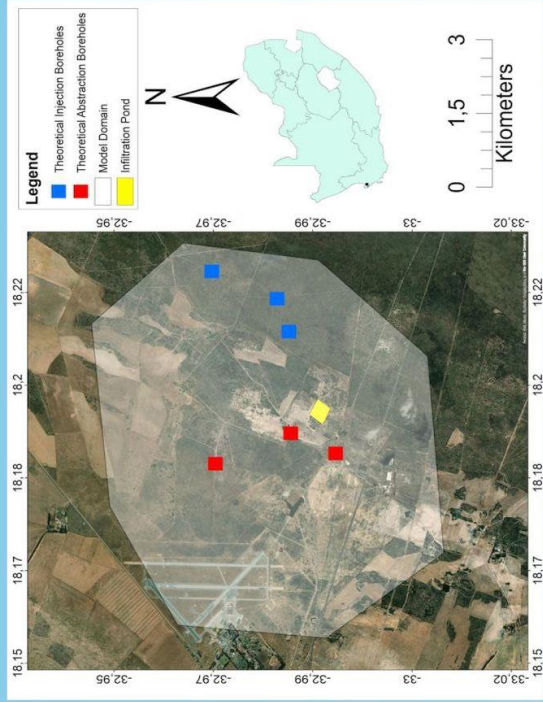


Figure 2: Location of theoretical injection and abstraction boreholes and infiltration pond in LRA wellfield

Model Calibration

Table 1: RMSE analysis for numerical groundwater model			
	Observed Head	Simulated Head	Residual ²
BG00137	42.58	38	21.03
G46109	34.3	33.64	0.44
G46108	48.27	37.63	113.09
G45634B	42.22	38.11	16.9
G45633B	38.26	37.88	0.14
G46032	35	36.55	2.41
G46110	30.25	32.9	7.04
Root Mean Square Error		4.8	

Results

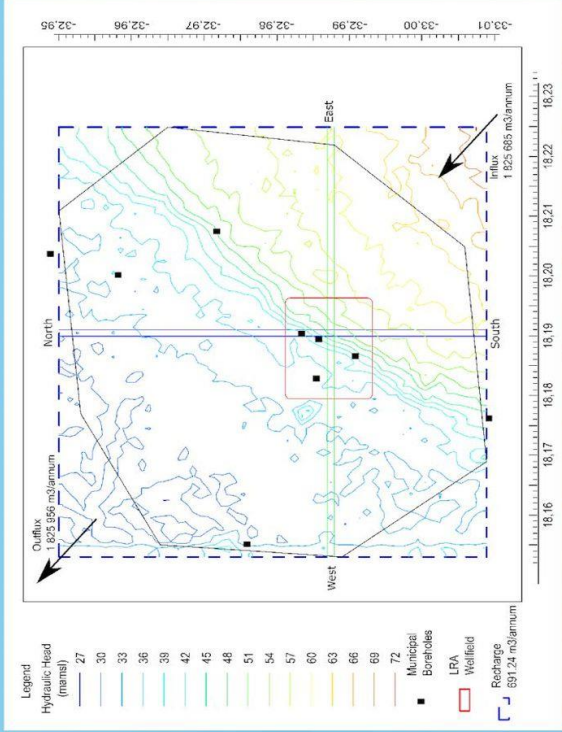


Figure 3: Conceptual groundwater flow model for the LRA wellfield

Table 2: Results of scenario 2 in the LRA wellfield

	Injection rate (m ³ /day)	Abstraction rate (m ³ /day)	Net Flux
Scenario 2.1	2730	-2730	0.27
Scenario 2.2	2730	-1365	1.12
Scenario 2.3	2730	-4095	0.76
Scenario 2.4	2730	-1911	-0.57
Scenario 2.5	2730	-3549	-0.11

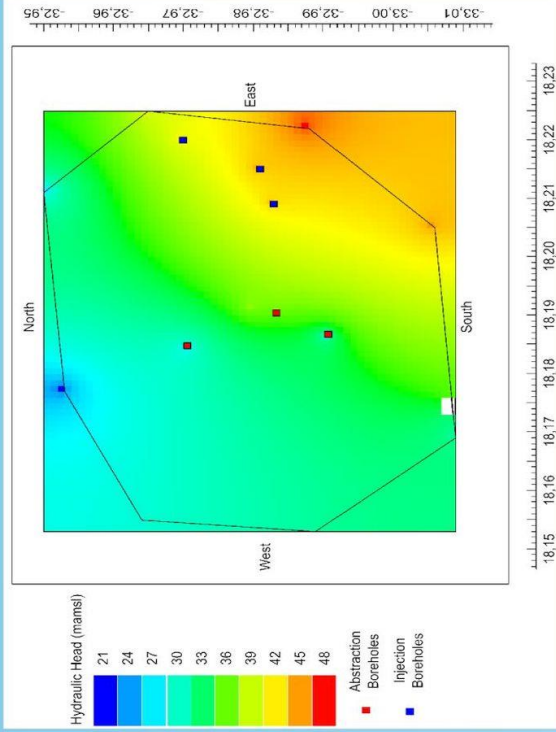


Figure 4: Simulated hydraulic head for scenario 2.3 for the Langebaan Road Aquifer wellfield.

Conclusion

Modelling results suggest injection of 2730 m³/day can sustain 4095 m³/day of groundwater abstraction. Development of **injection boreholes** should be in the **LRA wellfield**. **Simulated net flux** indicated that **no significant influence on the groundwater table** according to Scenario 2.3.

Hydro-geophysical Investigation and Groundwater Mapping for Managed Aquifer Recharge in Carnarvon: Enhancing Water Supply



water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA

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Background

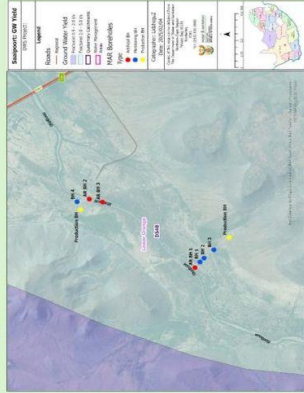
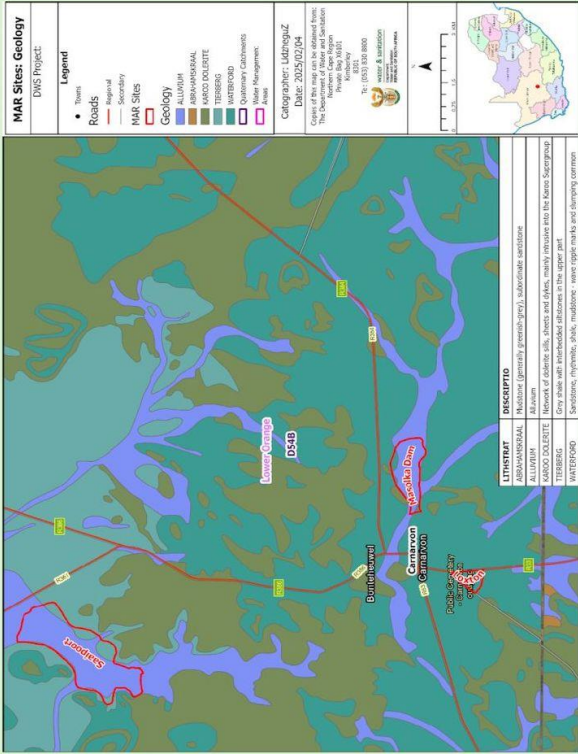
Groundwater investigation and mapping in Carnarvon were conducted using hydro geophysical techniques to support Managed Aquifer Recharge (MAR) and sustainable water management. These investigations utilized various geophysical methods to assess subsurface properties, identify groundwater resources and optimize recharge strategies. An aquifer as defined by Earle, 2019, is a geological formation that stores and transmit groundwater, serving as a crucial water source for drinking , irrigation and industrial use. Understanding aquifer characteristics such as porosity, permeability, and hydraulic conductivity is essential for effective water resources management as emphasized by Vaessen, et al., 2015.

According to Meles, et al., 2024, MAR is the intentional recharge of groundwater by directing surface water into aquifers, enhancing water availability especially in areas facing depletion and drought. The benefits of MAR include sustainable groundwater use, drought resilience and flood mitigation. However, challenges include high cost, site suitability and contamination risks. Effective MAR implementation ensures long term groundwater sustainability for communities dependent on these resources as highlighted by Hohne et al., 2021 and Alam, et al., 2021.

Aim & Objectives

This study is aimed at demonstrating the use of hydro geophysical techniques in mapping the groundwater for MAR and understanding aquifer characteristics. The investigations seek to demonstrate the use of 2D geophysical imaging to evaluate recharge potential and its variation across multiple basins utilized for managed aquifer recharge to enhance water supply.

