Water **2015**, *7*, 592-598; doi:10.3390/w7020592

OPEN ACCESS

water

ISSN 2073-4441

www.mdpi.com/journal/water

Editorial

Policy and Economics of Managed Aquifer Recharge and Water Banking

Sharon B. Megdal [1,*] and Peter Dillon [2]

[1] Water Resources Research Center, The University of Arizona, Tucson, AZ 85719, USA

[2] CSIRO Land and Water Flagship, Glen Osmond, SA 5064, Australia;
E-Mail: pdillon500@gmail.com

* Author to whom correspondence should be addressed; E-Mail: smegdal@email.arizona.edu;
Tel.: +1-520-621-9591; Fax: +1-520-892-8518.

Academic Editor: Miklas Scholz

Received: 6 January 2015 / Accepted: 29 January 2015 / Published: 9 February 2015

Abstract: Managed Aquifer Recharge (MAR) and water banking are of increasing importance to water resources management. MAR can be used to buffer against drought and changing or variable climate, as well as provide water to meet demand growth, by making use of excess surface water supplies and recycled waters. Along with hydrologic and geologic considerations, economic and policy analyses are essential to a complete analysis of MAR and water banking opportunities. The papers included in this Special Issue fill a gap in the literature by revealing the range of economic and policy considerations relevant to the development and implementation of MAR programs. They illustrate novel techniques that can be used to select MAR locations and the importance and economic viability of MAR in semi-arid to arid environments. The studies explain how MAR can be utilized to meet municipal and agricultural water demands in water-scarce regions, as well as assist in the reuse of wastewater. Some papers demonstrate how stakeholder engagement, ranging from consideration of alternatives to monitoring, and multi-disciplinary analyses to support decision-making are of high value to development and implementation of MAR programs. The approaches discussed in this collection of papers, along with the complementary and necessary hydrologic and geologic analyses, provide important inputs to water resource managers.

Keywords: managed aquifer recharge; water banking; groundwater; water scarcity; water policy; multi-disciplinary analyses; water resources management; decision-making; economics

1. Introduction

There is growing recognition of the importance of groundwater and aquifer health to meeting future water needs, as well as the crucial role for strong institutional and governance frameworks for water resources management. Managed Aquifer Recharge (MAR) is defined as the "intentional banking and treatment of waters in aquifers" [1]. The papers in this Special Issue of *Water*, entitled Policy and Economics of Managed Aquifer Recharge and Water Banking, demonstrate that MAR, which includes what is commonly referred to as water banking [2], is being utilized to buffer against drought and changing or variable climate, as well as provide water to meet growth in demand, by making use of intermittent excess surface water supplies and recycled waters. The papers, which are broad in their coverage of geography and methodologies, have been assembled to highlight how economic and policy considerations are being and/or can be incorporated into decision-making regarding deployment of MAR programs. The information and analyses demonstrate the breadth and complexity of issues that enter into MAR-related water resources management decision-making and provide information on the usefulness of MAR programs to meeting water policy objectives. We believe this is the largest collection of papers to date covering the economic and policy aspects of MAR and water banking.

The papers in this Special Issue can be seen as falling into four groupings: Economic and policy analyses for meeting water management objectives; Evaluation of MAR using alternative methodologies; Utilization of MAR for wastewater reuse in arid regions; Approaches to stakeholder engagement and monitoring. The following section summarizes the individual contributions following this grouping. The papers should be consulted for the details and rich list of references.

2. Contributions

Robert Maliva's paper, "Economics of Managed Aquifer Recharge," [3] serves as a primer on economic analysis, such as cost-benefit analysis including net present value methodology for assessing the economic feasibility of MAR systems. Concerning costs, Maliva claims that for drinking water supplies typical MAR costs are half the costs of brackish water desalination. He postulates that the primary sources of uncertainty are associated with monetizing the benefits of MAR. Hence the paper explains how the beneficial value of water stored or treated by MAR systems can be evaluated using direct and indirect measures of willingness to pay. These include; market price, alternative cost, marginal product value, damage cost avoided, contingent value methods, defensive (insurance) value and environmental value of *in-situ* groundwater. Drawing on the literature, Maliva also discusses the financing of MAR storage systems in relation to the benefits that accrue to a broad range of beneficiaries beyond those who subsequently withdraw banked water. Options for funding MAR projects will depend on the sector utilizing the stored water as well as the financial means of the jurisdiction contemplating investing in a MAR system.

