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Managed aquifer recharge (MAR): from global perspective to local planning

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ABSTRACT

Global and regional changes have significant financial, socio-economic and environmental impact on water resources. This is manifested in severe depletion of groundwater levels, salinisation of soils and aquifers, and increased water pollution levels. In many cases though, this can be compensated through carefully designed adaptation measures. One such example is represented by managed (artificial) aquifer recharge (MAR), method which implies the purposeful recharge of groundwater with surface water for subsequent recovery or environmental benefits. Over decades, MAR schemes were successfully installed worldwide for a variety of reasons: to maximize the natural storage capacity of aquifers (i.e., seasonal water storage), physical aquifer management (restoration of groundwater levels in overexploited aquifers, reduction of land subsidence and prevention of saltwater intrusion), water quality management (improvement of water quality through soil percolation), ecological benefits (such as maintaining the groundwater levels and flow requirements) and other benefits (such as saving on evaporation, storage of reclaimed water, etc.). The economic feasibility of MAR schemes increases for projects with high-value uses such as potable supply while the projects with low-value uses such as irrigation are usually characterized by low capital and operating costs. To emphasize the important role of MAR in the mitigation of global change impacts, the first part of this presentation brings evidence collected from over 1,200 MAR case studies from 60 countries, including data on historical development, site characterisation, operational scheme, objectives and recharge methods used, as well as quantitative and qualitative characterisation of both influent and effluent. In the second part, the talk will include also an overview on different planning and optimisation approaches with special emphasis on the newly developed web-based groundwater modeling platform for MAR applications (the INOWAS platform). The core of the system is represented by a compilation of public domain models of different levels of complexity ported on a web server for best data accessibility. The INOWAS framework presented includes several advantages over conventional simulation approaches: (a) allows the use of various model complexities; (b) provides best accessibility of project data and multi-institutional collaboration through web-based implementation; (c) makes use of a combination of widely available open-source tools; and (d) promotes the case-based reasoning approach as additional support for parameter estimation and solution finding. Overall, the paper emphasizes the relevance of MAR for groundwater replenishment around the world with specific focus on the Arabian Gulf Region and introduces new tools aimed at boosting the uptake of MAR in the near future.

Keywords: Managed aquifer recharge; Groundwater; INOWAS; MAR

1. Introduction

The past decades have been characterized by irregular availability of water resources. This was caused by several factors, including socio-economic conditions (groundwater overexploitation caused by rapid human concentration in urban areas), socio-political influences (sharp increase in human displacements caused by political instabilities), or climatic variations (high seasonal fluctuations of precipitations, extended drought periods, flooding events, and

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changes in temperature patterns). The direct impact of these constrains can be observed in reduced water availability and restricted accessibility to water resources worldwide.

2. Managed aquifer recharge (MAR) for sustainable water management

To address these challenges, adapted management strategies are required to provide for sustainable exploitation of water resources and increase resilience of water infrastructures to extreme hydro-climatic events. One very promising approach is expressed by the redesign of the hydrological water cycle, both in spatial and temporal terms. Specifically, this implies the high water demand in the dry season to be compensated during times of higher availability or lower consumption by replenishing the subsurface reservoirs, while also managing the quality of infiltration water. This intentional replenishment of aquifers is known as “managed aquifer recharge” (MAR), which represents the purposeful recharge of water to aquifers for subsequent recovery or environmental benefits (Dillon, 2005) from both quantitative and qualitative perspective.

2.1. Benefits of MAR

The benefits of storing water underground vs. conventional above-ground solutions (dams) are manifold, including:

- very small land area required for storing large water quantities;
- water can be stored within the perimeter of the urban area;
- the capital costs can be significantly lower for a scalable technological solution;
- evaporation loses are extremely low;
- substantial removal or pathogens during soil percolation;
- additional benefits for a variety of ecosystem services.

From a general perspective, the conjunctive application of MAR can be beneficial for:

- *maximisation of natural storage capacity of the aquifers*: for seasonal, emergency and diurnal storage – for example, storing water from desalination plants – as well as long-term storage, or “water banking”;
- *physical management of the aquifers*: restoration of overexploited groundwater levels and therewith the avoidance of land subsidence, prevention of saltwater intrusion in coastal aquifers, enhancement of production capacities of exploitations well fields;
- *water quality management*: water quality improvement during soil percolation – for example, in surface infiltration basins or during river bank filtration, additional treatment of sewage effluent;
- *ecological benefits*: such as maintenance of groundwater levels and baseflow requirements, minor environmental footprint and minimal land use, etc.

