Policy and Economics of Managed Aquifer Recharge and Water Banking

Edited by

Sharon B. Megdal and Peter Dillon

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Preface

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 growth in demand, by making use of intermittent excess surface water supplies and recycled waters. Institutions that perform the necessary permitting and monitoring are required so that a region's groundwater quantity and/or quality management can be furthered through MAR. While several jurisdictions have frameworks in place, many do not. Lack of enabling policy and governance frameworks limits the realization of MAR benefits.

Along with hydrologic and geologic considerations, economic and policy analyses are essential to a complete analysis of MAR and water banking opportunities. Yet, the peer-reviewed literature tends to focus more on the operational and physical aspects of MAR programs. We determined that the journal Water provides an excellent opportunity to publish a collection of papers on the policy, economic, and decision-making aspects of MAR and water banking. Along with the journal's announcement of an open call for papers, invitations were issued to several presenters at the Eighth International Symposium on Managed Aquifer Recharge (ISMAR8), which was held in Beijing, China in October 2013.

We are pleased to present these 12 papers, all of which were subject to peer review by at least two reviewers. They show the range of economic and policy considerations relevant to the development and implementation of MAR programs. Several papers show novel techniques that can be used to select MAR locations. The importance and economic viability of MAR to semi-arid to arid environments is evident from the use of MAR in both developed and developing regions. Papers demonstrate 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 studies explain 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.

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. 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. We thank the authors for contributing to increased understanding of MAR as a component of sound water management.

Sharon B. Megdal and Peter Dillon
Guest Editors

About the Guest Editors

Sharon B. Megdal is Director of The University of Arizona Water Resources Research Center and C.W. and Modene Neely Endowed Professor in the College of Agriculture and Life Sciences. Her work focuses on water resources management and policy, on which she writes and frequently speaks. She also holds the titles Professor, Department Soil, Water, and Environmental Science, and Distinguished Outreach Professor. Dr. Megdal places particular emphasis on how to achieve desired policy objectives in terms of institutional structures and possible changes to them. In addition to numerous articles, chapters and reports, she is the lead editor of the book, *Shared Borders, Shared Waters: Israeli-Palestinian and Colorado River Basin Water Challenges*.
Her international work involves transboundary aquifer assessment at the United States-Mexico border, evaluation of water governance and groundwater management approaches, and comparative analysis of water policy and management in water-scarce regions. She serves as an elected member of the board of directors of the Central Arizona Project, a large water conveyance project that delivers Colorado River water into Central Arizona in the USA. Sharon Megdal holds a Ph.D. in Economics from Princeton University. More information about Dr. Megdal's work can be found at http://wrrc.arizona.edu/sharon-b-megdal.

Peter J. Dillon has co-chaired the Commission on Managing Aquifer Recharge of the International Association of Hydrogeologists, since 2001. In 2014 he retired from CSIRO Land and Water where for 29 years he led research on groundwater quality protection, water recycling, stormwater harvesting and managed aquifer recharge (MAR). His team provided the scientific foundations for the Australian Guidelines for Managed Aquifer Recharge, and also to a framework for Natural Resources Management policies for MAR both of which are internationally pioneering contributions to practice. He has supervised or co-supervised 23 students including 8 PhDs. He is author or coauthor of more than 100 journal papers, he has edited or co-edited four books, and has led more than 24 short courses and workshops on MAR in more than 14 countries. His research team produced 30% of all journal papers on MAR in the last 5 years and contributed to the development of an active MAR industry in Australia. His continuing work addresses water quality barriers to water recycling for stormwater and treated sewage effluent, aquifer biogeochemical and physical processes, as well as policy and governance issues in integrated surface and groundwater management. (pdillon500@gmail.com)

Policy and Economics of Managed Aquifer Recharge and Water Banking

Sharon B. Megdal and Peter Dillon

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.

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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.

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Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 1

Economic and Policy Analyses for Meeting Water Management Objectives

Economics of Managed Aquifer Recharge

Robert G. Maliva

Abstract: Managed aquifer recharge (MAR) technologies can provide a variety of water resources management benefits by increasing the volume of stored water and improving water quality through natural aquifer treatment processes. Implementation of MAR is often hampered by the absence of a clear economic case for the investment to construct and operate the systems. Economic feasibility can be evaluated using cost benefit analysis (CBA), with the challenge of monetizing benefits. The value of water stored or treated by MAR systems can be evaluated by direct and indirect measures of willingness to pay including market price, alternative cost, value marginal product, damage cost avoided, and contingent value methods. CBAs need to incorporate potential risks and uncertainties, such as failure to meet performance objectives. MAR projects involving high value uses, such as potable supply, tend to be economically feasible provided that local hydrogeologic conditions are favorable. They need to have low construction and operational costs for lesser value uses, such as some irrigation. Such systems should therefore be financed by project beneficiaries, but dichotomies may exist between beneficiaries and payers. Hence, MAR projects in developing countries may be economically viable, but external support is often required because of limited local financial resources.

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1. Introduction

Managed aquifer recharge (MAR) is defined as "intentional banking and treatment of waters in aquifers" [1]. The term MAR was introduced as an alternative to "artificial recharge", which has the connotation that the use of the water was in some way unnatural [1]. MAR includes a great diversity of technologies to store and treat water including aquifer storage and recovery (ASR), infiltration basins, salinity barriers, soil-aquifer treatment, and riverbank filtration. The water resources management benefits of MAR are compelling. However, the question arises as to why MAR has not yet been implemented to an even greater degree. The answer often lies in that decision makers, such as water utility managers, water management agency officials, and political leaders, have not been provided an equally compelling, sound economic case for investment in the technologies.

Investments in infrastructure, whether for water or other purposes, need to be justified in terms of the benefits of the project equaling or exceeding the construction and operational costs. The costs of the projects should also be less than the costs of alternative projects that provide the same benefits. Cost–benefit analysis (CBA) can be used to evaluate MAR projects, where their costs and benefits can be accurately quantified in monetary terms. However, economic analyses of water projects are often hampered by the difficulty of accurately quantifying the value of water, which can vary greatly depending upon circumstances. Todd [2] in a pioneering paper noted with respect to the economics of groundwater recharge that "It is clear the analysis of the benefits of artificial recharging is dependent on what value can be assigned to a unit volume of water" and "in assessing the benefits of artificial recharge, consideration must be given to the importance of water to the total economy, to the value of water for various uses, as well as to the direct and intangible benefits that may accrue."

Water and wastewater projects are not necessarily evaluated solely based on their profitability to the system owner and operator. Water and wastewater utilities often have mandates to provide specified levels of services irrespective of the profitability of each individual system component. Water has social and environmental values as a necessity of life. Hence, water is often provided to poor communities even if the revenues generated do not cover costs. Governmental projects are also often funded all or in part by general revenues (rather than entirely from revenues from the sale of water) with the goal of achieving societal benefits. MAR projects may thus be economically evaluated by comparison to non-managed scenarios [3] or other water management or treatment options to achieve the same goals [4,5]. The feasibility of MAR projects also depends upon financial feasibility [6], which addresses whether funding is available for a project and how a project will be paid for. In developing countries, MAR projects are available that may be economically feasible (*i.e.*, their benefits exceed costs) and could materially improve the quality of lives of the people, but financial resources are not available. Water projects often have to compete for limited financial resources against other types of projects (e.g., health, transportation) that also provide societal benefits.

The procedures for analyzing the economic benefits of groundwater presented by Bergstrom *et al.* [7] and the National Research Council [8] provide a basic framework for evaluating the economics of MAR systems. The first step in the evaluation is an analysis of the changes in groundwater quality and quantity resulting from the implementation of a MAR project. The change is evaluated relative to a reference state, which would normally be current conditions. The changes in groundwater services resulting from the change in groundwater quantity and quality is next evaluated. Finally, the economic value of the change in groundwater services is evaluated.

Water has been recognized to be an economic good, but its price is seldom set by a free market. Water also has social and environmental values that are difficult to quantify in monetary terms. Indeed, some people object to the very notion that economics should enter into decisions concerning water supply. The value of water also varies greatly depending on local circumstances. As water is critical for life, water can be priceless during extreme shortages. In some water-scarce developing countries, there are often large social costs associated with both physically obtaining the daily water supply and health impacts associated with poor water quality. On the contrary, during periods of abundant supply, the market value of water can be very low, and in the case of flooding it is a liability (*i.e.*, has a negative net value).

2. MAR System Types and Benefits

MAR includes a wide variety of processes by which water is intentionally added into an aquifer or induced to flow into and through an aquifer for treatment purposes. MAR, as defined by Dillon [1], includes two main end-member types of technologies: (1) methods that are used primarily to increase the volume of water stored in aquifers; and (2) methods that are used primarily for water or wastewater treatment. MAR systems with a water storage goal include ASR, aquifer recharge using wells and infiltration basins, and river channel modifications to enhanced aquifer recharge (e.g., check dams). MAR using wells, including specifically aquifer storage and recovery (ASR), was reviewed by Huisman and Olsthoorn [9], Pyne [10], and Maliva and Missimer [11]. Surface spreading methods were reviewed by Huisman and Olsthoorn [9], Oaksford [12] and Roscoe Moss Company [13]. The benefit of storage-type systems is the net increase in the volume of water stored in the aquifer. The increased storage results in an increase in the volume of water available for later beneficial use (abstraction benefits). Additional potential benefits result from the water being in place in the aquifer (*in-situ* benefits). *In-situ* benefits include reduced groundwater pumping costs, and avoidance of the need to replace or deepen production wells, restoration or maintenance of environmental (e.g., spring) flows, avoidance of land subsidence, and prevention of saline-water intrusion [2,8].

MAR systems with a storage goal are primarily constructed in hydrological and engineering settings where there are at least periodic shortages of water and times when excess water is available that could be used to recharge aquifers. MAR is used in arid and semiarid lands, for example, to capture surface water that is episodically available during uncommon rainfall events. MAR is also employed in areas with humid climates, such as South Florida and parts of India, where there is a pronounced seasonality in rainfall. The systems are usually installed either where excess water is available (e.g., in-channel and off-channel infiltration systems in ephemeral streams and ASR systems at water treatment facilities) or where the water is used.

MAR systems with a primary treatment goal have been termed “aquifer recharge and recovery” (ARR) and include soil-aquifer-treatment (SAT) and aquifer storage transfer and recovery (ASTR). SAT is a high-rate land application system that involves the spreading of partially-treated domestic wastewater on the soil surface to provide natural treatment as the water infiltrates into the soil and flows through underlying aquifers. The vadose (unsaturated) zone is used as a natural filter to remove or reduce the concentrations of suspended solids, biodegradable organic matter, nutrients, metals, and pathogenic microorganisms, by a variety of filtration, sorption and biologically mediated reactions [14–18]. Additional filtration and removal of contaminants occurs as the water travels through the aquifer. ASTR involves the injection of water into an aquifer using wells and its recovery with separate production wells as a means of improving stored water quality by providing additional residence time and to take advantage of the filtration and other treatment processes provided by the aquifer [19]. The essential, defining feature of ASTR is the intentional use of water flow through an aquifer as a treatment method.

MAR systems vary greatly in their scale and thus how they should be evaluated by CBA. Large-scale systems owned and operated by water utilities or water management districts or agencies usually have well-defined costs and benefits, although there may be uncertainty in the quantification of benefits (e.g., monetary value of stored water in the absence of a free market). MAR also includes small-scale systems implemented in developing countries whose benefits, such as a reduction in labor, disease, and mortality due to the availability of a more convenient, reliable, and safer water supply, are difficult to express in monetary terms, but nonetheless have great value.

3. Cost-Benefit Analysis

According to the basic rule of benefit maximization, in which increasing the total value of scarce resources is assumed to be desirable, actions (such as the construction of MAR systems) should be undertaken if their total benefits exceed total costs [20]. Cost–benefit analysis (CBA) is addressed in microeconomic textbooks and some dedicated books (e.g., [21,22]). Environmental CBA is a specific area of investigation (e.g., [23–26]), which includes issues of water quality and supply.

The underlying goal of CBA is allocative efficiency. Policies should be adopted or investments made only if they provide net positive benefits. The policy or investment that yields the greatest net benefits should be selected. A limitation of CBA is that goals other than economic efficiency (e.g., equity and national security) may be of relevance to the policy [22]. CBAs are not performed in a moral vacuum and the social desirability of a particular set of costs and benefits may be a consideration [25]. However, even if decisions are not made solely on the basis of CBA, decisions should at least be informed by CBA such that it is at least an input into the decision-making process [25].

CBAs are commonly performed using the net present value (NPV) method, which considers both the initial investment in the project and benefits and costs expected to be achieved or incurred over the life of the project. Future benefits and costs are discounted at an appropriate rate. The basic NPV equation is

$$NPV = -C_0 + \sum B_i/(1 + r)^i - \sum C_i/(1 + r)^i \tag{1}$$

where C_0 is the initial (capital) costs in year 0; B_i and C_i are the benefits and costs in year “I” and “r” is the discount rate.

Cost-effectiveness analysis (least cost analysis) and lifecycle costs analysis consider only the costs to achieve a pre-set objective or criterion. Different options are considered that provide the same benefit or set of benefits. Cost-effectiveness analysis is suitable where valid and reliable estimation of benefits is not feasible [27]. It may be used to evaluate options to achieve a well-defined water supply or environmental goal. For example, if the decision is made to supply a given amount of potable water to a community as a social objective, then cost-effectiveness analysis could be used to evaluate different supply options. A limitation of cost-effectiveness analysis is that an entire list of projects could be ranked without any assurance that any of them are actually worth doing [25].

A basic requirement of CBAs is that accurate costs and benefits values be used. However, “appraisal optimism” is common, which is the tendency to exaggerate benefits and under-estimate cost escalations [25]. Appraisal optimism can be either accidental or intentional. In the latter case, those with a vested interest in a project may under-estimate costs or over-estimate benefits to gain support for a project, knowing that projects develop momentum for their continuation and thus become difficult to later terminate. For example, false economic analyses were widely used to give the perception that major water supply projects in the western United States made economic sense, when in fact they could never be economically justified because the farmers (the primary beneficiaries) could never afford the true cost of the delivered water [28].

The discount rate reflects time preference for benefits and costs, which varies between individuals. Individuals typically value a benefit more today, than they would value receiving the same benefit ten years from now. Discounting enables comparison of costs and benefits that occur at different times.

In economics, the discount rate is equal to the interest rate in a perfect capital market with no taxes or inflation [29]. Application of a discount factor reduces the importance of future costs and inevitably means that what happens long distances into the future has very little impact on decisions made today [30]. Discounting has been referred to as a "tyranny" that militates against the interests of future generations [24] and thus appears to be inconsistent with rhetoric and spirit of "sustainable development" as it violates the notion of intergenerational equity [25]. However, not discounting (*i.e.*, use of discount rate of zero) creates other problems in that the needs of generations very far into future are given equal weighting, which would encourage excessive saving at the expense of current needs [25]. Pearce *et al.* [25] present the arguments that a time-decreasing discount rate may be the most appropriate solution.

There is considerable disagreement as to what discount rate is appropriate. Freeman [29] suggested that a rate of 1%–4% is usually appropriate. Where the costs precede benefits, as is the case for most water projects, those who favor such projects may argue for a low rate while those who oppose them may argue for a high rate [23].

Not all costs and benefits of a MAR project are borne and accrued by the system owner. For example, all groundwater users in a basin may benefit from increased water levels in an aquifer resulting from a recharge program, whether or not they personally financially contribute to the project. Similarly, where a project receives external funding, such as a governmental grant, the system owner and participants may receive most or all the benefits of a system, while not having to pay the full costs. The results of a CBA that include all costs and benefits may thus differ from the results of a CBA that is limited only to the costs and benefits to the system owner. This dichotomy is addressed under finance.

It is important to also distinguish between financial CBA, which measures only the direct financial implications of a project, and social cost-benefit analysis, which measures the overall welfare impact of a project [31]. Social benefits associated with water projects include benefits associated with having a reliable, convenient, and safe source of water. Welfare impacts can also be considered to include environmental benefits and costs. Valuation of welfare effects in monetary terms brings with it problems and can lead to inappropriate interpretation of results due to the lack of agreement on appropriate valuation methodologies and a lack of evidence to support the underlying values of some variables used in the analysis [31].

CBA has been used to evaluate MAR projects with an environmental restoration goal, such as the proposed 6.06 Mm^3/d (1.6 billon US gal/d) ASR system for the Comprehensive Everglades Restoration Plan (CERP) in Florida (USA) [32,33]. Although explicit legal requirements to return damaged ecosystems to baseline functioning may be desirable from an ecological perspective, from an economic perspective it is important to know whether restoration costs generate environmental benefits of equal or greater magnitude [34]. The challenge lies in providing a defensible monetary evaluation of ecosystem services and, for water projects, how those services are affected by variations in water supply. There is a school of thought that CBA, particularly as it is widely applied, is not appropriate because it fails to adequate consider environmental costs and values (*i.e.*, externalities). It has been proposed that ecosystems, such as wetlands, have an existence value, which can be derived simply from the satisfaction of knowing that some feature of the environment continues to exist [24,35]. Ecosystems are also considered to have an intrinsic value, irrespective of the utility or the desires of humans, which lies beyond the scope of CBA.