The paper by Megdal, Dillon and Seasholes, "Water Banks: Using Managed Aquifer Recharge to Meet Water Policy Objectives," [2] focuses on how Arizona in the United States of America has deployed a large water banking program to store and recover water in anticipation of cutbacks in surface water supplies due to climate variability (droughts). Arizona has been able to rely on a strong legislatively-authorized and advanced groundwater storage and recovery program. A special state agency, the Arizona Water Banking Authority was established to carry out the water banking program, and has recharged 4 billion m^3 in 18 years. The Arizona Department of Water Resources, another state agency, oversees regulatory compliance and accounting. The paper discusses both water policy achievements and challenges and explores conditions under which a similar water banking approach could be implemented in other areas. The authors assert that a functioning groundwater entitlement system is a prerequisite for security of investment in water banking. They also illustrate means by which existing water infrastructure may be integrated in water banking to compensate for aquifers that are not as ideal as those used for water banking in Arizona. This suggests considerable potential for application of water banking in Australia and elsewhere by learning from and adapting Arizona's innovative policies and institutions.

A series of four papers demonstrates advances in evaluating the economics and feasibility of MAR systems. The paper, "The Economics of Groundwater Replenishment for Reliable Urban Water Supply," by Gao, Connor and Dillon [4] explores the potential for banking recycled water through a MAR program in Perth, Australia to meet increased water demand in an area subject to a drying climate. The authors explore a simplified case study using a Monte Carlo analysis with embedded Markov model and optimization algorithm to show that using aquifers to store water can help this urban community have "supply insurance" for drought conditions at considerably lower cost than other water supply alternatives, such as seawater desalination. They are careful to point out that actual costs savings and supply reliability will depend on aquifer conditions, including freshwater storage depreciation rate, which affect the ability to recover water, and for which they perform a sensitivity analysis. They demonstrate the economic efficiency of water banking with recycled water in an aquifer used for urban water supply and since publication, a US$100M first stage project for groundwater replenishment has been approved based on substantial investigations.

The paper, "Economic Assessment of Opportunities for Managed Aquifer Recharge Techniques in Spain Using an Advanced Geographic Information System (GIS)," by Escalante, Gil, Fraile and Serrano [5] addresses the whole of Spain. The authors report the results for their "DINA-MAR" project in which they evaluate a large geographic area using 23 GIS layers of physiographic features, which included geology, topography, land use, and water sources. They evaluate characteristics of existing MAR sites to "train" a model then use the attributes of the GIS layers to determine the potential for MAR. This part of their work concludes that there are significant MAR storage opportunities in 13% of the ~500,000 km^2 area studied and that this additional storage capacity is more than 2.5 times the total capacity of existing surface water dams in Spain. Additionally, the paper used GIS analysis to estimate the expected capital costs per unit volume of recovered water of the most appropriate type of MAR in each identified prospective zone. Again the model was trained on economic information and attributes of existing MAR sites and the resultant range of capital costs (Euro 0.08–0.58/m^3/year) is expected to provide economic information useful for decision-makers on implementing MAR for water supplies on the Iberian Peninsula and Balearic Islands of Spain.

