Advances in multi-stage planning and implementing managed aquifer recharge for integrated water management

Peter Dillon [1], Paul Pavelic [2], Adriana Palma Nava [3] and Weiping Wang [4]

[1] CSIRO Land and Water and NCGRT, Flinders University of S.A., Australia pdillon500@gmail.com

[2] International Water Management Institute, Vientiane, Laos p.pavelic@cgiar.org

[3] National Autonomous University of Mexico (UNAM) , Mexico City, Mexico APalmaN@iingen.unam.mx

[4] University of Jinan, China wangweipingwwp@126.com

Dillon, P., Pavelic, P., Palma Nava, A. and Weiping, W. (2018). Advances in multi-stage planning and implementing managed aquifer recharge for integrated water management. Sustainable Water Resources Management 4(2) 145-151. https://doi.org/10.1007/s40899-018-0242-8 This is the final accepted manuscript in author-provided format freely available at IAH-MAR web site https://recharge.iah.org with permission of Springer.
This paper introduces and overviews the other 18 papers in this Special Issue of Sustainable Water Resources Management Vol 4 Issue 2 June 2018, on "*Managed Aquifer Recharge in Integrated Water Resources Management*".
Papers were initially presented at ISMAR9 Mexico City, June 2016 and subsequently revised and extended to form this special issue.

Abstract: Managed aquifer recharge (MAR) is the umbrella term for a range of technologies that enable the integrated use and management of surface water and groundwater to achieve a wide and growing range of social, economic and environmental benefits. The extent and variety of its applications and benefits have mushroomed in recent years as demonstrated in the suite of papers contained within this Special Issue of Sustainable Water Resources Management. This paper introduces the Special Issue and draws together some insights arising from the findings of these papers. Managed aquifer recharge projects normally evolve through a development cycle that covers planning, investigations, pilot scale trials and then implementation of full-scale projects. This Special Issue starts with four papers that synthesize information from a large number of MAR sites, to demonstrate the scope and geographic distribution of international efforts in MAR, factors affecting the economics of MAR projects, and efforts to find metrics to compare their performance among sites and over time. Then there are four papers describing some significant and widely contrasting completed MAR projects in four continents covering their development, what has been learned and some operational issues. Given this context, the next five papers explore the implementation and evaluation of pilot projects in three countries. These papers address issues ranging from hydrogeological characterization, evaluating impacts on groundwater dependent ecosystems to community participation. All papers to this point give context to the final five papers that show the planning and preliminary studies performed to select MAR sites, to design pilot projects or to explore the feasibility of large-scale MAR programs. Arranging the sequence of papers in this way is intended to yield an understanding of the need for the investigations and modelling in order to produce viable projects, and to help readers to consider some important practical questions. What steps are needed for any given project to: define objectives; build partnerships; engage with communities; assemble evidence of technical viability, sustainability and safety; secure funding; design and construct efficiently; streamline operations; and finally to monitor the extent to which a completed project met its goals? These papers were developed out of a broader selection of papers presented at the 9th International Symposium on Managed Aquifer Recharge (ISMAR9), Mexico City, June 2016. They are a companion to another Special Issue arising from ISMAR9, published in the journal Water on the complementary theme "Water Quality Considerations for Managed Aquifer Recharge Systems" edited by Prof. Dr. Pieter Stuyfzand and Dr. Niels Hartog (2017). These Issues are a contribution of the International Association of Hydrogeologists Commission on Managing Aquifer Recharge (IAH-MAR) to the advancement and dissemination of knowledge for wise application of MAR.