4. Costs of MAR Projects

The costs of MAR projects include both capital, operations and maintenance costs, and finance costs (debt service). Capital costs are fixed, one-time expenses incurred during the design and construction of the MAR system. Capital costs include, but are not limited to:

- Land;
- Testing costs, feasibility analyses;
- Consulting services for the design, permitting, and supervision of the construction;
- Construction costs (e.g., roads, piping, instrumentation, controls, and pretreatment systems); and
- Regulatory testing requirements during construction and operational testing.

Operation and maintenance costs include the following:

- Labor (system operation, regulatory requirements, administration);
- Electricity;
- Consulting services;
- Regulatory testing requirements (e.g., water quality testing);
- Maintenance costs (e.g., parts replacement, well and basin rehabilitation);
- Pre-treatment costs (additional treatment prior to recharge);
- Post-treatment costs (e.g., chlorination); and
- Raw water costs.

Costs used in the CBA should be marginal not average costs. Sunk costs, which are costs that would be incurred whether a project proceeds or not, should not be included in the CBA. Sunk costs include items such as previously performed hydrogeological investigations, existing wells that are no longer used, and existing intakes and piping. The marginal operational labor cost is zero if existing plant staff can operate the system (*i.e.*, there is no increase in total labor costs). Labor costs are included in the CBA if additional staff (or contracted labor) are needed to operate and manage the system.

CBAs should consider opportunity costs associated with land. Opportunity costs are the benefits one could have received by taking an alternative action. In the case of land, it could be revenues that could have been obtained if the property was sold or rented, or the value of goods and services that would have been obtained if the land were put to an alternative use. MAR systems that utilize wells have minimal surface footprints and, if carefully sited, do not preclude other land uses. Therefore, the opportunity costs associated with MAR systems using wells may be negligible.

The cost of water stored in a potable water ASR system is the marginal cost to abstract and treat the additional recharged water by a water treatment plant, rather than the average production cost or the price charged to customers. Average water costs includes labor, depreciated capital costs, and finances costs (*i.e.*, sunk costs), which would be incurred whether or not the additional water was treated. Local water utilities may obtain water from wholesaler on a take-or-pay basis, in which case they pay for water not used during low demand periods. Hence, there may be a strong financial incentive to store water during low demand periods as the utility is paying for it anyways [34]. In the case of a take-or-pay contract situation, the cost of water would be considered a sunk cost if the water would still be paid for if not used.

The storage space in an aquifer is another potential cost, which is rarely priced in accordance with its scarcity value [36]. Inasmuch as MAR is in its initial stage of development in many areas, there is a low demand for storage space, and it thus has minimal monetary value. However, if MAR implementation locally increases and a scarcity of aquifer storage space with suitable hydrogeologic conditions develops, then one can envision the cost of storage space becoming a significant component of CBA.

5. Benefits of MAR Systems

Water has an economic value only when its supply is scarce relative to its demand. Scarce water takes on value because many users compete for it [20]. The benefits of MAR systems are either additional water being available in times of scarcity, improvement in water quality, or a combination of both. Recharge of water can create a new freshwater resource, such as occurs in some ASR systems in which freshwater is emplaced in a brackish aquifer. MAR can also provide benefits by adding water to storage in an aquifer and thus stabilizing or increasing water levels. The total economic value of the recharged water includes its abstraction value plus *in-situ* (non-use) values derived from groundwater being in place.

Economic value is measured on the basis of substitutability, which can be expressed in terms of willingness to pay (WTP) and willingness to accept compensation (WTA) [29]. WTP is the amount someone would be willing to pay rather than do without a good or service. WTA is the minimum amount of money someone would require to voluntarily forgo a good or service. WTP and WTA may not be the same for a given good. Individuals tend to demand considerably greater monetary compensation to give up things that they already possess than they are willing to pay to acquire the same exact items. WTP is also constrained by a person’s income in that wealthy people can afford and may thus be willing to pay more for a good or services than would poor people. The economic value to society of a good or service is the aggregate of the WTP of all individuals.

The economic value of water is not a fixed, inherent attribute of a good or service, but rather depends upon time, circumstances, and individual preferences [8]. The scarcity value of water changes with time, with its value increasing during times of decreased supply or increased demand. An important benefit of groundwater, whether placed through natural or enhanced recharge, is as a buffer against variation in surface water or other supplies [8]. Indeed, several studies have demonstrated that the greatest economic benefit of groundwater lies in the stabilizing of water supplies and avoidance of the economic impacts of shortages [37–41]. Surface freshwater flows should be the first source of water used, because they may otherwise be lost if not used when available. Fresh groundwater should optimally be reserved for strategic use in coping with water scarcity. MAR can enhance the ability of groundwater to play a stabilisation role by increasing the available supply of groundwater. Where global climate changes result in locally drier conditions, or a more viable water supply, then water stored in MAR systems would have an even greater value in the future, which needs to be considered in economic analyses.

A fundamental challenge with quantifying the economic benefits of water projects is that there is seldom a free market with respect to water and observed prices do not exist or fail to reflect its social value [42,43]. Often in both developed and developing countries, subsidization is common where water users do not pay the full cost of the construction and operation of the systems through water rates. Construction costs may have been paid for, at least in part, through general government revenues.

Water utilities are essentially monopolies and consequently price regulation is usually applied to protect the public. Publically owned utilities are usually either under direct governmental control or have an elected board. Privately owned utilities are commonly regulated by a governmental agency that has the authority to approve or deny rate increases. For publically owned water utilities, rates are typically determined to generate sufficient revenues to cover operation and maintenance (O&M) expenses, debt service payments, and capital expenditures financed by rates (as opposed to debt and governmental contributions and subsides). Pricing for privately owned utilities is commonly based on a “cost of service” approach, whereby rates are set to generate sufficient revenues to cover O&M expenses, depreciation, taxes (and tax equivalents) and an approved return on base rate.

From an economic perspective, consumers of water should actually pay the marginal cost of water (*i.e.*, the cost to obtain additional supplies) rather than the average cost [44], which is seldom the case. As is often the case for alternative water supply projects of water utilities, the marginal revenues from the additional supplies are less than the marginal costs, and the system is paid for by revenues from the sale of all water, both new alternative supplies and existing conventional supplies.

In developed countries, the price of water represents a small fraction of the household budgets and is usually given little thought. Water is provided at a much lower cost than what the consumer is willing to pay. The price that consumers pay for water can never exceed and seldom approaches the price that they would be willing to pay rather than go without, so the economic benefits derived from the use of water typically exceed the purchase price [20]. In economic terms, utility customers enjoy a substantial consumer surplus in that the value of the water they receive (in turns of WTP) exceeds the price that they pay for the water.

As a result of the consumer surplus, municipal water demand functions show a low elasticity. Rising prices over time may not significantly lower demands, particularly if real incomes are also rising [42]. Some uses are of great necessity to consumers (e.g., potable use, cooking) and there are no practical substitutes. At its limit, as supply approaches zero, the marginal value of water approaches infinity [42]. For example, strategic storage ASR systems are in various stages of development in some Middle Eastern countries that are highly dependent on desalination for the water supply [11]. In the event of a catastrophic disruption of the desalination facilities, due to a natural event, accident or war, millions of people could be without a water supply. The value of a strategic water supply to meet potable demands in an extreme emergency is inestimable [2], even though the probability of such an event is remote. There is thus a low probability that the strategic storage ASR systems could provide enormous benefits. However, placing a meaningful monetary value on the benefits of avoiding a very low probability catastrophic event is very difficult, because there are no precedents.

Since water is rarely priced at a market-determined scarcity value, comprehensive evaluation of MAR schemes require alternative nonmarket valuation methods [35,43,45]. Shadow pricing is typically used in which values are assigned or observed prices are adjusted to correspond to prices that would prevail in a competitive market. Shadow pricing is required, for example, to incorporate environmental costs and benefits in CBA of water projects. Some of the common methods to calculate or estimate the benefits of the water that might be supplied or treated by MAR projects are summarized below (Table 1).

Table 1. Methods to monetize benefits of managed aquifer recharge (MAR) systems.

Method	**Description**
Market prices	Value of water determined by actual prices set by willing buyers and sellers in a competitive market.
Alternative cost	Value of water storage or treatment is determined from the cost of the least expensive alternative that provides comparable benefits.
Value marginal product	The value of water is quantified from the marginal productivity of water, *i.e.*, the extra value of output that can be obtained from additional applications of water.
Contingent value	Survey-based methods to determine an individual's willingness to pay or willingness to accept compensation for a good or service.
Hedonic property value	Value of water is inferred from market transactions (e.g., real estate sales) that are linked to the value of water.
Defensive behavior	Value of a safe and reliable water supply can be estimated from expenditures to avoid exposure to unsafe water.
Damage cost	Value of water is estimated from damage costs avoided, such as health impacts or drought damage.
In-situ groundwater value	MAR system value is estimated from costs avoided resulting from groundwater being in place, such as pumping and land subsidence costs.

5.1. Market Prices

Quantification of the value of water is most straightforward where water is sold in a free market. Much has been written over the past two decades on the merits of free water markets as a means of promoting efficient use of water through pricing mechanisms. The principal objections to an entirely free water market system stems largely from the recognition that water is also a social good and that water trading can have significant third party effects (*i.e.*, externalities).

Market pricing systems result in water being allocated to where it results in the greatest net economic returns. The value of water can be determined from direct observations of transactions between willing buyers and sellers [45]. The spot market price under conditions at a given time is a direct measure of WTP. The limitation of using market pricing to determine the value of water is that there are few unfettered markets and that in the absence of a long-term time series of observations, the method may be of limited value for long-term planning purposes [45].

There are very few instances where free market trading prices have been use to quantify the benefits of MAR projects. One example is an evaluation of MAR in the Murrumbidgee region of New South Wales, Australia, in which the value of water was determined using temporary water trading prices (AU$450/ML) during a drought [46]. The spot market price for water will vary depending upon climatic conditions. Stochastic modeling of rainfall, water scarcity, and thus value of water, might be used to estimate potential future revenues from the sale of water over the operational life of a MAR system.

5.2. Alternative Cost Method

The alternative cost method is based on the notion that the maximum WTP for a good or service is not greater than the cost of providing that good or service through some other process or technology. The gross benefit of a project is considered to be the cost of the next higher cost alternative. The costs and benefits of MAR and other water projects would be considered relative to other water management options that would achieve the same goals [4–6,45,47]. The alternative cost method is similar to cost-effectiveness analysis in that it does not involve quantification of benefits for each project, which are considered to be constant for all options.

MAR systems with a storage goal can be compared against other options in terms of the unit cost of water recovered or delivered. Where the goal of the system is long-term storage, MAR systems could also be evaluated against other options in terms of the cost per unit storage capacity, with consideration given to recoverability. The alternative cost method is also appropriate for evaluation of MAR projects with a primary water treatment goal. The cost of systems that take advantage of natural vadose zone and aquifer treatment processes can be compared to the costs of alternative engineered solutions that provide the same water quality improvements.

A basic problem with the use of the alternative cost method is that a more expensive alternative can always be conceived, which would produce an inflated estimated project benefit [45]. The analysis should demonstrate that the alternative project might actually be built. It is misleading to compare the cost of a MAR project against that of a much more expensive alternative that would never be built. For example, a MAR project to be used for irrigation water supply would be substantially less expensive than a seawater desalination plant built for that same purpose. However, this would be a misleading comparison as the latter would not likely be built, because of the great expense of the desalinated water relative to the value of irrigated crops.

The alternative cost method is commonly used to evaluate water supply projects in which additional water storage capacity or peak demand period water supply are required. For example, potable water demand in South Florida is greatest during the winter and spring dry season, which also coincides with the peak in tourism and seasonal resident population. Permitting of additional fresh groundwater withdrawals is generally no longer possible. The widespread implementation of ASR in Florida starting in the late 1990's was driven by its being the least expensive option to meet seasonal peak water demands [48]. ASR is a less expensive option than the next less expensive option, which is the construction of brackish groundwater desalination capacity that would not be needed (and would thus be idle) for a large part of the year.

5.3. Value Marginal Product and Residual Methods

The value marginal product (VMP) method considers the marginal change in the total value of product with a change in input. The value of water is quantified from the marginal productivity of water, which is the extra value of output that can be obtained from additional applications of water [34,49]. With respect to irrigation, the value of water is the change in income with and without an irrigation project, which is a function of increase in crop yield and crop prices. The marginal productivity of water can be calculated from crop-water production functions, which are empirical functions of crop yield *versus* irrigated water applications [43,45]. The function may be either experimental or based on surveys of water users [45]. Production functions are often a function of numerous variables including soil type, fertility, temperature, rainfall, irrigation practices, crop type, and plant growth stage [20]. It can, therefore, be difficult to distill out the specific contribution of irrigation. The increase in yields attributable to irrigation can be alternatively estimated as the difference between irrigated and dryland farming, assuming all other factors being equal. The VMP for irrigation should not be mistaken for water productivity, which is usually defined as the total value of crops divided by the amount of water applied.

The residual method estimates the value of water as the remainder of net income after all other relevant costs are accounted for. The cost of all non-water inputs are deducted from the estimated total value of production. The residual method is most accurate where water constitutes a significant fraction of the value of the output [45,47]. The residual method can result in large potential errors where water is a relatively minor portion of the total value of the product [45]. The residual method tends to give higher estimated values than other methods and over estimates the value of water if other variables are not included in the analysis [45], which is referred to as the "omitted variable problem." Before and after comparisons (irrigated *versus* non-irrigated land) may ignore other variables that influence incomes [22]. There are also disagreements about whether or not and how to consider owned resources (versus contractual resources) such as land, capital, entrepreneurship, and management [45]. Land values can be obtained from rental and sales market.

Limited data are available on the marginal value of water in agriculture in general, and the reported values show a very wide range. Colby [43] reported estimated values of water in agriculture of USD4 to USD236 per acre foot (USD0.003/m^3 to 0.19/m^3) in the western United States. Hussain *et al.* [50] compiled more recent estimates of the value of agricultural water and documented that average values vary greatly across countries and regions, from as low as USD0.001/m^3 to 0.74/m^3.

The VMP has also been used to estimate the value of water in industrial uses. However, water costs are usually very often only a small fraction of total costs [42]. Water supply cost is thus a secondary decision. As water supply and wastewater disposal costs increase, recycling of water increases. However, scattered studies indicate that industrial water demand is quite inelastic [42].

VMP could be used to evaluate the environmental benefits of MAR, such as the restoration and protection of groundwater-dependent ecosystems, in a manner analogous to valuing water for irrigation use. The value of water would be related to the marginal increase in ecosystem services provided by the additional water. The difficult and contentious issue is monetizing ecosystem services. For example, the impacts of an aquifer recharge scheme on spring flows and wetland hydration can be determined through monitoring and modeling. Assigning a monetary value to the benefits of the increased spring flows and wetland hydration has a much greater uncertainty.

5.4. Contingent Value Methods

Contingent value methods (CVM), which are also referred to as expressed preference approaches, are survey-based methods used to determine individuals' WTP or WTA for a good or service. The methods involve asking people directly what they would be willing to pay contingent on some hypothetical change in the future state of the world. With respect to environmental issues, a description of conditions simulating a hypothetical market is presented, to which respondents are asked to express their WTP or WTA for existing or potential conditions not registered in any market [45]. A hypothetical application of the CVM to a MAR project is

> "*Your local water utility has completed an investigation of different options to address the current annual water shortages during the summer dry season. The shortages result in restrictions that curtail outdoors water uses, such as lawn and garden watering. The results of the investigation indicate that a managed aquifer recharge system could be constructed that would provide an additional 1 million m^3 of water in the summer. The additional water would reduce the need for water use restrictions to less than once in every ten years. Would you be willing to pay an extra \$2 per month on your water bill to pay for the MAR system?*"

The cost of the system could be expressed as a discrete choice or evaluated using an iterative bidding process. In the former case, which is referred to as the dichotomous choice or referendum method, a respondent is asked only whether or not they would be willing to pay a specified amount in a specified manner as a "take it or leave it" decision. Iterative bidding processes involve starting with an initial price and then adjusting it upwards or downwards to determine the maximum WTP. For example, if a respondent indicated that they would be willing to pay an additional $2 per month for the MAR system, then they might next be asked if they would be willing to pay $3 per month, and so on, until they indicated no. Conversely, if the response to the initial price is no, then the price would be incrementally reduced until the respondent indicated yes. It has been documented that the initial bid price used can impact survey results.

CVM are subject to a number of potential biases, which has been discussed at great length in the economics literature and was reviewed with respect to CBA and the value of water and the environment by Boardman *et al.* [22], the National Research Council [8] and Young [45]. A basic limitation of CVM is that people's statements about their preferences may not reveal their true preferences and actual behavior, because statement of a WTP does not involve an actual payment obligation. Due to the hypothetical nature of the process, declared intentions may not be accurate guides as to actual future behavior. The biases could either be unintentional or a strategic behavior. As an example of the latter, someone in favor of a water project may intentionally give an excessively high WTP in order to try to influence the survey results. Similarly, respondents may give a low WTP for a project with the hope that in by doing so they may keep future water rates lower. Strategic behavior may be detected as outliers. Sample bias and non-response biases occur when the respondents do not represent all the stakeholders for a project. Interviewer and neutrality biases occur when the respondent perceives that a particular response is preferred by the interviewer or when the question is framed in a manner that is not neutral.