Study Area



The study area is located in Carnarvon town, Karereberg Local Municipality, Northern Cape Province, South Africa and is part of the Karoo supergroup. The area is characterized as lowland, featuring scattered mountainous hills with river valleys passing between them. According to Hohne, et al., 2021 aquifers are classified as primary aquifers with shallow groundwater level

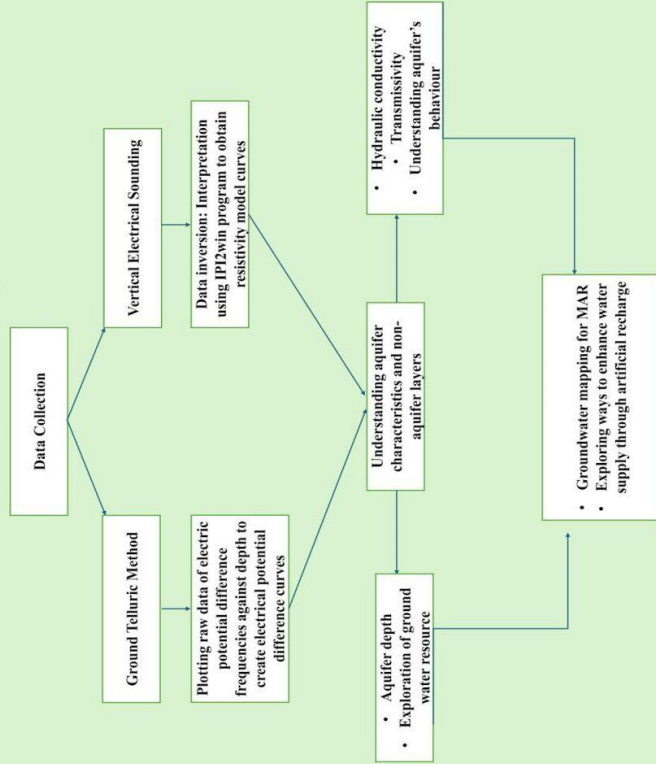


Data collection and analysis methods

Vertical electrical sounding (VES) is planned to be conducted at 3 sites as part of this investigation, using the Geotron Electrical resistivity meter model G42 by means of the Schlumberger electrode configuration to determine the subsurface apparent electrical resistivity. As explained by Inayat Ur Rahman, et al., 2023, in VES, an electric current is introduced into the ground using two electrodes, while the resulting potential difference is measured by a separate pair of electrodes positioned at a distance from the current electrodes. For the Schlumberger electrode configuration, electrodes will be arranged along a straight line, with the distance between the two potential electrodes kept significantly smaller than the distance between the current electrodes. The collected VES data will be processed using IP12win software to produce a 2D subsurface model.

In comparison to VES, the Ground Telluric Method will be used as a matching passive technique to distinguish between different aquifer layer systems. As emphasized by Oyegoke, et al., 2020, this method has been chosen for its high resolution, deep penetration capability, and strong resistance to external interference. According to Gomo, 2023, the ground telluric method uses the Earth's natural electromagnetic field to display subsurface electric resistivity structures to explore potential groundwater resources utilizing electrical potential difference measured in milliVolts. The PQWT –TC300 series equipment will be used in this process, where two non-polarized electrodes would be spaced at a distance from each other. . to procedure By using investigate subsurface electric resistivity

Data collection and analysis methods



Results and Conclusion

The VES results are expected to reveal a multi-layered subsurface structure, with each layer identified by differences in apparent electrical resistivity values. More data and analysis will be interpreted after data collection.



What can groundwater modelers in MAR applications learn from the geothermal energy industry

Introduction

A successful Managed Aquifer Recharge (MAR) or Aquifer Storage and Recovery project requires groundwater to be closely managed within a system that incorporates the aquifer body, groundwater flow, recharge and abstraction, to ensure the aquifer remains a sustainable resource for the supply of water. This in essence is very similar in concept to a geothermal project, where a groundwater reservoir is closely managed to ensure a system of production and injection wells provide a continuous and sufficient supply of thermally heated water (Figure 1).

We explore if software tools used in the Geothermal industry, specifically Volsung software for Geothermal Reservoir Simulation, could have the potential to be utilised by Geoscientists in MAR applications to improve operational outcomes and provide more efficient workflows in managing the aquifer resource.

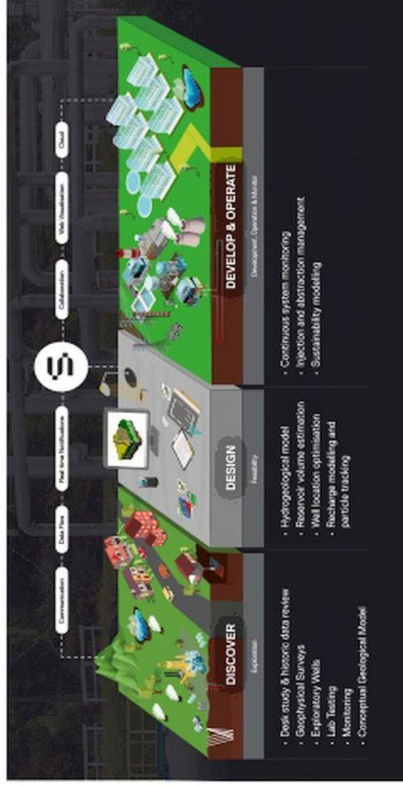


Figure 1: The profiles of project stages and activities for both MAR and Geothermal projects are largely aligned, from the initial discovery and evaluation of an aquifer resource through to the management of full operations and production.

Volsung Overview

Volsung is an integrated solution to comprehensively simulate geothermal processes from subsurface reservoirs to surface systems. This holistic simulation integrates reservoir, wellbore, and surface network simulators with advanced features such as microgravity and subsidence forecasting, tracer modelling, Monte Carlo analysis, and GPU-based parallel processing. Users gain unparalleled clarity and confidently make data-driven decisions while ensuring optimal system performance.

At Volsung's core lies a highly efficient reservoir simulator. Using heat and mass balance equations, Volsung replicates the flow of fluids through rock. A graphical interface is used to develop and execute geothermal reservoir simulations and enhanced 3D visualizations to interpret model results. Key features include clean visualizations of vector flows, and particle tracking. This enables collaborative model development, and a simplified workflow from conceptual to numerical modelling, and compatibility with Leapfrog Energy (Baxter, et al., 2019) (Figure 2).

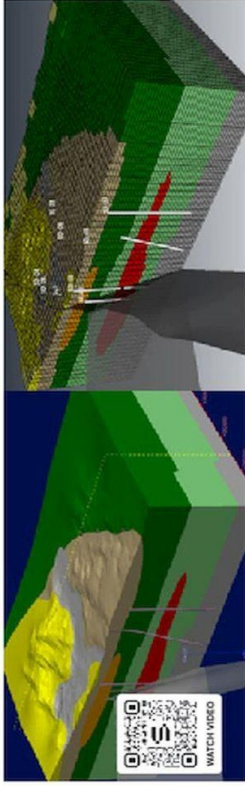


Figure 2: Using a Leapfrog conceptual geological model (left) as the basis for a Volsung numerical model (right)

Real World Geothermal Analogy

The Steamboat geothermal field is a Great Basin geothermal system in Reno, Nevada, generating 79 MW net electricity using five zero-greenhouse gas emission powerplants with full mass reinjection as of 2020. It has been in operation since 1987 and with consolidation of ownership under Ormat since 2004. As of 2024, the power plants are supported by 24 active production and 9 active injector wells, with all produced geothermal fluid being reinjected back into the system. Recent developments in computational tools, updates to the conceptual understanding of the geothermal system, and the need to develop a consistently up-to-date reservoir model, led to the creation of a numerical model in Volsung, fully calibrated to historical data.

This model is being used to guide operational and reservoir management decisions at Steamboat and will be continuously improved to reflect wellfield changes and observations. The calibrated model suggests that geothermal development in the area has not been a primary cause of any changes observed, and that the current operations are sustainably managing the geothermal resource (Dhakal et al., 2025). As would be reflected in a MAR scheme, the dependence of Reno's large population centre on a geothermal resource underscores the importance of monitoring and predicting changes in groundwater levels associated with the underlying aquifer body.

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Full System Approach – Combined Reservoir, Wellbore and Surface Network Simulations

A key feature of the Volsung system is that flow from the reservoir model can be coupled to a wellbore model so reservoir modelers can provide more useful operational information to those managing production. Typically, a manager or plant operator wants forecasts of geothermal liquid and/or steam availability at plant operating pressures or make-up well requirements. This is very difficult to provide accurately with a reservoir model that only forecasts reservoir conditions. Coupling a wellbore model to the reservoir model enables wellhead deliverability curves for mass flow and temperature to be calculated from reservoir conditions. These can then be linked to power plant requirements via a surface network model. This has the advantage that the full feedback loop between reservoir conditions, fuel availability, plant requirements and injection load is accounted for (Figure 3). The reservoir model can then be used to forecast power generation and make-up well requirements (Clearwater, et al., 2019).

Applying this approach to MAR projects would allow groundwater modelers the ability to sustainably forecast, manage and balance the available water resource of the aquifer with the usage demands of the abstraction and the recharge capacity back to the aquifer.

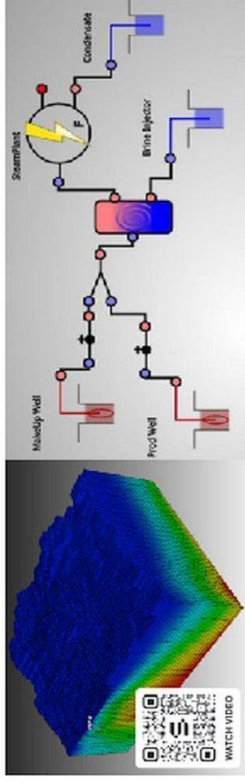


Figure 3: Volsung allows a Reservoir model (left) to be connected to Surface Network model (right) to manage and forecast the flow of water in a full feedback loop.

Tracer Modelling using Particle Tracking

Tracers provide quantitative data that can be analysed to aid in the understanding of reservoir connectivity and the characterization of reservoir flow-paths. This supports the sustainable, cost-effective development of geothermal systems by enabling better reservoir management and giving greater confidence in predictions of future reservoir behaviour. Reservoir management includes both production and reinjection strategies, and optimizes reservoir performance while decreasing risk, minimizing costs and mitigating negative environmental impacts (Franz, et al., 2025).

Volsung provides tracer modelling functionality by calculating a flow and velocity model for the reservoir and then modelling the dispersion of tracer particles through this model over time (Figure 4).

