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Editorial

# Managed Aquifer Recharge for Water Resilience

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**Abstract:** Managed aquifer recharge (MAR) is part of the palette of solutions to water shortage, water security, water quality decline, falling water tables, and endangered groundwater-dependent ecosystems. It can be the most economic, most benign, most resilient, and most socially acceptable solution, but frequently has not been implemented due to lack of awareness, inadequate knowledge of aquifers, immature perception of risk, and incomplete policies for integrated water management, including linking MAR with demand management. MAR can achieve much towards solving the myriad local water problems that have collectively been termed "the global water crisis". This special issue strives to elucidate the effectiveness, benefits, constraints, limitations, and applicability of MAR, together with its scientific advances, to a wide variety of situations that have global relevance. This special issue was initiated by the International Association of Hydrogeologists Commission on Managing Aquifer Recharge to capture and extend from selected papers at the 10th International Symposium on Managed Aquifer Recharge (ISMAR10) held in Madrid, Spain, 20–24 May 2019.

**Keywords:** groundwater recharge; water quality; water banking; managed aquifer recharge; water crisis

## 1. Introduction

The papers in this special issue explain how managed aquifer recharge (MAR) addresses water resilience challenges across the globe. A key water management objective is increasing the security of water supplies in droughts and emergencies. Another is improving water quality so that sources of water are able to supply drinking water or buffer against water quality decline due to ingress of saline or polluted waters. MAR is also used for ecological restoration of wetlands and stream habitats that have been impacted by surface water and groundwater extraction. Well-conceived and executed MAR projects therefore offer water managers the opportunity to realize water resilience benefits.

This collection of papers goes beyond enumerating these benefits in various climatic, geological and social settings. It also addresses the supportive measures to enhance the ability of MAR to proceed sustainably and effectively to achieve these benefits. Identifying suitable sites for MAR is one fundamental prerequisite. In recent years, a systematic way of doing this has been by overlaying layers of relevant variables within a geographic information system and taking combinations of these with predetermined weights and criteria for likelihood of success (multi-criteria decision analysis). Examples and a synthesis of this approach are presented in this special issue. In addition to aquifer suitability mapping, there is also a need to know where sources of water are available for recharge and where there are existing or projected demands for recovered water. The composite is known as opportunity assessment and examples are given. Time series modelling of water availability is also used in one paper to determine when recharge is possible and when recovery is needed to help with integrating MAR into a national water supply system.

Creating awareness of MAR, especially where it is an underutilised tool in water management, is an important step to increase its effective deployment and impacts. Hence, overviews of MAR practices at the national and continental scales help develop understanding of the relevant conditions where MAR has proven effective. Awareness of the policies and guidelines relating to MAR at the national and state scales, at which water is commonly managed, also helps water regulators determine the regulations warranted for effective implementation of MAR. Examples are presented where policies have had positive and unintended negative impacts on the usefulness of MAR.

Concerns by operators over chronic operational issues, such as clogging, must be addressed to avoid MAR projects becoming unsustainable and therefore not producing the water resilience intended over time. The largest cause of failure of MAR systems is that methods to manage clogging have been insufficient at some sites. Two papers focus on clogging—one in infiltration basins and one in injection wells. They show how well-constructed investigations and research can provide necessary information for the long-term successful operation of projects where recycled water is recharged.

Finally, the future of MAR is enhanced through innovation in MAR methods and monitoring. Several papers reveal highly innovative MAR methods. One paper describes a variety of ways to harness surface water irrigation canals to recharge aquifers where irrigation can draw from canals and aquifers. Another paper initiates an exploration of a method to simplify monitoring of microbiota in aquifers used for bank filtration, which has implications for pathogen removal.

Table 1 maps each paper to water resilience themes and the discussion of this introductory paper. The thematic categories include water security improvement, water quality improvement and environmental protection and restoration. Following these are some cross-lapping supportive themes referenced above: mapping of suitable MAR sites and identifying opportunities; continental-scale and national overviews of MAR practices and policies; operational issues including management of clogging; and innovation in MAR methods and monitoring. Table 1 shows the papers in order of mention. It highlights the section of this introductory paper where each paper is featured and also includes information on the type of source of water used; type of target aquifer involved; type of recharge method; end use of recovered water, and represented geographic area.