2.2. MAR worldwide

To facilitate access to different MAR experiences worldwide, to promote international sharing of information and knowledge about MAR and to demonstrate its feasibility, a comprehensive review of reported MAR studies was conducted by the research group INOWAS at TU Dresden within the MAR Commission of the International Association of Hydrogeologists (IAH-MAR). The survey identified about 1,200 MAR projects in over 60 countries worldwide, a very solid proof of MAR suitability under different climatic, geographic, social and economic conditions (Fig. 1). The collected

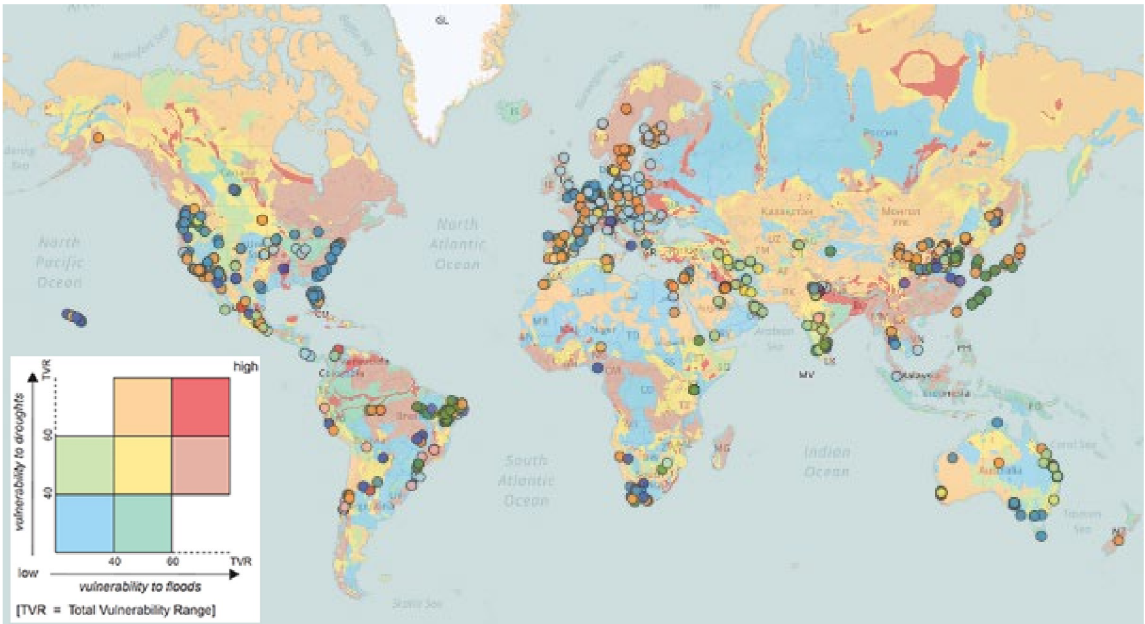

Fig. 1. MAR schemes worldwide (colored circles represent different MAR techniques) as measure implemented to reduce groundwater vulnerability to droughts and floods (source: Global MAR Portal, http://marportal.un-igrac.org).

case studies are included in the Global MAR Portal, a web-based repository freely accessible online under http://marportal.un-igrac.org (Stefan and Ansems, 2017).

According to data collected and reported in international literature, the first documented MAR schemes date from 1800s (Sprenger et al. 2017), although different forms of aquifers replenishment for water management have been used for more than 2,000 years. The review demonstrated a slow but steady increase in MAR implementation until 1940s, followed by a steep increase (in average, five times more case MAR projects per year) between 1950s and 1980s, when a third development phase can be observed with a worldwide average of more than 20 MAR projects being started every year (Fig. 2) – to note that this database is not comprehensive and it includes only projects reported in scientific sources. Unfortunately, the installed capacity of these schemes is not well documented but recent estimates place the numbers from 1 km^3 in 1965 to 10 km^3 in 2015 (Dillon et al., 2018). High recent growth rates of more than 8% per year (including in countries such as Oman and Qatar) indicate that MAR is becoming more and more relevant to a wide range of water-management issues (Dillon et al., 2018). In Europe, MAR plays an important role in the development of water supply systems and contributes substantially to the drinking-water production. Only in Germany, 59 active MAR schemes produce about 750 Mm^3 of freshwater per year, mainly through river bank filtration and direct surface infiltration (Sprenger et al., 2017). In Abu Dhabi Emirate (UAE), a recent project whose construction was completed in December 2017 involved about 300 wells that aim to recharge about 26 Mm^3 of desalinated seawater into the adjacent aquifer and subsequent recovery for potable use, enough to supply Abu Dhabi Emirate with emergency water for 90 d (GRIPP, 2018).