In MAR applications, the ability to numerically model tracers through Volsung's particle tracking methodology would allow Groundwater modelers to confidently ensure recharge paths are feeding back into the aquifer storage with suitable retention time within the aquifer body before abstraction. Through a better understanding of aquifer flow paths via particle tracking analysis enables better aquifer management, and because this impacts abstraction flow rates, decline rates and retention, it has a significant impact on overall project costs (drilling) and revenue (generation).

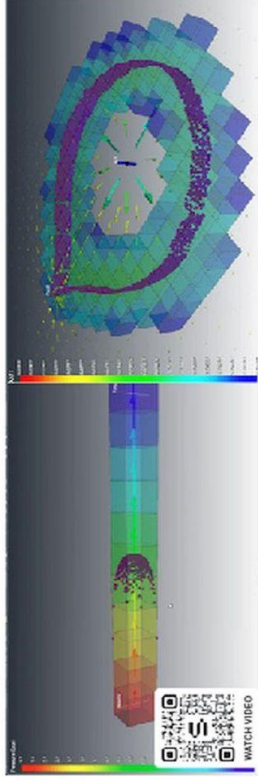


Figure 4: Tracer Particle Tracking examples in Volsung for a basic 1-dimensional flow (left), and dispersion between an injection well and production well (right)

Conclusion

Whilst the terminology between MAR and Geothermal applications may differ, the overall principle of sustainably managing a body of groundwater that can be utilised for social benefit remains the same.

This poster has illustrated how Geoscientists working in MAR applications could benefit from adopting established tools and technology, such as Volsung, which have been developed for Reservoir Engineers working in the Geothermal industry.

Having recognised the potential for Volsung to be applied in MAR schemes, the next step is to identify a MAR project to develop a pilot study and test its applicability.



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Evaluating the Hydrogeological Environment of Johannesburg and Surrounding Areas for Managed Aquifer Recharge

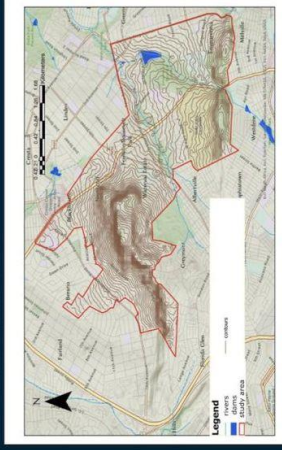


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1. Introduction

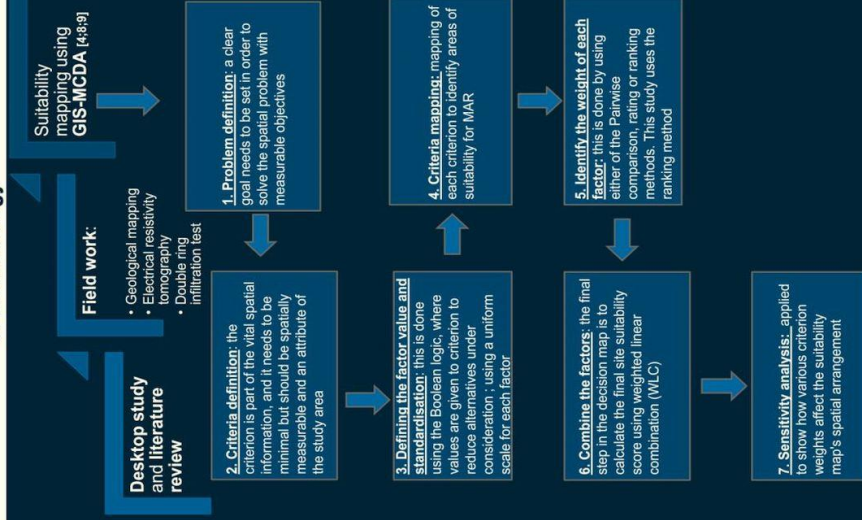
Johannesburg is a metropolitan area with a fast growing population. This population growth results in the increased demand for water. The increased water demand places strain on the existing infrastructure [10;11]. Increased water usage is also a result of the exponentially growing population [8]. Climate change and variability effects also cause a strain on water resources which comes as a result of changing rainfall patterns in these semi-arid areas [5;6]. These changes create natural disasters which halt economic activity [3]. Therefore, groundwater plays a significant role in maximising the resilience of water supply and therefore has large prospects for future growth for multiple uses. Managed aquifer recharge (MAR) is being proposed as a mechanism to provide alternate domestic water supply for the metropolitan area to meet water demand and to increase water security [7]. For towns and local settlements, MAR offers the most affordable source of new and safe water [1]. The study domain consists of steep and gentle areas dominated by urban built-up areas.



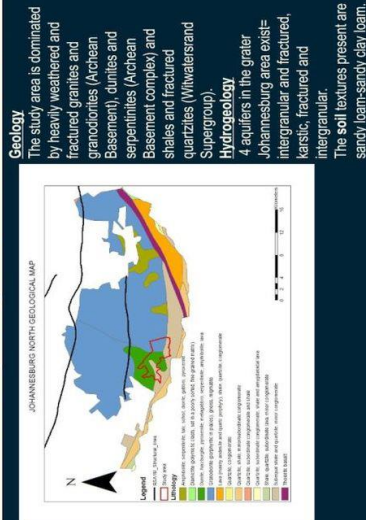
2. Aims

The aim of the study was to assess the feasibility of managed aquifer recharge (MAR) schemes in an area of Randburg (region B of City of Johannesburg) through hydrogeological assessment for the purpose of recovering groundwater as an alternate water resource for domestic use to augment surface water supply.

3. Methodology

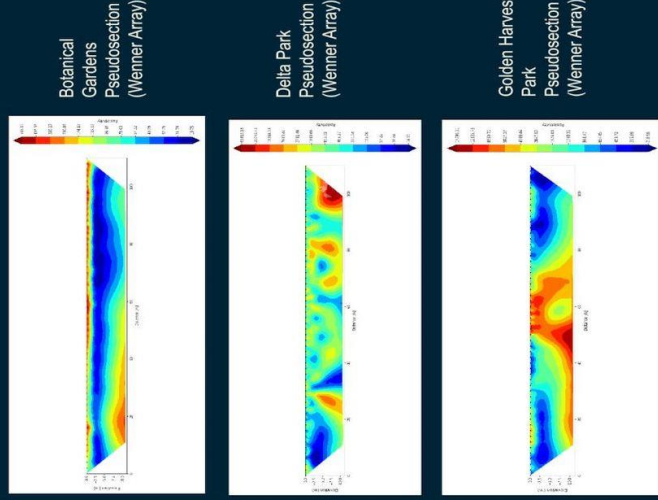


4. Desktop Study and Literature Review



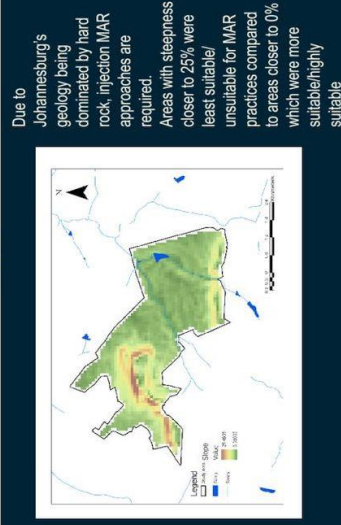
5. Field Work

The fractures on the quartzite and granite outcrops all displayed a W-E orientation, in accordance with literature, with some minor N-S fractures on the quartzites creating a blocky appearance. The sandy clay-sandy clam lam soil texture displayed a slow rate (~0.5 mm/min) of infiltration due to the abundance of clay minerals. The electrical resistivity methods revealed that in the Emmentania area, the shallow intergranular aquifer dominated with a deeper aquifer being present.



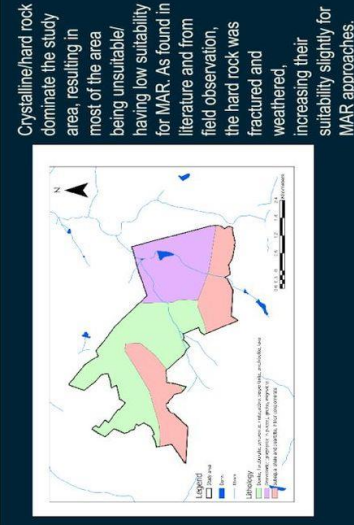
6. GIS-MCDA: Criteria Mapping

Slope



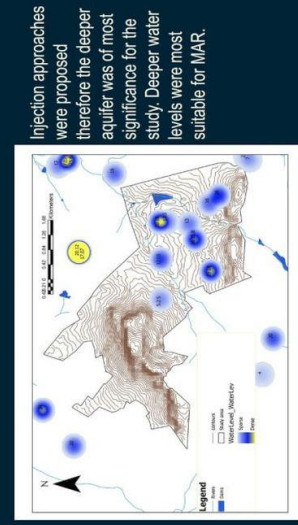
Due to Johannesburg's geology being dominated by hard rock, injection MAR approaches are required. Areas with steepness closer to 25% were unsuitable for MAR practices compared to areas closer to 0% which were more suitable.

Lithology



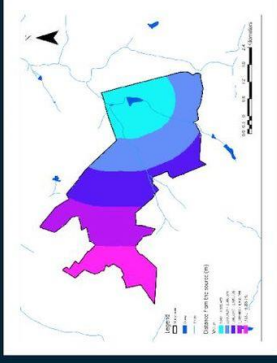
Crystalline/hard rock dominate the study area, resulting in most of the area being unsuitable/ having low suitability for MAR. As found in literature and from field observation, the hard rock was fractured and weathered, increasing their suitability slightly for MAR approaches.

