Electronic Supplementary Material - Hydrogeology Journal

Sixty years of global progress in managed aquifer recharge

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ESM1: National or Regional Summaries of Managed Aquifer Recharge

These national summaries, prepared especially for synthesis in the journal paper by members of a Working Group on 60 years history of MAR of the IAH Commission on Managing Aquifer Recharge, contain much more detail than could be included in the global summary. They give a snapshot in time prepared between 2016 and 2018 of the history of the development of MAR in these countries and serve as an enduring record. These summaries are also accessible for the foreseeable future at https://recharge.iah.org/60-years-history-mar . It is intended that when other countries produce summaries they will be placed on that web site, along with possible future updates of these current summaries.

There is also ESM2, a second set of electronic supplementary material to this paper, which consists of a small photo gallery of MAR projects with concise explanations to give those new to MAR an appreciation of the wide range of methods and applications.

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Recent inventories of MAR have been published in the 'Special Issue on Managed Aquifer Recharge in Integrated Water Management' in *Sustainable Water Resources Management* (a Springer journal). These include a global summary and a paper on Latin America and the Caribbean :

Stefan, C. and Ansems, N. (2018). Web-based global inventory of managed aquifer recharge applications. Sustain. Water Resources Manag. 4, (2) 153-162. https://link.springer.com/article/10.1007/s40899-017-0212-6

Bonilla Valverde, J.P., Stefan, C., Palma Nava, A. da Silva, E.B., Pivaral Vivar, H.L. (2018). Inventory of managed aquifer recharge schemes in Latin America and the Caribbean. Sustain. Water Resour. Manag. 4 (2) 163-178. https://doi.org/10.1007/s40899-018-0231-y

Further details on MAR sites around the world can be found on the International Groundwater Resources Assessment Centre (IGRAC) MAR Portal at https://www.un-igrac.org/special-project/mar-portal

MAR in Australia

by Peter Dillon

2016

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Managed aquifer recharge currently makes only a small contribution to water resources development in Australia, estimated at ~400 Mm^3 (Table 1) that is 8% of approximately 5,000 Mm^3 national groundwater use (Harrington and Cook 2014). However through storage for use of associated groundwater and urban stormwater it is a very significant enabler of more environmentally benign expansion of iron ore mining, the coal seam gas industry and urban development. Scaling up of groundwater replenishment with recycled water for potable supplies has recently commenced due to significant cost savings with respect to seawater desalination.

When Perth was first settled by Europeans in 1829 roof runoff was drained into sumps and basins and infiltrated the sandy soil to reach the unconfined superficial aquifer. The scale of unmanaged recharge grew as the village grew into a city with paved roads and planning regulations mandated drainage sumps. With the establishment of Managed Aquifer Recharge Guidelines (2009), a WA Operational Policy for MAR (2011) and water sensitive urban guidelines developed by councils (eg South Perth 2012) this can now be regarded as MAR and is estimated at ~200 Mm^3/yr.

The first intentional recharge began in 1965 on the Burdekin Delta of central Queensland where surface infiltration of river water using sand dams, pits and channels augmented groundwater irrigation supplies to grow sugar cane in a coastal area and prevent saline intrusion. Two parallel recharge systems were run, the North and South Burdekin Water Boards were cooperatively managed by cane growers who opted to invest in building and maintaining recharge systems rather than face potential cuts in consumption otherwise imposed by government to protect the aquifer. In 2015 the Boards were amalgamated and the combined systems have continued with a mean annual recharge of ~40Mm^3 with year to year fluctuations depending on needs for direct use.

A national conference on Artificial Recharge (Volker 1980 ed.) in Townsville near the Burdekin Delta helped give exposure to the scheme and pioneering research on algal growth, clogging, groundwater modelling and design and operational performance of recharge structures. The conference helped catalyze formative MAR development elsewhere in Australia. Among these were, in South Australia, aquifer storage and recovery in the Bremer River irrigation area and recharge releases from a new reservoir in the Little Para River upstream of the northern Adelaide Plains (Dillon 1984). In north-west Western Australia, Opthalmia recharge dam and four basins were built at Newman, in south-east Queensland recharge weirs were built on the Callide and Lockyer Rivers, and in Victoria recharge basins were established near Geelong, to augment groundwater supplies to a growing urban area (Parsons et al 2012).

Ironically, recharge basins built downstream of the Ophthalmia Dam constructed in 1981 as part of a conjunctive storage scheme to support mining operations and the local community were not used because the dam was so effective in recharging the aquifer (~12Mm^3/yr) with detained water (WA Department of Water 2009). This was a great advantage in an area with annual evaporation of 3m/yr. Lack of awareness of the potential for MAR in Australia was a deterrent to progress, but where projects were established and successful they soon became replicated in their local area.

With a growing appreciation of the potential value of urban stormwater and reclaimed water in the 1990s as an outcome of the Commonwealth Clean Seas and Better Cities Programs, there was a need to also identify the water quality issues associated with MAR with these water sources. CSIRO worked with partner organizations including state departments, water utilities and local government to develop demonstration projects and to apply the principles of Australia’s National Water Quality Management Strategy (NWQMS) to produce water quality guidelines for MAR that protected human health and the environment. Following review these were adopted by the Council of Australian Governments as 24th NWQMS document (NWQMS 2009). They are the first risk-based guidelines on MAR, account for all types of source waters, aquifers, recharge methods and end uses of water and allow for water quality changes, both improvements and deteriorations, in the aquifer between recharge and recovery. Subsequently some historical drainage wells have come under a revised management regime that accounted for water quality risks and are now considered as having transitioned from unmanaged to managed aquifer recharge.

Water entitlement issues associated with managed aquifer recharge were addressed in the National Water Initiative framework of entitlements, allocations and use conditions for each phase of harvest, recharge, recovery and use (Ward and Dillon 2011) that enabled fully articulated set of rights and responsibilities to mesh within existing groundwater and surface water management plans. Two states have adopted this framework within their water resources policies and other states are giving consideration.

Table 1: History of managed aquifer recharge in Australia (in $10^6 m^3$/year)

Decade	Total	Infiltration systems				Recharge wells			
		Rivers	Aquifers	Urban stormwater*	Recycled water	Rivers	Aquifers	Urban stormwater	Recycled water
1961-1970	79	10		69					
1971-1980	144	40		104	0	0			
1981-1990	185	53		130	0	2		0	0
1991-2000	213	53		156	0	2		2	0.2
2001-2010	257	53	3.5	182	0.6	0.1	0	17	0.2
2011-2015	410	53	3.5	208	1.8	0.1	113	29	1.5

* derived from estimates based on population, metropolitan area, impervious fraction, rainfall, runoff coefficient and proportion of runoff effectively recharged. Others values are based on measured data.

Uptake of MAR had been slow in Australia although following release of the MAR Guidelines there has been strong public acceptance and very rapid growth particularly in the resources industries and also by local government and water utilities as they identify opportunities for MAR to contribute to their portfolio of water management activities. Surprisingly there has been minimal effort in enhancing recharge in rural areas for agriculture since the foundational project that has operated effectively for 50 years. There are diverse drivers for MAR in Australia as revealed in the results of a national survey of 135 groundwater professionals in May-July 2015 (Fig 1). The dominant reasons given are to increase water security in drought, to meet growing demand for water and to mitigate decline in groundwater levels.

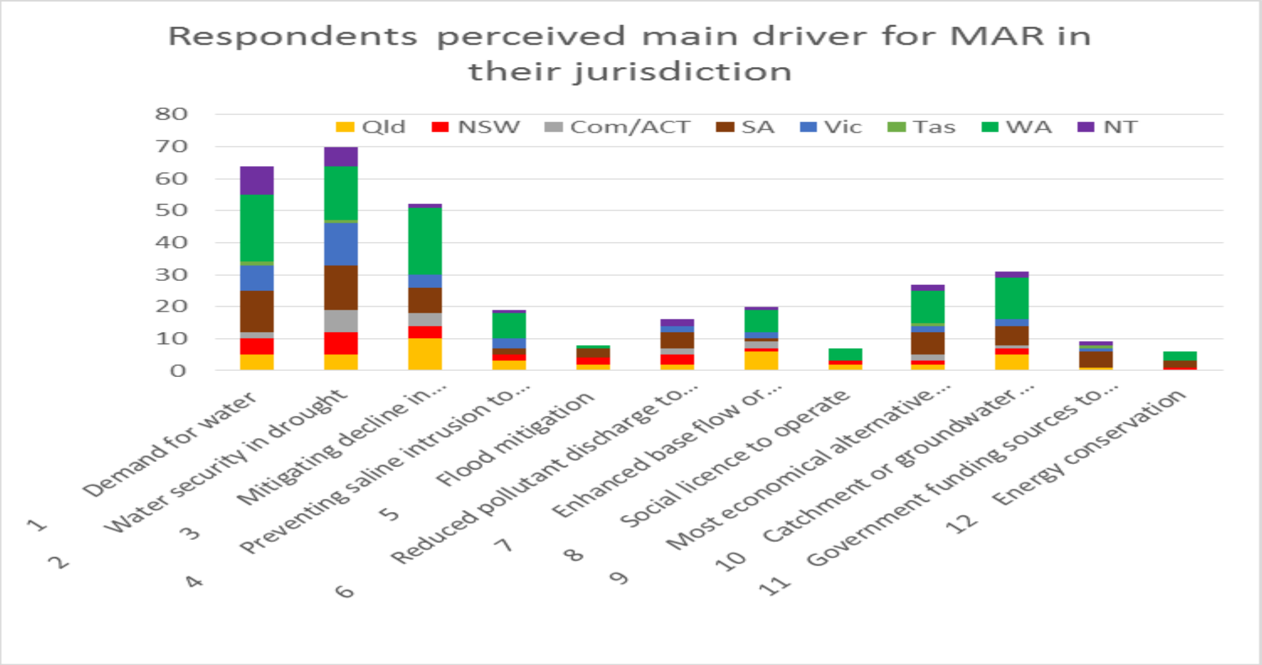

Figure 1. The main drivers for MAR perceived by 135 Australian respondents in a survey May-July 2015.

Two national symposia Volker (ed) (1980) and Sharma (ed) (1989) and International Symposium on MAR (ISAR4) (Dillon (ed) (2002) have been the dominant symposia in this field in Australia, and Australian authors have made significant contributions to ISMAR symposia since. Australian groundwater symposia conducted by IAH since 1994 have invariably included several papers on MAR and since 2000 this has also been reflected in OzWater and water recycling symposia conducted in Australia by IWA and AWA. At least twelve training courses and workshops have been run by NCGRT and its predecessor CGS since 1996 in various cities and encouragingly, two thirds of respondents to the survey claimed they had experience in MAR. There is now a MAR-Hub cluster of companies (http://marhub.net.au/) which collectively have experience in the full spectrum of MAR design and operation from hydrogeology to water treatment, systems integration, risk management, SCADA systems and wetland and water sensitive urban design. They are keen to apply their expertise internationally.

Research publications have largely focused on water quality in support of MAR guidelines and to lay the foundations for future updating of guidelines based on improved knowledge of the fate of pathogens and nanoparticles, and aquifer microbial ecology and fate of organic chemicals, natural organics and inorganics in relation to transitional thermal and geochemical conditions in aquifers and on development of robust field validation testing procedures. Clogging and its management also require improved predictive capabilities and development of comparative laboratory tests and field methods to optimize overall costs of operations and give greater assurance on preventative requirements.

Currently growth in MAR in Australia is soundly based and is expected to make a greater contribution than sea water desalination in the longer term due to lower costs. When the full benefits and costs of alternative water supplies are evaluated, it is expected that MAR will be increasingly adopted in Australia and could ultimately contribute 16% or more of national groundwater supplies.

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MAR in China for 60 Years

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China has a long history in managed aquifer recharge (MAR). The development was divided into 3 stages based on the summary combined with typical MAR projects since 1956, including the first stage applied for industrial energy saving, controlling urban land subsidence and augment agricultural water supply from 1949 to 1978, the second stage for ecological protection and augment of urban water supply from 1979 to 2000 and the third stage for multi-source MAR. In addition, geothermal reinjection and ground source heat pump are also effective use of MAR from 2001 to now(Weiping Wang et al, 2014).

1. The first stage

Groundwater recharge through deep tube wells located the geological conditions of coastal, alluvial, piedmont plain and karst aquifer with cooling water or tap water since 1960s for air-conditioning or heating and controlling land subsidence through Shanghai, Tianjin, Beijing, Shijiazhuang, Xi’an and Nanchang cities etc, characterized by factories being investors, beneficiaries and government being guide. For example, Shanghai city which represents a typical development of MAR for the first stage is located in the Yangtze River Estuary where the deep Quaternary sedimentary covers the area underlying carbonate rock layer, relying entirely on groundwater as urban water supply so resulting in land subsidence with a maximum ground drop depth of 2.63m in 1965. At the same time, five cotton mills in Shanghai carried out injection test with 4 different water sources and recharge techniques of intermittent injection, continuous and intermittent lifting, subsequently observing the groundwater level and land subsidence for many times. the result shows that groundwater recharge through tube well can not only alleviate to increase groundwater level and effectively control land subsidence but solve the problem of pumping groundwater, offering new cold source and heat source for factories with aquifer, that is water was recharged into aquifer in winter while exploited in summer and water was recharged into aquifer in summer while exploited in winter. In 1966, groundwater recharge was done through 134 of deep wells in more than 70 factories of the city at the same time so that average groundwater level raised more than ten meters and ground level up 6mm that meant it is first time to appear phenomenon of ground level rising until it had been fallen several decades(Weiping Wang et al, 2010). Since then, the techniques of groundwater recharge were improved constantly in Shanghai and achieved result showed that the underground water level rising from -10 m to -1.5 m in 1970, the land subsidence being stable at between 0 and 5 mm by 1990 (Yi Liu, 2000), the total amount of groundwater recharge with tap water of 100×10^6 m^3 in Shanghai by 2000, the annual average of groundwater recharge of 20×10^6 m^3 and urban land subsidence being controlled effectively (Shiliang Gong, 2006; Yi Liu, 2000).