Keywords: integrated water management; aquifer storage and recovery; seasonal and long term water storage; ASR wells; managed aquifer recharge

1. Introduction

There is a broad range of purposes for Managed Aquifer Recharge (MAR) as illustrated in this Special Issue. Papers here address: water quality improvement for drinking water supply in Finland and India; enhancement of groundwater storage for irrigation supplies in India; restoration of depleted aquifers and security against drought for urban water supplies in the USA, Portugal and Spain; preservation of groundwater dependent ecosystems stressed by irrigation in NZ and USA; flood water harvesting for productive use in India and Mexico; storage of recycled wastewater for irrigation in Mexico, Spain and Portugal, and for drinking water supplies in Namibia. In addition to a range of purposes, there is also a range of types of MAR described in this Special Issue:; streambed recharge structures, river bank and esker filtration, surface water spreading, and recharge wells. Types of water used for recharge include lake and river water, recycled water and urban stormwater. The types of aquifers used for storage or treatment in this issue cover alluvial, fluvio-glacial, fractured rock and karstic, and include unconfined and confined aquifers. **Table 1** summarises these attributes for the MAR projects and investigations reported in this Special Issue. These follow the order in which papers appear, starting with multi-site assessments, descriptions of individual operating projects, trials and pilot projects, and preliminary investigations.

Table 1. Summary of papers in special issue in relation to stage of development of project, purpose, method, source water, and location, with a keyword descriptor of main focus.

	Paper	Purpose	Method	Water type	Aquifer	Country	Prime focus
M	Stefan & Ansems	all	all	all	all	62 countries	inventory
M	Bonilla *et al.*	many	all	many	many	Latin America+ Caribbean	inventory
M	Ross and Sunail	many	all except RBF	many	many	USA, Aust, NL, NZ, India	economics
M	San-Sebastian *et al.*	many	water spreading & wells	natural, recycled	many	Portugal and Spain	descriptions of 7 sites and comparisons of effectiveness
O	Murray *et al.*	drinking water	well injection	natural and recycled	hard rock	Namibia	describes development process and results
O	Tanttu & Jokela	drinking water	water spreading and wells	lake water	fluvio-glacial esker	Finland	water quality improvement
O	Sandhu *et al.*	drinking water	river bank filtration	river water	alluvium	India	flood impacts on water safety
O	Humberto *et al.*	irrigation	water spreading	recycled water	alluvium	Mexico	modelling to identify impacts
T	Lluria *et al.*	drinking water	well injection	lake water	hard rock	USA (Arizona)	hydrogeological characterisation
T	Scherberg *et al.*	environmental flow and irrigation	water spreading	river water	alluvium	USA (Oregon)	modelling to assess impacts of expansion options
T	Painter	environmental flow and irrigation	water spreading	river water	alluvium	New Zealand	modelling and trial to assess impacts of options
T	Dashora *et al.*	irrigation & drinking water	streambed recharge structure	river water	hard rock	India	method for farmers to quantify recharge
T	Jadeja *et al.*	irrigation & drinking water	streambed recharge structure	river water	hard rock	India	community engagement to manage aquifer including MAR
P	Chinnasamy *et al.*	irrigation & domestic	well drainage	river water	alluvium	India	flood harvesting to replenish aquifer and reduce floods
P	Mäkinen *et al.*	drinking water	well injection	lake water	fluvio-glacial esker	Finland	hydrogeological characterisation and modelling to design MAR
P	Wurl and Imaz-Lamadrid	irrigation & avoid salinity	water spreading	river water	alluvium	Mexico	calibrate models to design system
P	Palma Nava *et al.*	irrigation	water spreading	recycled water	alluvium	Mexico	development of a pilot project
P	Sallwey *et al.*	drinking water	water spreading	river water	alluvium	Germany	unsaturated zone modelling to design a MAR experiment

M = multi site assessment; O = operating project; T = implementation and evaluation of trial/pilot;
P = planning and preliminary studies required to select or design pilot projects

2. Planning and implementing MAR projects

2.1 Synthesis from multiple sites

In every case these papers describe MAR projects that involve integrated management of surface water and groundwater resources, where excess surface water of some type is intentionally stored in aquifers either for water quality improvement before use, for increasing or sustaining supplies during dry periods, or for sustaining groundwater dependent ecosystems. Although there is a diversity of projects, they together affirm some basic messages that will be valuable to those contemplating MAR for the first time.