**Table 1.** Directory to the matters addressed and the characteristics of managed aquifer recharge (MAR) sites for each paper; Highlighting shows the introductory paper section assignment.

| Reference Number | Authors of Paper | Improve Water Security | Improve Water Quality | Improve Environment | Mapping/ Opportunity Assessment | National Summary/ Legislation/Policy | Clogging/ Operational Issues | Innovative MAR Methods | Source Water * | Aquifer Type | Recharge Method # | End Use | Geographic Area |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [1] | Fernández et al. (2019) | Y | y | y | | | | y | all | all | all | irrigation | Spain |
| [2] | Alam et al. (2020) | Y | | | | | y | y | N | alluvial | hybrid-basin & wells | irrigation | India |
| [3] | Soni et al. (2020) | Y | y | | | | | | N | hardrock | dug wells | irrigation | India |
| [4] | Kruć et al. (2019) | | Y | | | | | | N | alluvial | river bank filtration | potable | Poland |
| [5] | Masse-Dufresne et al. (2019) | | Y | | | | | | N | alluvial | bank filtration | potable | Canada |
| [6] | Patenaude et al. (2020) | | Y | | y | | | | N | all | bank filtration | potable | Canada |
| [7] | Valhondo et al. (2020) | | Y | | | | | y | R | alluvial | SAT | potable | Spain |
| [8] | Van Kirk et al. (2020) | y | y | Y | | y | | y | N | alluvial | infiltration | fishery, agric | USA |
| [9] | Sallwey et al. (2019) | | | | Y | | | | all | all | all | all | universal |
| [10] | Dahlqvist et al. (2019) | y | | | Y | | | | N | limestone | infiltration | potable | Sweden |
| [11] | Knapton et al. (2019) | y | | | Y | | | | N | laterite | all | all | Australia |
| [12] | Maréchal et al. (2020) | | | | Y | | | | N | alluvial | infiltration | non-potable | France |
| [13] | Lindhe et al. (2020) | y | | | Y | | | | N | alluvial | all | potable | Botswana |
| [14] | Ebrahim et al. (2020) | y | y | | y | Y | | y | all | all | all | all | Africa |
| [15] | Shubo et al. (2020) | y | y | | | Y | | y | N | all | all, incl. novel | any | Brazil |
| [16] | Cruz-Ayala and Megdal (2020) | y | y | | | Y | | | all | all | all | all | Mexico |
| [17] | Dillon et al. (2020) | | y | y | | Y | | y | all | all | all | all | Australia |
| [18] | Negev et al. (2020) | y | | | | | Y | y | R | sandstone | SAT | non-potable | Israel |
| [19] | Stuyfzand and Osma (2019) | | y | | | | Y | y | R | siliclastic | injection wells | non-potable | Australia |
| [20] | Liu et al. (2020) | y | | | y | | | Y | N | alluvial | all, incl. novel | irrigation | China |
| [21] | Narantsogt and Mohrlok (2019) | y | | | y | | | Y | N | alluvial | infiltration | potable | Mongolia |
| [22] | Adomat et al. (2020) | | y | | | | | Y | N | alluvial | river bank filtration | potable | Hungary |

Notes: * N = natural water; R = recycled water; # SAT = soil aquifer treatment; Y = primary contribution of paper; y = additional contribution of paper.

## 2. Synopsis of Contents of This Special Issue

### 2.1. Water Security Improvement

Most papers reported on water supply security improvements, with three of the papers providing an assessment of benefits. The broadest range of benefits is reported for a diversity of MAR projects in Spain. Fernández et al. [1] explains how additional storage enables adaptation to climate change by buffering water availability during reduced rainfall and extended droughts. For these cases, the additional storage has been quantified. In Los Arenales aquifer, Santiuste Basin, this is sufficient to supply farmers for three years with no rainfall. Another benefit is the quantified reduced energy demand for the pumping of groundwater, which itself is a step to reduce carbon emissions and mitigate climate change. Furthermore, the aquifer acts as a reticulation system to deliver water without pumping to farmers wells. The integration of treated wastewater in several projects enhanced groundwater recharge and its reliability and further increased storage.

In monsoonal North India, imbalance between supply and demand is an annual and interannual problem. MAR has been proposed by Alam et al. [2] as a possible solution to both. They conducted the first systematic, multi-year assessment of the performance of pilot-scale MAR designed to harness village ponds to replenish alluvial aquifers in an intensively groundwater-irrigated, flood-prone area of the Indo-Gangetic Plain. In Ramganga Basin, adjacent to an irrigation canal, an unused village pond in clay soil was equipped with 10 recharge wells, and volumes and levels were measured over each wet season for three years. Recharge averaged 44,000 $m^3$ $year^{-1}$ at a rate of 580 $m^3$ $day^{-1}$ (221 mm $day^{-1}$) during up to 3 months each year, enough to irrigate 8–18 ha dry season crop. This was up to 9 times the recharge without wells. Significant reductions in recharge rates occurred during each wet season due to clogging of the annular sand filters surrounding recharge wells and due to hydraulic connection with the aquifer. Authors conclude that the pilot has a beneficial impact on water security for village supplies but would need widespread replication to have an observable impact on flooding.