Water Levels



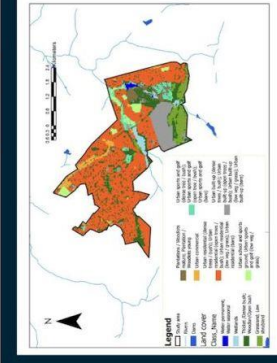
Injection approaches were proposed therefore the deeper aquifer was of most significance for the study. Deeper water levels were most suitable for MAR.

Distance to source



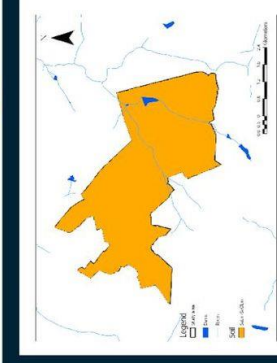
The closer an area was to the source water (Emmentania Dam) the more suitable it was for MAR.

Land use



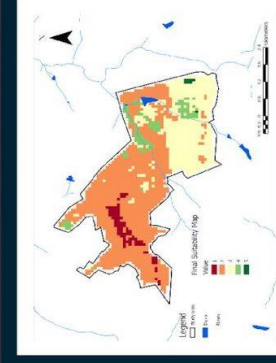
The study area is covered by mainly built-up residential areas and urban built-up which does not facilitate for MAR. The most suitable areas for MAR would include the urban school and sport grounds and golf.

Soil



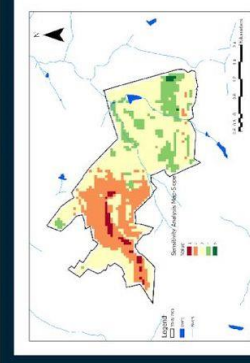
Sandy clay-sandy clam lam textures dominate the area of study. Due to injection approaches being suggested, the soil texture played a very minimal role in the suitability of MAR.

7. Final Suitability Map



Areas that displayed the highest suitability for MAR with each criterion considered were at the base of the Melville Koppies and closer to the proposed source water (Emmentania Dam) along the stream.

8. Sensitivity Analysis



When slope's weighting is altered to be more than that of land cover, the entire area's suitability changes meaning that the final suitability map is subjective to the decision-maker.

9. Conclusions and Recommendations

Due to the complexity of the highly urbanised area and dominance of hard rock, the aquifer storage and transfer (AST) technique was suggested for the few areas of high suitability. The implementation of socio-economic aspects to suitability mapping could provide a more accurate and reliable final suitability map.

10. Acknowledgements

The City of Johannesburg for funding this project.

11. References



Characterizing Paleochannel Aquifer Systems for Groundwater Development in the Western Cape, South Africa



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Introduction

The Western Cape, South Africa, faces water security challenges due to its semi-arid climate and reliance on surface water. The 2015–2017 drought highlighted the need for alternative water sources, including groundwater. Paleochannel aquifers, such as the Elsies Kraal and Geelbek paleochannels, offer potential for sustainable groundwater development. However, key knowledge gaps remain in their hydrogeological properties and role in water supply. This study aims to characterize these paleochannel systems to support groundwater management and enhance water resilience in the region.

Aim & Objectives

- Aim:**
- To characterize the Elsies Kraal and Geelbek paleochannel aquifer systems to support groundwater development for augmenting the Western Cape Water Supply System.
- Objectives:**
- Identify and map paleochannel aquifer systems for spatiotemporal analysis.
 - Investigate groundwater potential zones within these systems.
 - Determine key hydrogeological parameters and properties.

Data Collection methods

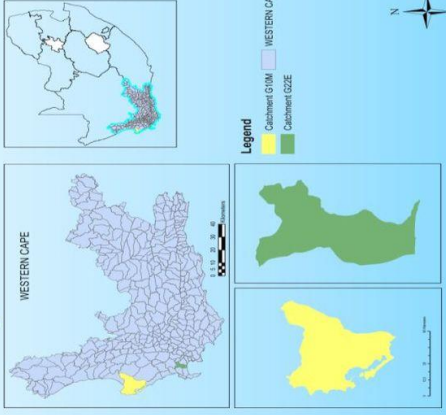
Geophysical surveys will be conducted using resistivity-based methods to map the extent and structure of the paleochannels. A pumping test will also be carried out to determine key hydraulic parameters such as transmissivity and storativity.



Data analysis methods

- Google Earth Engin will be used for spatial and temporal analysis.
- Utilize the RES2DINV geophysical software for inversion process of converting observed electrical resistivity data into a model of subsurface resistivity distribution
- The data set collected from hydraulic tests was analyzed using Flow Characteristic Method (FCM) for parameter estimation and aquifer hydraulic conditions.

Study area



The Western Cape is located in the southwestern part of South Africa, with study sites in catchments 10M (Geelbek) and G22E (Elsies Kraal). The region experiences a semi-arid Mediterranean climate with winter rainfall. Dominant geology includes coastal sediments and calcareous formations, with significant paleochannel features influencing groundwater flow(Seyler et al., 2008).

Preliminary Results

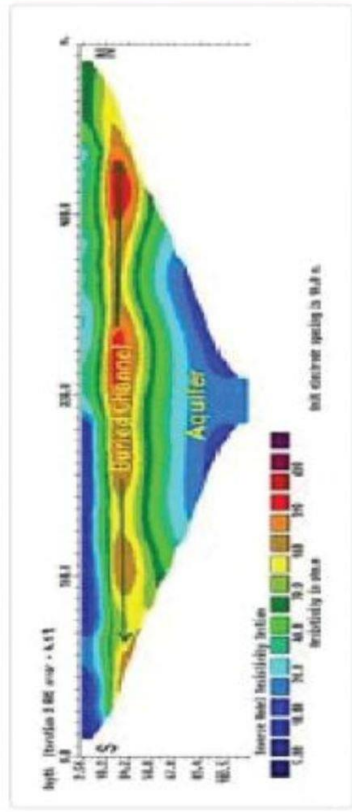


Figure 1. 2D inverted resistivity section (KA-2) showing the buried channel anomaly, variable thickness, and lateral aquifer extent (Kumar et al., 2012).

Output and expected outcome

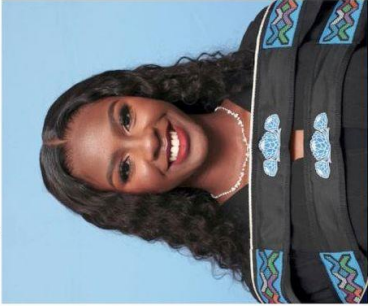
- **Mapped and characterized** Elsies Kraal and Geelbek paleochannel aquifers.
- **Assessed MAR potential** through hydrogeological and geophysical analysis.
- **Informed water management** to strengthen WCWSS resilience.
- **Recommendations for MAR Implementation** based on site-specific aquifer characteristics to guide future recharge projects.

Conclusion

Characterizing the Elsies Kraal and Geelbek paleochannels will provide valuable insights into their groundwater potential and support the integration of Managed Aquifer Recharge into the Western Cape Water Supply System. This research aims to strengthen regional water resilience and contribute to sustainable groundwater management under increasing climate pressures.

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Introduction

The safety and sustainability of managed aquifer recharge facilities remains a concern especially in poorly planned and monitored facilities. As effective MAR facilities can be, they do have a potential of introducing contaminants into the subsurface (Mumberg *et al.*,2024). The potential introduction of contaminants in aquifer systems during MIAR is an alarm for more comprehensive research to fully understand water quality dynamics , contaminant behavior and effectiveness of natural in-situ remediation especially in urban aquifers where anthropogenic activities introduce different organic and inorganic contaminants.

Aim & Objectives

The aim of the study is to evaluate the effectiveness of the urban aquifer material in removal of during managed aquifer recharge processes. To achieve the stated aim, there are three objectives that have been set and are mentioned below:

- Characterization of contaminants in the aquifer system
- Evaluate contaminant attenuation within aquifer system
- Application of hydrogeological conceptual model to assess aquifer attenuation efficiency

Study area

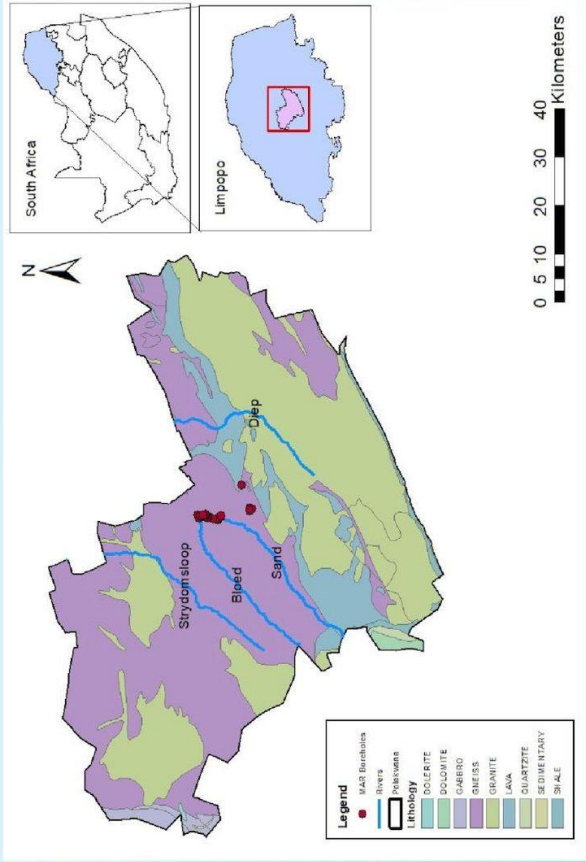


Figure 1: Location of the study area relative to South Africa

Methodology

Data collection methods



Figure 2: Water quality sampling in Polokwane Local Municipality

Data analysis methods

- Statistical analyses
- Removal efficiency method
- Surfer Software
- The Geochemist's Workbench