5.5. Hedonic Property Value Method

The hedonic property value method is a revealed preference method in which the valuation of non-market goods and attributes is determined by observing market behavior. Expenditures for market goods are linked to the value of nonmarket goods or attributes. The method assumes that an increment in price due to an increase in one characteristic will equal a buyer's WTP for the characteristic as well as the seller's marginal cost of producing that characteristic [45]. The hedonic property value method requires market data and assumes that market participants are able to recognize differences in characteristics. It is commonly based on real estate transactions. A commonly given example is that the value of a living next to a lake can be determined by comparing the sales price of homes with and without a lakefront.

With respect to water, the value of groundwater for irrigation use can be estimated from the difference in price of a unit of land with and without a groundwater right or supply. The hedonic property value method assumes that all other variables are equal. However, with respect to water rights in the western United States, the value of water rights depends upon their security (seniority), water quality, and location of use [43].

5.6. Defensive Behavior and Damage Cost Methods

The defensive behavior method is based on the WTP to avoid adverse environmental effects [45]. For example, the value of safe drinking water can be estimated from the amount of money that people would pay to avoid exposure to contaminants, such as by purchasing bottled water. The premise of the method is that a rational person will adopt defensive behavior as long as the value of the damage avoided is greater than the cost of the defensive step.

Benefits of MAR systems can be evaluated in terms of damage costs avoided. For example, the benefits of bank filtration systems to provide safer drinking water in rural areas of developing countries can be evaluated in terms of the costs of disease avoided. The costs of disease includes health care expenditures, lost wages and labor (e.g., farmers not be able to tend their fields), and human suffering and premature death. A challenge in evaluating the benefits of water supply and sanitation systems is monetizing the value of a human life and the effects of sickness [31]. An approach taken to evaluate the latter is to use the product of days of work lost and local wages. Similarly, a benefit of water supply projects may be a reduction in the labor required to obtain water, which is a large burden on women and school-age children in areas of some developing countries.

The benefits of an MAR system for irrigation water supply can similarly be estimated from the costs of crop damage during droughts that would be avoided as a result of the stored water. Such an evaluation would require a statistical (probabilistic) analysis of drought frequency and intensity, associated crop damage, and the economic value of lost crops.

5.7. In-Situ Values of Groundwater and MAR

In-situ values include a variety of benefits associated with additional groundwater being in place in an aquifer (*i.e.*, higher groundwater levels), as opposed to benefits associated with the abstraction and use of groundwater. *In-situ* benefits are the objectives of systems that involve aquifer recharge without recovery. Reduction in pumping costs is an often cited example of an *in-situ* value that would be a benefit of MAR. Higher groundwater levels result in less energy required to pump water and thus cost savings. The economic value of an MAR system with respect to pumping costs is a function of the change in water level, decrease in energy required to pump the water, and the energy cost. Pumping cost benefits of an MAR project in a given year (C_t) are estimated as [51]:

$$C_t = P_t L_t W_f \tag{2}$$

where P_t is the pumping cost per volume of water per unit of lift per year; L_t is the cumulative average lift change per unit area (ft); and W_t is the amount of water pumped within the affected area without recharge.

Reichard and Bredehoeft [52,53] performed an economic analysis of the Santa Clara Valley, California, aquifer recharge system. The system uses infiltration basins to recharge a heavily used alluvial aquifer system. A calibrated groundwater flow model was developed and used to calculate the hydraulic effects of the on-going aquifer recharge system. The energy savings was calculated from the modeled increase in heads, annual abstraction volumes, the energy requirements to lift an 1 acre-foot of water (1232 m^3) 1 foot (0.3 M) using a 100% efficient pump, and an average pump efficiency. The energy requirement for a 100% efficient pump is 1.02 KwH to lift 1 acre acre-ft one foot, which is equivalent to 2.71 KwH to lift 1000 m^3 of water 1 m. The benefits of reduced subsidence per foot of drawdown avoided were calculated using an estimate of the economic impacts of historic subsidence divided by the historic drawdown [52,53].

6. Risk and Uncertainty in CBAs

Perhaps the most neglected aspect of the economics of MAR is addressing risk and uncertainity in CBAs. Risk and uncertainty are often considered synonymous. However, the term "risk" implies that there is some idea of the probability of various events [24,27]. Uncertainty implies that the probability of future events is not known. Although there are without doubt risks and uncertainty associated with the implementation of MAR, as evidenced by some failed or underperforming systems, the existence of risk and uncertainty in projects is seldom acknowledged [11], much less explicitly incorporated into CBAs.

The principle risk and uncertainty associated with MAR systems is that they may fail to meet performance objectives. System performance depends local upon hydrogeologic conditions, which may turn out to be unfavorable for achieving system goals. Adverse results include:

- Recharge may not result in anticipated changes in aquifer water levels;
- Anticipated additional water may not be available when needed (*i.e.*, system has a poor recovery efficiency;
- Unexpected water quality changes due to fluid-rock interactions (e.g., leaching of arsenic into stored water);
- Well performance problems (e.g., low well capacities, well or formation clogging);
- Excessive infiltration basin clogging;
- Water treatment goals are not achieved; and
- Anticipated demand for water (and associated revenues) may not be realized.

For example, the USD150 million dollar Las Posas Basin ASR system in California is considered a failure as it did not achieve water storage goals [54]. The recharge of an enormous volume of water over operational life of the systems did not result in a corresponding increase in aquifer water levels, and thus the water that was "banked" on paper could never be recovered [11].

Some adverse results may be remedied at an additional cost and thus the systems may still be viable. Arsenic leaching and excessive well clogging may be avoided, for example, by pre-treating the recharged water. The additional costs would result in projects having lesser NPVs, but still being economically viable if the benefits are great enough. Some failed ASR systems provided eventual (salvage) value when the wells were put to alternative uses. For example, the Bonita Springs Utilities (Southwest Florida) potable water ASR system encountered hydrogeological conditions that were unsuitable for ASR. A very high degree of aquifer heterogeneity resulted in excessive migration and mixing of injected water and native groundwater [11]. The ASR well was subsequently put to use as the most productive brackish water supply well for their desalination system.

The main source of risk associated with MAR systems stem from a natural groundwater system being used whose hydraulic and geochemical properties can never be fully characterized. The possiblity thus exists that unexpected adverse conditions may be encountered. The risks associated with MAR systems can be reduced, but never entirely eliminated, through high-quality and more-detailed aquifer characterization [11]. Post-audits of both successful and unsuccessful systems can provide valuable lessons that can be a guide for future implementation of MAR [11].

It would clearly be negligent to assume in any CBA that a 100% favorable result will be obtained, when there is a real potential for poor results. Risk and uncertainty can be incorporated into CBA through an expected value analysis, as reviewed by Boardman *et al.* [22]. The future is characterized in terms of a number of distinct contingencies. To evaluate risks, one has to be able to assign probabilities to the occurrence of each possible contingency. Modeling of risk and uncertainty begins with a set of contingencies that are mutually exclusive and capture the full range of likely variations in the costs and benefits of a project or policy.

For example, the net economic benefits of water storage systems vary with the amount of rainfall (and thus demand for water) and the performance of the system (*i.e.*, how much additional water could be recovered when needed). Rainfall also effects natural recharge (thus aquifer water levels and storage space) and the amount of water available for recharge. The average net benefits can be calculated based on the probabilities of different rainfalls and probabilities of different recovery volumes over the operational life of the system. The basic procedure is to identify all potential contingencies and to assign a probability to each. The sum of probabilities for all of the contingencies is equal to one. Probability of each contingency can be based on historic experience (e.g., rainfall data) or subjective opinions of experts. The expected net benefits (ENB) are calculated as:

$$ENB = \sum P_i(B_i - C_i) \tag{3}$$

where P_i = probability of contingency "i"; and B_i and C_i are the present value of the benefits and costs of contingency "i". Not considering risk and uncertainty biases CBAs by increasing expected benefits.

Evaluation of expected net benefits is generally reasonable when there is a pooling of risk, which will make the actual realized values and costs close to the expected values [22]. A limitation of the net expected value method is that it does not capture relevant concerns about extreme negative outcomes [24], particularly where risk is unpooled. Individuals and organizations are often averse to bad outcomes. A low probability risk of a completely failed system may be unacceptable to a small utility with limited resources. The ENB can be weighted to give higher weight to negative outcomes, in the case of a risk-averse decision maker.

Risk analysis can be performed using Monte Carlos analysis, which involves the following main steps [22]:

(1) Specification of probability distributions for all important uncertain quantitative assumptions;
(2) Execution of a trial by taking random values drawn from the distribution for each parameter to arrive at a set of specific values for computing realized net benefits; and
(3) Repetition of the trial numerous times to produce a large number of realizations of net benefits.

The results of all the realizations are used to determine the probability distribution of net benefits.

Risk and uncertainty will also change as a project proceeds. Large MAR projects are implemented in a phased manner. Data collected during an exploratory well program and pilot testing reduce risk and uncertainty and should be used to re-evaluate project feasibility [11]. An updated CBA can thus be performed before the decision is made to construct a full-scale system.

7. Finance of MAR Projects

MAR projects are primarily funded in four main manners [2]:

- Revenues from the sale of water;
- Direct assessment (pump tax or assessment based on volume of groundwater used);
- Ad valorem tax on real property; and
- General tax revenues.

MAR projects in developing countries may also be funded by external sources, such as international agencies and non-governmental organizations (NGOs). Water users, the primary beneficiaries of projects, should ideally have responsibility for financing projects, through either water rates, direct assessments or ad valorem taxes. Small-scale projects may be constructed through self labor or some sort of cooperative structure. However, the beneficiaries of economically feasible projects may not have financial resources for projects. Construction costs are up front, while benefits occur in the future. The financial constraints are particularly acute in poor areas of developing countries.

The finance of large water supply and storage projects is often controversial because of a dichotomy between the primary beneficiaries of a project and parties that pay for a project. The dichotomy may work in both directions. Projects are often subsidized in that the direct beneficiaries do not fully pay for a project. Governmental and non-governmental agencies may subsidize MAR projects to vary degrees through:

- Projects financed through general revenues or governmental borrowing;
- Grants or low or no interest loans for utilities; and
- Projects entirely funded and constructed by a governmental agency.

Government projects are often favored where concentrated benefits are received by an influential target group and costs are shared in a diffuse manner by society as a whole [22]. Subsidies are commonly justified in terms of secondary benefits. Agricultural projects, for example, support agricultural communities, not just farmers. Subsidies could be justified to achieve societal goals, such as equity (*i.e.*, access of water to all) and food security. Subsidies are justified when the price of a good does not fully reflect its value [45], but can have the adverse impact of encouraging use in quantities greater than the economically efficient quantity.

On the other hand, the operation of a MAR system may provide broader societal and environmental benefits, but the costs may be borne entirely by the system owner (e.g., local water utility and customers). A project may be economically efficient in terms of its total benefits and costs, but not feasible to the owner, because the owner will not receive sufficient personal benefits to cover costs. In other words, there is not an adequate “business case” to justify the investment in MAR. In this case, some sort of governmental subsidy or other means of financial support from more (ideally all) beneficiaries may be justified.

The issue of finance is well illustrated by the Las Vegas, Nevada (USA) aquifer recharge system, for which Donovan *et al.* [55] provided a cost-benefit analysis for non-municipal water users. The Las Vegas aquifer system recharges an historically overdrafted alluvial aquifer with seasonally available excess treated surface (Colorado River) water, with the primary goals of increasing available water resources, slowing or reducing the decline in water levels, and reducing the rate of land subsidence. The recharge is performed using injection wells and water is abstracted by municipal users and non-municipal water users using privately owned on-site wells.

The net benefits of the system to non-municipal users were calculated to be about USD700 per 1230 m^3/year, which is largely from cost savings from deferment or elimination of the need to rehabilitate and replace wells. Well rehabilitation would consist of deepening wells and/or lowering pumps in response to a continuing decline of aquifer water levels that would otherwise occur without the recharge. There are additional minor savings from reduced energy consumption. Non-municipal users were receiving these benefits for free. The solution was to implement a groundwater management program (GMP) in which non-municipal users are charged on either a per well or permitted water use rate basis in order to support the system.

8. Discussion

Economic analysis of MAR systems are inherently project specific, depending upon the type of system, performance objectives, local hydrological and physical conditions, planned uses of the recovered and stored water, and alternative water supply and treatment options. General and system-specific feasibility is dictated by their benefits, which is determined by the value of water. ASR and other forms of MAR are usually economically feasible (*i.e.*, have a positive NPV), where water is used for municipal (potable) use in water scarce regions, provided that local hydrogeologic conditions are favorable for achieving system performance goals.

Multiple approaches may be appropriate to evaluate the economics of MAR projects. Consider, for example, a riverbank filtration (RBF) system to improve potable water quality in a developing country. The economic viability of the project could be considered using cost-effectiveness, by comparison of the costs of the RBF system with other options that would provide comparable water quality benefits. Alternatively, a CBA could be performed in which the present value of the costs of the systems is compared to the present value of the benefits provided. Expected benefits might be a reduction in sickness and premature mortality that are the result of ingestion of or contact with water-borne pathogens. Proposed systems should be economically viable using both approaches.

The actual costs of MAR systems in terms of total costs and cost per volume of recovered or treated water are highly system-specific. In general, MAR systems provide the greatest benefits where the water is put to a high value use and alternative, inexpensive options are not available. Potable water ASR in South Florida provides a good example of some of the economic issues associated with MAR for a high value use. ASR has been implemented primarily to meet peaks in demand during the winter and spring dry season. The current costs for brackish groundwater desalination (the least expensive alternative) are commonly now in the USD0.30/m^3 to 0.60/m^3 range, which is based on full-time operation of the plants. The costs of desalinated water from facilities constructed only to meet peaks in demand would be substantially greater than the above estimates (approximately USD0.70/m^3 to 1.50/m^3), because the large annual depreciated construction and fixed operational costs for a desalination system would be divided by a relatively small seasonal production volume, resulting in higher unit costs. Desalination costs would also depend upon whether an existing plant is expanded or a new plant is constructed, and the size of the plant and associated economy of scale.

There is a substantial economy of scale associated with wells. For example, doubling of the capacity of wells typically involves significantly less than a doubling in the cost of the well, wellhead, pump, and piping. The costs of regulatory compliance are also independent of well capacity. On the benefit side, cost per unit volume is directly proportional to the volume of water recovered, which is a function of system capacity, recovery efficiency, and demand (*i.e.*, amount of available water that is actually recovered). The annual cost for a 1 to 2 million gallons per day (3788 to 7576 m3/d) ASR system that is recovered for 90 days per year is on the order of USD0.30/m^3 to 0.60/m^3 in South Florida. The cost of ASR to meet peaks in potable water demand, therefore, can be 50% or less than the cost of brackish water desalination.

The economics of MAR for irrigation water supply are much more variable because of the wide range of monetary values of water associated with this use. The value of water for irrigation depends upon the crop type being grown, and is typically relatively low for cereal crops and greater for fruits and vegetables. The value of water in agriculture also depends upon local market prices for crops. A wide range of values has been presented for the value of water in agriculture with most being no more than USD0.001/m^3 to 0.79/m^3 [50]. Hence, MAR systems for agricultural water supply need to be low cost and passive (*i.e.*, do not require large amounts of energy and human intervention to operate). MAR methods most appropriate for irrigation water supply are systems that recharge untreated water (stormwater and flood water) using infiltration basins and ponds, and in-channel modifications (e.g., check dams).

Small-scale MAR systems for potable water supply are right-sized for some rural areas and developing countries. For example, production of water from riverbank filtration systems consisting of drilled or dug shallow wells located adjacent to a river can be a very cost-effective means to improve water quality with concomitant health benefits. Riverbank filtration has been demonstrated to be a less expensive option than conventional surface water intakes and filtration systems where local hydrogeologic conditions are favorable. One small-scale MAR application in India is the inexpensive retrofitting of existing tube wells to allow for aquifer recharge whenever excess rain or canal water is available [56]. The main cost elements are construction of a connecting channel to convey canal water and construction of a settling basin and filter tank [57]. A variety of other methods are employed in India to enhance recharge such as surface spreading using percolation tanks (ponds) and check dams constructed across or near streams, and drainage channels in order to impound runoff and retain it for a longer time to increase the opportunity time for recharge [58].

Managed aquifer recharge of recycled or reclaimed water can be a valuable water resources management tool as it may allow for more of this resource to be put to beneficial use and avoids the costs and environmental impacts of its disposal. For example, the primary economic benefit of a reclaimed water ASR system is Destin, Florida (USA), is that it is much less expensive there to store excess reclaimed water underground during periods when supplies exceed demands than to construct new disposal facilities due to limited land availability and regulatory and political objections to an offshore outfall [59]. The ASR system also has the important benefit of increasing the reliability of the reclaimed water supply, which makes potential customers more willing to commit to connecting to the reuse system. However, a widespread constraint on the implementation of reclaimed water ASR is that the water is often provided to customers at a low (and in some instances no) cost, so there is little financial incentive (benefits received) to invest in the systems, particularly where a low-cost disposal option is available.