Another multi-year pilot-scale trial, also in India but using gravel filters to filter field runoff before recharging farmers open dug wells in hard-rock terrain in Rajasthan, was undertaken by Soni et al. [3]. A total of 11 wells were recharged between 1 and 3 years, and depth to water level was monitored weekly for 5 years for all recharge wells and for two control wells near each. In this case, volumes of water recharged were too small to produce sufficient additional crop to justify the cost of recharge infrastructure. This is unlike check dams on streams in the same catchment that have a benefit to cost ratio greater than 4. Water sampling suggested lowered salinity and fluoride in recharged wells but increased turbidity and *Escherichia coli*. An unexpected finding of this study was that no sampled open dug well met drinking water standards. Hence, wellhead water quality protection measures, including parapet walls and covers and prevention of direct recharge, were recommended for wells used for drinking water supplies. Testing of larger-scale field infiltration pits is now planned.

### 2.2. Water Quality Improvement

Improving the quality of drinking water supplies through bank filtration was the focus of three papers. Kruć et al. [4] studied the fate of 25 pharmaceuticals in the Warta River at a bank filtration site in Poland. Thirteen compounds were detected in bank filtrate and removal increased with distance from the stream. Some chemicals were completely removed at distances less than 38 m, while a few known persistent chemicals were still present but at greatly reduced concentrations for wells up to 250 m from the river. At the most distant well, only carbamazepine and sulfamethoxazole were detected. Average removal of most parameters was 70–80% even at less than 100 m distance from the river, demonstrating the additional value of bank filtration in the drinking water treatment train.

Masse-Dufresne et al. [5] studied the quality of water at a bank filtration site near Montreal, Canada, where two lakes contributed to the supply, and the mixing ratios were dynamic depending on relative lake levels and the pumping regime for wells. Salinity contrasts between lakes and seasonal differences in iron and manganese concentrations allowed an understanding of how to modify pumping to improve the quality of water pumped.

In the same area of south east Canada that contains many streams and lakes and a huge number of municipal water supply wells, Patenaude et al. [6] posed the question "which of these are in fact induced river bank filtration wells that may require greater protection from potential surface water pollution?" They used a GIS with multi-criteria decision analysis (MCDA) to categorise the likelihood of wells inducing infiltration from surface water. Minimum distance of wells from lakes or streams and type of aquifer were the variables selected for categorising wells. It was found that almost one million people are supplied from wells within 500 m of either streams or lakes. The method is seen by authors as a starting point for a risk-based analysis that takes account of water quality, environmental tracers and contaminants in source waters.

Water quality improvement is also an objective of soil aquifer treatment systems that intermittently infiltrate recycled water. Valhondo et al. [7] tested the use of several types of organic-rich reactive layers placed at the bottom of infiltration basins to enhance water quality improvement during soil passage. Field tests were performed at two sites in Spain. Results showed that the reactive layers in most cases enhanced the removal of the selected organic chemicals analysed (pharmaceuticals and personal care products). Candidate mechanisms for removal were proposed but not evaluated, so further research is needed to discuss persistence and resilience. The reactive layer did not increase the removal of *E.coli* (a bacterial pathogen indicator) beyond the 2–4 $\log_{10}$ removals observed in controls.

An aquifer affected by seawater intrusion in Barcelona (Spain) has been preserved by a hydraulic barrier created by MAR, in a study by Fernández et al. [1], which demonstrated improved water quality by mitigating and preventing further water quality deterioration.

### 2.3. Environmental Protection and Restoration

In a novel case study in the Snake River catchment of Idaho, USA, Van Kirk et al. [8] used a groundwater model and stream and aquifer water temperature data to assess potential benefits of MAR to protect a trout fishery. Winter and spring MAR operations 8 km from the river supplement recharge incidental to irrigation and were calculated to increase streamflow in 2019 by 4–7% during the driest and warmest time of year by increasing cool groundwater discharge, rather than by reducing stream losses. This lowered the stream temperature from approximately 19 °C, where trout are under heat stress, to give cool refuges adjacent to springs at 14 °C, which is optimal for trout. This habitat improvement is an additional benefit of MAR that also supports agricultural irrigation. Well-developed water rights and water transaction systems in Idaho and other western states enable MAR. However, the authors note that there remain legal and administrative hurdles to using MAR for cold-water fisheries conservation in Idaho, where conservation groups so far are unable to engage directly in water transactions.