Firstly, any new MAR project developer is not alone. There are a host of projects undertaken around the world, with at least 1200 so far reported by Stefan and Ansems (2018) from 62 countries across all inhabited continents, as part of the outcomes of an IAH-MAR Global MAR Inventory working group. Information on each project is available on the MAR Portal (IGRAC 2018) that can be searched for attributes (purpose, water type, aquifer type, method, country) relevant to an intended project, to reveal existing experience. Considerably more information is available for MAR projects in Latin America and the Caribbean (Bonilla Valverde *et al.* 2018) that are also reported on the IGRAC MAR Portal. Among the 340 Mm^3/yr MAR reported almost half was in Mexico. Novel examples described were more than 50,000 small recharge structures in north east Brazil, stormwater injection wells in Cuba and injection for subsidence control in Mexico City. Increasing the information on projects on the MAR Portal would be most valuable particularly for attribute combinations that are currently missing or low in number, or in countries sparsely represented. Operators of such projects are encouraged to upload basic information on the brief proforma found on the MAR Portal.

Information on the economics of MAR on a site specific basis has been difficult to find in the past and Ross and Hasnain (2018), as part of an IAH-MAR working group on Economics of MAR, have assembled information on costs for 21 suites for which data were available. An important part of Ross and Hasnain's contribution is to lay out a pragmatic framework to allow consistent evaluation of costs appropriate for water supply or water banking types of projects. Several other papers as shown in Table 2 also provide cost information for specific projects. As stated by Ross and Hasnain, further work is needed to establish the benefit – cost ratio for MAR projects, and comparisons with regard to alternative water management projects that have equivalent impacts would be useful.

San-Sebastian *et al*. (2018) set out on an ambitious task to characterise and benchmark seven varied MAR projects in Portugal and Spain. Two Spanish projects had data for 13 years and one for 6 years and the four Portuguese sites were up to 2 years old. The attributes of each of the seven sites are systematically documented to give a description of their design, volumes recharged, means of operation, water quality status, capital and operating costs and energy use. Due to very large differences between site operations it was difficult to find metrics for meaningful benchmarking of the relative performance of sites. However one parameter, mean annual infiltration rate, was found to be a very valuable diagnostic at each site on rate of clogging and need for remediation. Low capital costs and low energy consumption were found, which would help favour MAR, but no alternatives to MAR were considered in benchmarking.

2.2 Reflections on Operational Experience

The next four papers describe four operational sites each of which has more than ten years history. Murray *et al.* (2018) describe the investigations and progress made in expanding a MAR scheme to secure drinking water supplies for Windhoek, the capital of Namibia. This uses a combination of natural water and advance-treated recycled water before injecting about 0.5 Mm^3/yr in complex fractured quartzite aquifers. This case was shown to be much more economic than alternative supplies and novel institutional arrangements were established to support sustainable operations. This project has been operating effectively since 2006.

Tanttu & Jokela (2018) describe the use of fluvio-glacial deposits to remove natural organic matter and reduce temperature variations of lake water before supplying drinking water in Finland. One month of residence time in the aquifer is sufficient to improve the quality for use. Basins, sprinklers, and injection wells are compared as alternative recharge systems. The issue of managing enriched levels of iron and manganese in recovered water is addressed, and demonstrates a sustainable, economic solution.

Riverbank filtration is a practical low cost way to improve the quality of river water for drinking water supplies and Sandhu *et al.* (2018) report typically 3 to 4-log removal of *E. coli* at riverbank filtration sites in India. However their paper focuses on a periodic operational problem of safety of water supplies from a riverbank filtration site adjacent a tributary of the River Ganges at Srinagar, Uttarakhand, India. Their work reveals that short-circuiting occurs in floods when bank filtration wells on the floodplain are submerged, in spite of the best efforts to prevent flood water entry. They suggest that shock chlorination is unlikely to be effective and that such wells need to be disconnected from the supply during flood.