An important area for additional research is the collection and analysis of accurate data on the economics of existing MAR systems. Data are needed on the construction and operational costs and benefits of the various types of systems and in different geographic locations. The conceptual framework exists for evaluation of the economics of MAR systems, but there is a paucity of hard data to perform meaningful cost-benefit analyses. The paucity of actual data on the economics of MAR systems, which demonstrates that their benefits exceed costs, is a continued impediment to the further implementation of the technology.

9. Conclusions

The economic feasibility of MAR can be evaluated using conventional CBA in which the NPV of system options are determined and compared against each other and other water storage and treatment options. The CBA process should be rigorous and consider all marginal costs and benefits, risks, and opportunity costs. The greatest uncertainty in CBA analysis of MAR relates to monetizing benefits, which ties into the more basic question of the value of water. In the absence of a free market-derived WTP price for water, shadow pricing is required to estimate project benefits, such alternative cost and value marginal product methods. A major deficiency of past economic analyses of MAR is the failure to consider risk, particularly the effect of possible system under-performance in reducing system benefits.

CBA of MAR systems is highly dependent on site-specific conditions. In general, systems are economically viable where the water is put to a high-value use, such as potable and some industrial and irrigation water supplies. MAR system for lower value irrigation water supply (e.g., cereal crops) should be low cost, passive systems. MAR systems should ideally be financed by the primary project beneficiaries. As is the case for many water projects in general, MAR projects are often subsidized when beneficiaries are unable or unwilling to pay the full costs. Finance of MAR can be particularly challenging in rural areas of developing countries where financial resources are limited and the construction costs have to be borne before benefits of the systems are realized.

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Conflicts of Interest

The author declares no conflict of interest.

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Water Banks: Using Managed Aquifer Recharge to Meet Water Policy Objectives

Sharon B. Megdal, Peter Dillon and Kenneth Seasholes

Abstract: Innovation born of necessity to secure water for the U.S. state of Arizona has yielded a model of water banking that serves as an international prototype for effective use of aquifers for drought and emergency supplies. If understood and adapted to local hydrogeological and water supply and demand conditions, this could provide a highly effective solution for water security elsewhere. Arizona is a semi-arid state in the southwestern United States that has growing water demands, significant groundwater overdraft, and surface water supplies with diminishing reliability. In response, Arizona has developed an institutional and regulatory framework that has allowed large-scale implementation of managed aquifer recharge in the state's deep alluvial groundwater basins. The most ambitious recharge activities involve the storage of Colorado River water that is delivered through the Central Arizona Project (CAP). The CAP system delivers more than 1850 million cubic meters (MCM) per year to Arizona's two largest metropolitan areas, Phoenix and Tucson, along with agricultural users and sovereign Native American Nations, but the CAP supply has junior priority and is subject to reduction during declared shortages on the Colorado River. In the mid-1980s the State of Arizona established a framework for water storage and recovery; and in 1996 the Arizona Water Banking Authority was created to mitigate the impacts of Colorado River shortages; to create water management benefits; and to allow interstate storage. The Banking Authority has stored more than 4718 MCM of CAP water; including more than 740 MCM for the neighboring state of Nevada. The Nevada storage was made possible through a series of interrelated agreements involving regional water agencies and the federal government. The stored water will be recovered within Arizona; allowing Nevada to divert an equal amount of Colorado River water from Lake Mead; which is upstream of CAP's point of diversion. This paper describes water banking in Arizona from a policy perspective and identifies reasons for its implementation. It goes on to explore conditions under which water banking could successfully be applied to other parts of the world, specifically including Australia.

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1. Introduction

Since the 1990s, groundwater recharge has been a key policy and water management tool in the state of Arizona and elsewhere in the United States of America (U.S.) [1,2]. In Arizona, recharge is being used in a variety of ways, including soil aquifer treatment to improve water quality, annual storage and recovery to satisfy regulations that require the use of surface water supplies in place of groundwater, and long-term water banking for drought mitigation and future use. In addition, a modest amount of water recharged remains in permanent storage and contributes to Arizona's management goal of reducing groundwater overdraft. The increasingly prominent role of managed aquifer recharge has been facilitated by favorable hydrogeology, the temporary availability of surface water supplies, a well-established regulatory framework, and institutional innovation, including the creation of the Arizona Water Banking Authority (AWBA).

This paper provides analysis of Arizona's large-scale implementation of managed aquifer recharge in the state's deep alluvial groundwater basins, for both intrastate and interstate purposes. The focus is on the sizable recharge activities involving the storage of Colorado River water delivered through the Central Arizona Project (CAP) into the most populated regions of the state. Much of that activity is associated with the AWBA, which is a pioneering example of policy and institutional reform that has elements that could be adapted elsewhere in the world. This paper considers some of those additional opportunities for water banking, including those under less favorable conditions by making use of existing water distribution infrastructure to transfer water between banking locations and water users. In addition to those physical attributes, a precursor for water banking is a robust water entitlement system.

2. The Arizona Physical Setting

More than three-quarters of Arizona's population lives in the central part and south-central part of the state, with more than half of the state's 6.5 million people living in the Phoenix metropolitan area [3]. A sizable share of Arizona's irrigated agriculture is also located in this semi-arid region, which is characterized by low precipitation rates and surface water resources available in limited areas [4]. However, groundwater is a relatively plentiful and widely dispersed resource. Natural recharge rates are low, but storage volumes are large in the deep and productive alluvial aquifers of the basin and range region. Post World War II population growth and improved pumping technology led to increased pumping of these deep aquifers. By the late 1970s, the issue of overdraft reached a political crisis point, and resulted in fundamental changes in Arizona water management [5]. Extensive new groundwater regulations were established, which in turn helped ensure Federal funding for the Central Arizona Project (CAP).

2.1. Groundwater Regulation in Arizona

In 1980, the Arizona legislature passed the Groundwater Management Act (GMA), which established an extensive regulatory regime, and created the Arizona Department of Water Resources (ADWR) to administer it [6]. Water use is particularly intensively regulated in Arizona's Active Management Areas (AMAs), which are delineated on the basis of groundwater basins. Figure 1 depicts Arizona's five AMAs. Within these AMAs, groundwater rights were created and quantified, long-term management goals were established, mandatory conservation programs were implemented, and a moratorium on new irrigated agricultural land was imposed. Use of water by the mining industry was made subject to conservation regulations but otherwise not limited quantitatively [7,8].

Figure 1. Map of Arizona showing the Active Management Areas (AMAs) and county boundaries. Source: Water Resources Research Center, The University of Arizona [1].

The existence of quantified rights and associated regulatory and administrative framework created the necessary preconditions for a number of additional responsibilities and programs overseen by ADWR, including the Underground Storage and Recovery Program, which has helped put Colorado River water delivered through the Central Arizona Project water to use [1].

2.2. The Central Arizona Project

Adoption of the GMA, which included provisions requiring new municipal growth to depend on renewable water supplies and not mined groundwater, helped ensure federal funding for the Central Arizona Project. The CAP is a large-scale water importation project that lifts and transports Colorado River water to the central and southern part of the state by means of pumps, canals, tunnels and siphons. The 542 km (336 mile) CAP system is capable of delivering more than 1850 million cubic meters (MCM) per year of Arizona's 3454 MCM (2.8 million acre-foot (MAF)) Colorado River entitlement to Arizona's two largest metropolitan areas, Phoenix and Tucson, along with agricultural users and sovereign Native American Nations. The CAP is governed by a 15-person elected board of directors, with representation from each of the three counties in the

CAP service area. The CAP canal and county boundaries, although not county names, are depicted on Figure 1.

The long-anticipated completion of the CAP altered Arizona's water resource portfolio, but political considerations at the federal level resulted in the CAP's Colorado River water allocation having junior priority on the Colorado River and thus is subject to significant reduction during declared shortages. Despite drought conditions on the Colorado River that have extended into their second decade, a Colorado River shortage has yet to be declared according to regulations established by the Secretary of the U.S. Department of the Interior, the Master of the Colorado River [9]. Furthermore, even though CAP deliveries began in 1985, the water supply was substantially underutilized into the early 1990s. It had been anticipated that it would take many decades for municipal and industrial demands to grow into the available supply. Agriculture was expected to utilize the supply in the intervening time. That assumption proved erroneous, as the cost of the CAP water was unfavorable relative to groundwater supplies for many agricultural districts. Farmers in Central Arizona were not prohibited from using groundwater, provided such use was consistent with the conservation and water rights provisions of the GMA.

The supply underutilization was a concern to the CAP because of its requirement to cover costs and repay the federal government for a sizable share of the project's $3.6 billion United States Dollars (USD) construction costs. Less than full utilization of Arizona's Colorado River entitlement was also a political concern. Water unused by Arizona was available for use by the rapidly growing neighboring state of California. Arizonans were concerned that the more politically powerful California might become accustomed to using Arizona's water to meet the growing demands of Southern California's, rather than Arizona's, municipalities. The response from Arizona's water managers to problems of: (1) anticipated delivery cutbacks due to shortage conditions on the Colorado River; and (2) lack of direct utilization of Arizona's full Colorado River entitlement upon completion of the Central Arizona Project in the early 1990s, was multi-faceted, but rested heavily on the use of managed aquifer recharge to store Colorado River water for future recovery.

2.3. Underground Storage and Recovery in Arizona

The statutory provisions authorizing aquifer storage and recovery were added to the GMA in the mid-1980s and then further refined in 1994. Arizona law recognizes two primary types of managed aquifer recharge—direct and in lieu. Direct recharge is called underground storage in the statutes, with in-lieu recharge called groundwater savings. A permitting system governs the three main components of the storage process: (1) the storage facility; (2) water storage; and (3) water recovery [1,10].

2.3.1. Direct Recharge

The state recognizes a number of different direct recharge methods: spreading basins, injection wells, vadose zone wells, trenches/infiltration galleys, and in-channel projects. There is an enormous range in scale of current projects—from a 0.6 MCM/year (500 acre-foot per year (AF/year)) vadose zone well project in Chandler, Arizona, to the 185 MCM/year, (150,000 AF/year), fully automated Tonopah Desert project west of Phoenix, as pictured in Figure 2 and where infiltration rates exceed one meter per day [11]. The largest projects utilize spreading basins that cover tens of hectares of land. Construction typically involves removal of the upper layers of soil, basin shaping, distribution works, and the installation of monitoring wells.

Figure 2. Tonopah Desert Recharge Project. Source: Central Arizona Project [11].

There are extensive permitting requirements for proposed recharge projects. For instance, an evaluation of hydrologic feasibility will typically involve the use of numeric groundwater flow models to determine the extent of expected groundwater mounding. Projects must also avoid potential damage to surrounding property owners that can occur with rising water levels, and water quality must also be considered.

Infiltration rates vary from site to site, and even among basins, but rates of one to two meters per day are common. These high infiltration rates help keep typical annual evaporation losses to less than five percent (5%), and provide a cost-effective means of storing water. Maintenance includes periodic drying of basins, surface scraping and weed control.

2.3.2. In Lieu Recharge

The GMA's quantification of groundwater pumping rights for agriculture in 1980 made it possible for the second method, groundwater savings, that is, in lieu recharge (also generally referred to as indirect recharge, and elsewhere is called conjunctive use). These irrigation rights form the basis of a type of exchange in which CAP water or effluent is delivered to an agricultural groundwater rightholder, and the party supplying the alternative supply is credited for the amount of groundwater that would have otherwise been pumped. The credits earned through in lieu recharge are legally identical to those earned through direct recharge. Irrigation districts and individual rightholders participate in this program by obtaining a Groundwater Savings Facility (GSF) permit from ADWR, and arranging partnerships with those seeking to earn recharge credits.

The GSF permitting process rests heavily on the existence of quantified groundwater rights and the prohibition on bringing new land into irrigation within Arizona's Active Management Areas, as well as financial arrangements regarding the price of the in lieu water to the irrigator.

2.3.3. Accounting

In addition to permitting a recharge project itself, those proposing to store water must obtain a separate permit from ADWR, and must establish the legal right to source water. There are also reporting requirements for deliveries and both water levels and water quality from monitor wells at direct recharge facilities. This system of permits, monitoring, reporting and accounting helps maintain the integrity of the process, which is necessary to assure users that the water they bank can be withdrawn at a later date. To further ensure that only the volume of water added to the aquifer is eligible for recovery, losses due to evaporation are calculated and excluded.

The storage credit system distinguishes between water stored for recovery in the same calendar year and that left in storage for future recovery. Colorado River water left in storage beyond the calendar year in which the water was stored at a recharge facility is typically subject to a one time five percent "cut-to-the aquifer", which is stored water that cannot be recovered. This is a small but important contribution to aquifer storage.

2.3.4. Recovery

Under Arizona state law, the recharge program offers additional flexibility by allowing the withdrawal of stored water to take place in a different area than where the water was recharged. In this respect, Arizona's regulatory system relies on a mass-balance approach; the extensive recharge permitting and monitoring determines the volume of water contributing to the regional aquifer system, and the regulatory accounting then authorizes an equivalent amount of pumping to occur. The "recovered" water may be hydrologically distinct from the recharge activity, but it retains the legal characteristic of the source water that was stored.

Over extended periods of time this hydrologic mismatch can be detrimental, but the regional aquifer systems in the largest AMAs are relatively tolerant of pumping stresses. Moreover, from a policy perspective, allowing this disconnect has facilitated the earlier and more extensive use of renewable water resources than would have occurred with conventional treatment plants and distribution systems. This same attribute has been a key underpinning of Arizona's Assured Water Supply program, which requires new housing developments to have a secure 100-year supply (which can be groundwater) while also requiring use of renewable supplies (through aquifer recharge).

The underground storage and recovery program established the essential building blocks—the regulatory infrastructure—for putting Arizona's Colorado River entitlement to full use, but that goal would require institutional innovation as well.

2.4. Arizona Water Banking Authority (AWBA)

The AWBA was established in 1996 to mitigate the impacts of Colorado River shortages, to create water management benefits, and to allow interstate storage [12]. However, each of those was in service to a larger policy objective—ensuring the full use of the available CAP supply, and thus Arizona's entitlement to the Colorado River, which was viewed as being at some risk from the neighboring states. Regulations enable California to utilize any Colorado River water not utilized by Arizona, and Nevada was exploring federal action to redress its comparatively small allocation. There was particular concern that the growing demands for water to support growth in these neighboring states would result in an effort to utilize Arizona's apportionment in the long-term. To meet its objectives, the AWBA would have to store several hundred thousand acre feet per year of CAP water that would have otherwise gone unused within Arizona. This task would require both political support and money. The 1996 state legislation establishing the AWBA received broad support [13].

2.4.1. Intrastate

The AWBA's role has grown over time, but its largest responsibility has been to improve the reliability of municipal CAP supplies during periods of extended drought on the Colorado River. The junior priority of the CAP supply leaves the supply susceptible to federally imposed reductions, which are expected to be an increasingly frequent occurrence in the coming decades. The cities in the Phoenix and Tucson metropolitan areas that depend on those supplies have been acutely aware of the risk posed by Colorado River shortages, and they supported the AWBA's goal of firming (increasing the reliability) of their supplies by banking the temporarily available CAP supply. Based on modeling of future Colorado River supplies and demands over a 100-year period, the AWBA set numeric storage targets based on the volume of CAP delivery contracts in each Active Management Area. Those firming targets totaled to more than 4493 MCM (3.643 MAF) (Refer specifically to AWBA Annual Report 2012, Table 5, p. 21.) [14].

In addition to municipal supplies, the AWBA was later given responsibility to firm certain CAP supplies allocated to American Indian tribes and to some western Arizona communities, whose allocations were equivalent to those of the CAP. CAP supplies have been instrumental in the settlement of contested surface water right claims by Native American Nations. Unsettled water rights create uncertainty for both the tribes and the cities, so settlement was a high priority for all parties.

To accomplish these ambitious goals, the AWBA was given access to several sources of funding, including a tax assessed on all property owners in CAP's three-county service area, a fee on groundwater pumping, and legislative appropriations from the state's general fund. Through 2012, the AWBA has expended some $197 million USD from these sources, and holds more than 3947 MCM (3.2 MAF) of long-term storage credits.