In rural area of North China Plain, artificial recharge of groundwater were widely applied through wells, ponds, ditches and basins in order to increase replenishment of the groundwater and ensure the agriculture with bumper harvest and stable production, characterized by farmers putting as free labor, government gave subsidence to these projects and collective economy benefited. For example, the irrigation district of Renmin Shengli Channel in He’nan province adopted a method of combination of well and channel, which use channel water for irrigation and recharge groundwater during the dry seasons, while use well water in contrast. In 1975, the irrigated area reached 300,000 hectare and the water table was maintained at 2m, the saline land area decreased and grain yield increased year after year. Now the module, groundwater recharge through channels diverting surface water and guaranteeing agriculture harvest by pumping groundwater through wells, has been widely applied in larger irrigation districts of diversion Yellow River water in Shandong and He'nan province. The way to be developed, for example, in Huantai county and Yanzhou county of Shandong province and Hebei province, where the water network of all rivers and ditches connection throughout the county were built to retain water by rivers and ditches, infiltrating to recharge groundwater and forming larger groundwater reservoir which played an important role in combating droughts of 1970s. In addition, practical intercepting underflow project in semi-arid and arid region were constructed to alleviate the contradiction between supply and demand of water resources effectively and strengthen the agricultural drought resistance. For instance, Alxa League city of Inner Mongolia has built 70 intercepting underflow projects since 1970s. Among them, the largest one in Alxa Zuoqi resolved tens of thousands of people's drinking water with 90L/s of daily water supply. Intercepting underflow project is an effective measure to exploit and utilize groundwater of river way and valley plain in hilly area (Qinde Sun et al., 2007; Honggu Luo, 1981).

2. The second stage

6 underground reservoirs to prevent salt water intrusion were built to prevent seawater intrusion in Shandong peninsular since 1990s, characterized by mostly government investing and farmers and factories being beneficiary. For example, the Huangshui River Underground Reservoir with total reservoir capacity of 53,59 million m^3, which was composed of a underground cement wall of 5842 m long and 10 m deep combating salt water intrusion and storing groundwater ,6 sluices retaining surface water when flood period 2,518 infiltration wells and 448 infiltration trenches directing flood water into aquifer. What is more, there is a serious water shortage in partial downstream plains. Since 2000, some reservoirs have turned into integrated ecological type instead of flood control and water supply merely. For example, the water in Taihe reservoir in Zibo City of Shandong province in dry seasons is discharged to supply downstream groundwater source by riverbed infiltration.

3. The third stage

Various water sources could be storied in MAR, such as urban stormwater, reclaimed water, foreign water transferred from the other basin such as Yellow River or Yangtze River, which were recovered for drinking water supply or agricultural irrigation, characterized by more experimental pilot project and larger scale of practical projects invested by government. For example, the first urban reclaimed water recharge project in China, Gaobeidian Groundwater Recharge Pilot Project in Beijing, which was completed in 2003 with 200m^3/d of design recharge amount composed with combination of a basin and rapid infiltration shaft system(Guichun Yun et al., 2004) that led to the first state standard of *Municipal wastewater reclamation and reuse and the quality of recharging water（GB/T19772-2005）*. The pilot project though wetland treatment and basin infiltration with municipal reclaimed was done in Zhengzhou city of Henan province in 2002 and recovered water can be used for fishery, industry and agriculture (Menggui Jin et al., 2009). For another example, a pilot project of karst aquifer recharge with urban treated roof water was established in Jinan in .2011. Continuous monitoring shows that both quality of roofwater and groundwater basically met groundwater quality standard with a recharge amount of 2000m^3 until 2015(Weiping Wang et al., 2015). In addition, the project of MAR through channel infitration with local surface water released from upstream reservoir and Yellow River water pumped along Yufu River of Jinan, Shandong was implemented to augment groundwater and improve drinking water in 2014, with annual released water quantity of 5,000-7,000 million m3 from 2014 to 2015. There is same project of MAR along Chaobai River with reclaimed water and Yangtze River water was implemented in Beijing(Ji Liang et al., 2013;Fandong Zheng et al.,2015). Furthermore, geothermal reinjection and ground source heat pump are also effective utilization of MAR. In recent years, ground source heat pump (GSHP) technique developed quickly. In 2009, the *Technical code for ground-source heat pump system (GB50366-2005)* was issued, which contributed to the development and application of GSHP technology.

There are some typical MAR projects since 1960s in Table 1 and symposiums on MAR in Table 2 as follows:

Table 1. Typical Projects on MAR in China since 1960 (Uncompleted statistics)

City/ county/ province	Region	Character	Aquifer	Types	Source water	End use	Date	Operation or not	Volume (m^3/yr)
Huantai	Wuhe River	Practical	Pore	Water spreading of open channel-under tunnel	Runoff in river	Irrigation	1962		
Shanghai	Urban area	Practical	Pore or karst	ASR, ASTR	Cooling water or tap water etc.	Energy saving and preventing land subsidence	1965	Yes	20×10^6
Tianjin									
Beijing									
Shijiazhuang									
Xi’an									
Nanchang									
Huantai	Piedmont plain	Practical	Pore	Water spreading of network of connected channels/diches/ponds	Runoff in the river	Irrigation	1970s		
Yanzhou									
Tengzhou									
Shandong and Henan Province	Yellow River flood plain	Practical	Pore	Water spreading of network of connected channels/diches and irrigation	Yellow River water	Irrigation	1970s	Yes	
Inner Mongolia	Arid and semi-arid area	Practical	Pore	Intercepting dam	Local groundwater runoff	Rural human and livestock drinking water and irrigation	1970s	Yes	2.85×10^6
Shanxi Province									
Hebei Province									

City/ county/ province	Region		Character	Aquifer	Types	Source water	End use	Date	Operation or not	Volume (m^3/yr)
Longkou	Balisha River		Pilot	Pore	Underground dam	Exceed flood water in the river	Agricultural, industrial and drinking water use	1987	Yes	0.6×10^6
Qingdao	Shiren River		Practical					1991	Yes	
Longkou	Huangshui River	Estuary	Practical					1995	Yes	
Qingdao	Dagu River		Practical					1998	Yes	
Laizhou	Wang River		Practical					1999	Yes	31.9×10^6
Yantai	Dagujia River		Practical					2000	Yes	
Zibo	Zihe River		Practical	Pore and Karst	Recharge release	Local surface water	Drinking and industry water	2000	Yes	
Beijing	Gaobeidian wastewater treatment plant		Pilot	Pore	Combination of well and basin	Reclaimed water	Augment groundwater	2002		73×10^3
Zhengzhou	Suburban		Pilot	Pore	Wetland, water treatment system and Basin	Reclaimed water	Irrigation	2007		113×10^3
Beijing	Chaobai River		Pilot	Pore	Natural channel	Multiple sources of Yangtze River water and reclaimed water	Drinking water and industry water	2012	Yes	
Jinan	University of Jinan campus		Pilot	Karst	ASTR	Roof water	Drinking water	2008	Yes	700
Linqing	Yellow River flood area		Pilot	Pore	Spreading of open channel-underground performed pipe-shaft	Yellow River water	Irrigation	2014	Yes	20×10^3
Jinan	Yufu River		Practical	Pore and Karst	Natural channel	Multiple sources of local surface water and Yellow River	Drinking water and keep springs flowing	2014	Yes	50×10^6

Table 2 Symposiums on MAR in China

Conference	Location	Date	Website
China-Australia Managed Aquifer Recharge (MAR) Training Workshop	University of Jinan, Jinan, China.	October 27-31, 2008	http://china-mar.ujn.edu.cn/
8th International Symposium on Managed Aquifer Recharge - ISMAR8	Tsinghua University, Beijing, China.	October 15-19, 2013.	http://china-mar.ujn.edu.cn/
The Role of Managed Aquifer Recharge in Water Resources Management in China: A Practical Guide for Piloting and Upscaling	Peking University, Beijing, China.	September 7, 2015	http://hydro.pku.edu.cn/

China obtained a great achievement on MAR used for land subsidence control, energy storage, geothermal utilization, prevention of seawater intrusion, augment of urban water supply, agriculture irrigation and alleviation of agricultural disasters etc. However, there are still many problems. It is needed to develop multiple feasible, convenient and economic techniques of MAR fitting to local hydrogeological conditions, prepare guidelines of MAR and management regulations together by establishing demonstration projects, making MAR standardized and the guidelines perfect led by Ministry of Water Resources, Ministry of Environmental Protection and Ministry of Land and Resources jointly.

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MAR in Croatia

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https://recharge.iah.org/60-years-history-mar

Managed aquifer recharge (MAR) is not discussed often in Croatia since groundwater reserves generally satisfy demand for water. Hence, the need to manage aquifer recharge is not pronounced. Nevertheless, there are some springs used for public water supply which require enhanced recharge during periods of hydrologic drought as well as public wellfields deliberately positioned near rivers in order to, either enhance the capacities of pumping wells through river bank filtration, or diminish wellfield protection zones which in many cases occupy urban areas.

Quaternary alluvial aquifers, typical in the northern part of Croatia which is situated in the southwestern part of the Pannonian basin, are mainly recharged by rivers Sava and Drava. Although river Drava is regulated with hydropower plants (HPP's) on one smaller upper tributary, the majority of the flow of the rivers Sava and Drava is still unregulated with respect to structures such as dams or weirs. Therefore the rivers not only recharge aquifers but also drain them during low flow periods (Posavec *et al*., 2017). Alluvial aquifers, mainly composed of sands and gravels are generally characterized by high hydraulic conductivities, ranging from 10^{-5} m/s (~1 m/d) in eastern parts of Croatia to 10^{-2} m/s (~1000m/d) in western parts. Such high hydraulic conductivities enable intensive aquifer recharge as well as aquifer discharge. High aquifer discharge potential therefore makes MAR inefficient in many cases. At the same time, high aquifer recharge potential as well as relatively thick alluvial deposits, make positioning of the pumping wells less demanding. Therefore, in many cases there was no need to position the wells near the river in order to utilize river bank filtration.

A study by the Croatian Geological Survey (2009) on assessment of state and risk of groundwater bodies indicates that artificial recharge of aquifers by recharge wells or channels is not present in the Pannonian part of the Republic of Croatia . Nevertheless, some wellfields located in the City of Zagreb, Croatia's capital (population of ~800,000), have been placed knowingly within the proximity of the river Sava with the intention that a proportion of the extracted water would be induced recharge from the river. Further, a structure was built in the river Sava, weir TE-TO. Although the intention of building weir TE-TO was not to increase aquifer recharge, it was one of the consequences which therefore indirectly increased the abstraction potential of some wellfields and the proportion of the water derived from the river. Therefore, this proportion of groundwater pumped at some Zagreb wellfields and derived from the river can be considered as bank filtration (MAR) (Table 1).

Table 1. Estimated volume of Managed Aquifer Recharge (bank filtration) (Million cubic metres/year)

Annual MAR volume in the decade centred on date (Mm^3/y)				**Annual Groundwater use (Mm3/y)**
1985	**1995**	**2005**	**2010-15**	**2010**
42*	48*	48*	46*	600**

*derived from measured data on abstraction and estimated percentage of abstracted volume gained from river bank filtration ** based on Zagreb Water Supply and Sewage Company data on abstraction for the City of Zagreb, ~125 Mm3/y (Hidroprojekt-Ing and Sl-Consult, 2014). Extrapolated for the entire region of Croatia.

The hydrogeology of the southern part of Croatia is characterized by karst aquifers and water is supplied mainly from springs. Managed aquifer recharge is generally not a common approach with some exceptions. One such exception and the first attempt in Croatia of managed aquifer recharge in karst aquifers is at the Gradole Spring located in Istria, and used for public water supply. Gradole Spring was artificially recharged from water accumulated in Lake Butoniga and pumped into sinkhole Čiže located in Tinjanska Draga. This resulted in a significant increase of spring discharge (Faculty of Geotechnical Engineering, 2009). From the late 1980's to early 2000's, an average 0.873 Mm^3/y was pumped from Lake Butoniga and discharged into the sinkhole Čiže. The maximum volume was pumped in year 1990 (2.8 Mm3/y) and the minimum was reached in year 1995 (0.1 Mm3/y) (http://www.ivb.hr/naslovna-hidden/30-akumulacija-butoniga). Although this solution was inefficient with respect to energy consumption required to pump water from Lake Butoniga situated at 40 m a.s.l. up to the sinkhole Čiže situated at some 350 m a.s.l., it helped to increase the discharge of the Gradole Spring during summer dry seasons. Later on, a water treatment facility was built at Lake Butoniga, which enabled direct distribution of drinking water to consumers and made further MAR actions unnecessary.

Another attempt of managed aquifer recharge of karst aquifers was done also in the late eighties on the island Krk by building the water storage Ponikve. Although managed aquifer recharge resulted with increase in groundwater quantity available, it also deteriorated the groundwater quality, due to which the concept was abandoned (Faculty of Geotechnical Engineering, 2009). Another aspect of MAR was related to construction of HPP's i.e. accompanying storages. Although detouring of rivers in order to build storages had a negative impact on downstream karst aquifer systems, it also helped in stabilizing the flowrate of some springs (Faculty of Geotechnical Engineering, 2009).

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Managed aquifer recharge in Finland

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In Finland the selection of the appropriate source(s) of raw water for urban water supply has been debated for more than a century. In rural areas ground water has traditionally been drawn from wells and springs for domestic use, whereby the needs of dairy farming also largely promoted common piped water supplies. The first managed aquifer recharge (MAR) system in Finland was used in Vaasa on the western coast in the late 1920s, and its use was also considered in Helsinki. Yet, the decision by Tampere to give up the ground-water option in 1920 encouraged other cities to use surface water, as ground-water deposits in Finland are generally fairly small. After WWII, surface water was adopted even by cities with available ground-water resources. (Katko 2016, 58)

After the establishment of the National Water Administration in 1970, the use of ground water became predominant, and around the same time, wider use of MAR started. In spite of its many advantages the use of ground water for community water supply is no longer automatically considered the best option, since the current aim is to keep all water sources as clean as possible. The debate between surface and ground-water use seems, however, to continue. (Katko 2016, 58)

By the 1960s and 1970s surface water had often become polluted, but efficient water pollution control and wastewater treatment have improved its quality dramatically. Yet, Finnish waters contain natural organic matter (NOM; humus) and are also soft, since the bedrock contains only a little calcium. Therefore, surface water needs more complicated treatment, often chemical, to meet domestic water quality requirements. (Katko 2016, 59)

During the last few decades, Finnish community water supply has increasingly relied on natural ground water and MAR as raw water source (Table 1). Currently, their combined share of the water supplied is some 67%. The share of MAR alone is roughly 17 %, including bank filtration. However, potential ground-water areas and places for ground-water recharge are sparsely situated. Thus, large city centres, with their increasing need for fresh water supply, are obliged to withdraw ground water from afar, often crossing municipal borders. (Katko, 2016)

The main objective of MAR in Finland is the removal of NOM from surface waters. A typical MAR procedure consists of the infiltration of surface water into an esker with subsequent withdrawal of the MAR-treated water from wells a few hundred meters down-gradient. The infiltrated water should have a residence time of at least approximately one month before withdrawal to provide sufficient time for the subsurface processes needed to break down or remove humic substances.