The final paper in this set on operational MAR sites describes ten years of experience in recharging reclaimed water via soil aquifer treatment at San Luis Rio Colorado in north-west Mexico. Humberto *et al.* (2018) record the water quality in ambient groundwater, the recycled water in the recharge pond and groundwater at various depths, and illustrate that the reported parameters are continuously within the regulatory requirements for Mexico and that the treatment rate is being sustained. They also demonstrate that limiting the total suspended solids concentrations in pond water and restricting the pond water depth to 0.3 m, together with periodic scraping or disking of basins has been effective in reducing the rate of clogging to a manageable level.

2.3 Implementation and evaluation of trials or pilot sites

The next set of five papers describe implementation and evaluation of trials or pilot sites. Lluria *et al.* (2018) describe the investigations that have enabled the locations for a mix of injection-only and aquifer storage and recovery wells to be determined that optimise the storage of surface water in a fractured granitic aquifer in central Arizona. Injection rates exceeded recovery rates due to fractures above the water table. This provides a good example of the value of characterising the aquifer well and being able to use that information for optimising the design of a system to recharge almost 4 Mm^3/yr.

The next two papers by Scherberg *et al.* (2018) and Painter (2018) describe schemes in temperate irrigated plains in Oregon USA and Canterbury NZ where seasonal groundwater-dependent streamflow is vital for aquatic ecosystems. In each location, irrigation with surface water and groundwater occurs. Irrigation canals are being lined to prevent leakage and reduce surface water diversions. However, this also reduces recharge to the alluvial aquifer and base flow. Hence infiltration basins are being introduced in strategic locations to boost environmental flows to groundwater-dependent streams. The aim in both cases is to site MAR structures to allow optimum conjunctive use of groundwater and surface water for irrigation while still protecting ecosystems. Scherberg *et al.* (2018) focuses on modelling of the surface water and groundwater system to optimise the scale and locations for MAR, based on expanding an existing 11 Mm^3/yr scheme. Painter (2018) also uses a model but the thrust of the paper is on understanding the water quality requirements and engaging with the community to more clearly define the project objectives. Initial field testing results suggest MAR could be an effective way to meet the groundwater dependent ecosystem requirements.

The next pair of papers are set in a semi-arid area of Rajasthan where check dams have been constructed in ephemeral stream beds for more than 30 years to harvest monsoon runoff allowing time for water to infiltrate and replenish a hardrock aquifer that supports irrigated agriculture. Dashora *et al.* (2018) evaluates recharge from four check dams over two years using a simple water balance method based on farmer measurements of daily water levels. Dashora *et al.* (2018) also reviewed published studies of almost 30 check dams and compared results in relation to hydrological variables. Jadeja *et al.* (2018) explored participatory approaches to groundwater management in India, explaining the capacity building program with farmers that enabled Dashora *et al.*'s work, and also provided rainfall data and detailed information on groundwater levels. That project, under the title Managed Aquifer Recharge and Village-level Interventions (MARVI) (Maheshwari *et al* 2014) helped farmers to interpret and share the information with the local village communities and form groundwater cooperatives to manage their use of groundwater, and assist in ensuring maintenance of streambed recharge structures, and improve linkages with catchment and water resources management programs.

2.4 Approaches to planning and preliminary studies

The final set of five papers involve planning and preliminary studies performed to select MAR sites, to design pilot projects or to explore the feasibility of extensive MAR programs. The first of these, by Chinnasamy *et al.* (2018), describes linking of hydrologic, groundwater and flood inundation models to estimate the potential impact of widespread recharge of floodwaters in the ~19,000 km^2 Ramganga river basin, a sub-basin of the River Ganges, India. The modelling revealed that if implemented, this could have significant benefits in restoring a depleted aquifer, would substantially mitigate peak flood flows and would increase base flows in the river. A field demonstration project at local level has subsequently commenced to enable ground-truthing and subsequent scale up if successful.

At a contrasting scale, Mäkinen *et al.* (2018) present the results of a field study over a 30 km^2 area of Finland where detailed characterisation of the esker depositional environment was required to refine the design of an aquifer storage transfer and recovery project (that is, with separated injection and recovery wells) in glacio-fluvial deposits to improve water quality (as discussed by Tanttu & Jokela 2018). Observation wells, geophysics, remote sensed temperature data for groundwater springs, and a 9 month tracer test were used to support refined groundwater modelling. This revealed a bifurcating flow path between injection and recovery with bi-modal travel times. As a result, the recharge site was relocated to produce a simpler to manage system.