In Spain, wetland restoration has also been achieved through MAR in Castilla y León to restore water levels and maintain a geochemical equilibrium vital for bacteria, vegetation and refuge for aquatic birds (Fernández et al. [1]). Since 1995, a deep recharge well in a karstic aquifer capable of accepting 1000 L/s has been used in Lliria (Valencia) for flood mitigation while also enhancing irrigation water security [1]. In Neila, Burgos, Spain, 15–40% of flow in streams is directed via constructed channels into contour bunds in forested areas to enhance diffuse source recharge while also increasing forest production [1].

### 2.4. Mapping of Suitable MAR Sites and Identifying Opportunities

A number of papers made use of geographic information systems (GIS) with multi-criteria decision analysis (MCDA) to identify suitable locations for MAR operations. Sallwey et al. [9] undertook a review of such studies and out of this developed two open-source web-based tools, a query tool and a tool to help standardise weight assignment and criteria. These will help users to make mapping of MAR site suitability more structured and assist in collaboration among multiple partners. Site suitability focuses on the presence of an aquifer capable of storage and recovery of water, as well as information on the unsaturated zone characteristics to indicate viability of infiltration type methods. Data availability and quality are important in the mapping process and the tools still depend on the assessor's expertise in choosing relevant datasets for each specific study.

Although not discussed in any of the GIS-MCDA papers, modern remote sensing methods, particularly those that are satellite-based provide a dense raster of data relevant to site selection. Spatial correlation ranges can be determined using geostatistics to suggest more robust predictors than possible from sparse point-scale measurements, such as aquifer parameters from pumping tests, although these are valuable to help ground-truth predicted aquifer suitability. It is hoped that in future, greater effort will be put into parameter selection for parsimonious and robust mapping of MAR suitability, and into validation of predictions.

MAR site suitability mapping is a foundational layer in assessing MAR opportunity, where the proximity of such aquifers to sources of water such as streams, dams and water recycling plants is also considered. One example is the Island of Gottland, Sweden, where Dahlqvist et al. [10] determined the role for MAR to contribute to future water supplies. They found that 7.5% of the area of Gotland was suitable for MAR compared with 3.3% suitable for surface water supplies through new dams. Although lacking detailed site-specific studies, which they recommend, they claim MAR to be a viable option. They estimated that the unit cost of MAR was four times that of expansion of conventional groundwater supplies where this was possible. However, MAR was comparable in unit cost and yield of expanded surface water supplies and approximately one-quarter of the unit cost of seawater desalination.

Knapton et al. [11] studied MAR options using a partially calibrated groundwater model for the Darwin rural area of northern Australia. The unconfined aquifer is characterised as a lateritic aquifer that refills each wet season and was previously presumed unsuitable for MAR. However, in specific areas, some wet season storage capacity remains, with potential for up to 1.2 $Mm^3$/year recharge. A confined part of this aquifer was identified to have up to 5 $Mm^3$ storage opportunity for water banking for Darwin's water security if a 20 m head increase is acceptable in the aquifer.

Maréchal et al. [12] aim to advance GIS-MCDA mapping approaches by adding an economic evaluation for siting a MAR facility anywhere on an aquifer. They assess the levelised unit cost of recharge from an infiltration basin, including capital and operating costs, implementing a GIS-tool in order to build maps of levelised costs at the aquifer scale. The method was tested in simplified form, with assumptions declared and dependent sensitivity analysis, for an alluvial aquifer in Southern France. Authors propose that this approach be integrated into a broader analysis of soil and aquifer parameters that would influence costs and refine the consequent maps.

GIS-MCDA was also used to map zones suitable for different types of innovative recharge operations on the North China Plain (as mentioned later by Liu et al. [20]).

A different type of opportunity assessment is not based on mapping, but instead uses time series analysis of water supply and demand to determine the need for MAR and the extent to which it can contribute to security of national water supplies. Such an analysis is performed by Lindhe et al. [13] for the north–south water carrier in Botswana. This combines large shallow dams that only irregularly fill, well fields that have small and reliable supplies but only low rates of natural replenishment, and possible future MAR systems of different capabilities. The water supply security model uses monthly time steps over 23 years to relate supply with demand and simulate the magnitude and probability of water supply shortages. Implementing large-scale MAR can be shown to improve the supply reliability from 88% to 95%. The model reveals system properties that constrain the effectiveness of MAR and suggest how to further improve its benefits for an integrated system.