There are currently 26 MAR plants in Finland and, in addition, a few plants are being planned. The MAR plants are operated continuously, also during winter. Basin infiltration is used most often, whereas sprinkling infiltration was initiated in the mid-1990s. Sprinkling infiltration includes an aboveground pipe network through which water is distributed on top of natural forest soil. Well infiltration or well injection is applied only in a couple of MAR plants in Finland. However, new infiltration wells are being planned and tested. (Jokela & Kallio 2015)

Table 1. History of MAR in Finland (approximate values)

Raw water is taken from lakes and rivers.

Period	**MAR production (10^6 m^3/a)**	**Infiltration methods**
1961 - 1970	< 1	basin (the first MAR plant started in 1970)
1971 - 1980	30	basin, dug well, bank
1981 - 1990	35	basin, dug well, bank
1991 - 2000	50	basin, sprinkling, dug well, bank
2000 - 2010	55	basin, sprinkling, well, bank
2011 - 2015	65	basin, sprinkling, well, bank (share < 10 %)

Most of the Finnish MAR plants do not have pretreatment and raw water is infiltrated directly into the soil. During a MAR process in an unconfined esker aquifer NOM is removed by physical, chemical, and microbial processes. Most of the NOM removal takes place in the saturated ground-water zone.

Most often, total organic carbon (TOC) concentrations of the raw waters vary roughly from 6.5 to 11 mg/L and after MAR the TOC concentrations of the abstracted waters are approximately 2 mg/L. The overall reduction of organic matter in the treatment (with or without pretreatment) is thus 70–85% (Jokela et al. 2017).

Mechanical pretreatment can be used for clogging prevention. Turbidity of the Finnish lakes used as raw water does not necessitate pretreatment in basin and sprinkling infiltration, however, pretreatment in well infiltration needs to be judged separately. River waters may have high turbidity requiring pretreatment. Natural conditions in esker aquifers are generally aerobic. Biodegradation of NOM in the saturated ground-water zone consumes dissolved oxygen. The higher the NOM content, the higher the dissolved oxygen consumption. If dissolved oxygen concentration in the ground-water zone sinks low enough, conditions for dissolution of iron and manganese from the soil increase. Iron and manganese dissolution may be avoided by the addition of chemical pretreatment for the raw water to cut the NOM content. According to the results from selected MAR plants, raw waters with TOC content up to at least approximately 8 mg/L are infiltrated without any considerations of chemical pretreatment. A higher share of natural ground water provides more dissolved oxygen. However, aquifer properties, including the soil composition, vary locally and have influence on the MAR process. (Jokela et al. 2017)

Eskers in Finland are glaciofluvial formations which were commonly deposited by streams in tunnels beneath the ice during the final deglaciation of the Scandinavian ice sheet. Typically, an esker consists of 20 to 50 m of gravel and sand that is covered by a thin humic soil layer (<10 cm). Eskers are preferred areas for potable water MAR treatment. However, they can also be centers of population, considered recreational areas or nature conservation sites, or they can be sources for extraction of gravel. When MAR plants are being planned, these interests may conflict. Public participation is an important feature of MAR planning in Finland (Jokela & Valtonen 2010, Kurki & Katko 2015). Sprinkling infiltration and well infiltration can be attractive for areas not suitable for the construction of basins, e.g., eskers with slopes, and forest areas having recreational values with restrictions on tree cutting. When sprinkling infiltration or well infiltration is used, there is no need to dig and construct basins and direct physical effects on the landscape are reduced. Recreational values, including minimizing the effects on landscape, are often emphasized in public participation.

Recycled water is not used at Finnish MAR plants. The MAR process removes pathogens efficiently, both bacteria and viruses. Risks of contamination of the recharge process are reduced by the choice of good quality raw waters and protection of the recharge areas from external, possibly harmful activities (such as gravel extraction or handling of petroleum). Before distribution to the trunk mains, water is disinfected by ultraviolet (UV) radiation, chlorination, or both, and, when necessary, the alkalinity and hardness are adjusted.

However, conventional ground-water management approaches, drawing from expert-based instrumental rationality, seem often to be insufficient for successful project planning and implementation. Based on an exhaustive study on two large MAR projects in Finland, Kurki (2016) suggested that in ground-water governance the core should be in collaborative rationality while some of the tools can be obtained from rationalistic expert-based planning. Thereby project legitimacy should be gained through joint knowledge production as well as interaction where addressing stakeholders' interests could help in finding mutual gains and new options for collaboration (Kurki & Katko 2015). Thus, water experts should be more facilitators rather than holders of the only legitimate source of knowledge, and the stakeholders like partners rather than informants.

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Managed Aquifer Recharge in France

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In France 67% of the volume of drinking water in France is produced by groundwater. For industrial and agricultural purposes, 40% of water supply comes from groundwater. French water regulations are fixed by the European Water Framework Directive (WFD) that defines the legal framework supporting the commitment to protect and restore water quality and aquatic environments.

“Good chemical status” of an aquifer is achieved when contaminant concentrations are not higher than the standards fixed by the WFD for groundwater. “Good quantitative status” of groundwater is achieved when the volume of water withdrawn is not higher than the renewal capacity of the water body and when the connected surface ecosystem health is maintained.

In 2013, 90.4% of the 645 identified groundwater bodies in France were in a good quantitative status but only 67% of them were in good chemical status (ANSES 2016).

With the constant population growth combined with climate change, the management of groundwater resources in France is mostly focused on water conservation and enhancement of natural recharge of aquifers (*eg*. hill reservoirs). But these actions are not sufficient to face water scarcity in some localities, and Managed Aquifer Recharge (MAR) could be an interesting and efficient way to maintain and improve groundwater quality and quantity.

Centralised governance of MAR practice in France is not established. However French regulation allows MAR on a case-by-case basis by prefectural authorization most often in the context of preventing saline intrusion or to meet the need of seasonal water demand as required depending on climatic conditions.

According to the WFD, the good status of the water bodies affected by MAR must be preserved. In France, the sources of water for enhancing recharge are mainly surface water (river) that is put into infiltration ponds.

Table 1 shows the major MAR sites in France. This shows there is considerable experience since the 1950s and there have been occasional periods of quite active development in the 1960s, 1980s and 2000s. A map showing MAR sites in France is found in Casanova *et al* (2016).

Table 1. ARTIFICIAL RECHARGE OF GROUNDWATER SITES FROM SURFACE WATER IN FRANCE

SITE	Starting date of operation	Artificially recharge water volume (Mm^3 y^{-1})	Recharge system
Donzere Mondragon	1952	$8.5m^3/s$*	Injection wells
Croissy sur Seine	1965	30.0 [a]	Infiltration ponds
Appoigny	1968	0.4 [b]	Infiltration ponds
Flins-Aubergenville	1980	8.0 [a]	Infiltration ponds/Bank filtration
Durance river	1980	5.0 [a]	Infiltration ponds
Vessy	1980	10.0 [a]	Infiltration ponds
Houlle Moulle	1983	4.4 [c]	Infiltration ponds
Flammerans	1997	6.6 [a]	Injection wells
Verneuil sur Seine-Vernouillet	2009	0.7 [b]	Infiltration ponds/Bank filtration
Hyères-les-Palmiers (France, Var)	2015	0.65 [b]	Infiltration ponds

[*] data in m^3 y^{-1} not available, [a] maximum capacity, [b] estimated annual value, [c] annual mean during activity period (still operating French major sites from Wuilleumier and Seguin, 2008; SIGESSN)

The Croissy-sur-Seine site can be cited as a pioneer in terms of MAR in France (Casanova et al., 2013). This site was put in operation in 1959 in order to increase the quantity of water withdrawn from the chalk aquifer for drinking water purposes (Detay, 1997). The Seine river water after pre-treatment is infiltrated into the aquifer through 9 infiltration ponds. The 12 hectares of replenishment basins help sustain 31 wells. 20 to 30 Mm^3 per year of water are infiltrated in the aquifer. Moreover, a bank filtration recharge system is coupled with infiltration ponds from Seine River under pumping wells action.

Since 2015, the active management of the main water resource of the city of Hyères-les-Palmiers (France, Var) has been developed to prevent saline water intrusion of the Bas Gapeau hydrosystem (AQUARENOVA project). This system is based on a real-time abstraction control, based on a continuous monitoring of water level and conductivity on specifically localized piezometers. The hydraulic gradients method shall optimize abstraction without risking saline intrusion (detected early 2000). In winter, aquifer recharge is operated by infiltration ponds, abstracting coastal river Roubaud water, in order to form a freshwater piezometric dome exploited in summer (Duzan *et al.,* 2016).

It is quite difficult to estimate the total amount of groundwater replenishment by MAR in France and Table 2 is based on the factual information of Table 1 and assumes that average annual recharge is approximately half the annual maximum capacity where actual volumes are unknown.

Table 2. Estimated volume of MAR in France over the last 60 years

Decade	Annual volume of MAR (10^6 m^3/y)
1951 - 1960	?
1961 - 1970	20
1971 – 1980	21
1981 – 1990	26
1991 - 2000	30
2001 - 2010	31
2011 - 2015	32

Recently, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) published opinion on the health risks related to MAR (2012-SA-0255) and put emphasis on MAR solutions using surface waters or treated wastewater to mitigate the decrease in French groundwater resources in the future. The quality of groundwater must be preserved during MAR practices and particularly to guarantee quality compatible with production of drinking water, without needing to use additional treatments funded by local authorities and consumers. ANSES recommends developing studies of MAR sites in France to ensure sustained quality of recharged groundwater and to better characterise the hazards to humans.

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MAR in Germany

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According to the Federal Statistical Authority of Germany (FSA, 2013), public water supply in Germany relies on groundwater extraction (60,9 %), spring water (8,4 %), lake and dam water (12,2%) and river water (1,2 %). The remaining 17,4 % originate from MAR, whereby 8,6 % is bank filtrate and 8.8 % is defined as “recharged groundwater”, consisting mainly of intentionally recharged surface water. In 2013, the public water supply produced ~5000*10^6 m^3 of water out of which ~3500*10^6 m^3 were domestic water provided for households and small businesses. According to these numbers approximately 870*10^6 m^3/year were abstracted via MAR. Surface water is the main source of MAR in Germany, recharged intentionally, for example via basins, or indirectly via induced bank filtration. MAR in Germany is generally done to achieve water quality improvements of the surface water used as a source, i.e. as a pre-treatment step, and to some extent also to preserve deeper groundwater resources. Since only a small fraction (~3 %) of the total amount of water available annually is required for the public water supply (Grischek et al., 2010), quantitative reasons for MAR are of lesser importance and strict legal regulations mostly impede the use of storm- or treated wastewater as well as the use of injection wells.

Table 1. Development of MAR in Germany and groundwater use

Annual MAR volume in the decade centred on date (Mm^3/y)						Groundwater Use (Mm^3/y)	MAR as % groundwater use	MAR as proportion of drinking water supply
1965	1975	1985	1995	2005	2010-15	2010	2010-15	2010-15
n.a.	867	766	875	765	872	3,077	28.2%	17.2%

The federal statistical agency in Germany collects the data only every 3 years. Data is based on public water supply only and was available from 1979 only for the years: 1979, 1983, 1987, 1991, 1995, 1998, 2001, 2004, 2007, 2010, and 2013.

Bank filtration has a long tradition in Germany. Amongst the sites exploited longest are those of the Düsseldorf-Flehe Waterworks on the River Rhine (Schubert, 2002), the Dresden-Saloppe Waterworks on the River Elbe (Grischek et al., 2010) and those of the Berlin Water Company along the lake-type extents of the rivers Spree and Havel in Berlin (Stadtentwicklung Berlin, 2016), all having provided drinking water since the 1870s. According to Lenk et al. (2006), decreasing river water qualities halved the amount of drinking water produced by bank filtration in former Western Germany between 1970 and 1990 and many sites were abandoned because of increasing chemical and organoleptic problems. Nowadays the water quality of major rivers has improved, possibilities for bank filtration are reviewed and new sites have been launched again (Lenk et al., 2006). Of the large river catchments in Germany, rivers within the Elbe (21 %) and Rhine (8,5%) catchments have the highest share of water originating from bank filtration in terms of % of total water production and also the largest total amount of water produced via bank filtration (Elbe:

189*10^6 m^3/year; Rhein: 140 *10^6 m^3/year; FSA, 2013). A literature review on bank filtration sites in Germany by Lenk et al. (2006) illustrates the clustering of sites identified as having >50 of bank filtrate in abstraction and observation wells in the Rhine and Elbe catchments (figure 1).

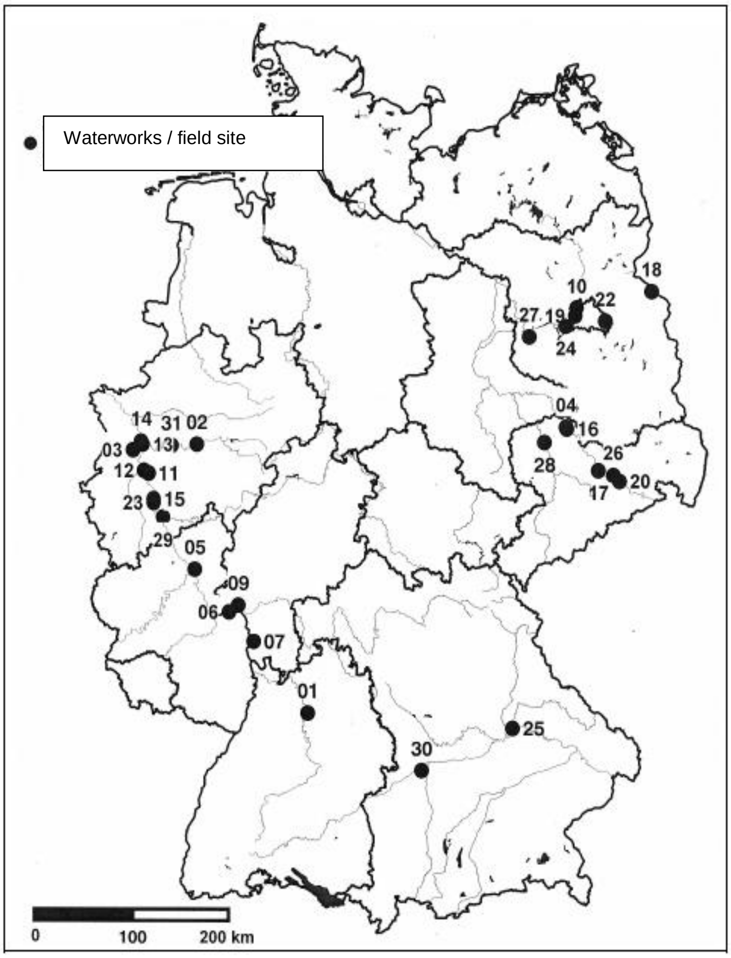

Figure 1: Water companies and field sites that were identified as having >50 of bank filtrate in abstraction and observation wells and studied in a large review on European bank filtration (Lenk et al., 2006).