Wurl and Imaz-Lamadrid (2018) address the design of a runoff harvesting system consisting of 4 dams upstream on different rivers with releases into stream beds and infiltration dams to augment recharge by more than 20 Mm^3/yr to help sustain levels and water quality in a 724 km^2 irrigation area in Baja California, western Mexico. Initially, the paper focuses on the model and its calibration, using data from soil texture analysis from 554 farms. Next, 8 sites were selected for hydraulic testing by drilling and coring for hydraulic tests leading to selection of 4 sites for recharge. The groundwater model, calibrated on monitored groundwater levels and known rates of groundwater extraction revealed that the recharge operation would help sustain the central Santo Domingo Valley and would slow but not prevent saline coastal saline intrusion due to excessive groundwater extraction.

The last two papers involve the application of an unsaturated porous media model as part of the design of pilot scale infiltration basins. Palma Nava *et al.* (2018) described the preliminary investigations required to establish a trial for recharge with recycled water via soil aquifer treatment to help sustain the depleting groundwater supply for the city of Chihuahua in northern Mexico. The site characterisation depends on surface geophysics using vertical electrical soundings and the lithology derived from a well. This was used in an unsaturated flow model (VS2DTI) to predict the results of a future infiltration basin trial and hence to design the trial and its monitoring regime. Water quality analyses as required under Mexican guidelines for recharge of recycled water, when completed would enable either approval for the trial with monitoring or require further treatment before such approval is given. Sallwey *et al.* (2018) also undertook unsaturated zone modelling (with HYDRUS3D) to assist with the design of a very small scale infiltration test. This was valuable in determining the timing and spatial distribution of vertical water flux at a depth corresponding with the water table under different potential operating regimes. They also used the model to explore the best locations for field monitoring equipment. Importantly, this paper also reviews a number of approaches to unsaturated zone modelling at MAR infiltration sites and probes the strengths and weaknesses of models for such applications.

3. Conclusions on planning and implementing MAR projects

Numerous MAR project implementers have reported on issues and information gaps that need to be addressed or would be helpful to know at various stages in establishing managed aquifer recharge projects. In this Special Issue, each paper, as discussed above, makes a contribution to the body of knowledge that helps fill these gaps, as shown in **Table 2**. This table may be used as a directory to help find information on issues most important to developers and regulators of future MAR projects.

Table 2. Contributions of the papers in this special issue with respect to information perceived to advantage the uptake of MAR.

Information that advantages uptake of MAR	**Papers addressing**	**Contribution**
Awareness of the scope and breadth of MAR	Stefan and Ansems Bonilla Valverde *et al*	Global inventory Latin America & Caribbean inventory and info
Information on the economics of MAR	Ross and Hasnain San-Sebastian *et al.* Humberto *et al.* Tanttu and Jokela Lluria *et al.*	Costs evaluated at 21 sites Costs evaluated at 7 sites Infiltration basin costs Esker water treatment costs Costs estimated for well vs basin recharge
Information on examples of established MAR projects	Murray *et al.* Tanttu and Jokela Humberto *et al.* San-Sebastian *et al.*	Strategic water replenishment for Windhoek Effective esker treatment of drinking water Finland 10 years' experience recharging recycled water Descriptions of seven operational sites in Europe
Awareness of models for community engagement	Dashora *et al*. Jadeja *et al.* Painter	Community participation in MAR monitoring Community participation in all aspects of groundwater management, including MAR
Awareness of models for institutional arrangements for MAR	Murray *et al.*	Agreement between partners established to give water security and buffer variability of income.
Hydrogeological information at the local scale	Mäkinen *et al.* Lluria *et al.* Murray *et al.*	Hydrogeological investigations to define flow field Identify target aquifer and best recharge well sites Identify competent strategic storage zones
Information to predict recoverability of stored water	Mäkinen *et al.* Lluria *et al.* Sallwey *et al.*	Investigations and modelling to revise MAR design Investigations and modelling to revise MAR design Modelling to refine design and predict fate of recharge water
Information on availability of water for recharge	Wurl and Imaz-Lamadrid Dashora *et al*.	Modelling to estimate capture volumes and design MAR Monitoring to estimate river water available for recharge
Awareness of clogging of infiltration surface or wells and how to manage it	San-Sebastian *et al.* Humberto *et al.*	Clogging rates defined at several surface recharge sites Clogging rate defined for basins
Awareness of risk management to prevent groundwater contamination*	San-Sebastian *et al.* Humberto *et al.* Sandhu *et al.* Palma Nava *et al.*	Pathogen removal data, organics removal Coliform bacteria removal Monsoonal flooding contaminates wells Follows Mexican regulations for infiltrating recycled water
Knowledge of impacts of MAR on connected surface water systems	Scherberg *et al.* Painter Chinnasamy *et al.*	Modelling approach to inform options Modelling and trial to assess impacts Modelling to assess scale and impacts