### *2.5. Continental-Scale and National Overviews of MAR Practices and Policies*

Awareness of existing, relevant MAR practices alerts water managers to the possibilities and is reassuring to those contemplating undertaking a MAR project. This special issue contains a summary of MAR practice in the African continent and at the national level in Brazil and Mexico for both practice and policies. These cover a wealth of experience that is, to date, underreported in international literature. A decade of experience in Australia with MAR guidelines for health and environment protection is also reported. These accounts each have unique and highly advanced elements that will be of interest not only to these geographic areas but also globally.

Ebrahim et al. [14] review and synthesize MAR experience in Africa from 52 reported cases in 9 countries, dating back to the 1960s and covering all main types of MAR. Cases were classified under 13 characteristics including objective of the MAR, hydrogeology and climate. It was found that MAR occurred most commonly in areas of high interannual variability in water availability. The most common objective for projects is to secure and augment water supply and balance variability in supply and demand, in both urban and rural areas. Results revealed a wide diversity of applications including reservoir releases (Morocco), surface spreading/infiltration (Algeria, Tunisia, Egypt, South Africa and Nigeria), riverbank filtration (Egypt), in-channel modifications (Kenya, Tunisia and Ethiopia) and recharge wells (South Africa). Africa also contains several of the world's most sophisticated MAR projects, including aquifer injection of highly treated recycled water into crystalline rock to secure city drinking water supplies (Windhoek in Namibia) and recycling of stormwater and treated sewage via infiltration basins for town water supplies (Atlantis in South Africa). In total, the estimated annual recharge volume is 158 $Mm^3$/year or 0.4% of the continent's annual groundwater extraction. Advancing MAR in Africa requires fostering awareness of existing MAR projects, mapping suitability of aquifers for MAR (as performed in South Africa) and informing account of MAR in water allocation and water quality protection policies.

A study of national advance in the practice and governance of MAR in Brazil is reported by Shubo et al. [15]. Community level and government-level programs have been implemented at many sites to address dry season and drought supplies. The Barraginhas Project alone has seen construction of more than 500,000 infiltration ponds in north east Brazil up to 2013. Another Brazilian MAR design, Caixa Seca (or 'dry box') is widely used to recharge road runoff and would also have international application. More than 90 in-channel modifications for MAR have been recorded. Urban drainage public policies have stimulated urban aquifer recharge initiatives mostly aimed to reduce runoff peak flows. Concerning MAR policies, Brazil has been progressive at the federal level since 2001, when the Water Resources National Council Resolution nº 15 encouraged municipalities to adopt MAR. By 2008, its Resolution nº 92 made prior authorization and mandatory monitoring a condition of aquifer recharge. At the subnational level, regulations in all states mention MAR ('artificial recharge') and two, Pernambuco and Ceará, give incentives and prescriptions for community- and company-established MAR projects. The authors also note where improvements could be made in the reporting, monitoring, and systematic appraisal of opportunities and water quality risk management aspects.

Cruz-Ayala and Megdal [16] reviewed the occurrence and legal framework for MAR in Mexico. They found seven documented operational projects, five pilot projects and five research activities since the 1950s involving natural waters, recycled water and stormwater. Their combined recharge restores depleted aquifers, reduces land subsidence, increases water availability and mitigates floods. There are also very significant opportunities to expand MAR. Regulations are discussed that involve at least three levels of governance from national to basin and user level. There are also Mexican National Standards (NOMs) that create a specific regulatory framework for water allocation and water quality standards that MAR projects must fulfill. These specify the information needed to obtain a permit. Some gaps in regulations are identified, such as on entitlements to recover recharged water, that, if addressed, would help to motivate new MAR projects to address critical needs.

Dillon et al. [17] reviewed the consequences of the Australian MAR guidelines for health and environment protection after 10 years of implementation. They found that, in those states where MAR is progressing, the guidelines are welcomed as giving certainty and objectivity to approvals and fitting broader risk management approaches to water quality. In the other states, there has been no progress, although the need for MAR is just as great. Only minor adjustments are suggested to the guidelines, such as taking specific account of temperature change as a hazard in geothermal settings, referencing advances in environmental genomics, and accounting more explicitly for cumulative impacts of multiple MAR projects. In the entry level section of the guidelines, more explicit water entitlement arrangements for sourcing water, recharging aquifers, recovering from aquifers and end uses are suggested for basins where groundwater management policies need to be strengthened to be effective in securing MAR entitlements. Its relevance for application in other countries depends on capabilities to monitor, sample and analyse water quality. If such capabilities are scant, other forms of guideline are more appropriate, and India's is given as an example.