In recent years, research on bank filtration in Germany has strongly focused on the behavior of organic trace pollutants during underground passage and a detailed report on the attenuation efficiency of the sub-surface for organic trace pollutants during bank filtration was presented by Schmidt & Lange (2006). Intensive research has, for example, been conducted regarding the semi-closed water cycle of Berlin, were 70% of the groundwater abstracted for drinking water purposes originates from bank filtration or infiltration via ponds and the fraction of treated sewage in the surface water courses is relatively high (e.g., Ziegler et al., 2002). Results from the NASRI and successive projects could show that most organic trace pollutants present in the surface water are readily removed, but a number of compounds behave persistent (e.g. Wiese et al., 2011). Overall, results also showed that the first meter of flow (i.e. the infiltration zone/river or lake base) is most efficient in removing trace pollutants and amongst other factors, redox conditions and temperatures strongly affect degradation (e.g. Burke et al. 2014). One of the largest challenges when assessing and quantifying organic trace pollutant attenuation during bank filtration and any other form of MAR is the transferability of attenuation parameters (such as first order degradation rate constants) between sites. This is mostly still impossible (e.g. Henzler et al., 2014; Nham et al., 2015; Hamann et al., 2016) and therefore prohibiting precise predictions on trace pollutant behavior at newly launched sites.

MAR with treated wastewater or stormwater is uncommon in Germany, the only exceptions being the cities of Braunschweig, where treated wastewater has been irrigated continuously for over 50 years onto agricultural fields (Ternes et al., 2007) and Wolfsburg, which irrigates ~$4*10^6$ m³/year of treated wastewater onto agricultural soils (WEB, 2014). In these two exceptional cases, MAR is practiced as soil-aquifer treatment and aims at stabilizing groundwater levels in addition to irrigation and fertilization of crops used for energy production.

Elsewhere in Germany the practice of treated or formerly even untreated sewage irrigation, which often lead to unintentional (and rather unmanaged) aquifer recharge, has been abandoned. A prominent historical example of "sewage farming" is the capital city Berlin, were untreated sewage was applied directly onto fields above unprotected aquifers from 1876 to the 1980s (Hass et al., 2012). Often, the remainders of this unintentional MAR practice continue to contaminate groundwater downstream of the former sewage farms (Scheytt et al., 2000; Richter et al., 2009; Hass et al., 2012).

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Artificial Recharge of Groundwater in Israel

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Artificial recharge of groundwater aquifers (AR), performed through infiltration ponds and through recharge wells, has been practiced in Israel since the 1960’s as an important component of the integrated management of surface and groundwater (Schwarz,1980) for the following objectives:

1. Seasonal storage of excess surface water in the National Water Supply (NWS) system, which carries water from the Jordan sources in the north to the central (coastal) regions.
2. Reclamation of over-exploited aquifers,
3. Utilization of rainwater runoff and flash floods, where surface storage is unavailable.
4. Soil – Aquifer Treatment (SAT) of sewage treatment effluents, aimed at the removal of residual contaminants by filtration and adsorption on the aquifer’s solid skeleton, by upper soil aeration and by long retention time in the aquifer.

The NWS system, inaugurated in 1964, supplies water for domestic, industrial and agricultural purposes. It conducts and integrates Jordan River surface water, through Lake Kinneret, with groundwater from the coastal sandstone and mountain limestone aquifers, which are the major groundwater basins in Israel. Since 1964, AR has been implemented for seasonal storage, as part of the NWS’s operation, to increase the yield during years of high demand and low rainfall. The water carried by the NWS is recharged both into the Coastal (sandstone) and Mountain (limestone) aquifers.

In the first years of the NWS system, AR was implemented also for the reclamation of the sandstone Coastal Aquifer, which had been heavily overpumped prior to 1964. In fact, already in 1958, while planning the NWS, AR experiments were conducted in order to establish the capacities of AR facilities and to investigate the fate of the recharged water as it spreads in the aquifer.

AR has been implemented within the framework of the NWS system through spreading grounds, by dedicated (single purpose) wells, and by dual purpose wells operating alternately for pumping water to the water supply system and for AR.

AR of flash floods started in the 1960's in two of the main coastal River Basins by diversion to specially constructed spreading basins.

SHAFDAN is the main Waste Water Treatment Plant (WWTP) in Israel. Presently, it is serving a population of 2 million people in the Greater Tel-Aviv Region. Within the framework of this project, effluents of a conventional secondary WWTP are delivered to SAT/AR facilities, composed of percolation ponds, in a dedicated portion of the Coastal Aquifer, These ponds are surrounded by pumping wells. The pumped water is delivered through a separate pipeline system for irrigation in most Southern Israel farms, replacing fresh water supply.

The evolving role of AR can be traced in the records of the Hydrological Service (Weinberger et al 2012). Recently, the role of AR as a storage procedure has declined due to the replacement of water from the NWS by reclaimed sewage as the main source of irrigation water and the introduction of sea-water desalination. In recent years, most of AR is of reclaimed sewage effluents. Table 1 shows the development of AR in Israel since 1960.

Table 1: Artificial recharge in Israel since 1960 (in $10^6 m^3$/year)

ARTIFICIAL RECHARGE OF GROUNDWATER IN ISRAEL [$10^6 m^3$/year]

Decade	Total	Wells		Spreading Grounds		
		Limestone	Sandstone	Sandstone		
		Water Supply System		Water Supply System	Floods	SAFDAN Reclaimed Sewage Effluents
1961-1970	87	18	36	14	20	
1971-1980	91	32	27	15	17	10
1981-1990	127	18	42	12	9	46
1991-2000	132	5	11	13	15	89
2001-2010	144	3	2	6	14	119
2011-2013	134	0	0	1	10	122

AR operations have posed challenges which called for theoretical and field research (TAHAL, 1969, Schwarz *et al*, 2016). This research led to the development of planning tools. For example, research provided a better understanding of the process of mixing in the aquifer of water of different qualities (the Kinneret water being more saline than aquifer water), and produced tools for calculating the quality of pumped water (Bear and Jacobs, 1968). Another challenge was to overcome the clogging of soil beneath infiltration ponds and around screens of recharge wells (e.g. Rebhun and Schwarz, 1968).

The main challenges of AR that required intensive research and studies aimed at establishing diagnostic and remedial methodologies were:

1. The travel and mixing in the aquifer of recharged and indigenous water.
2. The impact of AR on the quality of pumped water in dual purpose wells and in nearby pumping wells.
3. Clogging and capacity degradation of recharge wells and spreading basins.
4. Contamination of AR wells.
5. Proper design and maintenance of AR facilities.
6. Cost allocation of AR operations within the National Water Supply System

At present, Israel's water economy is characterized by the introduction of large scale sea water desalination within the framework of the NWS system. AR of this water is required, but it raises new economic and technical challenges that are currently under intensive research.

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Managed aquifer recharge in Italy

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Italy has a long history of managing aquifer recharge. In Venezia, man-made water-banking of rainfall in the soil dates back to the end of the middle-age as the main source of drinking water (Vanzan Marchini, 2009). Rainwater was harvested and then conveyed to city "squares" (*campi*). These were filled with sand and stored all the harvested water that then drained through the sand medium to supply a large well (with its characteristic "*vera*") in the middle of the square. There is also substantial recharge enhancement from traditional means such as river weirs and wells near the embankments of surface water bodies. These techniques are detailed in M. Canavari Engineering Geology Primer (1928). Unintentional incidental enhanced recharge through excess irrigation also occurs as elsewhere in the world. However, in the last 60 years other forms of intentional artificial recharge in Italy have occurred only at experimental or demonstration level. Since 1969, 40 experimental pilots have been established, but not yet made a major contribution to water supply. So, it may be said that in spite of the long history in some locations, aside from riverbank filtration, managed aquifer recharge in Italy is still in its early stage of development.

While in Italy water scarcity is a major issue in the southern part of the country, the bulk of the pilots are located in the northern area (Fig. 1). The aim of these pilots is to maximize natural storage in aquifers, combat saltwater intrusion and to improve water quality. Infiltration ponds comprise the most widespread method followed by dry wells, with Forested Infiltration Areas being the most innovative type. These are rural areas where farmers store water while growing trees (for wood production), by using irrigation channels during the non-irrigation season. However, Induced River Bank Filtration (IRBF) is by far the largest managed aquifer recharge scheme currently used, even though it is not widely recognized as such, and the hydraulic connection between the surface water body and the aquifer is often disregarded by practitioners and technicians in governing authorities. It is crudely estimated that more than 400 Mm^3 of drinking water is supplied from IRBF wells. This estimate is based on the assumptions that IRBF schemes exist at rivers where average yearly discharge is higher than 30 m^3/s and that an average of 10 Mm^3 per scheme are then used.

Since the beginning of 2010, some projects on managed aquifer recharge were co-financed by the European Commission mainly through the LIFE program (TRUST - Tool for regional - scale assessment of groundwater storage improvement in adaptation to climate change (Marsala 2014); AQUOR - Implementation of a water saving and artificial recharging participated strategy for the quantitative groundwater layer rebalance of the upper Vicenza's plain (Mezzalira *et al.* 2014); WARBO - Water re-born - artificial recharge: innovative technologies for the sustainable management of water resources; Nieto Yabar *et al.*, 2012). Nearly all of them, use the terminology of artificial recharge instead of MAR. The evolution of MAR capacity in Italy is shown in Table 1.

In 2014, the Regional Authority of Emilia Romagna started a pilot on the Marecchia River fan to alleviate water scarcity in the Rimini area resulting from recurrent drought periods (Severi *et al.* 2014) using a recharge basin. The pilot was terminated two years later after having recharged about 2 Mm^3 while currently awaiting permitting of the full-scale plant.

One of the main characteristics of these pilots is that they are focused on site characterization, investigation and hydrodynamics issues, while little attention is generally paid to water quality aspects. In many cases, a very small number of piezometers (in some cases only one) are set in place in order to monitor recharge effects. This is a critical point, and unless addressed has potential to turn public perception of MAR from an opportunity to a threat to ground-water. Within the EU FP7-ENV-2013 MARSOL project (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought; www.marsol.eu), a dedicated focus was posed on water quality issues at the 15 Mm^3/year IRBF plant in Sant'Alessio (Rossetto *et al*. 2015), demonstrating that IRBF may constitute a reliable (when care is paid to water quality aspects) and important source of water.

Table 1. Evolution of MAR in Italy

Decade	Induced River Bank Filtration (Mm^3/yr)	Other forms of MAR (Mm^3/yr)	Total (Mm^3/yr)
1961-1970	172	6	178
1971-1980	258	36	294
1981-1990	301	0	301
1991-2000	344	4	348
2001-2010	387	4	391
2011-2015	430	31	461

IRBM are estimated values only, based on population growth. Other forms of MAR values are derived from cited reports. This represents about 8% of total domestic water supply in Italy in 2012 (5000Mm^3/yr).

The main barrier to development of aquifer recharge in Italy has been until 2016 the lack of a piece of legislation on licensing MAR plants. While recharge of aquifers has been allowed since September 2013, as foreseen by the EU Water Framework Directive (EU, 2000), the regulation on licensing and permitting MAR plant (*impianti di ricarica della falda in condizioni controllate*) was promulgated only in June 2016 (DM 100/2016). This piece of legislation strongly focuses on monitoring issues, especially regarding water quality. The above-mentioned Emilia Romagna MAR plant, following the permitting application, is now under consideration to become the first Italian operational MAR scheme conforming to this framework. A new MAR pilot is under development within the EU LIFE REWAT (sustainable WATer management in the lower Cornia valley through demand REduction, aquifer REcharge and river Restoration) in Tuscany.

So far, there is growing interest in this low-cost, potentially low-energy technique, as it may constitute a valid alternative to traditional water treatment or allow conjunctive management of surface-water and ground-water bodies. At the same time, lack of knowledge at the level of intermediate governing bodies, as well as among professionals, is preventing the application of these techniques. For example, MAR plants, even though more economic and environmentally benign, are overlooked in favour of building of small surface water reservoirs. Therefore, dissemination of MAR scientific findings and technical know-how among governing authorities and the general public is crucial for the application of MAR techniques.

Finally, it is of utmost importance to identify the financial instruments to set up and sustain these water infrastructures, so as to guarantee routine operations and maintenance, and thereby opening a new market in the water sector.

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Figure 1. Locations of MAR experimental sites in Italy

Managed aquifer recharge in Jordan

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Managed aquifer recharge (MAR) has been practiced in Jordan since the 1960s and is firmly anchored in the national water strategy (MWI 2016) with the main goal to augment groundwater availability. Schemes for flood water recharge have been implemented and treated wastewater is proposed to be used in the future. However, the latter is only allowed to be recharged to aquifers that are intended for irrigation and not for drinking water purposes. In such cases, the use of reclaimed water for MAR is controlled by the standard regulations and legislations (MWI 2001) which preset the maximum concentration for diverse parameters. Further considerations by the Ministry of Water and Irrigation (MWI) may adapt these standards in order to achieve a more flexible approach for individual MAR sites, e.g. to allow the recharge of less treated wastewater to aquifers of poor quality that are still suitable for irrigation purposes (MWI 2001).

MAR is mainly performed using percolation reservoirs, recharge and release dams, and by injection wells (Xanke *et al.* 2015), both into alluvial deposits and limestone aquifers. In some cases, the reservoirs showed high infiltration rates despite being constructed with the primary purpose of surface storage (e.g. Shueib dam, Kafrein dam). However, heavy sediment loads, as a result of the sparse soil cover in these desert catchments, reduce the life span of many of the reservoirs by causing a loss of the storage capacity and a reduction in infiltration rates. As yet there are no applicable solutions to avoid the sedimentation. There is also a high risk that the outlets of the recharge and release facilities, such as at Wala dam, may become blocked by sediments. This has occurred for some conventional dams between the early 1960s and the early 1990s (Steinel 2012).

Table 1 List of dams in Jordan used for MAR (modified after Steinel 2012; Riepl 2013; Hadadin 2015; Xanke *et al.* 2015).