2.4.2. Interstate

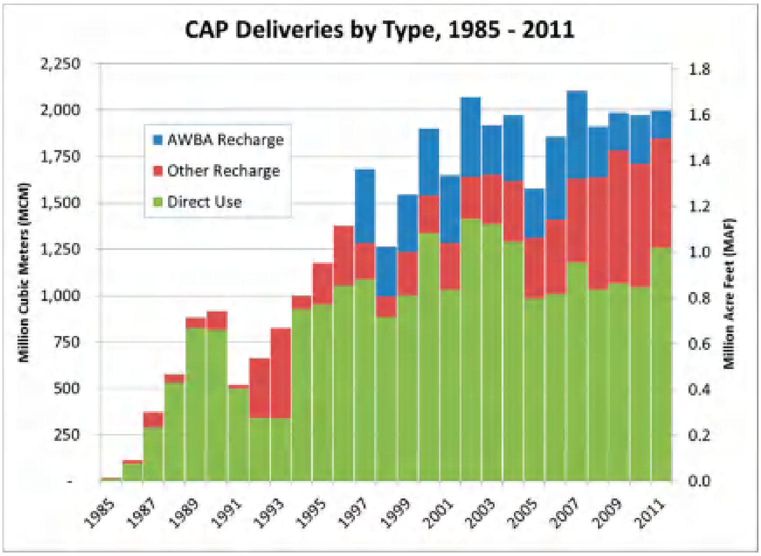
The creation of the AWBA helped establish water banking as a major water management strategy within Arizona, but it also allowed for an innovative interstate banking arrangement with the neighboring state of Nevada. The overall program allows Arizona to use a portion of its

Colorado River supply for the benefit of Nevada, but without altering the basic framework for how Colorado River water is allocated (the so-called "Law of the River") [15].

Interstate banking between Arizona and Nevada is governed by a series of agreements involving the AWBA, CAP, the federal government and counterparties in Nevada. The storage in Arizona is accomplished in the same manner as the AWBA's other recharge, but the recovery of the stored water is accompanied by an equal reduction in the diversion of Colorado River water into the CAP. That reduced diversion allows Nevada to divert a like amount of water from its upstream diversion point. Once again, it is the existence of an accounting system tied to quantified rights that permits this kind of complex transboundary exchange to take place. The scope of Arizona's interstate agreement with Nevada has undergone a number of revisions, with the most recent change reducing the likelihood that significant additional interstate banking will be undertaken. However, the AWBA has stored more than 740 MCM (0.6 MAF) on behalf of Nevada, at a cost of more than $109 million USD, and Nevada is also obligated to pay the cost associated with the eventual recovery of that stored water.

Figure 3 shows the breakdown of CAP water deliveries over time in acre-feet per year. The blue bar shows deliveries for AWBA storage, and the red shows deliveries for other recharge activities. It demonstrates graphically the critical role Arizona's storage and recovery statutes have played in enabling utilization of Colorado River water delivered through the CAP.

Figure 3. CAP water deliveries by type over time. Source: Central Arizona Project [16].



3. Policy Achievements

Arizona's key policy objective—putting its entire allocation of Colorado River water to use—was first achieved in the year 2000. That benchmark occurred in large measure because of managed aquifer recharge, particularly the storage performed by the AWBA. By taking all of the otherwise unused CAP water, the AWBA helped strengthen Arizona's negotiation position among the

Colorado River basin states, particularly with California. Arizona's full utilization also contributed to pressure applied to the federal government to confront long-standing disputes about River accounting and management practices, including changes to the operation of the two largest reservoirs on the Colorado River.

The AWBA has not yet fully achieved all of the storage necessary to satisfy all of its 100-year in-state firming goals, but the overall progress is impressive. In aggregate, 3976 MCM (3.224 MAF) have been stored for intrastate purposes, compared to the target volume of 4493 MCM (3.643 MAF). That 88.5% overall ratio does mask some variation among the goals due to the differing funding sources available for storage. At 45%, the Tucson AMA's firming goal is the furthest from completion because of a comparatively unfavorable ratio of supplies requiring firming to the revenue from local property taxes. While the firming goal is based on a percentage of municipal and industrial water contracts, the revenue available is based on assessed property valuation. Given the costs of recharge and the firming target, the revenues available over the 20-year authorization of the AWBA are not projected to be sufficient to meet the firming goal.

The AWBA is expected to continue to store CAP water for at least the next ten years. The most recent ten-year projection indicates an additional 777 MCM (630,000 AF) of storage, and all of the goals being satisfied, with the exception of the Tucson AMA. During that period the AWBA's largest revenue source—the property tax—is scheduled to end in 2017, and the annual availability of CAP water for the AWBA has been diminishing as long-term CAP contractors have been using a greater portion of their entitlements. In the face of climate change and other supply challenges on the Colorado River, the sufficiency of the existing targets has been called into question, so an upward revision of the targets, along with an extension of funding is under consideration. It should be noted that the AWBA is not the only entity storing water at the several recharge facilities. Therefore, the future status of operations at the recharge facilities used by the AWBA will depend on the storage activities of others, such as holders of long-term contracts for CAP water.

The interstate banking arrangements with Nevada (upstream on the Colorado River) have also been successful, though the benefits are a bit more difficult to quantify. The most frequently cited benefit has been the cooperative spirit it has engendered between the two states, which is not a trivial feat given the potential for conflict over the terms of the Law of the Colorado River. With a much smaller allocation (370 MCM (0.3 MAF) for Nevada *versus* 3454 MCM (2.8 MAF) for Arizona), an explosively growing population, and few water resource options, Nevada's interests had the potential to align with California's in constraining Arizona's Colorado River water use. By storing some of Arizona's water for Nevada's future benefit, the interstate banking program provided a pressure release at a critical point in the changing circumstances on the Colorado River. The most recent modifications to the interstate banking agreements reduce the scale of what had been originally contemplated, but that too is an indicator of the willingness of the parties to reach accommodation as financial and water resource situations have changed.

4. Policy Challenges

The use of managed aquifer recharge has been an important and successful tool for advancing several of Arizona's long-term policy objectives. However, it is predicated on the future ability to recover (pump) the stored water in a manner that is hydrologically and economically feasible and is also consistent with Arizona's regulatory framework. While there had been several modest planning and policy efforts that have attempted to address recovery of the AWBA's stored water, it has taken until 2014 for the parties to release a recovery plan setting out the numerous scenarios and the framework for future recovery of stored water [17].

Recovery of the AWBA's stored water will involve close coordination between the AWBA and Central Arizona Project, along with state regulators and CAP customers who are willing and able to receive a portion of their CAP order in the form of previously stored water (*i.e.*, long-term storage credits earned by the AWBA). There are a number of methods that can be utilized to make these voluntary partnerships work, each of which relies on Arizona's regulatory and accounting system to track the credits and the associated pumping.

Concerns have also been expressed related to the long-term implications of Arizona's underground storage and recovery program. The program offers an important degree of flexibility, but some of that flexibility could be in conflict with sound long-term water management. In particular, the ability to recharge in one place and recover in another could exacerbate areas of localized overdraft. Through the statutorily required Management Plan process, ADWR has recently developed draft concepts that would vary the volume of stored water that is eligible to be recovered, depending on the location of storage and recovery [18]. The status of those specific proposals is unclear at this time, but the intent to examine the longer-term implications of the program is clear. In addition, should surface water for groundwater savings projects no longer be available physically or priced economically, irrigators have the legal right to return to groundwater pumping pursuant to the GMA. This reversion to groundwater pumping has implications for groundwater tables and physical availability of the stored water for recovery by the groundwater savings partners.

5. Possibilities for Water Banking Elsewhere

Experience in Arizona suggests that characteristics favoring water banking for water security include:

- An awareness that augmentation of water resources may be necessary to address groundwater depletion or future water imbalances of supply and demand, particularly those related to climate variability;
- Availability of a source of water that enables intermittent or continuous recharge;
- Favorable hydrogeology—e.g., an extensive, transmissive aquifer with significant storage capacity;
- A well-established regulatory and accounting framework that is adhered to by water users;
- Funding mechanisms to facilitate investment in water banking, water resources planning and management, and monitoring;
- An institutional arrangement that links policy with investment.

While it is desirable for all of these elements to exist, water banking can also be undertaken in places where hydrogeological conditions may be not nearly as favorable as in Arizona.

In many places there is an awareness of groundwater depletion, which is a global problem that has been accelerating [19]. However, water banking is not very common at present, with most managed aquifer recharge currently oriented to short-term storage, which has an early return on investment. Given the value placed on secure water supplies, it is possible to make better use of aquifers through appropriate conjunctive use of surface and groundwater resources, and the long-term banking of water in aquifers that are not exposed to evaporative losses [20].

In the last few decades research on managed aquifer recharge has also shown that water quality improvements occur within the aquifer, and when combined with complementary engineered treatments, as necessary, recovered water can be fit for a full range of uses [21,22]. This has the potential to expand the use of recycled water and urban stormwater as sources for recharge. This demonstrates that sources of water for recharge are more abundant than may be perceived when intermittent excess flows in natural streams were considered the sole untapped resource.

Storing and recovering fresh water in brackish aquifers may offer an additional opportunity for water banking. The generic suitability of brackish aquifers for recovery of stored fresh water using aquifer storage and recovery (ASR), which involves recharge and recovery via the same well, has been evaluated by Ward *et al.* [23]. Miotlinski *et al.* [24] have also demonstrated that if the conditions are favorable, aquifer storage transfer and recovery (recharge and recovery via separate wells) is possible in a brackish aquifer.

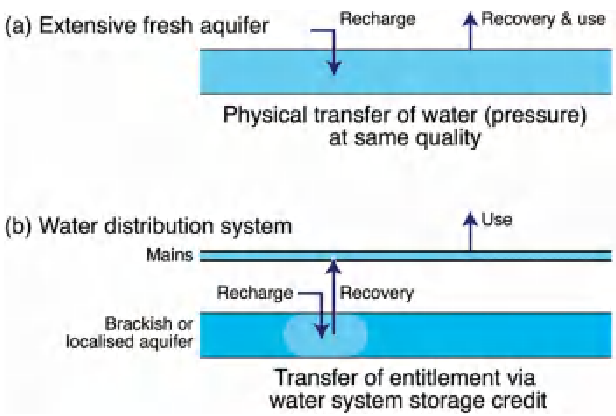
With the exception of hydrogeological conditions, the remaining factors for successful water banking relate to regulation and management.

For those considering the value of water banking and envious of Arizona's favorable hydrogeology and land availability for spreading basins, it should be pointed out that these are desirable, but not essential conditions. For example in the absence of an extensive transmissive aquifer, water may be banked in localized aquifers via a network of smaller recharge facilities connected to an existing water distribution system. In Australia, aside from Perth, few cities have aquifers similar to those of Tucson or Phoenix, but if water can be recovered from local, less transmissive and even brackish aquifers at drinking water quality, then the transmission and distribution system can act as a means to transfer entitlements generated at one place to a user located at another, as illustrated in Figure 4 [25].

Arizona also makes use of alternative forms of recharge, such as vadose zone recharge wells and buried infiltration galleries, in urban areas where land for infiltration basins is not available. One of the most advanced facilities is operated by the City of Scottsdale, which serves 87,000 active accounts within a 480 square kilometer (185 square mile) service area [26]. Scottsdale employs advanced reclaimed water treatment in conjunction with vadose zone injection and ASR wells [27]. ASR wells are used elsewhere in Arizona, and the method is equally suitable for confined aquifer systems, but, because this requires pre-treatment of the water, this is a more costly and less utilized approach [28,29].

In Australia, aquifer storage and recovery with urban storm water in a semi-arid area was found to be about ten times more expensive than the best infiltration basins but still considerably cheaper than seawater desalination [25]. Aquifer storage and recovery of recycled water was more expensive than infiltration basins but had significantly lower unit costs than storm water ASR and may provide material supplies of water for urban areas needing to secure water supplies in confined aquifers, as seen in Orange County, California [30]; Windhoek, Namibia [31]; and Perth, Australia [32]. However, a need for augmentation of water resources does not necessarily assure the existence of funding for water banking. Market failures can arise from poorly defined water rights, institutional fragmentation, incomplete accounting for the costs of evaporative losses from surface water storage, pricing that fails to fully account for supply reliability, a mismatch between the benefits of banking and those who bear the costs, and insufficient public or investor confidence to raise capital for water banking.

Figure 4. (**a**) In Phoenix the extensive fresh aquifer acts as a means to transfer credit from water recharged at one place to recovery at another, subject to water quality constraints; (**b**) Where aquifers are brackish or not highly transmissive, water needs to be recovered close to the point of recharge, and if this water is of suitable quality for transmission through the existing distribution system, this can create a credit that is transferable to other points on the system. Source: Dillon *et al.* [25].



6. Water Rights or Entitlements as a Precursor to Water Banking

In Arizona, the well-developed system of rights to use Colorado River has been key to the establishment of Arizona's water banking program. This system of contractual rights, coupled with a strong regulatory framework for water storage, has enabled successful operation to date of the AWBA. Awareness of the need for separation of entitlements to land and water is a starting point for reform in many parts of the world, including Australia, South Africa and now in at least one state of India, Jammu and Kashmir. The concept of an entitlement is required. In Australia, for example, an entity may hold an entitlement to water as a proportion or share of the total allocatable resource (that is after allowing for environmental flows). Allocations are the volumetric currency of the entitlement, and change if the allocatable resource changes. If the native groundwater system is over-abstracted, storage is in decline. Successive determinations of the allocatable volume will diminish and, in proportion, so will the allocations of all groundwater entitlements holders. In the case of source waters for recharge an entitlement is also required. A framework for incorporating managed aquifer recharge within this entitlement system is given by Ward and Dillon [33].

In Australia, an entitlement system for storm water and treated sewage effluent is not yet in place for most jurisdictions [34] but custodianship of storm water by municipal councils and of recycled water by urban water utilities is acknowledged, and so far dispute has not arisen concerning harvesting of these waters for recharge.

7. Conclusions: Tailoring Water Banking to Local Conditions

Different regions face different hydrological conditions and systems. Arizona has developed an approach to water banking based on its aquifer and surface water supply conditions in the context of its water infrastructure and regulatory framework. Currently, Australian water utilities are tasked with providing for future drought supplies, but there is no policy framework that builds incentives for investment in securing water supplies. During a recent drought, utilities in five cities established seawater desalination plants, most of which have subsequently been mothballed. The capital investment was massive and considerably greater than could have been achieved in most cases with managed aquifer recharge. (An example is described in a companion paper by Gao *et al.* [35].) So far there are no established funding mechanisms to facilitate investment in water banking in Australia. The costs of water delivered by the desalination plants have been more than 15 times higher than the previous marginal costs of supply. This is now being paid for by water utility customers through considerably higher water prices. It is timely, given that emergency supplies are in place for the short to medium term, to consider seriously an institutional arrangement that links policy with investment to ensure efficient achievement of water security objectives. The Arizona Water Bank Authority provides a salutary, and at this stage quite unique, example of institutional and policy reform, that combines an accounting framework and funding mechanisms for supply augmentation to improve the reliability of water supplies in the future. While motivations and potential for water banking will clearly vary across regions, it is hoped that this paper will inspire broad interest in uptake of such advanced groundwater management approaches.

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Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 2

Evaluation of MAR Using Alterative Methodologies

The Economics of Groundwater Replenishment for Reliable Urban Water Supply

Lei Gao, Jeffery D. Connor and Peter Dillon

Abstract: This paper explores the potential economic benefits of water banking in aquifers to meet drought and emergency supplies for cities where the population is growing and changing climate has reduced the availability of water. A simplified case study based on the city of Perth, Australia was used to estimate the savings that could be achieved by water banking. Scenarios for investment in seawater desalination plants and groundwater replenishment were considered over a 20 year period of growing demand, using a Monte Carlo analysis that embedded the Markov model. An optimisation algorithm identified the minimum cost solutions that met specified criteria for supply reliability. The impact of depreciation of recharge credits was explored. The results revealed savings of more than A$1B (~US$1B) or 37% to 33% of supply augmentation costs by including water banking in aquifers for 95% and 99.5% reliability of supply respectively. When the hypothetically assumed recharge credit depreciation rate was increased from 1% p.a. to 10% p.a. savings were still 33% to 31% for the same reliabilities. These preliminary results show that water banking in aquifers has potential to offer a highly attractive solution for efficiently increasing the security of urban water supplies where aquifers are suitable.

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1. Introduction

Growing population is increasing demand for water in many cities. In some arid and semiarid regions, climate change is projected to lead to reduced inflows to surface water reservoirs that have traditionally been the main sources of city water supply [1–4]. Municipal water utilities typically face requirements to ensure that customer water demand is satisfied with a prescribed reliability. For example, Water Corporation, the utility serving Perth, Australia has an objective of ensuring that the annual probability of a complete sprinkler ban is less than 0.5%, or a 1 in 200 year occurrence [5].

Declining, more variable surface water supply and growing demand means that many urban water utilities are contemplating or have already made additional investments in less rain dependent supply sources. For example, Australia's thirty largest utilities invested $30 billion in new municipal water infrastructure between 2006 and 2012 [6]. Choosing from a range of possible water supply sources, timings and scales to meet supply reliability criteria cost effectively is challenging. Many supply options are long-lived capital assets and they often involve scale economies favouring large increments of investment. However, unknown future inflows and thus unknown supply reliability from existing surface water reservoirs mean that if the future turns out wetter than anticipated, large capital investments can be underutilised and the full capital plus operating cost of small amounts of water supplied to ensure demand is met reliably may be very large [7].