For urban areas, MAR can be used in combination with other water management approaches such as wastewater recycling, stormwater harvesting, saline groundwater intrusion and flood mitigation and management. A recent study by Page et al. (2018) describes in detail the use of MAR in urban water management, including urban water sources, suitable urban aquifers, water quality considerations and international examples, including from Australia. By comparison, Bonilla et al. (2018) compiled an inventory of MAR schemes in Latin America and the Caribbean and emphasized the benefits of MAR utilisation in irrigated agriculture.

2.3. Recharge techniques

Over decades, the technical capacities increased and different recharge techniques were developed and adapted to local hydrogeological conditions. Table 1 describes the common MAR classification based on two main categories: techniques that refer to getting water infiltrated into the ground (either through spreading the water above surface or by subsurface injection), and techniques referring primarily to water interception through engineered modifications of regular surface and groundwater flow.

Among these techniques, the infiltration basins and the infiltration wells (Fig. 3) are utilised in more than half of the MAR applications worldwide (Stefan and Ansems, 2017). The infiltration basins (or ponds) are based on the retention and spreading of water over a mostly flat area in order to enhance infiltration to the unconfined aquifers. This type of recharge technique is used when the site surface and subsurface characteristics allow the aquifer to be recharged from ground level. In case of aquifer storage and recovery, water is injected into the targeted aquifer by a constructed well. This technique known as ASR (or ASTR if the recovery is not from the same well) is mostly used when thick and low permeability strata are present above the aquifer. Moreover, well infiltration requires a higher water quality but a smaller surface area for the well construction.

The selection of the suitable technique should be made according to the local climatic and hydrogeological conditions, available water quantity and quality, as well as

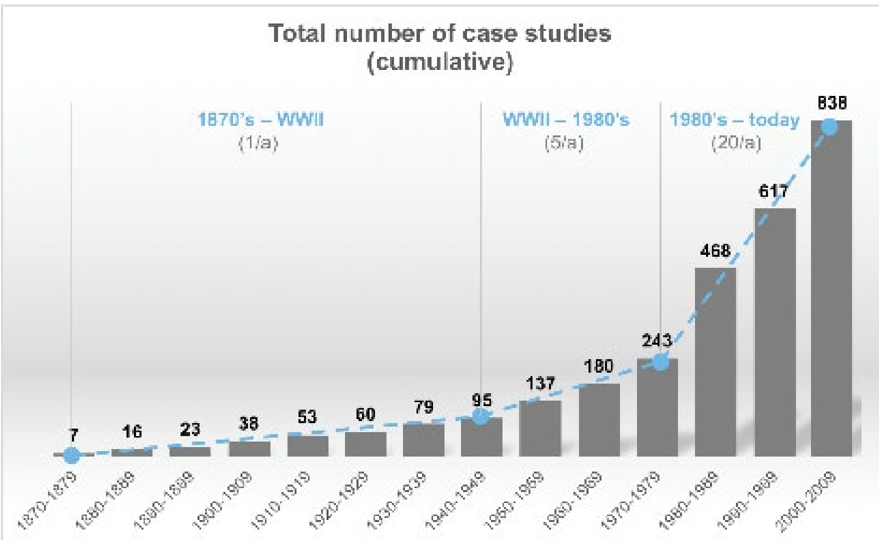

Fig. 2. Historical development on MAR applications as reported in scientific literature (after Stefan and Ansems, 2017). In reality, the number of recharge structures is estimated to be way much higher (in the order of millions!), however only a small percentage of these are well documented and monitored.