Preliminary Results

Table 1 : Groundwater Descriptive statistics

PARAMETER	MIN	MAX	MEAN	MEDIAN	STD DEV	SANS 241 Drinking Water Standards
pH	7.52	8.77	8.22	8.40	0.38	5.0-9.7
EC mS/m	10	239	126.22	8.40	42.14	170
TDS mg/l	77	1158	730.66	0.62	197.90	1200
Total Alkalinity CaCO3/L	40.9	713	415.25	8.40	118.59	
NO3-N mg/l	0.29	15.7	2.47	1.47	3.42	11
NH4-N mg/l	0.013	3.19	0.71	0.25	0.93	0.1
Mn mg/l	<0.001	2.59	0.62	0.31	0.72	0.1
Cr mg/l	<0.002	0.24	0.07	0.02	0.11	0.05
Cu mg/l	<0.003	0.15	0.05	0	0.07	2
Ni mg/l	<0.002	0.63	0.11	<0.002	0.16	0.07
Co mg/l	<0.002	0.20	0.08	0.047	0.09	
Cd mg/l	<0.003	0.06	0.02	<0.003	0.03	0.003
Pb mg/l	<0.004	0.25	0.08	<0.004	0.12	0.01

Expected research outcomes

- Identification of contaminants in source water and groundwater
- Identification of major contaminant sources
- Improved groundwater quality
- Better understanding of attenuation mechanisms in study area

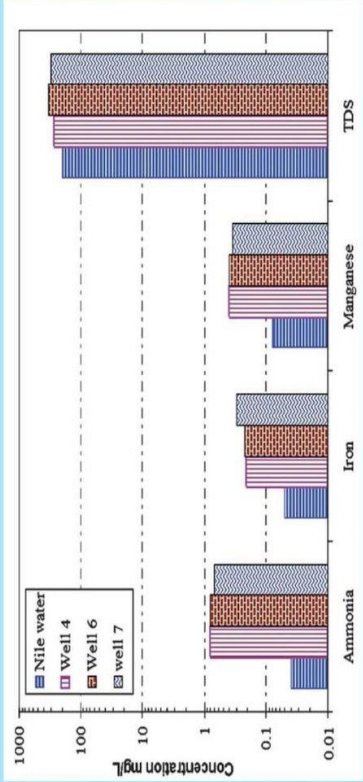


Figure 3: Comparison of water quality parameters in the Nile and bank filtered water, (Abdalla et al., 2011)

Conclusion

This findings of the study demonstrated that MAR using treated wastewater is a viable method for improving water quality through highlighting the effectiveness of the aquifer system in contaminant attenuation. Trough continued monitoring and evaluation of groundwater quality post-recharge the long-term sustainability and safety of the managed aquifer recharge facility will be guaranteed.

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Evaluating Possible Microplastic Contamination in a Managed Aquifer Recharge System



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Introduction

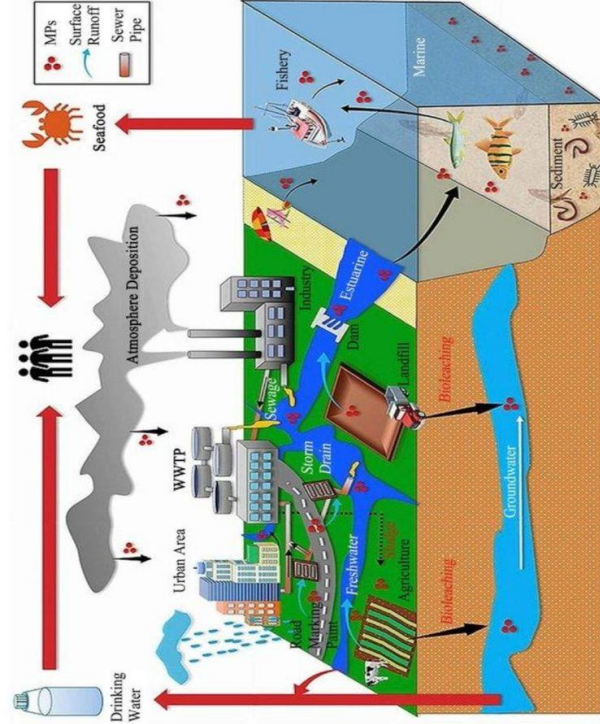


Figure 1: Sources and distribution of microplastics (Wu et al., 2019).

Aim and Objectives

To investigate how the Atlantis aquifer and its receiving environment are affected by the treated effluent water from the WWTP.

1. Assess the presence and concentration of microplastics in the WWTP, stormwater, recharge basins and groundwater.
2. Determine the aquifer's ability in reducing concentration of microplastics in the system
3. Develop a spatial distribution map of microplastics in the area.

Data Collection Methods

- Composite sediment samples at different soil depths across the basins were collected.
- A steel core was used to get an undisturbed soil profile for the column experiment.
- Water samples were collected at the inlet at basin 7, boreholes around the aquifer and at distribution.



Figure 2: Sediment and water sampling at and around the aquifer.

Data Analysis

- A multi parameter probe was used to measure physical parameters on site
- Soil samples underwent different process in preparation for analysis
- Fourier Transform Infrared Spectrometry was used for the identification of MPs
- A paired t-test was used to analyse the concentration of MPs from the source to the distribution point.



Figure 3: The process of acquiring data, from sampling, sample preparation, to analysis, and identification of MPs

Expected Outcomes

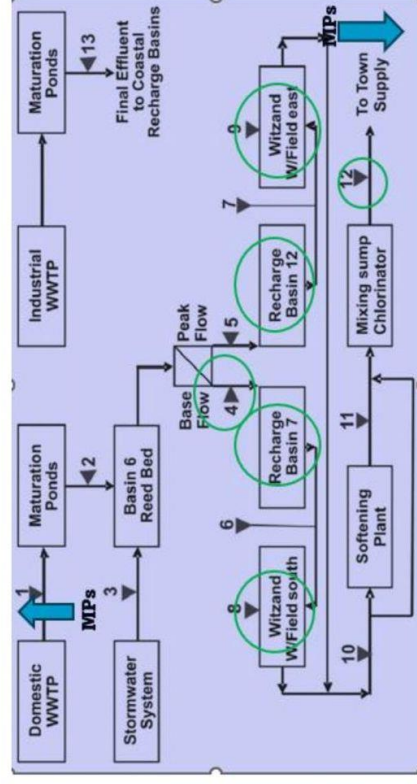


Figure 4: Systematic diagram of the Atlantis water system with the sampling points.

- Reduced MPs in the distributed water compared to the source water
- Increased MPs in the sub-surface.
- Less MPs in the groundwater

Conclusion

- WWTPs are a source of MPs, which are discharged into the MAR system.
- MAR works as a treatment process in reducing MPs in GW.
- Further research into remediation techniques to remove MPs from source water.

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MARSOLUT POLICY-BRIEF + MARSOL STATEMENTS: Essentials on Managed Aquifer Recharge for policy makers and water managers

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MARSOLUT POLICY BRIEF



MARSoluT Policy Brief

Essentials on Managed Aquifer Recharge for policy makers and water managers

Background

Water Management in Europe is facing an uncertain future, as established management frameworks are being challenged by the pressures resulting from climate change. Prolonged dry periods are increasing the occurrence of droughts and associated water scarcity, an increasing number of high intensity rainfall events is resulting in flooding, associated with comparably low groundwater recharge. In addition, the projected increase in temperatures are generating increased water demands.

Despite uncertainties in global climate projections, the anticipated reduction of renewable freshwater resources especially in Southern Europe can be as high as 50% until 2100, hitting regions that anyway 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 principle can be used to increase water availability in general, in periods of high demand, or as a strategic reserve. Ensuring a high level of resilience in the water sector is increasingly becoming a priority for the EU and concepts have to be developed and implemented.

This is not only relevant for ensuring security in the provision of water services, but also in view of the contribution of water to the energy sector, food production, and ecosystems. Increased resilience is generally addressed through the application of traditional tools such as water demand management and water supply augmentation measures. But it can also be addressed through the restoration and augmentation of existing natural freshwater resources.

Managed Aquifer Recharge is one of the tools which can support a move towards a more water resilient Europe, improving the quantitative (and qualitative) status of groundwater whilst enabling the reservoir capacity of aquifer systems to be exploited for balancing water storage between wet and dry periods. In doing so, surplus water resources during wet periods for which there is no immediate use can be stored, and made available during dry periods when water resources are scarce. With this the sustainable use of groundwater resources can be promoted, ensuring their contribution to water security in Europe for the future.



Is Managed Aquifer Recharge safe?

Quality aspects of water sources used for MAR are of major concern, especially the presence of micropollutants, such as pharmaceuticals, in treated wastewater and in receiving surface waters. In particular direct MAR methods, using such waters through the introduction 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.

However, it has been shown that chemical and biological reactions, as the infiltrated water flows through the unsaturated and saturated zones, can improve water quality. The capacity of the unsaturated zone to retain pollutants in indirect MAR techniques varies considerably depending on the hydraulic and biogeochemical factors of each specific site as well as on the pollutants present.

Infiltration basins can be designed to incorporate reactive layers which can aid the improvement of water quality to make MAR a trusted technology. In addition, water quality requirements can be coupled to intended use in a 'fit for purpose' approach. Careful and tailored design of MAR systems and monitoring of MAR sites is therefore crucial for performance evaluation and management of sites. However, water quality is still the key issue in implementing MAR systems, as the regulatory background is not well defined.



CONCLUSIONS



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 water resources management in a long-term strategy.