Moving to another part of the world, Niazi, Prasher, Adamowski and Gleeson in their paper, "A System Dynamics Model to Conserve Arid Region Water Resources through Aquifer Storage and Recovery in Conjunction with a Dam," [6] rely on a systems dynamics approach to modeling. They examine the potential in the Sirik region of Iran to use aquifer storage and recovery to minimize evaporation losses and aquifer depletion while expanding agricultural activities and show that ASR, in conjunction with water storage on an ephemeral river, provided benefits to farmers and the groundwater system. Groundwater depletion declined and evaporation from the reservoir was reduced. They conclude that a systems dynamics model, consisting of a stocks and flow model of the conjunctive water system, coupled with a finite difference model of the groundwater system and cost benefit analysis reveal the hydrologic and economic performance of alternative ASR options. The analysis considers economic factors, the quantity of water available for environmental flows, the quantity of water to be released from spillways, as well as social acceptability. This information can assist decision-makers in identifying opportunities to utilize MAR in conjunction with surface storage to conserve water resources and reduce groundwater depletion particularly in arid and semi-arid regions facing uncertainty associated with climate change.

The fourth paper addressing alternative methodologies for evaluating MAR is "Assessing the Feasibility of Managed Aquifer Recharge for Irrigation under Uncertainty," by Arshad, Guillaume, and Ross [7]. They perform a cost-benefit analysis to compare the economics of harvesting occasional high surface water flows in either shallow surface storages (as is current practice in the Namoi Valley, Australia) or in the underlying unconfined aquifer via either infiltration basins or aquifer storage and recovery wells. In each case the stored water is used for irrigation of commercial crops, such as cotton and faba bean. Although more than 35% of water in surface storages is lost due to evaporation, there are high levels of uncertainty on infiltration rates in basins, recoverability of stored water and financial variables used in analyses. They offer a methodology to assess the financial feasibility of MAR under uncertainty, which provides thresholds for several key variables (including infiltration rate and pumping cost) denoting cross-over points in break-even analysis, where MAR and surface storage have equal financial returns. When applied to the Lower Namoi catchment in the Murray-Darling Basin of south-eastern Australia this indicated that infiltration basins can be more economic than surface storages where soils are permeable and pumping costs are low. Recharge wells are considered uneconomic due to costs of water treatment presumed to be required to maintain recharge rates. They conclude that their approach to modeling under uncertainty can indicate where MAR is potentially more cost-effective than surface water storage, and conversely where investment in geophysical and hydrogeological investigations may not be warranted.

Two papers in the Special Issue address wastewater reuse in arid regions. "Managed Aquifer Recharge (MAR) Economics for Wastewater Reuse in Low Population Wadi Communities, Kingdom of Saudi Arabia," by Missimer, Maliva, Haffour, Lieknes and Amy [8] compares alternative approaches to providing remote villages with water for potable and irrigation uses. They compare the costs of desalinated seawater with that of treated wastewater delivered via a MAR system. Treated wastewater can be used directly for irrigation and indirectly, after soil aquifer treatment. Implementation of a MAR reuse system enables avoidance of environmental, tourism and fishery costs associated with discharge of wastewater to marine environments. The authors indicate that avoiding these costs can more than offset the amortized cost of constructing the MAR system. They also clarify the position of Islamic Law on reuse of treated wastewater and address the issue of subsidizing village water supplies. Finding significant cost advantages associated with the MAR systems, they conclude that MAR and the reuse system can provide wadi valleys with needed water.

The second paper in this grouping is "Impact Assessment and Multicriteria Decision Analysis of Alternative Managed Aquifer Recharge Strategies Based on Treated Wastewater in Northern Gaza," by Rahman, Rusteberg, Uddin, Saada, Rabi and Sauter [9]. As suggested by the title, the analysis considers multiple factors, such in its analysis of a MAR system to utilize treated wastewater in the Northern Gaza Strip. They evaluate the impacts of three MAR reuse strategies developed in consultation with decision-makers on groundwater resources, considering agricultural, environmental, health, economic, and societal criteria. The authors find that MAR strategies improve scores in each of the four aggregated criteria, with the largest MAR system evaluated being superior in each category. A "do nothing" strategy has the worst outcomes and its net benefits decline with time reflecting current over-exploitation of groundwater with declining levels and increasing salinity. The authors tested several multicriteria methods and concluded that ranking of options was robust and suggest that the multicriteria integrated approach may also be useful for evaluating other water resources development projects.

The final four papers include a pair of papers on the San Pedro River in Arizona, USA, by the same group of authors, along with two papers addressing MAR implementation in India. They all emphasize stakeholder engagement in model formulation, selection of options and/or monitoring.