Location	Period of operation	Mean annual infiltration (MCM)	Initial and current storage capacity (MCM)	Geological formation (labeling)	MAR techniques/ Comment
Wala dam	2002 - today	*6.7	9.3/7.7	Limestone (A7)	percolation reservoir, injection wells
Shueib dam	1968 - today	**0.7	2.5/1.43	Alluvial deposits	percolation reservoir
Kafrein dam	1968 - today	n.a.	8.5/6.0	Alluvial deposits	percolation reservoir
Wadi Madoneh	2003 - today	n.a.	0.09	Limestone (A7)	4 recharge and release dams
Wadi Butum	2011 - today	n.a.	0.47	Limestone (B4)	3 percolation reservoirs
Sultani dam	1962 - n.a.	n.a.	1.2	Limestone (B2/A7)	percolation reservoir/clogged
Qatrana dam	1964 - n.a.	n.a.	4	Limestone (B2/A7)	percolation reservoir/clogged
Rajil dam	1992 - n.a.	n.a.	3.5	Limestone (B4/B5)	percolation reservoir/clogged
Siwaqa dam	1993 - n.a.	n.a.	2.5	Limestone (B2/A7)	percolation reservoir/clogged

*2002-2012; **2001-2009

A successful example of MAR is the Wala reservoir, where about 6.7 MCM/a, on average, infiltrate into the underlying karst aquifer. The water is abstracted at the 7 km downstream Hidan wellfield and contributes about 11.7 MCM/a, on average, to the drinking water supply of Jordan's capital Amman, Madaba city and smaller communities in the immediate surroundings (Xanke *et al.* 2015). Further comprehensive hydraulic and numerical studies have been done by Xanke *et al.* (2016), which revealed a decrease of the mean groundwater table on the long-term as a result of accumulating sediment in the reservoir and the associated reduction in the infiltration rate. In the case of the Kafrein and Shueib dams, the natural seepage from the reservoirs augment groundwater availability for irrigation purposes in the Jordan Valley, but only the water balances of the Shueib dam has been calculated by Riepl (2013) to be about 0.4 MCM/a in average. However, in the most cases the recharge rates are not well documented.

Further research in Jordan is commissioned by the MWI (Steinel *et al.* 2016) to evaluate the potential of MAR in porous aquifers (Steinel 2012).

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MAR in Korea

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In South Korea, which depends heavily on surface waters for water resources, there has been interest in the development of indirect water intake systems, such as riverbank filtration, in order to solve problems such as water quantity variability and water pollution. The development of riverbank filtration in Korea is mostly operated by municipalities in relatively small and medium sized facilities in Gapyeong, Haman, Iryong, and Daesan areas. A facility currently under construction has the capacity of 180,000 m^3/day, and it is scheduled to be completed in 2017. And, the Korea Water Resources Corporation is carrying out large-capacity Nakdong riverbank filtration business of 68,000 m^3/day in Changnyeong area (K-water, 2016).

The annual amount of groundwater use in South Korea reached 3,807 Mm^3 in 2010 (Ministry of Land, Transport and Maritime Affairs, 2011). Water supply by managed aquifer recharge totals 146.4 Mm^3 per year, accounting for 3.8% of total groundwater use. Riverbank filtration accounts for 89.1 Mm^3/year and underground dams and 57.3 Mm^3/year. Six underground dams have been developed and competed in the 1980s and 1990s, of which 5 are used for agriculture and 1 is used for drinking water (Ministry of Land, Transport and Maritime Affairs, 2012).

In Jeju Island, reservoirs for flood mitigation have been combined with well injection systems since 2010 to produce what is called Jeju-friendly Aquifer Recharge Technology(J-ART). The system has been built in the Hancheon upstream area, and proved to be effective in intentional increase groundwater recharge by about 2 Mm^3/year (Korea Institute of Geoscience and Mineral Resources, 2011). In addition, several empirical studies have been conducted over the past decade to recirculate the abandoned groundwater for heat utilization in green house areas to replenish groundwater and reduce the groundwater drawdown (Korea Institute of Geoscience and Mineral Resources, 2011).

Table 1. Growth in volume of Managed Aquifer Recharge (Million cubic metres/year)

Annual MAR volume in Korea in the decade centred on date (Mm^3/y)						Annual Groundwater use (Mm3/y)	MAR as % groundwater use
1965	1975	1985	1995	2005	2010-15	2010	2010-15
	3.7	12.4	46.0	91.3	146.4	3,807	3.8%

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History of managed aquifer recharge in The Netherlands

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General overview

In the Netherlands, unmanaged aquifer recharge started in the early 1900s with the centralized disposal of sewage water in large cesspools, the disposal of groundwater from deep construction pits, and the irrigation of some polder areas where watertables declined due to e.g. groundwater abstraction for drinking water supply.

Currently, there are -- for drinking water supply -- 13 'intentional' basin artificial recharge (BAR), 2 aquifer transfer recovery (ATR), 1 ASR and 23 River Bank Filtration (RBF) systems. They contribute about 17, 1, 0.1 and 6% to a total annual production of 1,100 Mm^3 of drinking water in the Netherlands, respectively.
In addition, there is a rapidly growing number of small-scale ASR systems for agricultural water supply, which store rainwater from the roof of greenhouses or fresh surface water. Urban runoff is increasingly being decoupled from sewage systems and introduced directly into local infiltration ponds or subsurface systems.

Artificial recharge through basins (BAR)

BAR started on a large scale in the coastal dune area, with later expansions inland (Fig.1, Table 1). The reasons to recharge the dune area were to: (i) reverse the severe salinization due to groundwater mining for drinking water supply of cities such as Amsterdam and The Hague; (ii) continue with producing drinking water from the dunes, benefitting from the existing infrastructure; and (iii) reverse the severe decline of groundwater tables in the dunes, which are considered a major nature reserve where wet dune valleys are essential to maintain biodiversity.

The dune infiltration involves a pretreatment near the intake, transport to the dunes, recharge and recovery in the dunes, and a post-treatment. In the period 1965-1975 , public opposition against BAR in the dunes was roused by ecologists who discovered serious eutrophication phenomena in plant communities in and around infiltration ponds. This led to gradual optimizations of the BAR systems through the NESTOR (NEw STyle Of Recharge) approach, which aims at reducing the adverse effects of dune infiltration on nature (Peters et al. 1998).

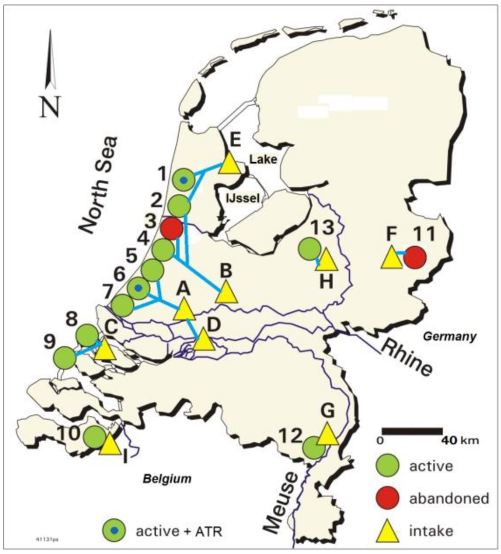

Fig. 1. Location of 11 operational and 2 abandoned BAR production sites in the Netherlands, together with their surface water intake points. On sites 1 and 6 also ATR is applied. Further information in Table 1.

Table 1. Some details on the 13 BAR production sites of which 2 were abandoned, with their surface water intake points.

Site in Fig.1			Start		Intake	Recharge		Pretreatment	System $
No.	Near city	Name	grwater	BAR	Fig.1	Source	Mm3/a	#	Inf / Recovery
1	Castricum		1924	1957	E + (B)	Lake IJssel	25	B+R+C	C/W
2	Wijk aan Zee	Kieftenvlak	1885	1975			17		C/W
3	Overveen	Groot Olmen	1898	1975-1999 †	B	Rhine R.	1	R	B/W
4	Zandvoort	Leiduin	1853	1957			52		C/C+D
5	Katwijk	Berkheide	1878	1940	D or A	Meuse or Rhine R.	25	B+R	B/C+D+Q+W
6	Scheveningen	Meijendel	1874	1955			47		B/D+W
7	Monster	Solleveld	1887	1970			7		B+C/W
8	Ouddorp	Oostduinen	1934	1955	C	Rhine/Meuse estuary	3.5	R	C/D+W
9	Haamstede		1930	1978			3.7		P/W
10	St. Jansteen		1936	1944-1998 ‡	i	Brook	2		C/W
11	Enschede	Weerseloseweg	1892	1952-2004 †	F	Canal	5.5	B+R+pH	B+C/W+Q
12	Heel	Lange Vlieter	-	2002	G	Meuse R.	15	S	P/W
13	Epe		1954	1999	H	Brook	1-2	S	B/W

#: B = detention in basin or abandoned meander loop; C = Activated carbon filtration + O3 + UV
R = sedimentation or microfiltration + coagulation + RSF; S = sedimentation
$: B = Basin; C = Canal; D = Drain; P = Pit; Q = horizontal well; W = vertical well. ‡ : since 1998 for industry

ATR and ASR

In the Netherlands, Aquifer Transfer Recovery (ATR) utilizes separate wells for infiltration and recovery at 100-200 m distance, mainly for continuous production of drinking water, but also to store some volume. In 1990 after many trials since the 1930s, 2 systems were put in operation (Fig.1), where ~4 Mm3 of highly pretreated surface water is annually feeding about 20 recharge wells on each location.

Aquifer Storage Recovery (ASR) is being applied for drinking water supply only on a very small scale. ASR is, however, rapidly expanding in the supply of (i) rainwater from roofs for crop irrigation in greenhouses, and (ii) freshwater for irrigation of orchards (Zuurbier 2016).

River Bank Filtration (RBF)

The first river bank filtrate was pumped for public drinking water supply in the Netherlands, probably in 1879 along the Rhine River at pumping station Nijmegen (Site 42 in Fig.2). In 1950 15 well fields pumped 11 Mm3 and in 2014 23 pumping stations produced 59 Mm3 of Rhine bank filtrate. In 1998 the first Meuse bank filtrate was pumped near Roosteren (site 80 in Fig.2).

The quality deterioration of the Rhine River, especially in the period 1920-1975, had at least 3 impacts on the preparation of drinking water from Rhine River water: (a) a switch in the period 1928-1962 from the direct intake and treatment of river water, to the pumping of Rhine bank filtrate on 10 stations; (b) the closure of 17 well fields pumping Rhine bank filtrate in the period 1944-2000; and (c) extension of the classical treatment (aiming at removal of iron, manganese, ammonia and methane), with processes removing organic contaminants.

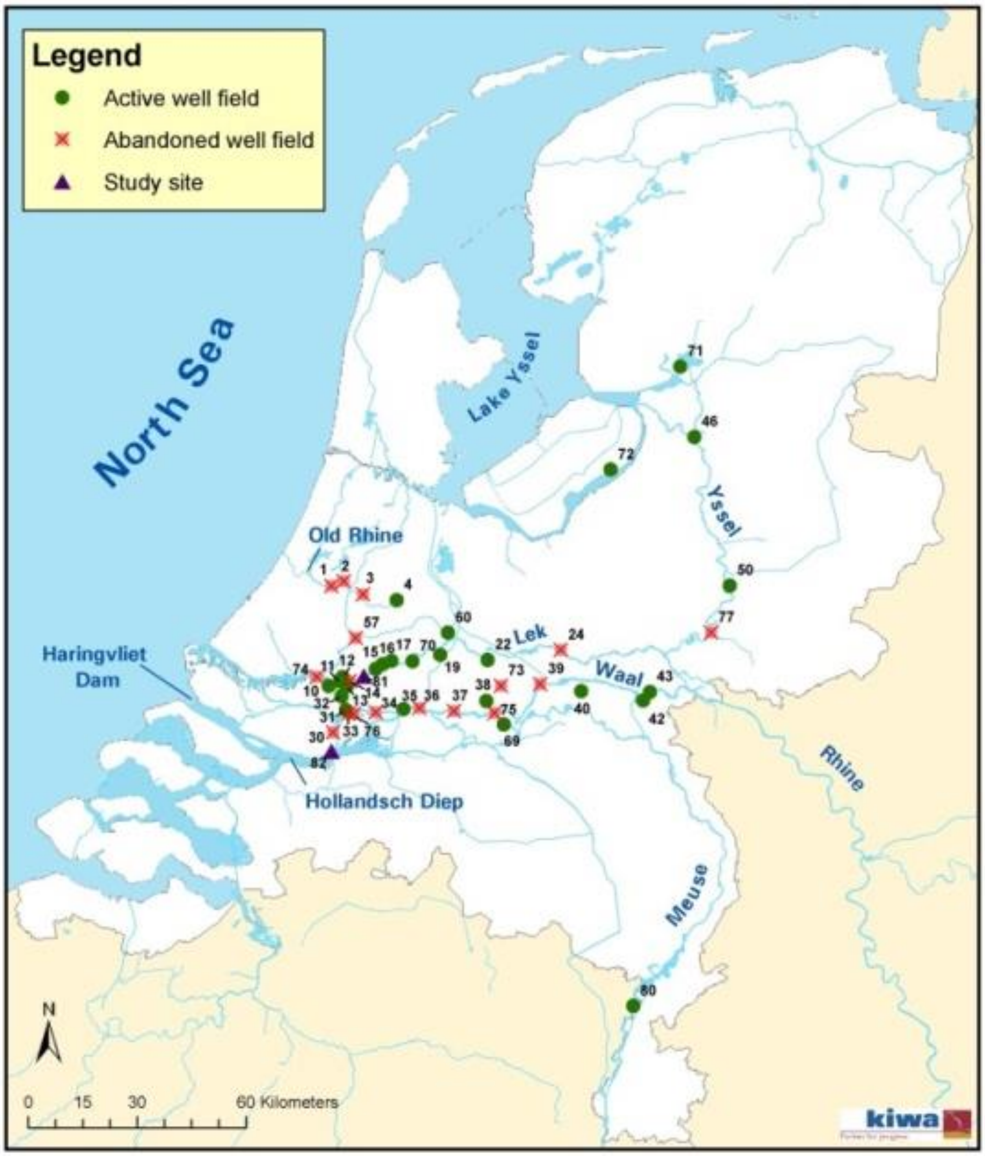

Fig. 2. Location of all public supply well fields pumping >10% river bank filtrate in the Netherlands, with distinction between active and abandoned sites.

Research

The introduction of MAR systems in the mid 1900s raised and continues to nurture many technical and scientific questions. In the period 1940-1975, research mainly focused on the engineering aspects of MAR systems, regarding the minimum travel time needed to remove pathogens, the attenuation of salinity and temperature fluctuations in the infiltration waters, the clogging of basins and wells, and the effects of aquifer passage on main constituents. This knowledge fueled the bulk of the handbook on artificial recharge by Huisman & Olsthoorn (1983).