Legal challenges

The Water Framework Directive (WFD, 2000/60/EG) and the Groundwater Directive (GWD, 2006/118/EC) set obligations upon Member States to both safeguard the quantitative and the qualitative status of groundwater. Article 4(1)(b) of the WFD provides for the environmental objectives to be achieved by Member States in respect of groundwater. Specifically, WFD Article 4(1)(b) lays down (i) an obligation to 'implement the measures necessary to prevent or limit the input of pollutants into groundwater, and to prevent the deterioration of the status of all bodies of groundwater', subject to limited exceptions, while in WFD Article 4(1)(b) it concurrently lays down (ii) an obligation to 'protect, enhance and restore all bodies of groundwater' and to 'ensure a balance between abstraction and recharge of groundwater'.

Article 19(2) of the Treaty on the Functioning of the European Union (TFEU, 02016E/TXT) states that 'Union policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Union'. It is acknowledged that vulnerability to climate change is becoming increasingly widespread throughout the Union, giving rise to a potential conflict between these two seemingly complementary obligations.

Managed Aquifer Recharge may become an inevitable necessity moving forward and thus some elements of legal uncertainty require addressing. These relate mainly to (i) the lack of a formalized position with regards to the 'prevent and limit' concept, (ii) to judgements of the Court of Justice of the European Union and grey areas in the law, and finally (iii) to monitoring issues.

It is acknowledged by the GWD 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 GWD, under Article 6(3)(d), introduces a series of exemptions. Artificial recharge is considered as one of these exemptions.

With this, the basis for the broader application of MAR is given. However, applications of MAR in various regions of the EU are still scarce, mainly as a result of the uncertainties of legal aspects. European guidelines are needed to build up the trust in MAR technologies and to ensure stakeholders that MAR is a measure well supported by EU Member States and the Commission.



Outcome (collection of ideas):

- 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 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.
- MAR is a sound, safe, and sustainable strategy for climate variability preparedness that can be used with great confidence, and through MARSOL and its demo sites the awareness & the acceptance among stakeholders for MAR solutions has been greatly increased.

MARSOL STATEMENTS

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.

Andreas Kallioras

Our challenge is to synthesize everything into a methodology that appeals to responsible persons in authorities' regulators and industry. Quality issues, issue of certainty are still open. If we look from the point of view of somebody who disapproves MAR, what is the barrier, can we argue with them? Currently, no recharge will be possible in case of dogmatic view of the current directives. When you need water you take the risk of introducing pollutants, at least if the concentrations are very low. We need to present MAR as a safe technology.

Manuel Sapiano

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 -> need for improved waste water treatment facilities.

Peter Dietrich

Due to newly collected data a comprehensive modelling of the water budget is possible. Need to put all the little pieces and small projects within MARSOL together, to combine them into a coherent story.

MAR can serve different purposes, it is a difference if it is for drinking water or, e.g., for raising water table in a nature reserve or for combating seawater intrusion; here the legislation should be less strict. But that might not work under current EU legislation.

Joao Paulo Lobo-Ferreira

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. ARO concentrated on the unsaturated zone which cannot replace industrial pretreatment. MECK 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).

Yossi Guttman (Mekorot)

We know all scenarios around MAR, but still there are uncertainties related e.g. to legal issues. We know the processes during MAR, we know how to construct a MAR site, we even know what will happen during infiltration with water components. We need to put all these things together into concrete, presentable suggestions/recommendations.

Christoph Schütt

Within all different water management techniques currently available, we have truly increased the state-of-the-art for Managed Aquifer Recharge, nowadays one of the most important activities to face frontally climate change adverse impacts. It is, perhaps, its biggest capacity together with extreme water-related events response. We have realized the technique is powerful by itself, and a good reaction to water scarcity and drought impacts. Anyway, its full capacity is achieved by means of integration with water transfers, the never arriving low cost desalination, etc. Thanks to MARSOL, I have the feeling the message has been disseminated around, not only to technicians and scientists, but to the whole population.

Enrique Fdez. Escalante

GENERAL DISCUSSION

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.

MARSOL STATEMENTS VIDEO:

<https://www.youtube.com/watch?v=nnSlwCzrim0> (EN)
<https://www.youtube.com/watch?v=hBmzFy12cm8> (ES-SP)

Sustainability in Managed Aquifer Recharge Projects: A Case Study of ThreeEuropean Union Funded Projects

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Introduction

- Over the past decade, MAR has frequently been presented and promoted as a sustainable water management strategy (Fernández-Escalante et al., 2023; Szabó et al., 2023; Dillon et al., 2020).
- EU promotion of applied research of MAR has been done through various funding schemes aimed at addressing the challenges posed by European funding for water projects often tied to broader **environmental, social, and economic** goals that align with the EU's Green Deal, Climate Action, and the United Nations Sustainable Development Goals (SDGs) (REA, 2024). These funding initiatives emphasize long-term sustainability.

Presentation of MAR as a ‘vital tool

Incorporate a variety benefits and sustainability dimensions: institutional and social dimension of sustainability in MAR projects emphasizes aspects related to environmental justice, human health, participation, representativity, resource security, and community engagement (Fernández-Escalante and Gunn, 2021; Zheng et al., 2021).

- Lazersfeld (1958) framework to characterize the objects of empirical investigations
- MARSOL, MARSoluT and Deepwater-CE.
- Interviews to project members and practitioners

Results

The three analysed projects, numerous key indicators were used to assess the performance of the MAR projects. These indicators range from technical and economic to ecological to social and institutional indicators. However, in all the projects technical and economic indicators were noticeably prioritized.

Projects	MARSOL			MARSoluT			Deep Water CE		
Indicators	Number of workshops held; number of farmers' participation; Served population; Proposed regulatory scheme.	Type of water source; Pumping time; air inflow; Flow velocity of MAR water; water level; Slope; Infiltration rate; current irrigable area; mean annual aquifer extraction; Electricity cost; Energy saving; Infrastructural cost; Cost per unit of product; productivity per unit of time; Amount of stored water, surface deposit area of materials; Amount of silt deposit. Effect of water from MAR in irrigation supply m3/ha.	Heat flux; volume of water diversion; Restoration area; Increased of water table after MAR.	Farmers' income after MAR scheme; Participation of different group of stakeholders.	Precipitation rate; Type of water source; Pumping time; Flow velocity of MAR water; water level; Gas control; air inflow; maximum infiltration rate; Mean annual aquifer extraction; electricity cost; Energy saving; Total of Dissolved Solids; Total Solids Suspension; Turbidity; Salt; mass; pH; Temperature.	Infiltration capacity; Type of plant species used in the project for land restoration	Number of Workshops conducted with stakeholders and farmers.	Hydraulic conductivity (K); Aquifer thickness (M); Volume of water supply; Chemical, biological, micropollutants; air inflow; Storage flow capacity; Precipitation; Cost per unit of product; Increased water availability for tourism and agriculture; Number of new jobs	Decrease of the inflow of contaminated groundwater from the industrial zone; Stable water level; creation of infiltration ditches; new ecological niches;
Dimensions	Social and Policy	Technical Economic	Ecological	Social	Technical Economic	Ecological	Social	Technical Economic	Ecological

Discussion and Conclusion

Promoting Success: Following the Funder

- MAR projects need to be viewed in the context of the funder's vision of seeing MAR as being “strategic for the EU Green policy;
- Making MAR more appealing to these actors then revolves around convincing them that MAR is technically feasible and economically worthwhile
- Obtaining funding is dependent on the applicant's ability to reflect the norms and values of the funder (see Brunsson, 1989).
- Project timeline and available resources for the projects were mentioned as reasons why social and institutional dimensions of sustainability did not figure prominently in the projects (C1,18).

Normative Isomorphism, limits of participation

- Individuals involved in the consortiums implementing the studied MAR projects overwhelmingly had a specific technical background related to aquifer recharge.
- Broader interpretation of sustainability is desirable in MAR projects
- Narrow attention to MAR sustainability may well promote initial success of MAR projects in a technical and economic sense, but it raises concerns about the long-term functioning and equitable benefits of these projects over time.

References REA (European Research Executive Agency). (2024). EU to invest almost €164 million in sustainable and environmental research. <https://rea.ec.europa.eu/> (accessed August 2024). Escalante, E. F., Stefan, C., Brown, C. J., & Hutchinson, A. (2023). Managed aquifer recharge: A key to sustainability. Water, 15(23), 4183. <https://doi.org/10.3390/w15234183>. Dillon, P., Fernández Escalante, E., Megdal, S. B., & Massmann, G. (2020). Managed aquifer recharge for water resilience. Water, 12(7), Article 7.<https://doi.org/10.3390/w12071846>

MEDIEVAL SYSTEM OF MANAGED AQUIFER RECHARGE IN SLOPING AQUIFERS OF SIERRA NEVADA (SPAIN)

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Introduction

Artificial groundwater recharge has been a key strategy for adapting to water scarcity in the Sierra Nevada mountain range in southern Spain (Fig. 1) – at least since the Islamic period (VIII–XV centuries) [1] and described in written historical documents dating from 1572 [2]. The practice is based on ‘acequias de caño’, which are unlined channels used to divert water from headwater streams during peak flow periods, usually in spring snowmelt, to infiltrate along the steep slopes of the mountain range. In this way, the local communities improve groundwater discharge from the area’s sloping aquifers, which is vital to meet higher water demands during the hot and dry summer months. This form of water management is known as Water Sowing and Harvesting (WS&H). It is a living example of a resilience and climate change adaptation tool [2] that can be qualified as a nature-based solution and can contribute to the so-called ecological transition [3].

In recent years, considerable scientific effort has led to a better understanding of the hydrological effects of the aequifus careo at the catchment scale [4,5,6,7]. It is known that careo recharge can equal the natural diffuse recharge in the catchment, thus providing a valuable water resource in semi-arid areas [6]. However, the functioning of the whole hydrological system is still poorly understood, especially considering that careo recharge occurs in sloping aquifers developed in low-permeability materials (e.g. shale). This work focuses on the characterisation of the infiltration capacity of two careo channels located in the adjacent Berchules and Mecina basins (Fig. 2).