The paper, "Application of Hydrologic Tools and Monitoring to Support Managed Aquifer Recharge Decision Making in the Upper San Pedro River, Arizona, USA," by Lacher, Turner, Gungle, Bushman and Richter [10], should be read in conjunction with "Development of a Shared Vision for Groundwater Management to Protect and Sustain Baseflows of the Upper San Pedro River, Arizona, USA," by Richter, Gungle, Lacher, Turner and Bushman [11]. Together, these papers describe how a consortium has approached addressing the depleted base flow conditions along the Upper San Pedro River north of the U.S. border with Mexico. The Lacher *et al.* paper reports on how a groundwater model of the basin, prepared by the U.S. Geological Survey, served as the basis for simulations and mapping of flow capture due to pumping and stream flow restoration associated with managed aquifer recharge. The simulations showed the extent to which recharge could compensate for stress on the water table due to pumping. Combining data from 15 years of wet-dry mapping with simulation tools provided technical information useful to decision-makers attempting to balance accommodating the growing water demands of the region with continuing baseflows in the San Pedro River.

The paper by Richter *et al.* reports on the collaborative work of the Upper San Pedro Partnership (Partnership) of diverse governmental and non-governmental entities. Over a period of many years, the Partnership developed models and technical/simulation tools. The paper explains how the analysis detailed in Lacher *et al.* [10] resulted in a paradigm shift, with the partners moving to a "spatially-explicit optimization process". Based on the optimization analysis, a group of collaborators worked for several years to acquire the lands needed to accomplish strategic recharge near the river. The authors suggest the steps necessary for developing a shared vision of sustainability for integrated water management and provide a set of lessons learned from the experiences of this long-standing collaboration.

The final two papers focus on India. "The Role of Transdisciplinary Approach and Community Participation in Village Scale Groundwater Management: Insights from Gujarat and Rajasthan, India," written by Maheshwari and 23 co-authors [12], highlights the importance of effective engagement with local communities. This paper reports on work in the States of Gujarat and Rajasthan, India through the project Managed Aquifer Recharge through Village Level Intervention. The project involved developing an approach for citizen and community participation so as to improve groundwater management. Collection of hydrologic, agricultural and socioeconomic data engaged local villages and school communities in groundwater monitoring, field trials, photovoice workshops, and other educational and communication activities. Of particular importance is the participation of trained volunteer farmers in regular groundwater monitoring, plotting and facilitated interpretation of data in relation to seasonal recharge and pumping, and then explaining their findings in community meetings to provide a scientific foundation for groundwater management. After providing details for each of the two communities of focus, the authors conclude that transdisciplinary approaches can enable communities and their farmers to work with research and other partners to develop groundwater management solutions that are holistic and sustainable.

Finally, "Policy Preferences about Managed Aquifer Recharge for Securing Sustainable Water Supply to Chennai City, India," by Brunner, Starkl, Sakthivel, Elango, Amirthalingam, Pratap, Thirunavukkarasu and Parimalarenganayaki [13] analyzes water supply policy options and preferences for Chennai City, India. The authors elicit stakeholder preferences from about 25 stakeholder groups regarding MAR through infiltration ponds as a means of addressing groundwater depletion. The authors discuss the lack of legal framework for managed aquifer recharge in the periphery of Chennai, as well as the absence of a common vision. Their research indicates that there is stakeholder support for establishing an authority that would be responsible for licensing groundwater withdrawals and implementing and overseeing a MAR program.

3. Conclusions

This collection of papers demonstrates the wide-ranging opportunities for implementing Managed Aquifer Recharge programs. Taken together, the analyses of these 12 papers underscore the importance of enabling institutional and legal frameworks, careful economic and financial analysis, multi-disciplinary approaches that incorporate the necessary geophysical and hydrological information, and stakeholder/community engagement in program implementation and success. The variety of locations, water use situations, and environmental settings indicate the importance, robustness and attractiveness of MAR as an element of sustainable water management. It is intended that disseminating knowledge of MAR and water banking from policy and economic perspectives from a geographically broad range of experiences will help achieve consideration of their full potential alongside traditional options and their adoption, wherever superior.