In the period 1965-1985, the worsening quality of the Rhine and Meuse Rivers provoked research into the behavior of macroparameters, nutrients, heavy metals and some classical organic micropollutants during detention in spreading basins and aquifer passage (Piet & Zoeteman 1980; Stuyfzand 1988, 1998a). It also stimulated research into the effects of eutrophication on algae blooms in recharge basins and on oligotrophic phreatophytic plant communities in dune valleys around them (Van Dijk 1984). It was discovered in the 1980s that rainwater lenses can form in between infiltration ponds and remote recovery systems, and that flow-through (seepage) lakes in between can disrupt these lenses and stimulate local eutrophication (Stuyfzand 1993). This research was based on multitracing to discern infiltrated riverwater from autochthonous dune groundwater (locally infiltrated rainwater). Later hydrochemical studies yielded further insight in the performance of various (potential) tracers (Stuyfzand 2010), the behavior of trace elements (Stuyfzand 2015), the behavior of organic micropollutants (Noordsij et al. 1985; Hrubec et al. 1986, 1995; Stuyfzand 1998b; Stuyfzand et al. 2007; Eschauzier et al. 2010) and pathogens (Schijven 2001; Medema & Stuyfzand 2002).

Various modeling approaches were pursued to simulate and predict the behavior of pollutants, radionuclides, bacteria and viruses, and main constituents during detention in recharge basins and during aquifer passage. One of the first models was Easy-Leacher (Stuyfzand 1998c), which is a 2D reactive transport code set in EXCEL spreadsheet, combining chemical reactions (volatilization, filtration, dissolution-precipitation, sorption, (bio)degradation), with empirical rules regarding the reaction sequence. It assumes a constant input quality, flow and clogging layer conditions, but takes account of the leaching of reactive aquifer constituents. More sophisticated models were built using the MODFLOW/MT3DMS and PHREEQ-C based reactive multicomponent transport model PHT3D incl. reaction kinetics (Prommer & Stuyfzand 2005; Wallis et al. 2010; Antoniou 2015). On the other hand, simpler models set in Excel spreadsheet were developed such as Reactions+, a mass balance (inverse) model to identify and quantify the inorganic mass transfer between for instance the infiltrating surface water and a well downgradient (Stuyfzand 2010), and INFOMI, an analytical model to predict the behavior of trace metals and organic micropollutants (Stuyfzand 1998c).

In the period 1973-1982, extensive research on the clogging mechanisms of infiltration wells was carried out by Kiwa (renamed KWR in 2006). This yielded the new clogging potential indicators Membrane Filter Index (MFI; Schippers & Verdouw 1980) and Assimilable Organic Carbon (AOC; Hijnen et al. 1998). Also, the insight was born that a cumbersome clogging can only be prevented by a thorough pretreatment (incl. at least a coagulation step and rapid sand filtration) leading to MFI < 2 and AOC <10 μg C/L, combined with frequent backpumpings of short duration (Olsthoorn 1982; Peters et al. 1989).

The clogging of recovery wells or drains has always been a hot topic in MAR systems, because of their extreme vulnerability. Studies by Van Beek (2010) revealed among others, that BAR and ATR systems are more vulnerable to (bio)chemical clogging by hydrous ferrihydrite, whereas RBF wells in the anoxic fluvial plain are prone to clog by aquifer particles that are retained by the borehole wall if damaged by residual drilling muds.

The current research is mainly on the following key topics:

- Optimizing ASR systems in brackish to saline aquifers (e.g. for agriculture) by reducing bubble drift and bubble buoyancy, and thereby raising the recovery efficiency (Zuurbier 2016),
- Optimizing ASR systems for drinking or rain water storage by reducing water-sediment interaction (Anthoniou 2015),
- Determining the capacity of BAR systems to cope with intake stops, while minimizing the potential damage to wet dune valleys and reducing water quality problems due to e.g. changing redox conditions.
- Determining and predicting the behavior of emerging priority pollutants such as pharmaceuticals, personal care products, new pesticides, nanoparticles etc.
- Identifying weak points in BAR systems where pathogens in the infiltration water or from land bound animals can survive on their way to the recovery system.

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Historical Overview of Enhanced Recharge of Groundwater in Qatar

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Introduction

Qatar occupies a peninsula which projects into the Arabian Gulf and occupies an area of 11,627 km^2. Qatar has a warm desert climate with mild winters and hot summer. The mean annual rainfall is approximately 70 to 80 mm. Qatar is known for its scarcity of renewable water resources. Until 1953 the population of Qatar was entirely reliant on groundwater for its potable and agricultural water. In 1953 the first desalination plant was commissioned and the country's desalination capacity has been increased over the years so that in 2017, almost all water demand for municipal and industrial use is produced by desalination. However, water for agricultural irrigation is almost entirely derived from pumped groundwater. In 2013, the volume of groundwater pumped for agricultural use was estimated to be 218 Mm^3. This abstraction resulted in a small decline in water level together with an associated deterioration of water quality (MoE 2009). Managed aquifer recharge with natural waters is estimated at almost 10.7 Mm^3/yr and so significantly augments the estimated natural recharge (rainfall and irrigation return) of 75Mm^3/yr. There is managed recharge of deep aquifer with stormwater and recycled water in urban areas which is estimated at almost 33 Mm^3/yr. Thus total managed aquifer recharge contributes about 44 Mm^3/yr which has reached 17% of the total groundwater use of 260 Mm^3/yr in 2010 (Margat and van der Gun 2013) and there is potential for further expansion of MAR.

MAR Projects and Efforts

Eccleston and Harhash (1982) have described the hydrogeology of Qatar. The extent of the aquifers of Qatar has been subdivided into two main hydrologic provinces: Northern and Southern. Smaller groundwater provinces have subsequently been added to this conceptual model, the Abu Samra, Doha and Aruma Groundwater Basins. The main aquifers where MAR is practised in Qatar are the Eocene-age Rus Formation and the underlying Paleocene-age Umm er-Radhuma (UER) Formation. In some areas these two layers are interconnected and in hydraulic continuity to the extent that they can be considered as forming a single aquifer (Abdel-Wahab et al. 2008). There are two small members which are Simsima Member; and Abarug (Dammam) Member.

The bulk of the aquifer recharge in Qatar is derived from rainfall; other recharge inputs include urban recharge (mainly restricted to the area of Doha) and agricultural irrigation returns which are isolated throughout the country. Two different types of recharge mechanism are generally recognized in Qatar. Direct or diffuse recharge from widespread infiltration of rain water at or near to the point where rain falls. The second one is localized recharge (also called indirect or focused recharge) where surface water runoff accumulates in localized depressions with no surface water outlet. Previous estimates have shown that the contribution from focused recharge appears to be the most important recharge mechanism in Qatar being, on average, 4 to 9 times greater than diffuse recharge (Kimrey 1985, Entec 1994 and MoE 2009). This is considered to be due not only to the concentration of surface runoff in the depressions, but also due to the elevated storage capacity and permeability of the bedrock underlying the depressions.

In 2009, a significant project was carried out in Qatar to study the artificial recharge of aquifers (MoE 2009). To augment the natural recharge, a total of 313 passive recharge wells as identified by MoE Study have been installed across Qatar. The recharge wells installed in Qatar are 'passive' gravity recharge wells in which no active injection is undertaken and water accumulated above ground-surface enters the recharge well and infiltrates into the aquifer under the force of gravity. 166 of these recharge wells to enhance natural recharge from rainfall have been identified as occurring within depressions and the remaining 147 recharge wells outside of depressions. To facilitate modeling of rainfall-runoff-recharge, the SWAT2005 model has been applied. Analysis of groundwater level data from 44 recharge wells in Qatar for the period 2001 to 2007 and injection tests from 27 recharge wells show that capacity for a recharge well to infiltrate surface water varies widely. Recharge well infiltration capacity has been determined from 30 injection tests.

Modeling results indicate that the 161 existing recharge wells which are included in the model contribute 10.7 Mm^3 to groundwater recharge in an average hydrological year in addition to the natural recharge which the model calculates as being 75 Mm^3. The model has been used to estimate the optimal number of recharge wells required to enhance and infiltrate all surface water accumulations within 5 days after the most extreme rainfall event in the average hydrological year. Using only those depressions that were retained after applying the selection criteria to determine the most favorable depressions in non-urban areas, the model predicts that 1502 recharge wells are required to inject all the ponding water generated during the largest storm (~20 mm) in an average hydrological year within a 5 day period. It is observed that there are already 114 of those 161 existing recharge wells in the depressions selected as being the most favourable (thus, 1,388 additional recharge wells are required). Model indicated that 47 existing recharge wells are not required in the optimal total number of recharge wells. The managed aquifer recharge contribution of both the optimum and current number of recharge wells (i.e. 1,549 wells) for the average year would amount to 33.5 Mm^3, as shown in Figure 1. A plan to construct more recharge wells has been produced but implementation is not yet decided.

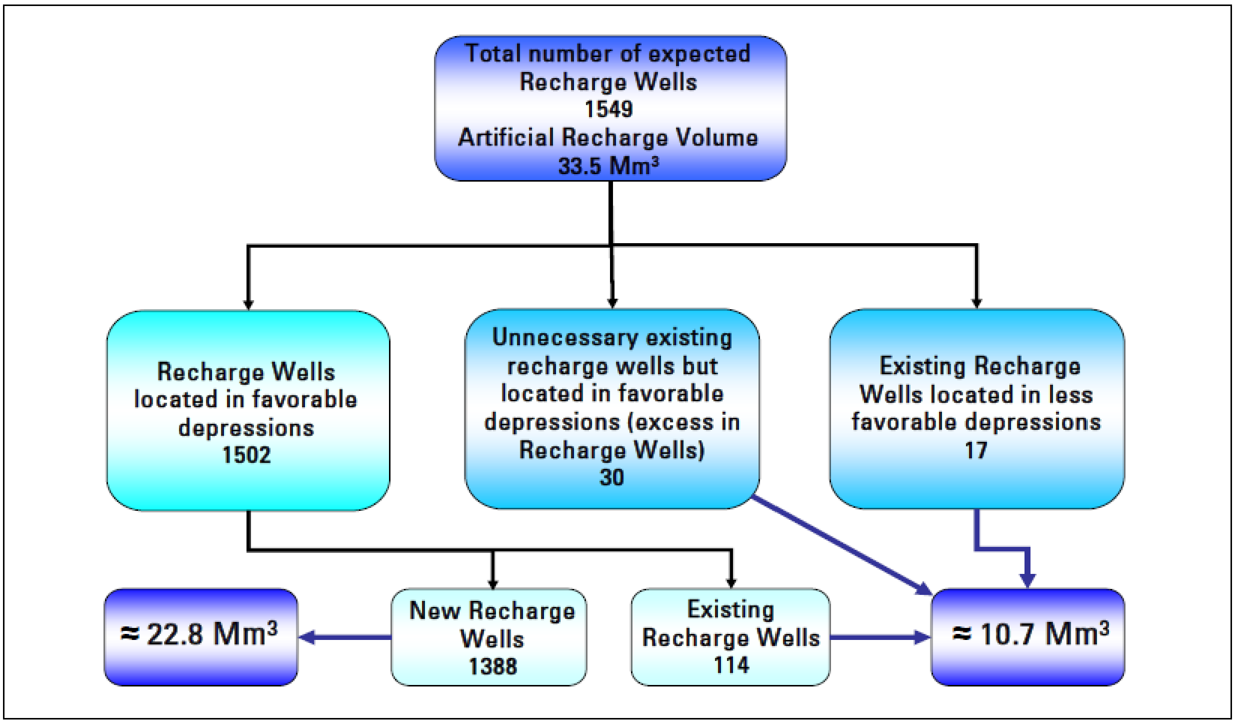

Figure 1. Optimal number of recharge wells and quantity from MoE 2009 Study

A sensitivity analysis indicates that the cost-benefit of any future recharge well array is highly dependent on the permeability of the sub-surface, the allowed time of ponding of water in depressions, the selection of favorable depressions, and the storm rainfall amount used in the design. It is important to note that the model results show that the potential for managed aquifer recharge is similar in the southern and northern parts of Qatar although this is dependent on the rainfall distribution (MoE 2009).

Two other types of MAR are implemented in the urban area of greater Doha. Excess recycled water (mainly high quality treated effluent) and collected stormwater combined with surficial groundwater are recharged using deep wells. This managed practice started in 2008. The main objective of this recharge is to dispose the excess recycled water and to improve the quality of deep groundwater. Recharged water is of better quality than the groundwater in the receiving aquifer. For example, Total Dissolved Solids (TDS) in recharged water is 1,100-6,000 mg/l which is considerably fresher than the deep groundwater having 15,000-25,000 mg/l TDS. This practice of urban MAR is in an experimental phase, with precise environmental monitoring and is seen as a temporary solution until it is evaluated. Ongoing work continues to assess and evaluate this MAR practice in urban areas in Qatar. There is continuous monitoring of quantity and quality of both the recharged water and the receiving environment (i.e. deep groundwater between 100 and 400m) and shallow groundwater (i.e. less 50m). 3D groundwater simulations are applied to help in this assessment of managed recharge in the urban area.

Current Types of MAR in Qatar

As mentioned above, there are three types of MAR in Qatar. The first type is the recharge wells in depressions in non-urban areas to augment the natural rainfall recharge in north and south groundwater basins. The second is the use of deep recharge boreholes in Doha basin for disposal of relatively fresh recycled water. The last involves the recharge via deep boreholes in Doha basin for temporary disposal of the collected urban stormwater combined with surficial groundwater after necessary treatment. This temporary disposal is helping to improve the quality of deep groundwater by reducing its salinity. Table 1 shows the recharge amounts of the three categories.

Table 1: History of managed aquifer recharge in Qatar (in 10^6 m^3/year)

Period	Recharge wells			Total
	Rainwater and stormwater (non-urban area)	Recycled water (urban area)	Stormwater and shallow groundwater (urban area)	
1981-1990	5.3	0	0	5.3
1991-2000	8.0	0	0	8.0
2001-2010	10.7	26.0	0	36.7
2011-2015	10.7	31.0	2	43.7

Data derived from MoE 2009 study and from Qatar government internal reports.

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MAR in Southeast Asia

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The level of progress in MAR in Southeast Asia is considered to be limited (Table 1). This review could only identify a handful of case studies worthy of note. Literature based on general discussions or on hypothetical modelling has not been considered. Across the region, there has been a tendency for applying deep recharge methods (wells) over surface methods (basins) owing to an absence of favorable shallow geological conditions in targeted areas or limited access to land. Most studies have been carried out in Thailand, with a lesser number carried out in Vietnam, Malaysia and Indonesia.