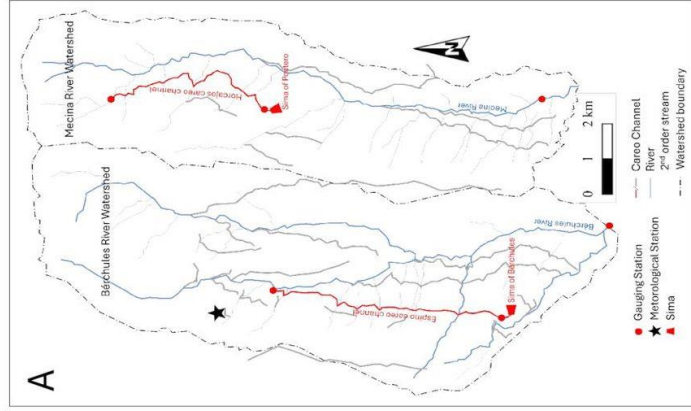


Fig. 2 (A) Sketch of the Bérchules and Mecina watershed; (B) Measuring the careo channel flow rate; (C) Sima de Bérchules during the recharge period of the aquifer.

Results

The flow rates along the Espino Channel were between 240 and 61 L/s (Fig. 3A). On the way to "Sima de Bérchules" 173 L/s were infiltrated, and 6L L/s at "Sima de Bérchules" itself; therefore, all the diverted water from the river was entirely infiltrated at the schist weathered zone.

The inflow rates in the Horcajos channel are smaller than in the Espino channel case. In the Horcajos channel, the streamflow evolution shows a similar pattern for the three differential gauging campaigns conducted in the channel (Fig. 3B). Net streamflow gains from surface runoff through major gullies were observed after the channel intake and after around 3 km of channel length. For the remaining parts of the channel, the differences between gauging spots indicate a net flow reduction, indicating water infiltration and therefore recharge. All the water flowing along the Horcajos channel and getting the terminal point of the channel is infiltrated through “Sima del Postero”.

Crack Channel	Year	Crack Period	Infiltrated volumes during crack period			Specific flows		
			$V_{\text{total}} \text{ (mm}^3\text{)}$	$V_{\text{dissolved}} \text{ (mm}^3\text{)}$	$V_{\text{solid}} \text{ (mm}^3\text{)}$	$V_{\text{dissolved}}/V_{\text{total}} \text{ (-)}$	$q_{\text{total}} \text{ (L/s/km}^2\text{)}$	$q_{\text{diss}} \text{ (L/s/km}^2\text{)}$
Epilimnion	2015	01/June-03/June	1.57	1.30	0.27	4.81	34.61	1283
Hypolimnion	2015	18/June-21/June	1.29	0.70	0.59	1.18	16.00	866
	2022	23/May-12/June	1.16	0.65	0.50	1.29	28.21	3095
Horizon	2021	03/June-16/June	0.43	0.25	0.19	1.39	6.24	676

In the case of the Espino careo system, The total infiltration capacity (q_{Total}) of the Espino channel is 18% higher than that of the Horcajos system. Besides, the in-channel infiltration capacity of the Espino channel ($q_{channel}$) is 44% higher than that of the Horcajos channel, indicating that the Espino channel works better in terms of streambed infiltration. Conversely, if we look at the infiltration capacity of the sima zone (q_{Sima}), in the case of Horcajos infiltration capacity is up to 2.4 times greater than that of the Espino system. Such a high infiltration zone is capable of infiltrating 3095 L/s/km² and makes the total infiltration capacity (q_{Total}) of the Horcajos recharge system higher than that of the Espino Careo system.

Conclusions

The so-called careo practice is based on simple unlined channels that divert water from mountain headwaters to infiltrate as seepage into sloping aquifers composed of low to medium permeability hard rocks. During the careo season, a single careo channel can recharge more than 0.5 hm³/month. The results emphasise that the investigated careo channels are clear examples of MAR that work efficiently, with a low-cost strategy that uses gravity and requires minimal maintenance. In addition, the MAR system has many potential positive environmental and social benefits, qualifying it as a Nature-based Solution (NbS) that may inspire other similar climatic and geographical settings in their efforts to adapt to climate change. Moreover, the very existence of the careo system in the Sierra Nevada, probably for more than 1000 years, demonstrates the usefulness, sustainability and resilience of this "water sowing and harvesting" system.

References

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INTRODUCTION

- Water scarcity:** a growing concern in Croatian coastal areas due to tourism and climate change

- MAR** - a sustainable solution to seasonal increase in water demand
- The **BLUE RECHARGE project** - MAR implementation in karst environments



Fig. 1. Dinaric karst in Croatia [1]

CHALLENGES OF MAR IN KARST SYSTEMS

- Unpredictable water behavior**
- difficult to track flow paths
 - short mean residence times

Quality concerns

- rapid conduit flow = minimal filtration
- low self-purification capacity
- Monitoring difficulties**
- complex geometry complicates network design



Fig. 2. The image with the black frame shows the position of Croatia in the Mediterranean. The red frame highlights the island of Krk and the Ponikve reservoir [2]

Fig. 3. Before completion of the Butoniga system (red lines), two auxiliary recharge systems operated for Gradole spring: a pipeline from Buaž spring to Gradole and a "natural" pathway through the Čiže sinkhole (yellow lines).

Case Study 1: MAR of the Gradole Spring with Water from the Butoniga Reservoir through Ponor Čiže

SYSTEM OVERVIEW

- Location:** Istria
MAR Method: Natural sinkhole recharge
Operation: 1989-2001
Capacity: Sinkhole 600-800 l/s

HYDROGEOLOGICAL CHARACTERISTICS

- Tracer tests confirmed connection (35-day travel time)
- 93% recovery rate in tracer tests
- Two interconnected underground reservoirs with capacities of $0.3 \times 10^6 \text{ m}^3$ and $0.9 \times 10^6 \text{ m}^3$ respectively

CHALLENGES

- Significant difference in water quality between spring water and reservoir water.
- During the tracer test difference in values between Gradole and Butoniga water was noticed: total coliforms, organic matter, nitrate and oxygen saturation.
- After mixing, no significant effect was observed, there was only slight drop in the oxygen saturation of Gradole water.
- The assumption is that the highest ratio of added water to "natural" spring water was 16%: 84%, and differences in quality were not noticed.



GRADOLE SPRING



BUTONIGA RESERVOIR



PONOR ČIŽE – ČIŽE SINKHOLE

ARTIFICIAL CASCADE AND STREAM CHANNEL

Case Study 2: The Ponikve Reservoir on the Island of Krk

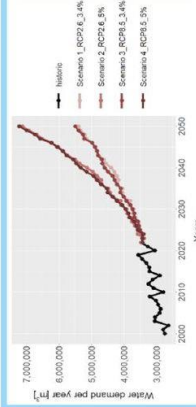


Fig. 4. Projections of Krk island annual water demand extrapolated from tourist numbers under strong and weak climate change scenarios, each coupled with tourism growth rates of 3.4% and 5% based on previous observations. [3]



PONIKVE RESERVOIR

SYSTEM OVERVIEW

- Location:** Island of Krk
MAR Method: Reservoir-based infiltration
Operation: Since 1986, ongoing
Capacity: Reservoir area 0.75 km^2

FUTURE PLANS

- There are plans to raise the dam to ensure complete independence from mainland water supply system.
- This expansion would enhance the island's water security in the face of climate change projections indicating reduced rainfall and more severe drought periods.

Lessons Learned for MAR Implementation in Karst Environments

- Understanding Hydrogeological Connections:** Both cases demonstrate the importance of thorough hydrogeological investigations to understand the complex flow paths in karst environments before implementing MAR.
- Water Quality Management:** The differences between spring water and recharged water quality require careful monitoring and adaptive treatment processes.
- Operational Flexibility:** Both systems demonstrate the value of flexible operational strategies that can adapt to seasonal variations in both water availability and demand.
- Long-term Planning:** The evolution of both systems over decades shows that MAR implementations should be planned with long-term changes in mind, including potential climate change impacts and growing water demand.
- Integration with Other Water Infrastructure:** The Gradole-Čiže case illustrates how MAR can be part of a broader water management strategy that evolves over time as new infrastructure components are developed.



Climate Change Adaptation Potential

Both MAR systems demonstrate significant potential as climate change adaptation measures by:

- providing buffer capacity against increased rainfall variability
- helping manage extreme precipitation events by capturing and storing excess water
- reducing vulnerability to extended drought periods

As climate models predict more extreme weather patterns for the Mediterranean region, including the Croatian coast, these types of MAR systems may become increasingly important components of regional water security strategies.

Acknowledgments

This work was co-funded by the European Union through the Interreg Italy-Croatia program as part of the *Blue credits for water aquifers recharge and sustainability* (BLUE RECHARGE) project.

1. Background

The City of Johannesburg (CoJ), South Africa's economic hub, aims to achieve water security by 2040 to support sustained economic growth, social well-being, and ecological health. This study explores the feasibility of Managed Aquifer Recharge (MAR) to diversify water supply and strengthen resilience. Guided by Aboelnga et al.'s (2019) definition of urban water security, which promotes equitable access to safe, affordable, and sustainable water, this research aligns with CoJ's broader water security strategy. Currently reliant on imported surface water, CoJ is investigating non-surface sources such as groundwater.

The study focuses on MAR defined as the intentional recharge of aquifers for later recovery or environmental benefit as a potential long-term solution to enhance the CoJ water resilience amidst climate variability and increasing water demand.