Acknowledgments

The authors of this paper, who also served as Guest-Editors of the special issue, wish to thank the journal editors for the generosity of their time and resources, the authors of the 12 papers, and the many referees who contributed to improved versions of the published papers.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Dillon, P. Future Management of Aquifer Recharge. *Hydrogeol. J.* **2005**, *13*, 313–316.
2. Megdal, S.B.; Dillon, P.; Seasholes, K. Water Banks: Using Managed Aquifer Recharge to Meet Water Policy Objectives. *Water* **2014**, *6*, 1500–1514.
3. Maliva, R.G. Economics of Managed Aquifer Recharge. *Water* **2014**, *6*, 1257–1279.
4. Gao, L.; Connor, J.D.; Dillon, P. The Economics of Groundwater Replenishment for Reliable Urban Water Supply. *Water* **2014**, *6*, 1662–1670.
5. Escalante, E.F.; Gil, R.C.; San Miguel Fraile, M.Á.; Serrano, F.S. Economic Assessment of Opportunities for Managed Aquifer Recharge Techniques in Spain Using an Advanced Geographic Information System (GIS). *Water* **2014**, *6*, 2021–2040.
6. Niazi, A.; Prasher, S.O.; Adamowski, J.; Gleeson, T. Correction: Niazi, A., Prasher, S.O., Adamowski, J.; Gleeson, T. A System Dynamics Model to Conserve Arid Region Water Resources through Aquifer Storage and Recovery in Conjunction with a Dam. *Water* **2014**, *6*, 2300–2321. *Water* **2014**, *6*, 3957–3959.
7. Arshad, M.; Guillaume, J.H.; Ross, A. Assessing the Feasibility of Managed Aquifer Recharge for Irrigation under Uncertainty. *Water* **2014**, *6*, 2748–2769.
8. Missimer, T.M.; Maliva, R.G.; Ghaffour, N.; Leiknes, T.; Amy, G.L. Managed Aquifer Recharge (MAR) Economics for Wastewater Reuse in Low Population Wadi Communities, Kingdom of Saudi Arabia. *Water* **2014**, *6*, 2322–2338.
9. Rahman, M.A.; Rusteberg, B.; Uddin, M.S.; Saada, M.A.; Rabi, A.; Sauter, M. Impact Assessment and Multicriteria Decision Analysis of Alternative Managed Aquifer Recharge Strategies Based on Treated Wastewater in Northern Gaza. *Water* **2014**, *6*, 3807–3827.
10. Lacher, L.J.; Turner, D.S.; Gungle, B.; Bushman, B.M.; Richter, H.E. Application of Hydrologic Tools and Monitoring to Support Managed Aquifer Recharge Decision Making in the Upper San Pedro River, Arizona, USA. *Water* **2014**, *6*, 3495–3527.
11. Richter, H.E.; Gungle, B.; Lacher, L.J.; Turner, D.S.; Bushman, B.M. Development of a Shared Vision for Groundwater Management to Protect and Sustain Baseflows of the Upper San Pedro River, Arizona, USA. *Water* **2014**, *6*, 2519–2538.
12. Maheshwari, B.; Varua, M.; Ward, J.; Packham, R.; Chinnasamy, P.; Dashora, Y.; Dave, S.; Soni, P.; Dillon, P.; Purohit, R.; *et al*. The Role of Transdisciplinary Approach and Community Participation in Village Scale Groundwater Management: Insights from Gujarat and Rajasthan, India. *Water* **2014**, *6*, 3386–3408.
13. Brunner, N.; Starkl, M.; Sakthivel, P.; Elango, L.; Amirthalingam, S.; Pratap, C.E.; Thirunavukkarasu, M.; Parimalarenganayaki, S. Policy Preferences about Managed Aquifer Recharge for Securing Sustainable Water Supply to Chennai City, India. *Water* **2014**, *6*, 3739–3757.