Table 1
Different MAR techniques (adapted from IGRAC, 2007). Detailed description of each recharge technique can be found at https://inowas.hydro.tu-dresden.de/managed-aquifer-recharge/ (including recommended system scale, suitable geology, topography, soils type, water sources, relative costs objectives, advantages and limitations)

	Main MAR methods	Specific MAR methods
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds & basins
		Flooding
		Ditch, furrow, drains
		Irrigation
	Induced bank infiltration	River/lake bank filtration
		Dune filtration
	Well, shaft and borehole recharge	ASR/ASTR
		Shallow well/shaft/pit infiltration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams
		Subsurface dams
		Sand dams
		Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting
		Barriers and bunds
		Trenches

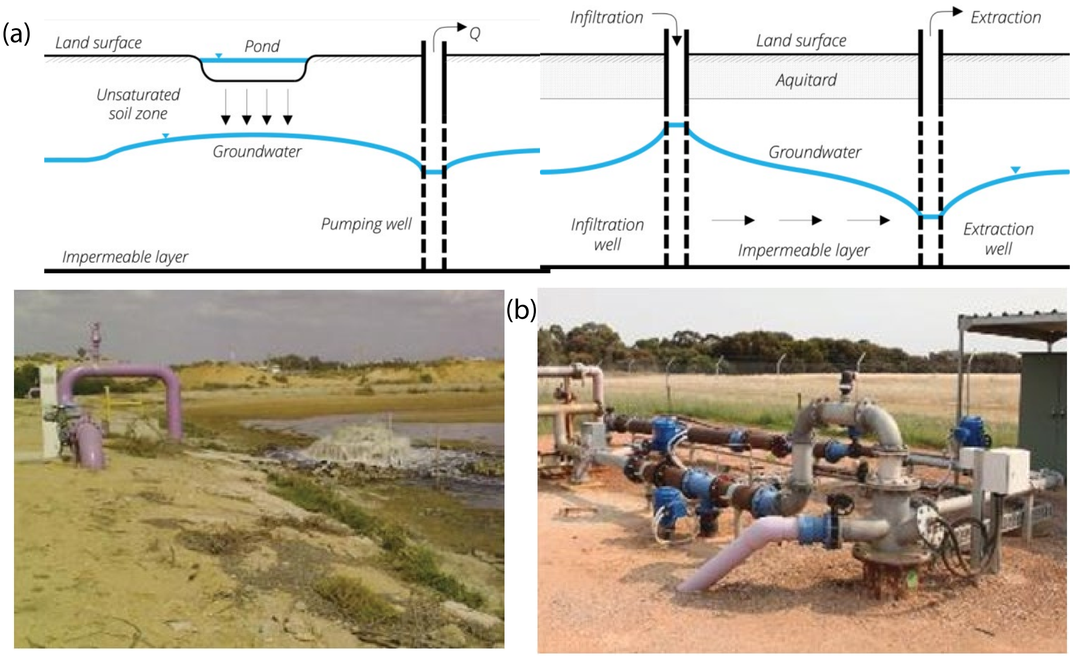

Fig. 3. Most common MAR techniques: infiltration ponds used for soil-aquifer-treatment (SAT) applications (a) and infiltration wells, used in aquifer storage and recovery (ASR) or aquifer storage, transport and recovery (ASTR) applications (b). Photos: Catalin Stefan.

following the specific demand for the recovered water. In Arabian Gulf countries, ASR has been tested and applied with success to recharge underlying aquifers. In Kuwait, for example, the technical feasibility of ASR was tested since 1970s, with further tests conducted in the 1990s in the carbonate and clastic aquifers indicating that ASR is technically possible (Mukhopadhyay et al., 1994). Nevertheless, the insufficient treatment of water to be infiltrated leads to severe clogging of the infiltration wells, which is the major reason of failure of ASR systems. Alternatively, pilot studies have been used to investigate the feasibility of infiltrating secondary to tertiary treated wastewater through surface recharge basins in Kuwait (Al-Senafy and Sherif, 2005). Besides the replenishment of underlying aquifer, the system also provides further purification of infiltration water through soil aquifer treatment (SAT). The advantage of SAT vs. ASR is that water of lower quality can be infiltrated for seasonal storage (specifically treated wastewater, which is widely available throughout the year). The drawbacks of this approach are given by the often unsuitable lithology and high evaporation rates. Nevertheless, these constrains can be partially addressed through carefully selected operational conditions. These include the construction of several shallow basins and their operation in alternative, short wet-dry cycles to maximize efficiency and enable full restoration of the infiltration rates.

2.4. Planning and assessment of MAR schemes

Despite their demonstrated benefits, solutions such as managed aquifer recharge (MAR) are still not widespread, partly due to poor access to information and lack of knowledge about the associated risks to human health and environment. So far, only few countries developed strategic guidelines for MAR (including Australia, India, Mexico, USA), among them Australia being the leader in having the first risk-based guidelines for managed aquifer recharge (NRMMC et al., 2009). In most cases, preliminary studies are required to design the process parameters and assess operational scenarios. This can be done by using pilot cases or laboratory tests, approach usually prone to boundary limitations and scale-related issues. Alternatively, computer simulations provide an excellent opportunity for analysis of scenarios and future predictions of MAR efficiency (Ringleb et al., 2016; Sallwey et al., 2018). They are used for modeling water balance at watershed scale, solute and reactive transport, transport processes in unsaturated zone, and saturated flow processes (Fig. 4).