* *Stuyfzand and Hartog (eds) (2017), also a special issue from ISMAR9, focuses on water quality aspects of MAR operations.*

Each paper has been briefly discussed above, and although these papers cover a wide range of situations and stages of implementation there are some common threads. Projects proceed from a concept to on-the-ground reality by a sequence of steps to validate the concept, select sites, allow practical demonstration to win community and regulator support, prove economic viability, and to learn how to monitor, manage and regulate projects to ensure they are sustainable. These steps may take considerable time, especially for projects that have great strategic value or have high perceived risk. In cases such as Windhoek (Murray *et al.* 2018), it has taken a decade to confidently produce crucial strategic reserves in complex geology. A key message is to start investigations well before the MAR project is actually needed to provide the necessary confidence that it will perform as required.

The importance of aquifer characterisation stands out in the completed projects. Wherever geology is complex, such as for heterogeneous aquifers, fractured hardrock aquifers, karstic aquifers, in or near fault zones, where aquitards are thin and variable, where basements are contorted, boundaries are unknown, stream-aquifer interaction occurs or aquifers contain water of variable or poor water quality, the attention to understanding groundwater dynamics needs to be considerably greater than for simpler settings. This may require multiple lines of evidence such as drilling and coring, geophysics, aquifer pumping tests, piezometers, hydrochemical, isotope and tracer studies and modelling to gain an adequate understanding of the storage or treatment zone. This will be needed to determine the capacity of the aquifer to accept water, the rate at which water may be stored, the fate of stored water and the ability to recover it in the short and long term and the uncertainty associated with these estimates.

As scientific and technical methods and knowledge advance it is anticipated that the future key issues may shift. Institutional arrangements, and community engagement will become increasingly important for integrated water management and are touched on by several papers here. Governance arrangements for MAR such as entitlements to water for recharge, to storage space in aquifers and to recover water are also expected to become increasingly important as demand grows. Uptake of frameworks to do this (such as Ward and Dillon 2011) has been slow and not addressed in this special issue, but will be needed to accelerate to address cumulative impacts of proximal MAR projects, and to embed MAR as a tool in conjunctive management of water resources (Evans and Dillon 2018) as called for in the ISMAR9 Call to Action: Sustainable Groundwater Management Policy Directives (Parker and Villarreal 2016).

Acknowledgements

The Guest Editors thank the authors and reviewers of all manuscripts evaluated for this Special Issue for their valuable contributions. We are grateful to the Organising Committee of ISMAR9 for making possible this enduring record by allowing a selection of papers to be extended, reviewed and accepted into this Special Issue. We also thank the publisher Springer for inviting us to produce this Special Issue. We are grateful that Springer has given permission to IAH-MAR to publish all final papers in the author-provided format on the IAH web site https://recharge.iah.org/thematic-issues-journals where they can be downloaded freely for the foreseeable future. This URL also links to other MAR thematic issues of journals which have open access status.

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