### *2.6. Operational Issues Including Management of Clogging*

Two papers focus on operational procedures to manage clogging in MAR projects utilising recycled water. The first of these describes changes to tilling operations in intermittent infiltration basins (soil aquifer treatment) at the Dan Region Reclamation Project (Shafdan) near Tel Aviv, Israel (Negev et al. [18]). After 20 years of stable operation, infiltration rates declined over a 3 year period due to changing water quality, reduction in drying periods, and seasonal effects. Tillage changes introduced in a replicated full-scale trial increased recharge capacity up to 95% for deep ploughing and 15% for chisel knife cultivator treatments, both with improved tractor power and depth control systems. Measurements included infiltration rates and soil compaction depths. Minimising compaction by allowing complete drainage before tillage is important for sustaining higher infiltration rates.

Stuyfzand and Osma [19] evaluated clogging at a pilot-scale recycled water aquifer storage and recovery (ASR) well in a confined siliclastic aquifer near Melbourne Australia. They recorded head build up during an injection and recovery trial, analysed water quality and purged solids, and developed some novel tests to predict clogging by suspended particles and biofouling. These revealed that additional water treatment would be needed and reduced rates of injection, requiring more wells to achieve the injection volume target.

### *2.7. Innovation in MAR Methods and Monitoring*

Two novel recharge systems called a "well–canal combination mode" and an "open channel–underground perforated pipe–shaft–water saving irrigation system" as practiced in the Yellow River irrigation district on the north China Plan are described by Liu et al. [20]. These are among the described numerous types of agricultural MAR practiced since the 1970s in the North China Plain. Adaptive measures to compensate for diversion of more Yellow River water to cities, to sustain conjunctive use during irrigation efficiency improvement, and to prevent clogging by fine sediment are described. Further, a GIS system using a multi-criteria decision analysis (MCDA) was developed to identify zones for sustainable development of MAR projects in the Yellow River Irrigation District of Shandong Province. Mapping revealed highest opportunities for MAR systems in the western part of Liaocheng City irrigation area, where deeper water table and greater sand thickness gave more storage potential.

Non-conventional methods for recharge enhancement are proposed by Narantsogt and Mohrlok [21] to secure the depleting water supply for Ulaanbaatar, the capital city of Mongolia. They modelled several configurations for ice storage and melting in the dry season, when groundwater levels are low and there is no river flow in this cold semi-arid area. Combining these with recharge releases from a dam is predicted to meet the ongoing water needs for the city.

Advances in monitoring methods are important to the efficient operation of MAR and protection of public health and the environment. Microbially-mediated processes in porous media are important for the removal of viruses, bacteria, and protozoa that are pathogenic to humans. Measuring bacterial biomass concentration and enzymatic activity is an innovative way of improving understanding of these processes. Adomat et al. [22] did this using flow cytometry and two precise enzymatic detection methods to monitor dynamic fluctuations in bacterial biomass at three riverbank filtration sites. They also performed online flow cytometry in an ultrafiltration pilot plant. The method showed promise as a rapid, easy and sensitive future alternative to traditional labour-intensive methods for assessing the microbial quality of RBF water, but this is still an early stage of development. Findings of bacterial regrowth on membranes reinforce the value of river bank filtration as a pretreatment for ultrafiltration for drinking water supplies.

## 3. Summary

The water security improvement is, perhaps, the biggest target and advantage of MAR, understood as an integrated water resources management (IWRM) technique. Examples from more than ten countries demonstrate MAR as a climate change adaptation mechanism (no regret technique) towards securing long-term groundwater availability. It also facilitates the transmission of water throughout an aquifer to users' wells; a reduction in pumping energy costs due to higher groundwater levels; and, in karst areas, can assist flood mitigation by infiltrating water to the aquifer, thereby increasing the concentration time of the storm and reducing erosion.

Another major motivation to conduct MAR is the fact that the water quality of the source water generally improves during subsurface passage. Bank filtration for drinking water production is discussed in several papers in this special issue. These cover aspects from studies of passive removal of organic chemicals, modifying mixing of waters by adjusting pumping rates, and efforts to differentiate unintentional bank filtration from other groundwater supplies for managing water quality risk. Several studies mentioned MAR in the form of hydraulic barriers to prevent saltwater intrusion, and one used reactive organic-rich layers placed at the bottom of intermittent infiltration basins to accelerate degradation of constituents of recycled water.