This paper evaluates the economics of aquifer injection and banking of climate independent supplies to enable increased use of groundwater during drought when there is a low surface water supply. Another approach to balancing demand and supply pursued in places such as Arizona involves influencing household conservation ethics for example through landscaping changes that lead to reduced water demand [8]. Conceptually, this water banking strategy would be cost effective because investment can be reduced through a rainfall-independent infrastructure that meets peak demand in drought, but is otherwise left idle. An additional reason to consider storage underground to meet demand during droughts is that evaporative losses from dammed reservoirs can be large in arid and semiarid settings. In contrast in some aquifers, particularly fresh aquifers, there may be potential to store water with little loss [9].

2. Case Study Area

The case study described is based on Perth, Western Australia where demand for water has outstripped conventional supplies [10], and surface water inflows to reservoirs are diminishing due to a changing climate. Perth has a population of 1.8 million with 2008 annual consumption of public supply water of 280 Mm^3/year [11]. Its population is expected to grow to nearly 2.5 million by 2030. The utility providing public water expects demand to grow to between 380 (base case) and 425 Mm^3/year (worst case) by 2030, with actual demand depending on climate driven outdoor consumption growth, success of conservation measures, yard sizes in new housing development and actual population growth [11].

Water is currently provided from three major sources, surface water storages in the hills located to the east of the metropolitan area, regional aquifers located below the metropolitan area, and seawater desalination plants. An important characteristic of the existing surface water supply is that it is highly variable. Perth has experienced a steep change in climate leading to systematically lower inflows in the past 35 years than the mean of the previous 100 years.

While there have recently been new supply investments, additional investments are still required over the coming decades, and an adaptive plan for these investments over the next ten years has been developed by the Water Corporation [12]. Much of the focus for future investment in regional water plans is on two sources of rain independent supplies: seawater desalination and water recycling plants. The Water Corporation has developed an innovative strategy of replenishing confined aquifers with recycled water that has been treated to a very high standard [13] to address an agreed regulatory framework [14]. The utility would then withdraw more groundwater in times of drought. This would increase aquifer net recharge and net extraction in some years but would not increase cumulative net withdrawal of groundwater. Groundwater replenishment has been trialed and proven feasible at small scale (1.5 Mm^3/year) and it is likely it can be upscaled to large facilities with much lower unit costs.

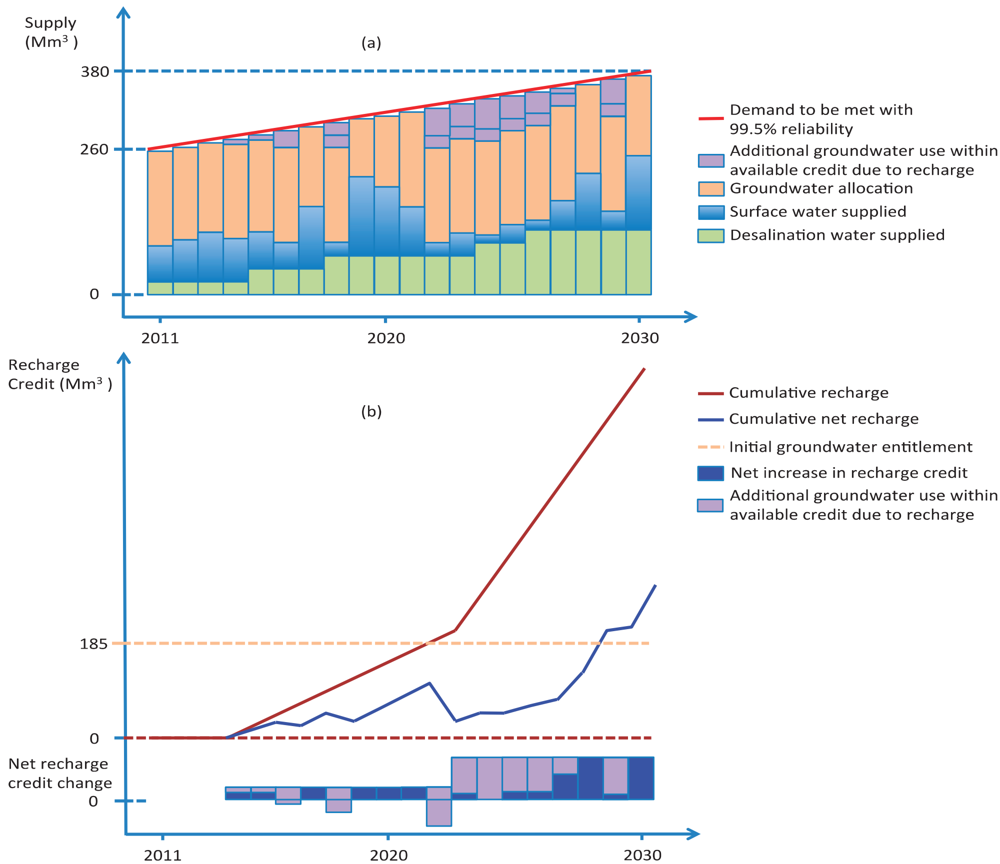
This analysis investigates the cost effectiveness of groundwater replenishment as a potential future supply. The present analysis is built on readily available data and is a generalised approximation of Water Corporation's Perth water supply sources and their potential uses, at annual time scale and aggregated at metropolitan area scale. Still we are able to demonstrate significant potential to meet a supply reliability constraint for Perth with less infrastructure investment and at considerably less cost, when replenishing groundwater and increasing withdrawals in drought is part of the supply solution. The paper concludes with a discussion of the relevance of these results for aquifers with different rates of storage loss.

3. Methodology

Demand for water in the Perth metropolitan area in 2030 is projected to exceed the recent portfolio of supply (a mix of groundwater, surface water, and seawater desalination), as shown in Figure 1a. If managed aquifer recharge is used to create sufficient groundwater credit this can be drawn on in dry years to secure the required supply, as shown in Figure 1a,b as an additional volume to the original groundwater entitlement. Groundwater recharge accumulates through the operation of the installed recharge capacity. The net recharge credit may be discounted annually to allow for losses of recharged water or fresh native groundwater as a consequence of the recharge operation over the losses that would have occurred without it. For example any increase in discharge of groundwater to the ocean due to increased hydraulic gradient attributable to recharge, which would be evaluated for specific recharge proposals, would be included in this depreciation term. In any year, this net recharge credit is diminished by the amount of additional withdrawals to meet water supply shortages over the pre-recharge entitlement.

Modelling was done to simulate two strategies to meet the growth in water demand 2011–2030 and to assess their water supply reliability. Consistent with Water Corporation planning documents we assume that one strategy involves new investments in desalination and in water recycling and water banking. In both treatments groundwater extraction levels in Perth for public water supply are restricted in line with current government regulation. In the without aquifer banking scenario the annual allocated groundwater extraction (120 Mm^3/year) is assumed to be constant across years and supply to meet shortfall is dominated by desalination. In the with aquifer banking scenario any installed recharge capacity is used to replenish groundwater and gain accumulated recharge credits to allow additional extraction, when needed, over and above the pre-existing allocated groundwater extraction.

Figure 1. An example of a portfolio of water supply and corresponding recharge credit: (**a**) the varying water supply portfolio to meet demand each year (taken from one Monte Carlo simulation; and (**b**) recharge credit accumulates based on operation of the installed recharge capacity. The net recharge credit available for extraction is the difference between accumulated recharge allowing for depreciation (losses) and accumulated withdrawals to meet water supply shortages.



A Monte Carlo analysis was used to account for variations in the annual amount of surface water available and this depended on inflows in the current and previous years and storage operation rules. In contrast, recycled water and desalinised water can be expected to be available for supply at levels up to plant capacity on a relatively constant basis. Though this is a slight simplification given that plants can experience operational problems or oil spills into ocean water can render a plant unusable for public water supply, these probabilities were considered to be sufficiently small to ignore.

Analysis is a two-step process. The first step is to determine the probability of supply meeting or exceeding demand, for a wide range of possible combinations of levels in investment in desalination and water recycling for groundwater replenishment. The supply, demand comparison algorithm accounted for stochastically varying surface water supply and the dynamics of aquifer water injection, withdrawal, losses and available recharge credits in the with aquifer banking scenario. For each possible combination of investment in desalination and recycling over a period of 20 years, 10,000 Monte Carlo realisations of surface water availability were run to calculate the percentage of the years that demand exceeds supply.

This process of calculating supply reliability is repeated for the "with-" and the "without aquifer banking" scenario. The results along with estimates of the capital and operating cost associated with a set of possible desalination and water recycling investments produce a set of cost and reliability estimates. These are input into an optimisation that solves for the cost minimising combination of investments that meets specified reliability criterion.

4. Case Study Detail

This analysis is built on readily available data and includes no detail of how Water Corporation and Perth water supply is currently configured and operated. As such, the study should be considered a somewhat stylised demonstration of the significant potential to meet a supply reliability with less infrastructure investment and at less cost, when banking is part of a supply solution.

Estimates of current water supply, and projected 2030 demand were extracted from Water Corporation and State Government reports that are readily available. The Water Corporation [14] estimates 2030 yields from currently existing supply will be 260 Mm^3 in its "base case" planning scenario. It estimates 2030 demand for this scenario at 380 Mm^3 for the 2030 base case. Thus, there is a "gap" of an average of 120 Mm^3 that will have to be filled with new supply investment to meet projected 2030 base case scenario demand.

The stochastic nature of surface water supply was modelled using information from Water Corporation annual reports characterising how much water was actually supplied from surface water storages from 1996 to 2011 [15]. A key feature of stochastic surface water supply that requires consideration in meaningful planning to reliably meet demand is how supply variability can involve multiple year sequences of relatively dry, normal or wet inflow. The length and duration of dry, normal or wet inflow year sequences are key parameters determining the reliability of surface water supply reliability. This is represented by a Markov process [16] and assumes the climate regime of each year switches between three states: high, medium and low supply. We model evolution of these state variables as a discrete Markov chain process where one type of supply year is followed by one of the three possible states based on random probability draws. The probabilities of one state following another are defined with a matrix of transition probabilities for each state variable switching to another state. Note that the Markov chain was used to describe the volume of water supplied by reservoirs in successive years, not the volume of inflow to those reservoirs.

Actual observations of volumes of Perth water supplied from reservoirs from 1996 to 2011 were used to define several levels of supply states and the transition probability matrix between states. Ideally, Markov transition models are based on hydrology and storage operating process models backed by long hydrology time series and future improvement of this study could include such modeling. Still the Markov process approach does provide an opportunity to provide evaluation of reliability and cost effectiveness implications of long dry runs.

Reliability of supply was evaluated with all possible combinations of discrete increments of investment in desalination in 25 Mm^3 increments up to 150 Mm^3 of capacity above what now exists and discrete increments 10 Mm^3 capacity to recycle water up to 80 Mm^3. We assume that the capital cost per Mm^3 level of investment in desalination ccd is \$20 million; the capital cost per Mm^3 level of investment in recycling capability ccr is \$15 million; and the operating costs per Mm^3 level of investment in desalination and recycling capability are \$0.8 and \$0.6 million, respectively based on the Science Matters report [17]. While it is true that in some circumstances recharge and withdrawal of water can be much less expensive than desalination. For our case study it is only slightly less expensive because in Perth the recharge water is highly treated prior to aquifer injection. Note that detailed modelling of cost per unit desalination is beyond the scope of this study and only flat estimation of cost is used here. We also model three levels of banked aquifer storage credit loss rate: 1%, 5% and 10% per annum. This represents a range of aquifer loss rates from typical small losses seen in slow moving large regional aquifers to much larger loss rates.

5. Results and Discussion

Results are shown below from simulations with- and without aquifer banking at two reliability criteria levels (95% and 99.5%) and for three annual rates of aquifer recharge credit loss. The minimum costs, optimal choices of Mm^3/yr capacity of desalination (D_{opt}) and water recycling and aquifer replenishment (R_{opt}) and estimated reliabilities (α) derived from 10,000 simulations for each scenario are summarised in Table 1.

Table 1. Minimum costs, optimal choices, and reliabilities under different model scenarios and reliability requirements.

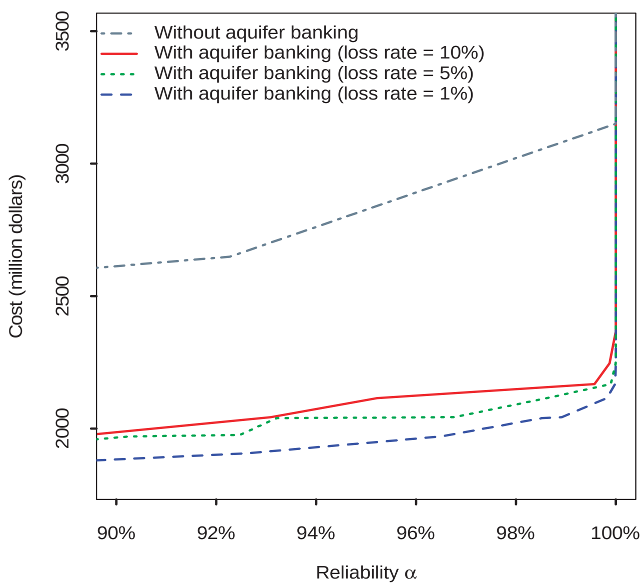
Scenario	Cost (A\$M)	Optimal Investment Choices (Mm^3/yr)	α
		***Reliability* ≥ 95%**	
		With aquifer banking	
Loss rate = 1%	1970	$D_{opt} = 25$, $R_{opt} = 50$	96.51%
Loss rate = 5%	2040	$D_{opt} = 25$, $R_{opt} = 60$	96.77%
Loss rate = 10%	2110	$D_{opt} = 25$, $R_{opt} = 60$	95.22%
		Without aquifer banking	
	3150	$D_{opt} = 125$	100%
		***Reliability* ≥ 99.5%**	
		With aquifer banking	
Loss rate = 1%	2110	$D_{opt} = 25$, $R_{opt} = 60$	99.82%
Loss rate = 5%	2170	$D_{opt} = 25$, $R_{opt} = 70$	99.90%
Loss rate = 10%	2170	$D_{opt} = 25$, $R_{opt} = 70$	99.57%
		Without aquifer banking	
	3150	$D_{opt} = 125$	100%

The results show that highly reliable water supply to meet Perth 2030 urban demand is possible with or without groundwater banking. However, the level of infrastructure investment required and hence cost to achieve a given reliability can be much reduced when aquifer banking is possible.

Both 95% and 99.5% supply reliability can be achieved with between 20 and 30 Mm^3 less new water supply infrastructure capacity and at all aquifer loss rates considered. Aquifer banking appears to be a particularly attractive strategy especially when losses from banked storage are low. Estimated savings through water banking over strategies without water banking for a 1% aquifer loss rate, over the 20 year horizon exceed A$1 billion or 37% to 33% of total supply augmentation costs at 95% and 99.5% supply reliability criteria respectively. When the hypothetical recharge credit depreciation rate was increased from 1% p.a. to 10% p.a. savings declined but were still 33% to 31% for the same reliabilities.

Figure 2 presents the trade-offs between cost and reliability (represented by the optimal pareto fronts) for with- and without aquifer banking scenarios and different rates of banked aquifer storage loss. With lower loss rates, the cost effectiveness advantage of ASR is greater, than with higher loss rates. To provide a certain security level of urban water supply, the aquifer banking scenarios outperform the without banking scenario in terms of cost for any given level of reliability.

Figure 2. Optimal pareto fronts of different model scenarios for with- and without water banking and showing the effect of rates of storage depreciation between 1% and 10% per annum.



6. Conclusions

A simplified case study based on Perth, Australia shows that an increasing demand for water can be met at the required reliability with less supply infrastructure and at less cost when it is possible to replenish the local aquifer and build a credit that can be drawn on in drought. This is because without such banking, "supply insurance" must be provided for droughts through infrastructure investments that are only infrequently used to achieve the required high reliability of supply at significantly higher average costs of supply. Hence it is demonstrated here that water banking in aquifers in order to provide drought and emergency supplies or “strategic storage” can provide a relatively low-cost insurance for cities with suitable aquifers. The economic analysis shows that aquifer banking provides greatest cost saving where there is little loss of the aquifer banked water. In aquifers with greater loss rates of stored water, the economics are still attractive compared with solutions that exclude water banking. It should also be noted that there are abstraction constraints that can limit the use of banked water in poor years depending on abstraction capacity. Finally, this study can be considered to be a qualitative demonstration of the potential benefit of groundwater banking; additional detailed analyses would be required to estimate benefits for an actual operational model.

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Conflicts of Interest

The authors declare no conflict of interest.