With very few exceptions, all available software codes and decision support systems for MAR planning and assessment are desktop-based, which represents a significant constrain in the development and dissemination of smart IT solutions to a large audience, especially from an international perspective. Moreover, a large percentage has a steep learning curve and training is often linked to significant human and financial resources.

2.5. Free, web-based INOWAS modeling platform

The main idea around our approach is thus the portability of desktop-based groundwater modeling to web- and cloud-based systems. For this purpose, we developed the INOWAS platform, a web-based groundwater modeling platform that aims to facilitate online collaboration for the development of smart MAR solutions worldwide (available online at http://inowas.hydro.tu-dresden.de). The platform combines modern web-based technologies and design elements with powerful computational capabilities to deliver reliable browser-based simulations. The platform is addressed to scientists and engineers from planning offices, environmental agencies, local and regional planners and decisions makers, as well as academia and public sector. The system is developed to provide decision-support in solving different groundwater related issues with focus on planning, assessment and optimisation of MAR schemes. To increase its attractiveness and applicability among a wider range of users, the platform contains tools grouped on three levels of complexity for empirical, analytical and numerical groundwater modeling.

The main advantage of using the INOWAS platform compared with other solutions lies in the easy set-up, calculation and dissemination of groundwater models to a wider audience using only the web browser and regular internet connection. In contrast to desktop-based computing, which requires the installation of additional computer programs and plugins (often not a straightforward process due to system incompatibilities), web-tools hold the advantage of increased software availability, device and location independence, easy maintenance and updating, independence of platform, hardware and operating system, as well as resource pooling. In addition to technical advantages, the system offers further benefits such as multi-user collaboration via internet and a short learning curve resulting from the combination of intuitive design with modern, standardized graphical user interface. Even more, the platform contains web-based implementation of well-known equations and open-source software code for groundwater management, which makes it compatible with other conventional platforms and interfaces.

The platform contains collection of simple, practical and reliable web-based tools of various degrees of complexity (Fig. 5):

- *empirical tools* – simple tools derived from data mining and empirical correlations;
- *analytical tools* – practical implementation of analytical equations of groundwater flow;
- *numerical tools* – reliable simulations using complex numerical flow models.

For numerical modeling, the INOWAS platform offers a brand-new MODFLOW interface which is accessible only from the browser, without the need for the installation of any additional software of plugins. As being the first web-based implementation of an integrated groundwater modeling platform, INOWAS brings a global perspective to water resources management.

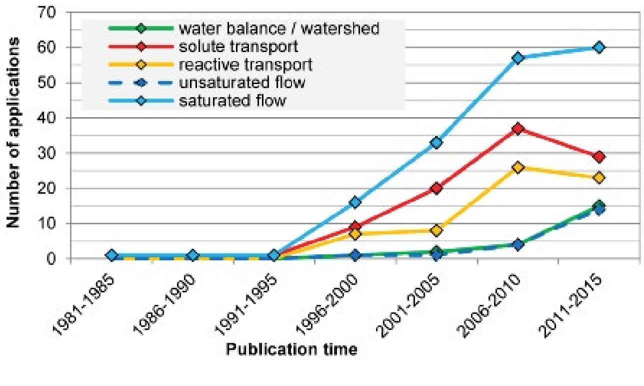

Fig. 4. Historical development of different model types for simulation of MAR-related processes (Ringleb et al., 2016).

3. Conclusions

The free, web-based INOWAS platform supports planners and decision makers in different steps of planning and assessment of MAR applications. The web-based implementation offers a whole new range of opportunities for collaboration while the multi-layered toolbox complexity

Fig. 5. Screenshots of simulation tools included in the INOWAS platform. Left: analytical tool for the calculation of saltwater upconing under a pumping well (Glass et al., 2018a). Right: scenarios analysis of a MODFLOW-based groundwater model (Glass et al., 2018b).

makes the platform easily accessible. With its technical innovation, the INOWAS platform is expected to actively contribute to the promotion and expansion of MAR applications, therewith supporting the shift to sustainable water resources management.

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