The earliest known work dates back to the early 1970s in Thailand where a pilot injection trial was carried out in response to land subsidence issues in the Bangkok metropolitan area due to heavy groundwater withdrawals resulting in groundwater quality deterioration and increased flood risk. The trial, carried out by government hydrogeologists, experienced two major sets of problems – high rates of aquifer clogging due to inadequate pretreatment of source water and rapturing of overlying clay layers due to excessive injection pressures (Ramnarong, 1989). Subsequent tests in a nearby area, carried out two decades later by local academics involved eight months of recharge testing which yielded successful results as evidenced by observations of rebound in pore pressures in adjacent aquitards (Phien-wej et al. 1998).

Efforts to test the viability of ASR in a coastal province of the country (Rayong) in the early 2000s was unsuccessful, once again due to irreversible well clogging (Pavelic et al. 2010). This result may be attributed to a degree of institutional memory loss on behalf of the government hydrogeologists, although international technical assistance was also provided.

A more concerted program of ASR testing extending over two phases from 2008 to 2014 was carried out in the Central Plains of Thailand (Sukhothai province) to address groundwater overexploitation caused by high groundwater use for agriculture. This testing has concluded that high levels of system maintenance are needed to address inherent well clogging problems (Bral et al. 2015).

Basin recharge methods based on harvesting wet season river flows were applied in an alluvial floodplain setting of Phitsanulok province between 2008-2011 to restore depleted groundwater levels in irrigation command areas. This was the first known trial of its kind in Thailand and one of the first in the region. A stage-wise, integrated approach was followed covering site suitability mapping, recharge system performance, hydrology & numerical modelling, hydrochemistry and cost-benefit analysis. Results of the trial appeared to be technically and economically promising (Nadeeet al. 2012; Pavelic et al. 2012; Srisuk et al. 2012; Uppasit et al. 2013). The large land area needed for wetland pretreatment of canal water prior to the recharge step may be a constraint unless methods with lower areal footprints can be identified. The study provided the foundation for the development of technical guidelines of a range of different MAR technologies to be applied (Chusanatus et al. 2012).

MAR assessments have been carried out in the coastal sand dunes of Binh Thuan province in Vietnam to examine the role of MAR in mitigating drought impacts by restoring groundwater storage capacity and improving ecosystems. Whilst extensive baseline studies of the water resources were carried out to characterize the baseline hydrology and hydrogeology of the area, it would appear that the project did not advance to the stage of conducting pilot recharge testing (Thoa et al. 2008; Hoanh et al. 2013).

Small scale testing of recharge into dry wells with rainwater to restore depleted groundwater levels and control impacts of land subsidence has also been applied in the highly water stressed Bandung basin in West Java, Indonesia. It was proposed that implementation should focus on industrial areas where large roof areas could be harnessed (Taufiq, n.d.). In Batu Pahat district, Malaysia, a favorable feasibility assessment led to the recommendation of recharge testing to boost groundwater storage in area of high demand and flooding. The documentation available suggests that the pilot testing had yet to proceed (Tjahjanto et al. 2008; Musa et al. 2009).

Enabling conditions for MAR

MAR has received minimal interest in SEA, with cases limited to feasibility studies or trial. The enabling conditions for consideration of MAR would appear to be three-fold, namely:

i) pressing groundwater quantity or quality issues
ii) local technical expertise in groundwater and an appropriate institutional setup to allow human and other resources to be mobilized
iii) links to international networks and institutions

The importance of these 3 pre-requisite is exemplified for several of the case studies described above (Table 2). By deduction, this also serves to explain the absence of MAR experience in countries such as Laos, Cambodia and the Philippines where problems are either not apparent, or unable to be addressed with current technical capacity. Singapore, with the most highly developed economy contrasting with the lowest per capita water availability in the region, has invested heavily in rainwater harvesting and water recycling in order to reduce its dependence on imports from Malaysia. This appears not to have extended down to harnessing the storage potential of underlying aquifers.

There are no known cases of MAR moving beyond feasibility studies or trials into larger scale, long term schemes. The rationale for this is possibly more case specific and diverse. In the case of the ASR trials carried out in Bangkok, whilst recommendations were made for larger-scale testing, policy mechanisms other than MAR ultimately provide more expedient and were found to successful in addressing the subsidence issue across the Bangkok metropolitan area (Foster, 2002). Raising the profile of MAR and its merits under specific contexts, has not yet advanced to the policy level in SEA and has remained largely within the scientific community. It is the role of the scientific community to change the perceptions of the policy makers that water resources problems do not justify the exploration into technologies which are not yet mainstreamed and therefore risky.

Table 1. Compilation of MAR case studies in Southeast Asia

No.	Site	Project type	Objective	Aspects covered	Problems faced	Impacts achieved	References
1	a) Bangpoon (1972) b) AIT campus (1993-94), Pathumthani province, Thailand	pilot injection trials (single injection well)	restore depleted GW levels and control impacts of land subsidence	aquifer characterization, well hydraulics, ground movement	- rupturing of overlying clay - clogging when untreated canal water was used	- policy mechanisms other than MAR proved successful in addressing the subsidence issue	a) Ramnarong, (1989) b) Phien-wej et al. (1998)
2	Nong Taphan, Rayong province, Thailand	pilot ASR trial	trial ASR technology using treated canal water	aquifer characterization, recharge performance & well clogging	- trial abandonment due to excessive well clogging		Pavelic et al. (2010)
3	Sawankhalok, Sukhothai province, Thailand	pilot trial (multiple ASR wells)	restore depleted GW levels in an irrigation command area through recharge of wet season river flows	aquifer characterization, recharge performance & well clogging, hydrochemical tracing, solute transport modelling	- well clogging even with physioco-chemical treatment requiring high levels of system maintenance		Mallonee, (2013) Bral et al. (2015) Mungkang et al. (2015)
4	Ban Nong Na, Phitsanulok province, Thailand	basin recharge pilot trial	restore depleted GW levels in irrigated areas through infiltration of wet season river flows	site suitability mapping; recharge performance & clogging; hydrology & numerical modelling; hydrochemistry; cost-benefit analysis	- large land area sacrificed for wetland pretreatment of canal water	- foundation for guidelines to be developed over the wider area affected by similar problems - led to new work being initiated on MAR for co-managing floods and droughts	Chusanatus et al. (2012) Nadeeet al. (2012) Pavelic et al. (2012) Srisuk et al. (2012) Uppasit et al. (2013)
5	Hong Phong district, Binh Thuan province, Vietnam	basin recharge pilot trial	arrest drought impacts and restore GW storage capacity and improve ecosystems	hydrological and hydrogeological characterization, hydrochemistry, modelling	- project carried out extensive baseline studies of the water resources but does not appear to have recharge the piloting stage		Thoa et al. (2008) Hoanh et al. (2013)
6	UTHM campus, Batu Pahat district, Malaysia	pilot recharge trial	boost groundwater storage in area of high demand and flooding	aquifer characterization (geophysics, grainsize, analytical modelling)	- feasibility assessment was favorable but pilot testing had yet to proceed		Tjahjanto et al. (2008) Musa et al. (2009)
7	Bandung Basin, Indonesia	pilot recharge of dry wells	restore depleted GW levels and control impacts of land subsidence	pilot recharge, laboratory test of pretreatment, risk assessment modelling		- roof water harvesting in industrial areas proposed, following treatment (zeolite) to neutralize pH of rainwater	Taufiq, (n.d.) Fildebrandt et al. (2003)

Table 2. Enabling conditions for MAR implementation

No.	Country	Problem	GW expertise / institution	International linkages
1-4	Thailand	GW depletion and/or land subsidence	Department of Groundwater Resources (formerly Department of Mineral Resources)	Intl technical assistance, IAH
5	Vietnam	drinking/domestic/agricultural water provision in drought prone areas	Vietnamese Academy of Science and Technology (Institute of Geophysics, Institute of Geological Sciences)	Vietnam Atomic Energy Commission, UNESCO (Jakarta office), University La Sapienza (Italy)

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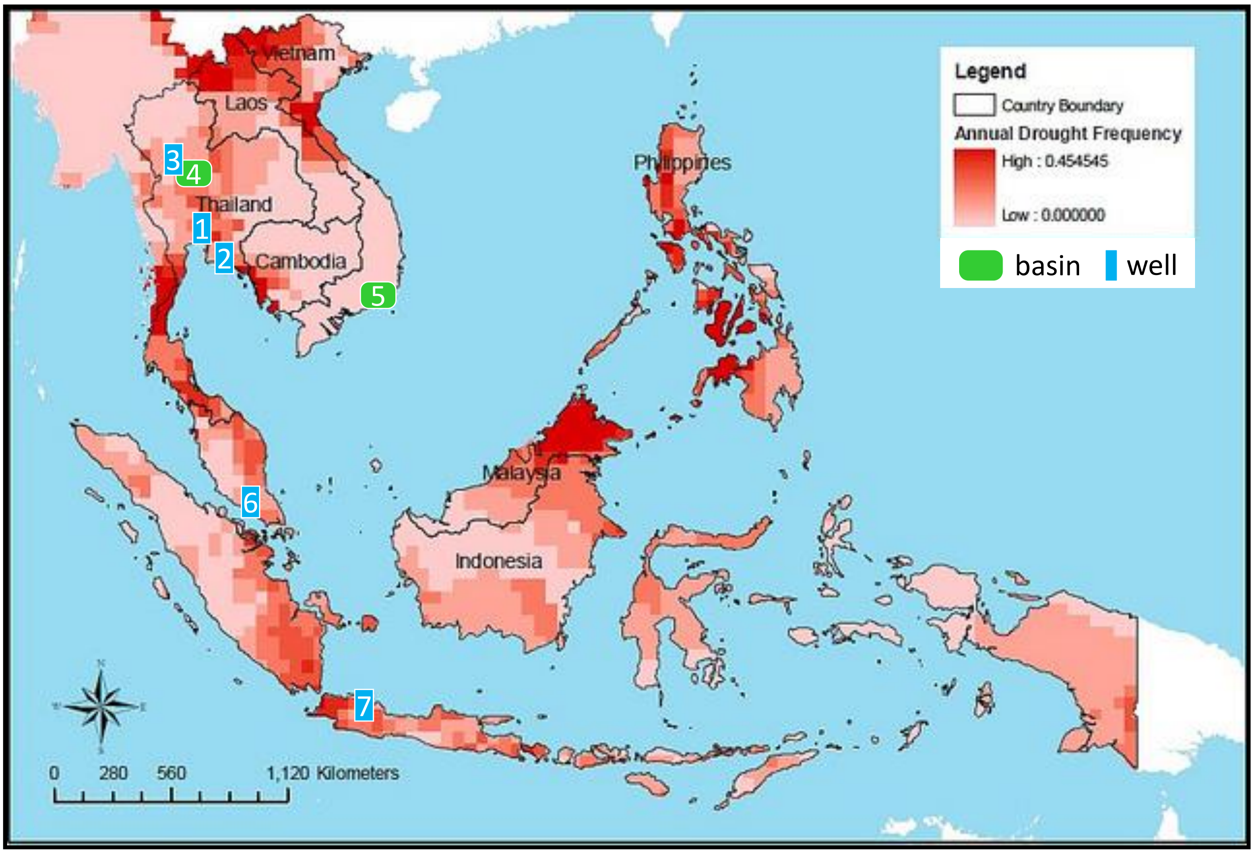

Figure 1. Map of MAR trial sites in SEA, identified according to recharge technology. Base map is taken from Yusuf and Francisco, (2009)

An overview of Managed Aquifer Recharge in Southern Africa

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2016

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MAR is not a new concept in Southern Africa. In the early-mid 1900s sand storage dams were constructed in stages in Namibia for the storage of water in artificial "aquifers" (Wipplinger, 1953), and in South Africa, the Atlantis scheme near Cape Town started infiltrating storm run-off and treated waste water in 1979 (DWAF, 2010a). In addition to these, farmers over the years have built numerous earth dams for the purpose of enhancing groundwater recharge. In recent times, there have been three major contributions to the advancement of MAR in the region. It started with a surge of research in the late 1990s and early 2000s (Murray and Tredoux, 1998 and Murray and Tredoux, 2002) which had two significant spin-offs: The construction of a major borehole injection scheme for the City of Windhoek, Namibia; and the South African government developed and rolled-out its national MAR strategy.

Southern Africa is dominated by hard-rock hydrogeology, so the research focussed primarily on assessing the feasibility of recharging these fractured aquifers. One of the identified test sites was in Windhoek, Namibia, where a successful MAR scheme could prevent the construction of a 700 km pipeline to the nearest perennial river and save the city the vast costs associated with major surface water transfer schemes.

Besides being the cheapest water supply option for the city, the Windhoek's MAR scheme is of particular interest because it involves large-scale borehole injection and recovery in a highly complex, fractured quartzite aquifer. Prior to this scheme, MAR had not been practiced anywhere in the world at a large scale in complex geological environments – the risk of losing water was generally considered too high. By undertaking a comprehensive feasibility study it was demonstrated that water losses would be negligible if designed and operated correctly (Murray, 2002). As a result the scheme was built and has been under permanent expansion since the first injection boreholes were commissioned in 2005. Its current injection capacity is 420 m^3/hr and with the new boreholes that have been drilled, this will increase to over 1 000 m^3/hr.

South Africa's MAR strategy (DWAF, 2007 and DWS, 2010b), like all comprehensive strategies, sets out objectives and tasks required to meet the objectives, and so far a number of the tasks have been completed. Examples of resources produced as part of South Africa's MAR strategy are:

- A check-list for implementing successful MAR projects (DWA, 2009a)
- A national map of potential MAR areas in South Africa (DWA, 2009b)
- Guidelines for planning and authorising MAR schemes (DWA, 2010c)
- Examples of MAR feasibility studies (DWA, 2010d).

Besides the larger schemes of Windhoek and Atlantis mentioned above, a few small-medium scale MAR schemes have been implemented in South Africa (mostly borehole injection), and a number of feasibility studies have been conducted with the intention of implementation in the near future. In addition to these a major feasibility study was undertaken for the Botswana government with the aim of assessing the value of MAR for the more industrious eastern part of the country (Murray, 2012 and Lindhe, et al, 1014). In most cases, the main purpose of MAR in Southern Africa is to augment water supplies and to enhance water security. Two schemes, however, are for mine water disposal in order to comply with environmental regulations. In these cases, it is not permitted to dispose surplus water from the mines' dewatering processes on the land surface, so aquifer recharge has become the alternative, and as a by-product, local farmers benefit from it. Table 1 presents an estimate of MAR volumes since 1960.