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Economic Assessment of Opportunities for Managed Aquifer Recharge Techniques in Spain Using an Advanced Geographic Information System (GIS)

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Abstract: This paper investigates the economic aspects of Managed Aquifer Recharge (MAR) techniques considered in the DINA-MAR (Depth Investigation of New Areas for Managed Aquifer Recharge in Spain) project. This project firstly identified the areas with potential for MAR for the whole of the Iberian Peninsula and Balearic Islands of Spain using characteristics derived from 23 GIS layers of physiographic features, spanning geology, topography, land use, water sources and including existing MAR sites. The work involved evaluations for 24 different types (techniques) of MAR projects, over this whole area accounting for the physiographic features that favor each technique. The scores for each feature for each type of technique were set based on practical considerations and scores were accumulated for each location. A weighting was assigned to each feature by "training" the integrated score for each technique across all the features with the existing MAR sites overlay, so that opportunities for each technique could be more reliably predicted. It was found that there were opportunities for MAR for 16% of the area evaluated and that the additional storage capacity of aquifers in these areas was more than 2.5 times the total storage capacity of all existing surface water dams in Spain. The second part of this work, which is considered internationally unique, was to use this GIS methodology to evaluate the economics of the various MAR techniques across the region. This involved determining an economic index related to key physiographic features and applying this as an additional GIS overlay. Again this was trained by use of economic information for each of the existing MAR sites for which economic data and supply or storage volume were available. Two simpler methods were also used for comparison. Finally, the mean costs of MAR facilities and construction projects were determined based on the origin of the water. Maps of potential sites for Managed Aquifer Recharge (or "MAR zones") in the Iberian Peninsula and Balearic Islands of Spain and the results of the previous economic studies developed at the beginning of the project were used as the foundation for the economic analysis. Based on these data, a new specific mapping of the total expected costs for all "MAR zones" (€/m^3) was proposed based on the techniques that were considered most appropriate for each Spanish study case. Capital costs ranged from Euro 0.08–0.58 per m^3/year. Overall, this study investigates the opportunity and economic feasibility of implementing new MAR projects and provides support to decision makers in Spain. The novel mapping provides valuable guidance for the future development of Managed Aquifer Recharge projects for water managers and practitioners.

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1. Introduction

This study analyzes the economic aspects in the DINA-MAR project related to the price of Managed Aquifer Recharge (MAR) water. These aspects range from simple ratios to advanced proposals based on GIS. This analysis was conducted to study the feasibility of implementing new building works and to provide support to decision makers in Spain. DINA-MAR (Depth Investigation of New Areas for Managed Aquifer Recharge in Spain) is a project financed by the Tragsa Group with the aim of determining the most suitable areas for MAR and how to implement MAR activities within Spain.

The use of GIS for determining opportunities for MAR is broadly mentioned in hydrogeological literature. Some other approaches have been consulted, especially in papers or reports from Portugal, India, Australia and Italy, which provide a different GIS mapping approach than the one displayed in this article.

A regional scale study was performed by Dudding *et al.*, 2006, [1], for the Melbourne region for ASR potential as well as for depth aquifers.

An explanation of the main features in relation to opportunities for water banking is exposed in Hostetler, 2007 [2], although the aggregated features differs from specific opportunities for MAR.

Some papers from India on GIS approaches have been consulted, as for instance the analysis from Kallalia *et al.*, 2007 [3] (pp. 111–119), for potential wastewater aquifer recharge sites, which assesses mapping MAR opportunities.

A GIS based expert system for selecting recharge methods is reported by Masciopinto *et al.*, 1991 [4] (pp. 331–342). No reference could be found on the previous use of GIS for costing of MAR projects.

The study by Pedrero *et al.*, 2011 [5] (pp. 105–116), describes a GIS-based multi-criteria analysis for site selection of aquifer recharge with reclaimed water. Another regional scale study was performed by Smith & Pollock, 2010 [6], who evaluated the artificial recharge potential for a superficial aquifer by means of GIS in the Perth region.

Three different lines of action have been accomplished and presented in the paper to analyze the economics of MAR.

First, the investment ratios of construction costs to storage volume and the mean life of the existing MAR projects with various techniques were evaluated and compared to dam and irrigation pond costs. Numerous examples were collected for statistical analysis.

Second, an advanced GIS methodology determined the “MAR zones” in Spain. After the identification of these zones, the most ideal devices were identified according to the inventory of 24 categories that were proposed in the project [7] (pp. 303–318).

Third, the origin of the water sources in the above two methods was considered. Water resources originating from either fluvial or sewage waters were then compared. Both of these water sources were budgeted.

The fluvial water is provided by a diversion structure in a river to an adequate aquifer for underground storage. Different premises have been considered according to the available flow, ease of application, suitability studies, feasibility studies and cost including exploitation and maintenance expenses. The sewage water option injects reclaimed water into deep boreholes and wells that are generally located near a sewage treatment plant. Economic studies have considered water flow, tertiary treatment, desalination, method of recharge to aquifers, construction costs, conservation costs, study costs and project costs.

Using the maps of potential sites or "MAR areas" for MAR in the Iberian Peninsula and Balearic Islands of Spain and the results of economic studies as the starting point of this study, we proposed a new specific mapping of the total expected costs for all "MAR zones" (€/m^3) that depended on the most appropriate device for each case. This novel mapping provides guidelines that are intended to be valuable for water managers and practitioners for future development of Managed Aquifer Recharge projects.

2. Materials and Methods

The methodological approach consisted of a GIS study based on ARC/GIS and DINA-MAP programs. This process determines the most appropriate areas in Spain to apply MAR techniques with potential fluvial or waste waters.

The process is recursive because the method tests different algebraic map options on constructed maps with up to 83 layers and GIS coverage. Various parameters such as permeable outcrop layers, lithology, aquifers, water levels, fluvial riverbeds, water purifying plants, data collection stations with flow-rate measurements, slopes, altitudes, and distance to the coasts have been loaded in the system and taken into consideration (Table 1 and Figure 1).

To identify the MAR zones, 11 chloropeth maps of hydrographic basins were created. An example of the results for one of the most prospective basins is shown in Figure 2. The entire map series is available at DINA-MAR website [8].

This deductive process supported by algebra maps and analysis in GIS has two major drawbacks in information processing: different projection systems and an incorrect boundary overlay of the layers and thematic coverages used. An effort to unify the map was required.

Table 1. Relating "Managed Aquifer Recharge (MAR) zones" by hydrographic major basins. Columns: basin name, the MAR zone area contained in the basin, the basin area, the percentage of the basin covered by a MAR zone and the percentage of an individual MAR of the total MAR area.

ID	Major basin	MAR Zones Areas within Basin (km^2)	Total Basin Areas (km^2)	% MAR Zones/Basin	% Total
1	NORTH	1,953	53,781	3.6	2.9
2	DUERO	21,565	78,955	27.3	32.3
3	TAGUS	10,186	55,815	18.2	15.2
4	GUADIANA	5,184	60,125	8.6	7.7
5	GUADALQUIVIR	4,878	63,298	7.7	7.3
6	SOUTH	1,458	18,408	7.9	2.2
7	SEGURA	2,283	18,833	12.1	3.4
8	JUCAR	7,892	42,682	18.5	11.8
9	EBRO	8,686	85,936	10.1	13.0
10	PYRENEES	1,746	16,555	10.6	2.6
11	BALEARIC	1,023	5,038	20.3	1.5
	Total	**66,854**	**499,428**	**13.4**	**100**

In total, 23 main layers were employed with the assigned original number as follows:

- Geology of Spain, scale 1:200 000. MMA, 2006;
- Control of nitrates in the groundwater network;
- Vulnerable areas to nitrates;
- Irrigated areas and source of water;
- Concentric polygons around rivers and reservoirs;
- Risk of flooding;
- Tilt cartography;
- Tagus-Segura aqueducts;
- Quality of water: conductivity;
- Mines into aquifers. MMA, 2006;
- Groundwater piezometric monitoring network;
- Forest mapping for Spain, scale 1:50 000);
- Hydrogeological units;
- Sewage treatment plants;
- Detailed urban areas;
- Marine intrusion control network;
- Altitude;
- Dry wetlands;
- Watersheds with water surplus;
- Distance from shore;
- Dune systems;
- Administrative boundaries;
- Current MAR sites.

Figure 1. Location map of the operative Managed Aquifer Recharge (MAR) sites in Spain.

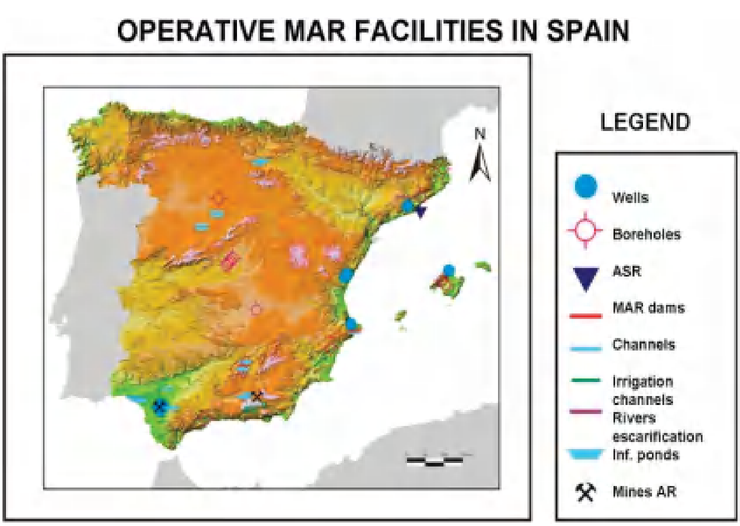
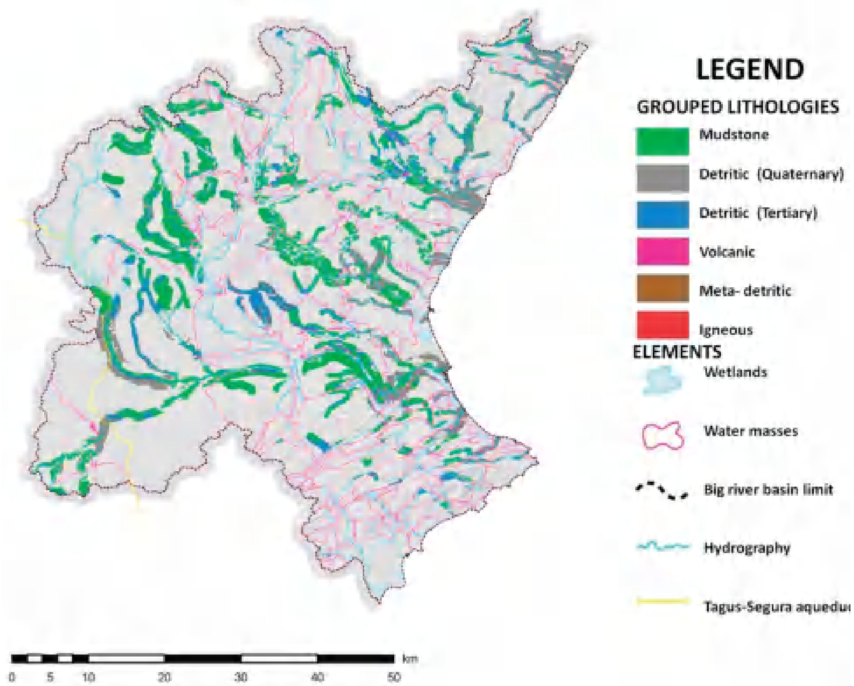


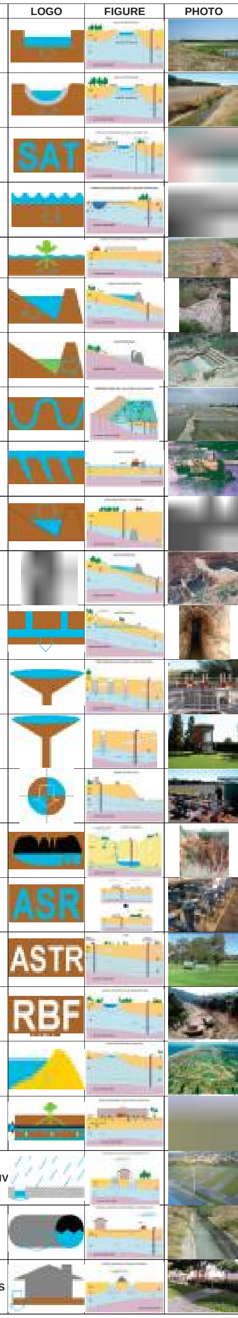
Figure 2. Example of the distribution of "MAR zones" in the Spanish Jucar basin.



The main objective of this study was to identify a process producing similar results in existing inventories. The "MAR zones" in Spain were defined after several trials. The procedure that best represented these MAR activities in Spain was adopted (detailed explanation of this process in DINA-MAR, 2010 [7]). The pixel size for map overlays was 1 km × 1 km.

To determine the ideal devices for each "MAR zone", an inventory of 24 devices previously proposed (Figure 3) was distributed and classified according to their characteristics and their most suitable environments.

Figure 3. Inventory of feasible and applicable MAR devices, modified from Fernández & San Sebastián [9] (pp. 5–6).



N	SYSTEM	MAR DEVICE	LOGO	FIGURE	PHOTO	LEGEND
1	DISPERSION	INFILTRATION PONDS/ WETLANDS				Artificial wetland to recharge in Sanchón, Coca, Segovia (Spain). Photo: DINA-MAR
2		CHANNELS AND INFILTRATION DITCHES				Artificial recharge channel of the Basin of Santiuste, Segovia, Spain, operative since 2002. Photo: DINA-MAR.
3		RIDGES/ SOIL AND AQUIFER TREATMENT TECHNIQUES	SAT			Ridges in the bottom of a infiltration pond. California. Photo: D. Peyton.
4		INFILTRATION FIELDS (FLOOD AND CONTROLLED SPREADING)				Infiltration field in Omdel (Namibia). Photo: G. Tredoux.
5		ACCIDENTAL RECHARGE BY IRRIGATION RETURN				Artificial recharge by irrigation return. Extremadura, Spain. Photo: Tragsa
6	CHANNELS	RESERVOIR DAMS AND DAMS				Artificial recharge dam in basin head. Alicante, Spain. Photo: DINA-MAR
7		PERMEABLE DAMS				Permeable dam in Huesca, Spain. Photo: Tragsatec.
8		LEVEES				Levees in Santa Ana river, Orange County, California, USA. Photo: A. Hutchinson.
9		RIVERBED SCARIFICATION				Scarification at Besós riverbed, Barcelona, Spain. Photo: J. Armenter.
10		SUB-SURFACE/ UNDERGROUND DAMS				Sub-surface dam in Kitui, Kenya. Photo: Sander de Haas.
11		DRILLED DAMS				Drilled dam. Lanjarón, Granada, Spain. Photo: Tragsatec.
12	WELLS	QANATS (UNDERGROUND GALLERYS)				Qanat at Carbonero el Mayor, Segovia, Spain. Photo: E.F. Escalante
13		OPEN INFILTRATION WELLS				Infiltration well. Arizona, USA. Photo: DINA-MAR
14		DEEP WELLS AND BOREHOLES				Artificial recharge well. Cornellá, Barcelona, Spain. Photo: DINA-MAR
15		BOREHOLES				Borehole (ASR) in Adelaida. Photo: P. Dillon
16		SINKHOLES, COLLAPSES...				Sinkhole called"El Hundimiento". Alicante, Spain. Photo: DINA-MAR
17		ASR	ASR			ASR device in Scottsdale, Arizona, USA. Photo: DINA-MAR
18		ASTR	ASTR			ASTR device in California, USA.
19	FILTRATION	RIVER BANK FILTRATION (RBF)	RBF			MAR RBFsystem in Eritrea. Photo: A. Twinhof.
20		INTERDUNE FILTRATION				Interdune filtration near Amsterdam, Netherlands. Photo: Allus.
21		UNDERGROUND IRRIGATION				Underground irrigation in Andalucía, Spain. Photo: Tragsa.
22	RAIN	RAINWATER HARVESTING IN UNPRODUCTIV				Rainwater harvesting in unproductives for MAR techniques. Photo: GIAE
23	SUDS	ACCIDENTAL RECHARGE PIPES AND SEWER SYSTEM				Artificial recharge from sewer system in Spain. Photo: Tragsa
24		SUSTAINABLE URBAN DRAINAGE SYSTEMS				SUDS. Gomeznarro park. Madrid, Spain. Photo: E.F. Escalante.

Numerous “if-then” conditions were designed into the system for each device or technique to obtain a group of ranked results for each area according to the specific conditions (Table 3).

A system of grades-weights was applied after studying each device individually; these values are presented in the "weight" column in Table 2.

Table 2. Initial indicator to determine the suitability of MAR techniques according to costing based on the ratio between the investment costs and the initial storage volume. Mean costs taken from Tragsa Group projects performed for the Spanish Ministry of Agriculture.

MAR facilities	Number of projects costed of this type	Mean investment cost ratio (€/m^3)
Ponds	18	9.75
Dams	16	0.80
Surface MAR facilities (ponds, channels)	8 ponds/58 km channel	0.21
Deep boreholes	4	0.58
Medium-deep boreholes	25	0.36

After classifying the building projects performed by the Tragsa Group for the Spanish Government according to the origin of the water, a new specific mapping was proposed for total expected costs for all "MAR zones" (€/m^3). This map depended on the most appropriate device for each case and featured a series of alternatives sorted according to technical suitability and cost.

The final map viewer is called "HydroGeoportal DINA-MAR" and is available at DINA-MAR "Visor cartográfico" website [10].