To date, less in the spotlight are the benefits of MAR for environmental protection and restoration. Examples herein show that MAR may increase streamflow by increased groundwater discharge to adjacent rivers, hence decreasing water temperatures in summer to benefit a trout fishery. Moreover, wetland restoration can be achieved by increasing water levels following MAR, as shown for cases in Spain.

Mapping of aquifer suitability for MAR has used geographic information systems (GIS) with multi-criteria decision analysis (MCDA) in several areas and web-based tools are emerging aiming to simplify the process. Overlaying aquifer suitability maps with maps of water demand and water sources has allowed MAR opportunity maps to be produced. A pioneering attempt to extend these to levelised cost mapping for MAR has been included. Modelling of the historical operation of a national water grid with and without MAR has helped to define how to integrate MAR with the existing infrastructure for maximum benefit.

The enormous diversity of experience in MAR globally means that many different countries have undertaken initiatives to advance aspects of MAR. Two examples are Brazil's 500,000 Barraginhas (infiltration ponds) and the injection of highly treated recycled water into crystalline rock in Namibia for supplying drinking water. Countries with emerging and growing economies see real opportunities for making precious water supplies resilient and are moving ahead to do so at a faster pace than some countries with more established economies. A number of countries, including Mexico, Brazil and Australia, have for some time recognised the need for MAR regulations to protect aquifers. In Australia, regulations have assured sustainable operations and assisted uptake of MAR. There remain some challenges. An example is in Mexico, where existing water allocation policies give no incentive for investing in MAR to increase water supply.

Clogging, the most frequently encountered threat to successful MAR, has been addressed by a range of methods to maintain the infiltration rates and to improve water quality. In this special issue, field studies of infiltration basins and injection wells have been combined with innovative measurement methods and solutions to trial or recommend strategies. These start with problem avoidance, by improving the quality of source water, monitoring to detect and reject water with key parameters exceeded, removing residual drilling fluids and preventing air entrainment. Then small cycle improvements become the focus, such as improved practices with valves, metering, drying times and flow rates. Finally, longer-term maintenance and remedial measures such as changing the method of purging of injection wells or tillage in infiltration basins are tested and adopted.

Innovations in MAR methods and monitoring are continuously developed and implemented, and a number of very diverse approaches are presented herein. These include non-conventional methods for recharge enhancement, such as melting of ice storage and underground ice dams in semi-arid cold Mongolia, innovative MAR types for agricultural irrigation in the "open channel–underground perforated pipe–shaft–water saving irrigation system" developed for the North China plain, and new methods to monitor dynamic fluctuations in bacterial biomass at riverbank filtration sites applied in Europe.

The analyses in this special issue strongly indicate that MAR innovations will continue, as will the sharing of results, as exemplified by the following 22 papers. With increased project diversity, and changing climate leading to tighter constraints on availability of surface water and increased needs for recovery of stored water, MAR operations will themselves need to become increasingly resilient and efficient. Good monitoring of demonstration projects to improve process understanding, and good site selection, as illustrated in this special issue, will be foundational for achieving reliable MAR systems that produce resilient water supplies.