2. Aims

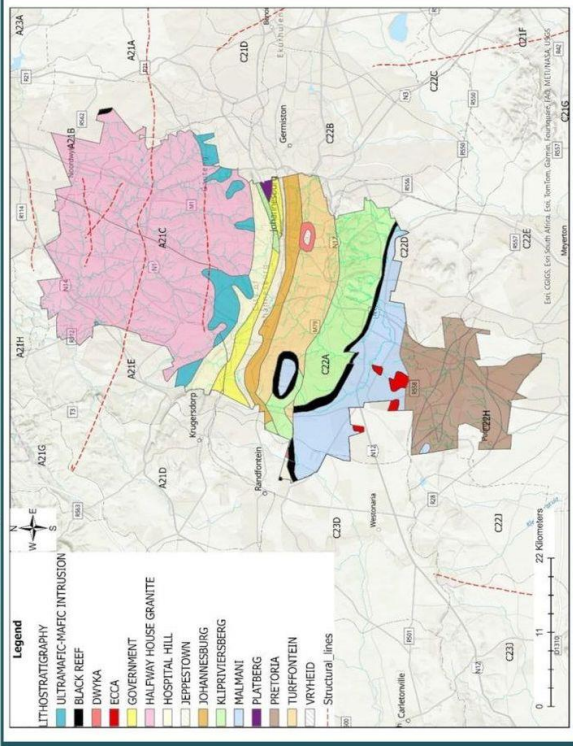
The aim of the study is to assess the feasibility of using Aquifer Storage and Recovery (ASR) and Aquifer Storage Transfer Recovery (ASTR) to diversify water supplies and enhance water security in the City of Johannesburg, particularly during droughts and periods of high demand.

5. Summary of weighting thematic maps for suitability mapping

The focus is on MAR via injection wells; therefore, thematic maps depicting subsurface characteristics were given a higher weighting compared to land surface features. The thematic layers were weighted and normalized to a total of 100. Measurements from the thematic maps were scored using criteria for potential MAR sites.

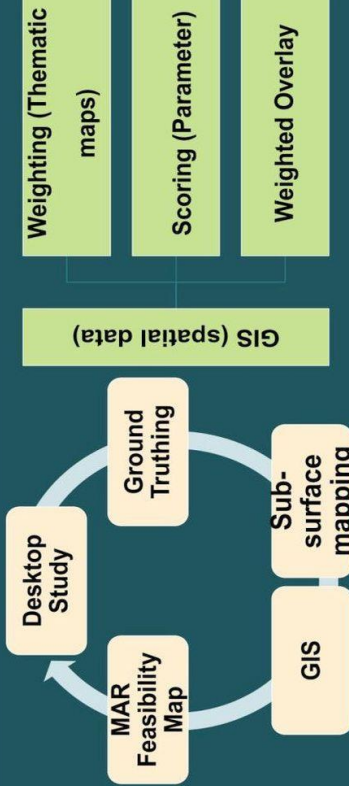
Sub-surface characteristics		Surface characteristics	
Thematic maps	Weighting (%)	Thematic maps	Weighting (%)
Transmissivity	18	Dams	10
Fractured zone thickness	12	Water levels	8
Storability of fractured zone	12	Land use/cover	7
Recharge	12	Slope	5
Lithology	10	Proximity to rivers	4
		Proximity to roads	2

3. Geological Framework of the CoJ

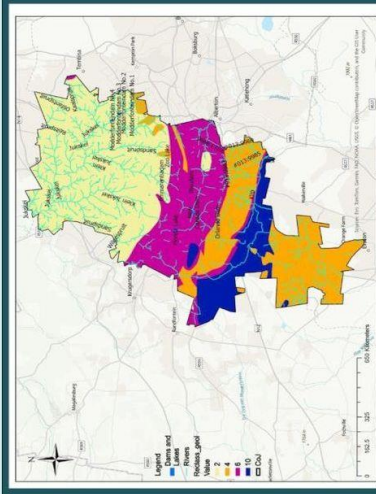


Geological map of the City of Johannesburg (Source of geological data: Council for Geosciences, South Africa)

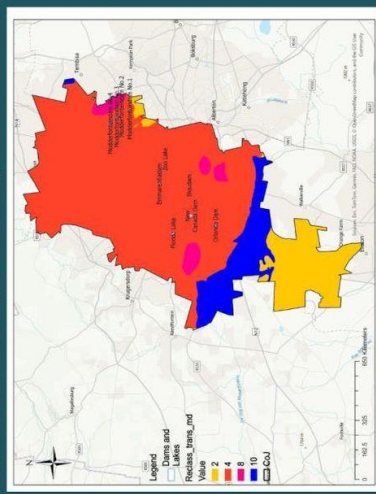
4. Methods



6.Results

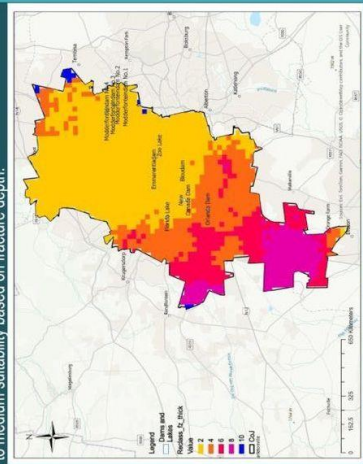


Recharge potential is strongly influenced by lithology. The CoJ features diverse rock types. Dolomite, a carbonate rock, is highly suitable for MAR due to its interconnected cavities and fractures. In contrast, metasedimentary and volcanic rocks have lower suitability, with groundwater flow limited to weathered and fractured zones. The map above shows dolomite as having the most suitable areal extent for MAR. While lithology is important, transmissivity also plays a key role (see map below). The dolomite aquifer, the most productive in the region, shows high transmissivity values (250–3,000 m²/day), whereas much of the CoJ has low suitability based on transmissivity.

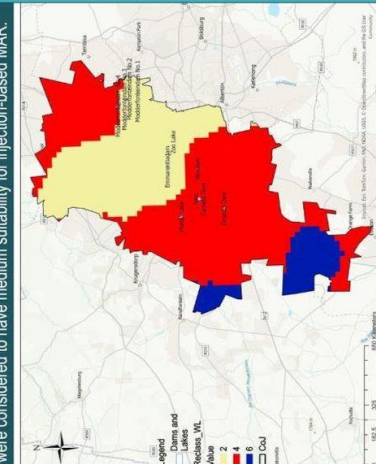


In the northern CoJ, dominated by crystalline rocks, fractured zone thickness is key to groundwater recharge. Fracture depths increase southward—from 137–148 m in the north to 146–157 m in karst areas, with some zones reaching 237 m.

Deeper fractures, assumed to be more hydraulically active, were rated highly suitable for MAR via injection. Overall, most of the CoJ has low to medium suitability based on fracture depth.



In the CoJ, groundwater levels range from 10 to 38 m, reflecting shallow, weathered, and fractured zones. Shallow levels (10–16 m) were rated very low, and 15–24 m as low for MAR suitability, as they may indicate limited aquifer storage capacity. Levels between 24–38 m were considered to have medium suitability for injection-based MAR.



The CoJ is highly reliant on inter-basin water transfers. This dependence on remote water sources increases its vulnerability to water supply shortages—an identified urban water risk (McDonald et al., 2014). Despite its limited spatial extent, the CoJ's land use and cover characteristics are favorable for MAR via injection in select areas. As the economic hub of South Africa, the CoJ is characterized by extensive urbanization and industrial activities, including mining and steel manufacturing. These land uses typically score low to medium for MAR suitability due to the elevated risk of contamination. Conversely, less developed open spaces—particularly those distant from abandoned mines and other pollution sources—are rated highly suitable for MAR. However, the high level of urban development across the CoJ restricts the feasibility of MAR techniques that require large surface areas.

7. Preliminary Insights

- A key consideration is whether the fractured rocks—particularly those with shallow fracture zones—possess sufficient storage capacity to accommodate recharged water.
- The presence, density, and interconnectedness of fractures play a critical role in facilitating groundwater flux in hard-rock aquifers; however, there is a need to map these fractures with depth to determine if they are hydraulically active.
- Existing spatial datasets provide useful insights; however, they are largely derived from limited point-based measurements, which may not capture the full subsurface heterogeneity.
- The geological complexity of the CoJ, characterized by varying lithologies and structural settings, necessitates a more integrated approach to subsurface characterization.
- A joint application of geophysical methods (e.g., ERT, magnetics) is recommended to enhance understanding of subsurface conditions and fracture networks.
- Integrating geophysical data with existing hydrogeological information will improve the accuracy of identifying and validating suitable MAR by injection sites

References



Acknowledgements

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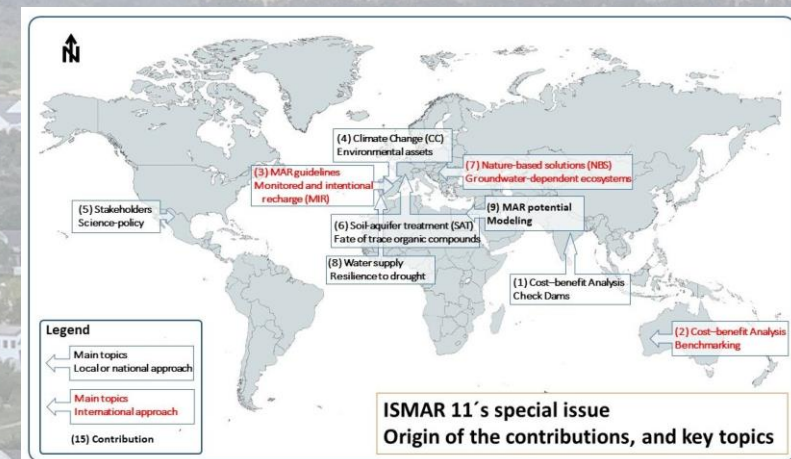
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