Table 1. Growth in Managed Aquifer Recharge 1965-2015 (in million cubic metres / year)

Date	Atlantis	Polokwane	Windhoek	Williston	Kolomela	Total
1965	0	1	0	0	0	1
1975	0	2	0	0	0	2
1985	2.7	3	0	0	0	5.7
1995	2.7	3	0	0	0	5.7
2005	2.7	4	0	0	0	6.7
2015	2.7	4	2.83	0.09	0.65	10.3

While the current scale of MAR activities is very small in Southern Africa, the potential for up-scaling is huge. The additional storage that could potentially be gained over and above natural groundwater storage if MAR was implemented in all prime MAR areas is South Africa is estimated to be 7.9 billion m^3 (7 944 million m^3) (DWAF, 2007). Considering that South Africa uses an estimated 2.7 billion m^3/annum (2 723 million m^3/annum) (DWA, 2016) it is evident that MAR practices on a large- and wide-scale could substantially enhance the country’s water security.

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Managed Aquifer Recharge in Spain

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2016

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Managed Aquifer Recharge or artificial recharge (there is not still consensus on terminology in Spain) has been applied intentionally, according to chronicles, since the 12th century on the South slopes of Sierra Nevada Mountains. MAR devices used for irrigation are called *"careos"* Fernández-Escalante *et al.*, 2005) and some authors attribute their origin to the Muslim period whilst others state it was originally from the Roman era. Interestingly, they have many aspects in common with the Peruvian *"amunas"* of the pre-Columbian period.

In the early 1960's a pioneering large diameter recharge well was constructed in Barcelona by the water supply company (Custodio, 1986) as a complementary source for urban supply, starting a new phase in the classical Integrated Water resources Management (IWRM) schemes in Spain.

By the late 1980´s well-documented use of infiltration wells in Daimiel National Park were underway for environmental restoration. These were to mitigate the serious impact of drought on the wetlands and related ecosystems and to decrease the risk of the aquifer provisionally declared over-exploited due to the high pumping rate for irrigation.

At the same time the Spanish Geological Survey (IGME) drilled a deep borehole in the bank of Esgueva River (Valladolid) to test deep infiltration and injection (De la Orden *et al.*, 2003). Also some infiltration ponds were built related to an iron ore mine in Granada, further broadening MAR applications.

In the 1990´s several projects were carried out, testing the feasibility of the different MAR types in different areas. A detailed description for most of these sites can be found in DINA-MAR, 2009 and http://www.dina-mar.es/post/2010/04/29/documentacion-tecnicanoticias.aspx.

In addition new investments were made in short duration R&D projects, with the big disadvantage that many of these were abandoned after the supporting funds finished.

Currently there are more than 32 different MAR projects scattered around Spain (figure 1), with diverse facilities and methods to enhance recharge. Most of these activities were promoted by agents such as the Spanish Ministry of Agriculture by means of Tragsa Group, the Spanish Geological Survey (IGME) and the Catalonian Water Authorities, broadening the historical uses.

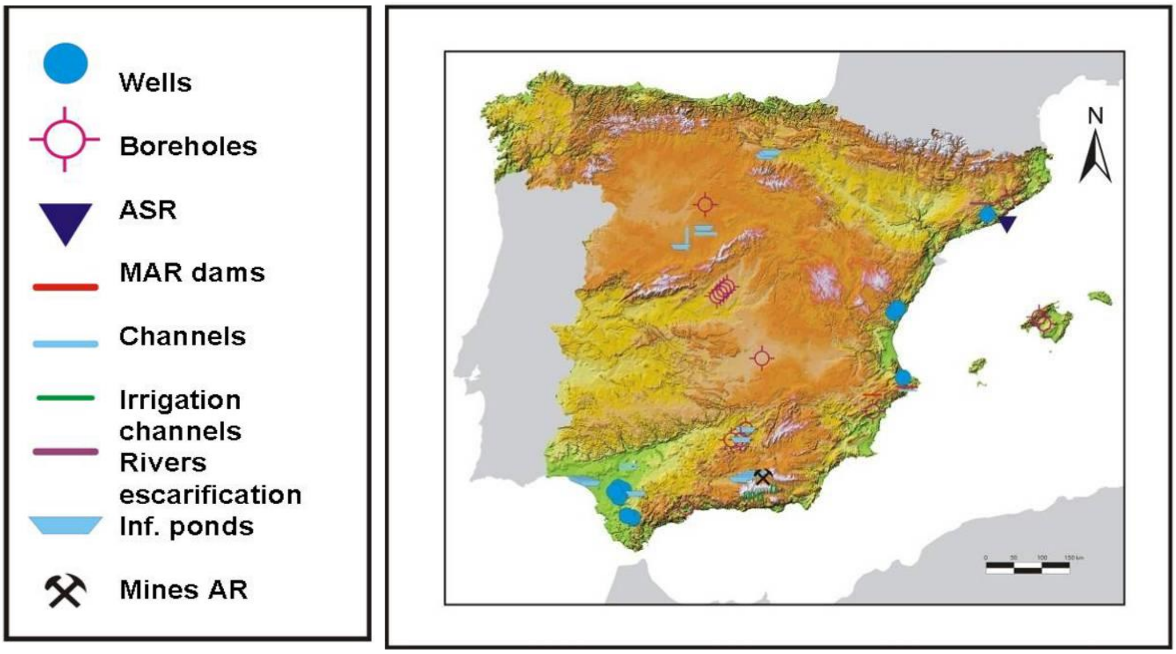


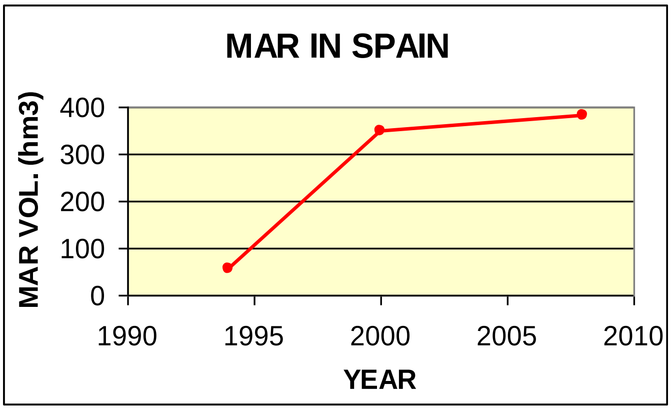
Figure 1. MAR facilities inventory in Spain, modified from DINA-MAR, 2009.

In general there are good examples of application for mining in the Southern area (Andalusia; Alquife; Cobre las Cruces). In the central area there are abundant canals and infiltration ponds for MAR. For example, starting in 2002, Los Arenales aquifer is the biggest large scale MAR area in Spain actively involving many agro-industries and becoming good examples of cooperation between farmers and researchers and Public-Private Partnerships (PPP). The deepest boreholes for ASR have been drilled in the big cities (Barcelona since 1969 and Madrid since 1995) so as to enhance reliability and increase supply of urban water. Along the Mediterranean Arc are many examples of detention structures such as dykes, check dams and dams to slow down the floods called “gotas frías” that are common in the Mediterranean area, diverting high flows to recharge aquifers.

According to Fernández (2018) the biggest volume of intentional recharge infiltrated into the aquifer is conducted by about one thousand dykes and dams constructed along the upper catchments of river basins, to reduce flash-floods and their devastating effects. Although these facilities (constructed by the Institute for the Nature Conservation, ICONA, since the 1950´s) have multiple uses, they retain water and considerably enhance the natural recharge by about 200 Mm^3/year.

Among all the examples reported, the vast majority were promoted by the public sector. Among the exceptional private initiatives it is worth mentioning those at Marbella and Majorca Island. The official estimate of the annual volume of water recharged via MAR in Spain has grown from 50 to 60 Mm^3/y (LBAS, 1994) to 350 Mm^3/y (LBAE, 2000).

In 2008 the total volume of MAR in Spain was about 380 Mm^3/year (DINA-MAR; 2009). About three quarters of this was by means of these dykes and check dams in the upstream sections of the river basins, especially on the East coast. Some of these facilities were developed around the year 2000 for intentional recharge by institutions such as Diputación de Alicante.



(1994, LBAS)	**50-60**
(2000, LBAE)	**350**
(2008, DINA-MAR)	**380**

Figure 2. Artificial recharge of groundwater in Spain [$10^6 m^3$/year]

According to the catalogue of European MAR applications for 23 countries DEMEAU (2014) classified according to 10 different MAR types (Figure 3) the biggest number of sites are in the Netherlands and in Germany, and Spain is the country with the biggest diversity with 8 of the 10 different MAR types represented.

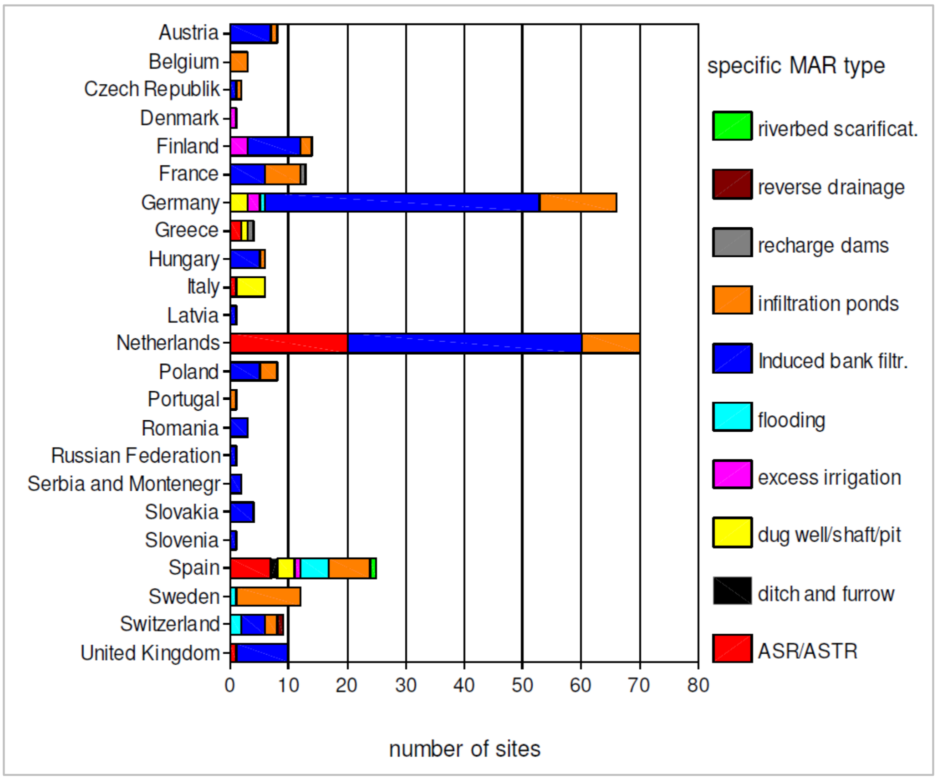


Figure 3. MAR sites *vs* MAR types for 24 European countries (DEMEAU, 2014).

A large number of MAR activities or demonstration sites using reclaimed water from waste water treatment plants (WWTP) have spread throughout Spain (Figure 4). Important experience is being gained in Costa Brava (e.g. Port de la Selva) and in Barcelona airport area, where saline water intrusion is inhibited by means of reclaimed water recharge in Llobregat river delta.

In summary, MAR has been present in Spain for several centuries and today there is a great variety of MAR facilities, that makes Spain an excellent country to visit to observe different working examples of most types of MAR. It is also worth mentioning there are more than 24 MAR facilities envisaged (especially for Ebro and Guadalquivir river Basins) in the second generation of Basin Plans, already published, which are commitments of the Spanish Government with their citizens and with the European Commission.

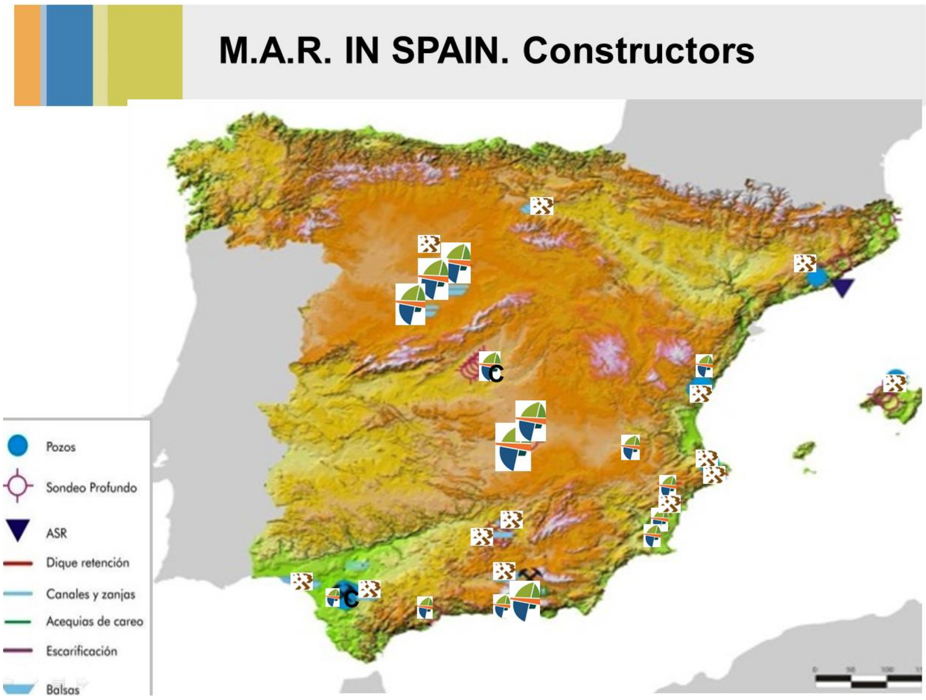


Figure 4. Map of MAR sites in Spain (DINA-MAR, 2009).

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International Association of Hydrogeologists

Commission on Managing Aquifer Recharge

This is one of IAH's family of Commissions and Networks

Aims

IAH's MAR Commission 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. through:

- increasing awareness of MAR among IAH members and the greater groundwater community;
- facilitating international exchange of information between members;
- disseminating results of research and practical experience;
- informing policy development that enables benefits of MAR to be realized;
- facilitating members to conceive, undertake and deliver joint projects of international value.

Actions

To do this we have :

- resources on the IAH-MAR web site and a publications repository
- an email list that you can join from the IAH-MAR website
- working groups to undertake specific international projects
- symposia including ISMAR and workshops
- links to national networks

How to join

Join the email list at https://recharge.iah.org/ (its free) and on average circulates less than 8 emails a year.

Join a working group (cost is free but there is an assignment to do as a contributor to an international project team) https://recharge.iah.org/working-groups

Come along to a Plenary Session (free and no obligation) at an IAH Congress or at an ISMAR Symposium to discover how IAH-MAR could be helpful for you or your colleagues.

We encourage you, if you find this Commission useful, to also join IAH (this has annual subscription fees and you receive Hydrogeology Journal, IAH Book Series, newsletters, discount registration to IAH Congresses and ISMAR Symposia)