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## References

1. Fernández Escalante, E.; San Sebastián Sauto, J.; Calero Gil, R. Sites and indicators of MAR as a successful tool to mitigate climate change effects in Spain. *Water* **2019**, *11*, 1943. [CrossRef]
2. Alam, M.F.; Pavelic, P.; Sharma, N.; Sikka, A. Managed aquifer recharge of monsoon runoff using village ponds: Performance assessment of a pilot trial in the Ramganga Basin, India. *Water* **2020**, *12*, 1028. [CrossRef]
3. Soni, P.; Dashora, Y.; Maheshwari, B.; Dillon, P.; Singh, P.K. Managed aquifer recharge at a farm level: Evaluating the performance of direct well recharge structures. *Water* **2020**, *12*, 1069. [CrossRef]
4. Kruć, R.; Dragon, K.; Górski, J. Migration of pharmaceuticals from the Warta River to the aquifer at a riverbank filtration site in Krajkowo (Poland). *Water* **2019**, *11*, 2238. [CrossRef]
5. Masse-Dufresne, J.; Baudron, P.; Barbecot, F.; Patenaude, M.; Pontoreau, C.; Proteau-Bédard, F.; Menou, M.; Pasquier, P.; Veuille, S.; Barbeau, B. Anthropic and meteorological controls on the origin and quality of water at a bank filtration site in Canada. *Water* **2019**, *11*, 2510. [CrossRef]
6. Patenaude, M.; Baudron, P.; Labelle, L.; Masse-Dufresne, J. Evaluating bank-filtration occurrence in the Province of Quebec (Canada) with a GIS approach. *Water* **2020**, *12*, 662. [CrossRef]
7. Valhondo, C.; Carrera, J.; Martínez-Landa, L.; Wang, J.; Amalfitano, S.; Levantesi, C.; Diaz-Cruz, M.S. Reactive barriers for renaturalization of reclaimed water during soil aquifer treatment. *Water* **2020**, *12*, 1012. [CrossRef]
8. Van Kirk, R.W.; Contor, B.A.; Morrisett, C.N.; Null, S.E.; Loibman, A.S. Potential for managed aquifer recharge to enhance fish habitat in a regulated river. *Water* **2020**, *12*, 673. [CrossRef]
9. Sallwey, J.; Schlick, R.; Bonilla Valverde, J.P.; Junghanns, R.; Vásquez, F.L.; Stefan, C. Suitability mapping for managed aquifer recharge: Development of web-tools. *Water* **2019**, *11*, 2254. [CrossRef]
10. Dahlqvist, P.; Sjöstrand, K.; Lindhe, A.; Rosén, L.; Nisell, J.; Hellstrand, E.; Holgersson, B. Potential benefits of managed aquifer recharge on the island of Gotland, Sweden. *Water* **2019**, *11*, 2164. [CrossRef]

11. Knapton, A.; Page, D.; Vanderzalm, J.; Gonzalez, D.; Barry, K.; Taylor, A.; Horner, N.; Chilcott, C.; Petheram, C. Managed aquifer recharge as a strategic storage and urban water management tool in Darwin, Northern Territory, Australia. *Water* **2019**, *11*, 1869. [CrossRef]
12. Maréchal, J.-C.; Bouzit, M.; Rinaudo, J.-D.; Moiroux, F.; Desprats, J.-F.; Caballero, Y. Mapping economic feasibility of managed aquifer recharge. *Water* **2020**, *12*, 680. [CrossRef]
13. Lindhe, A.; Rosén, L.; Johansson, P.-O.; Norberg, T. Dynamic water balance modelling for risk assessment and decision support on MAR potential in Botswana. *Water* **2020**, *12*, 721. [CrossRef]
14. Ebrahim, G.; Lautze, J.; Villholth, K. Managed aquifer recharge in Africa: Taking stock and looking forward. *Water* **2020**, *12*, 1844. [CrossRef]
15. Shubo, T.; Fernandes, L.; Montenegro, S.G. An overview of managed aquifer recharge in Brazil. *Water* **2020**, *12*, 1072. [CrossRef]
16. Cruz-Ayala, M.B.; Megdal, S.B. An overview of managed aquifer recharge in Mexico and its legal framework. *Water* **2020**, *12*, 474. [CrossRef]
17. Dillon, P.; Page, D.; Vanderzalm, J.; Toze, S.; Simmons, C.; Hose, G.; Martin, R.; Johnston, K.; Higginson, S.; Morris, R. Lessons from 10 years of experience with Australia's risk-based guidelines for managed aquifer recharge. *Water* **2020**, *12*, 537. [CrossRef]
18. Negev, I.; Shechter, T.; Shtrasler, L.; Rozenbach, H.; Livne, A. The effect of soil tillage equipment on the recharge capacity of infiltration ponds. *Water* **2020**, *12*, 541. [CrossRef]
19. Stuyfzand, P.J.; Osma, J. Clogging issues with aquifer storage and recovery of reclaimed water in the brackish Werribee aquifer, Melbourne, Australia. *Water* **2019**, *11*, 1807. [CrossRef]
20. Liu, S.; Wang, W.; Qu, S.; Zheng, Y.; Li, W. Specific types and adaptability evaluation of managed aquifer recharge for irrigation in the North China Plain. *Water* **2020**, *12*, 562. [CrossRef]
21. Narantsogt, N.; Mohrlok, U. Evaluation of MAR methods for semi-arid, cold regions. *Water* **2019**, *11*, 2548. [CrossRef]
22. Adomat, Y.; Orzechowski, G.-H.; Pelger, M.; Haas, R.; Bartak, R.; Nagy-Kovács, Z.Á.; Appels, J.; Grischek, T. New methods for microbiological monitoring at riverbank filtration sites. *Water* **2020**, *12*, 584. [CrossRef]