3. Results and Discussion

3.1. Investment Ratios of Building Costs against Storage Volume

The initial indicator to determine the suitability of MAR techniques according to costs was based on the ratio between the investment costs and the initial storage volume. The mean life of the devices was evaluated and compared to the cost of dams and irrigation ponds that have a 25 year lifespan.

The examples considered in this study were buildings constructed by the Tragsa Group for the Spanish Ministry of Agriculture for 18 irrigation ponds and 16 medium size dams *versus* the ratios for MAR facilities in the Arenales Aquifer (four projects) for surface infiltration facilities and in the Guadiana basin for 25 medium-depth infiltration boreholes.

Data for MAR deep boreholes was collected from Spanish water supply companies.

Mean Investment Ratios

Data sets were treated by statistical methods (eliminating the maximum and the minimum, *etc.*). The resulting ratios are as described in Table 2.

According to these results, the MAR technique results are rather cheap for basic economic indicators in comparison with other water management techniques.

3.2. Advanced GIS Methodology Based on Linear Combination of Map Layer Attributes

3.2.1. Previous Legal Considerations

In Spain, the legal and technical framework is suited to integrate more MAR devices in water management schemes, although several implementation issues remain: Currently, regulations consider MAR as a spill, which is an obstacle to the development and the implementation of this technique. Royal Decree 1620/2007 is too restrictive in terms of water quality whereas the regulations in other countries are more permissive. The laws in these other countries consider the sanitation aspects of MAR and do not regulate several effects such as the changes in sodium concentration during deep injection.

3.2.2. Determining “MAR Zones” in Spain

The main aim of this project was to determine the most suitable areas for MAR in Spain (excluding the Canary Islands on which desalination is the typical water management technique). The calculation methodology is summarized in the previous section. A detailed description may be found at DINA-MAR, 2010 [1] (pp. 215–216).

From the results, approximately 16% (67,000 km^2) of the Spanish peninsular and Balearic Islands territory is suitable for recharge management. The most ideal basins are the Duero and Balearics basins, and the least ideal are the North and Guadalquivir basins.

The determined “MAR zones” or areas notably suitable to apply MAR activities are grouped by hydrographic basins in Table 1.

3.2.3. Potential for the MAR Technique in Spain

Based on the premise defined by DINA-MAR that the future of water depends on the storage capacity, the storage potential of currently unsaturated Spanish aquifers was compared to the storage capacity of dams.

Based on the storage in dams in Spain in January 2005, which reached 53,198 hm^3, and the definition of the MAR zones, a GIS was used to compare the capacities based on the water level depth, aquifer permeability and storage coefficients. Spanish subsoil (excluding the Canary Islands) was found to have a storage capacity of, approximately, 2.0 hm^3/km^2 in the MAR zones. Therefore, approximately 260% of the stored volume in the dams could be stored in aquifers in safeguarding the quality and utility of the water. Utilizing underground storage would also enable surface occupation of the land.

Despite the uncertainty inherent in the calculations, these figures indicate the high potential for MAR activities in Spain to provide new integrated water management schemes.

3.2.4. Search Criteria Used to Associate Devices with Each “MAR Zone”

With the physical elements well defined and the specifications of the 24 inventoried AR techniques known (Figure 3), determining the most suitable technique was performed by a grades/weights system as the main association criteria. This system was designed and automated in such a way that each device receives a weight according to its suitability. This score is adjusted to the physical characteristics and other indicators with GIS support.

The established grades are the distribution of permeabilities, lithologies, nitrate contaminations, irrigable areas, irrigation origin, proximity to forests, purifying plants (with treatment types), dams (with associated capacities), wetlands, rivers (with average associated flows), distance to the coast, major aqueducts, slope, height, flood risk, water level, water quality, meteorological stations with sufficient rainfall or streamflow and urban areas. The weights range between zero (inadequate) and three (highly favorable).

By establishing a relational structure between physical factors and indicators with GIS support for MAR devices, an association matrix that supplies the HydroGeoportal DINA-MAR (Table 3) was designed and automated.

The weight columns appear to be subjective based on the suitability of each device. Because of the important role that the devices hold in the final ranking, additional criteria are adopted to minimize the subjectivity and are presented as ranges (Table 3, column 3). The ranges have been defined by the breakdown of each "layer" in different classes, generally distinguishing the different major types and establishing relevant groups to work with a reduced number of types. For example, the "water origin" layer distinguishes five types: surface water, groundwater, irrigation returns, water from treatment plants and water from desalination plants.

The weights (Table 3, column 4) appear in hierarchy according to their suitability and fit to the physical characteristics and remaining indicators. The weight assigned to each case and code directly intervenes in the process of SIG calculation because the database is associated with the calculation engine; then, an individual score is assigned to each polygon. For example, the calculation method to score device D1 (infiltration pond) is as follows. First, the fields D1, D2..., D24 are included in the layer in which all layers have been previously crossed to calculate the score for each device in these fields. The crosses table is then connected to the different facilities leader board, starting with the permeability, and D1 is calculated. Successive "joins" must be performed for each of the topics, and the formula of ranges-weights is applied to obtain a final value.

This process automatically calculates a score for each of the 24 techniques and the highest score determines the most appropriate technique.

The result is a large-scale map ranking the most to the least recommended devices (Figure 4).

The results of these calculations are expressed in the "Favorable Device" map (Figure 4).

This system has enabled several highly ideal MAR zones to be identified. For example, up to 11 MAR devices could be concentrated in the Lower Guadalhorce aquifer (Malaga) when water is withdrawn from the river and a wastewater treatment plant (Figure 5).

Table 3. Relating physical factors and indicators (based on GIS support) for different MAR devices.

Mar techniques and devices				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mar zones				Dispersion					Channels						Wells							Filtrat.			Rain	Suds	
	cases 1	code	weight	infiltration ponds/ wetlands	channels and infiltration ditches	ridges/ soil and aquifer treatment techniques	infiltration fields (flood and controlled spreading)	accidental recharge by irrigation return	reservoir dams and dams	permeable dams	levees	riverbed scarification	sub-surface/ underground dams	drilled dams	qanats (underground gallerys)	open infiltration wells	deep wells and boreholes	boreholes	sinkholes, collapses	asr	astr	river bank filtration (rbf)	interdune filtration	underground irrigation	rainwater harvesting in unproductive	accidental recharge pipes and sewer system	sustainable urban drainage systems
permeable outcrops mma 2006		very high	3	3	3	2	3	2	3	2	2	3	1	2	1	3	3	1	3	1	1	1	3	1	1	1	1
		high	2	3	3	1	3	2	2	2	3	2	1	2	1	3	3	1	1	1	1	1	3	1	1	1	1
		medium	1	2	2	1	1	2	2	2	1	1	1	2	1	2	2	1	1	3	3	1	2	1	1	1	1
geology of spain. escale 1:200.000, mma 2006		aluvial	7	3	3	2	3	1	3	3	3	3	3	3	1	3	3	3	0	3	3	3	0	1	1	1	1
		detritic	5	3	3	2	1	1	2	2	1	0	3	3	3	2	2	3	0	3	3	0	3	1	1	1	1
		karstic	6	2	2	2	2	1	3	3	2	0	1	2	3	3	3	2	3	2	2	0	0	1	1	1	1
		metamorphi c	4	0	2	2	0.5	1	2	2	0	0	1	3	1	1	1	1	0	1	1	0	0	1	1	1	1
		volcanic	3	0	2	2	0.5	1	3	3	0	0	2	2	3	1	1	1	0	1	1	0	0	1	1	1	1
		intrusive	2	0	2	2	0.5	1	2	2	0	0	2	2	1	2	1	1	0	1	1	0	0	1	1	1	1
		evaporitic	1	0	0	0	0	0	1	0	0	0	1	1	1	2	1	1	0	1	1	0	0	0	1	1	1
nitrates network for groundwater	nitrate content	<50	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		≥50	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1

Table 3. *Cont.*

Mar techniques and devices				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mar zones				**Dispersion**					**Channels**						**Wells**							**Filtrat.**			**Rain**	**Suds**	
vulnerable zones 2005	1:vulnerable zones, 0: no vulnerable zones		1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1
water origin		surface water	4	3	3	3	3	3	3	3	3	3	1	3	1	3	3	1	3	1	3	1	1	2	1	1	1
		groundwater	2	1	1	1	0.5	1	1	1	0	0	1	1	1	1	1	0	0	2	2	1	0	2	0	0	0
		irrigation return	4	0	3	1	2	3	1	1	0	0	1	1	0	1	1	1	0	0	0	0	0	1	0	0	0
		ww treatment plants	6	1	1	1	1	1	1	1	0	1	2	1	0	1	2	1	1	1	1	0	1	2	0	0	1
		desalination plants	4	2	1	0	1	0	0	0	0	0	1.5	0	0	2	2	2	1	2	1	0	1	2	0	0	0
areas up to 2 km far from dams	1:zone 2 km dams 0 bigger distance	≤ 2 km	1	2	2	2	0	1	2	0	2	2	1	1	1	1	1	3	3	3	3	3	0	2	0	0	0.5
concentric poligons close to medium flowrate rivers (1 to 5 km)	0–0.45	≤ 1 km	3	3	1	3	3	1	2	0	3	0	1	2	1	1	1	3	2	3	3	3	0.5	1	0	0	0
	>0.45–1.65	>1 to ≤ 2	3	1	2	1	1	1	1	1	0	0	1	0	2	1	1	3	1	3	3	0	1	1	0	0	0
	>1.65–7.26	>2 to ≤ 3	4	1	2	1	0.5	1	1	0	0	0	1	0	2	2	2	1	1	2	3	0	0	1	0	0	0
	>7.26–27.5	>3 to ≤ 4	5	1	2	0	0.5	1	1	0	0	0	0.5	0	2	2	2	1	1	1	2	0	0	1	0	0	0
	>27.5	>4 to ≤ 5	6	1	3	0	0.5	1	1	0	0	0	0.5	0	2	3	3	3	1	1	1	0	0	1	0	0	0
overflood risk		no risk	4	3	2	1	0	3	0	0	0	0	1	0	1	3	3	3	1	3	3	0	1	1	1	1	0.5
		maximum	1	0	0	2	3	0	3	2	3	3	1	2	0	0	0	0	1	0	0	2	1	0	0	0	1
		mean	2	1	1	2	3	0.5	2	2	1	0	1	3	1	1	0	0	1	0	0	1	1	0.5	0	0	1
		minimum	3	2	1	1	2	1	1	1	0	0	1	2	1	3	3	1	1	1	1	0	1	1	1	1	1

Table 3. *Cont.*

Mar techniques and devices				**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mar zones				**Dispersion**					**Channels**						**Wells**							**Filtrat.**			**Rain**	**Suds**	
slope intervals	%	0–10	2	3	3	1	3	1	1	1	3	3	3	1	1	3	3	3	1	3	3	3	1	1	1	1	1
		10–20	2	2	2	1	0	1	2	1	1	1	2	1	1	3	2	1	1	2	2	0.5	0	1	1	1	1
		20–30	3	1	1	2	0	0.5	2	2	0	0	1	3	2	2	1	1	1	1	1	0	0	1	1	1	1
		30–40	4	0	0	2	0	0	3	2	0	0	0	2	2	1	1	1	1	1	1	0	0	0	0	0	0
		40–50	5	0	0	2	0	0	3	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
areas until 1 km far away from wetlands	1:influency zones from wetlands/ no	≤1 km	0.5	1	2	0	3	1	2	2	0	1	2	1	1	2	3	1	1	0	0	1	1	1.5	0	0	0
areas distant up to km from tagus-segura acueduct	1:zones influency tagus-segura/ no	≤1 km	2	2	2	1	1	1	0	0	2	1	0	0	1	2	2	2	2	2	2	0	0	1	0	0	0
water quality. conductivity › 2500 us/cm	1: zones conduct < 2500	< 2500	1	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	3	2	2	1	1
	2: zones conduct > 2500	> 2500	1	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0
mines in aquifers. buffer 2 km	1:zones influency mines/0:zones no influency	≤ 2 km	2	2	2	1	1	0	1	0	0	0	1	1	3	3	1	1	0	1	2	0	0	0.5	0	0	0
land use. from corine land cover	forestry		1	0	2	3	0	0	3	3	0	0	3	3	2	1	0	0	3	0	0	0	1	0	0	0	0
	subdesertic		1	0	0	0	1	0	1	0	2	0	3	3	3	2	2	0	1	1	1	0	0	0	0	0	0
	meadows and pastures		4	1	2	2	2.5	2	1	1	1	2	0.5	0	0	2	2	1	2	0	0	0	0	1	2	0	0

Table 3. *Cont.*

Mar techniques and devices				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mar zones				**Dispersion**					**Channels**						**Wells**							**Filtrat.**			**Rain**	**Suds**	
weight according to artificiality	agrary		4	3	3	2	3	3	1	2	2	3	1	3	0	3	3	3	0	3	3	1	0	3	2	0	0
	barren		2	1	0	0	0	0	1	1	1	0	2	1	2	2	2	1	3	1	1	0	3	0	0	0	0
	glaciars & permanent snow		1	0	0	3	0	0	3	3	0	0	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	wetlands		3	2	2	0	3	1	2	2	2	3	1	0	0	0	0	0	0	0	0	2	1	0	0	0	0
	infraestruct. hidraulic		4	3	3	0	0	0	2	2	1	0	3	3	1	0	0	0	0	0	0	0	0	0	0	0	0
	infraestruct. transport		5	0	0	0	0	0	0	2	0	0	1.5	0	0	0	0	0	0	0	0	0	0	0	3	2	1
	urban		5	2	1	0	0.5	1	0	0	0	0	0.5	0	0	3	3	2	0	2	2	3	0	2	3	3	3
	industrial		5	0	0	0	0	0	0	0	0	0	0	0	0	2	2	3	0	2	2	2.5	0	0	3	2	2
buffer 1 o 5 km urban areas	1 km	nº InhabitantS < 20.000	1.5	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	3	2	2
	5 km	nº InhabitantS ≥ 20000	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	3	3	3
groundwater table 2008	isolines purple color	<25	1	3	3	1	3	3	3	1	3	3	3	1	3	3	1	0	1	0	0	3	1	3	1	1	3
		>25 to ≤ 50	2	2	2	1	1	2	1	1	1	2	3	1	2	2	3	1	1	1	1	0.5	1	2	1	1	2
		>50 to ≤ 150	3	1	1	0	0	0.5	0	0	0	0	0	0	0	0	2	3	1	3	2	0	0	0	1	1	2
		>150	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	3	3	0	0	0	0	0	2
depth groundwater table 2008	isolines pink color	P >200 m	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	0	0	0	0	0	0

Table 3. *Cont.*

Mar techniques and devices				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Mar zones				**Dispersion**					**Channels**						**Wells**							**Filtrat.**			**Rain**	**Suds**	
forestry masses. escale 1:50.000	forests		3	1	1	2	1	1	3	3	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	3
hydrogeology units suitable to be recherged according to igme, 1991			3	2	2	1	1	1	2	2	1	1	2	1	1	2	1	1	1	1	1	2	1	1	1	1	1
areas distant up to 1 km from waste water treatment plants	buffer of 1 km and eq inhabitant data	<20.000	1	1	1	1	1	1	2	1	1	1	1	1	1	3	1	1	3	1	1	1	1	1	1	1	1
		≥20000 to <200.000	2	1	1	1	1	1	2	1	1	1	1	1	1	1	3	3	1	2	2	2	1	1	1	1	2
		≥200.000	3	2	2	1	1	1	2	1	1	1	1	1	1	1	1	2	1	3	3	2	1	1	1	1	3
lagoon wwtp	buffer of 1 km		2	3	1	1	2	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1
areas up to 5 km away from marine intrusion	buffer of 5 km ptos intrusion	5 km	3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	3	3	0	0	0	0	0	1
altitude range	masl	> 0 to <20	1	2	0	2	2	2	0	1	2	1	1	1	1	2	2	2	1	2	2	1	2	1	1	1	1
		>20 to <1500	2	2	2	2	2	2	2	2	2	1	1	1	1	2	2	2	1	2	2	1	1	1	1	1	1
		>1500	1	1	1	0.5	0.5	0	3	2	0	0	0	0	1	1	0	0	1	0	0	1	0	1	1	1	1
arid zones	precipitation	>400 mm	3	2	1	0	2	2	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		≤400 mm	1	1	0	0	0.5	0.5	3	0	0	0	3	2	3	1	1	1	1	1	1	0.5	3	2	2	1	1

Table 3. *Cont.*

Mar techniques and devices				**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mar zones				**Dispersion**					**Channels**						**Wells**							**Filtrat.**			**Rain**	**Suds**	
meteo stations with water surplus	sub-basins water surplus		2	2	1	1	2	2	2	2	2	1	1	2	1	3	1	1	2	1	1	2	2	1	2	2	3
distance to the coast		< 2 km	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1
		> 2 to < 5 km	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
		≥ 5 km	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	3	1	1	1	1	1
dunar systems (corine)			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	0

Figure 4. Map of MAR areas and the most appropriate MAR devices. The "HydroGeoportal DINA-MAR" [10] package also provides additional options for each zone.

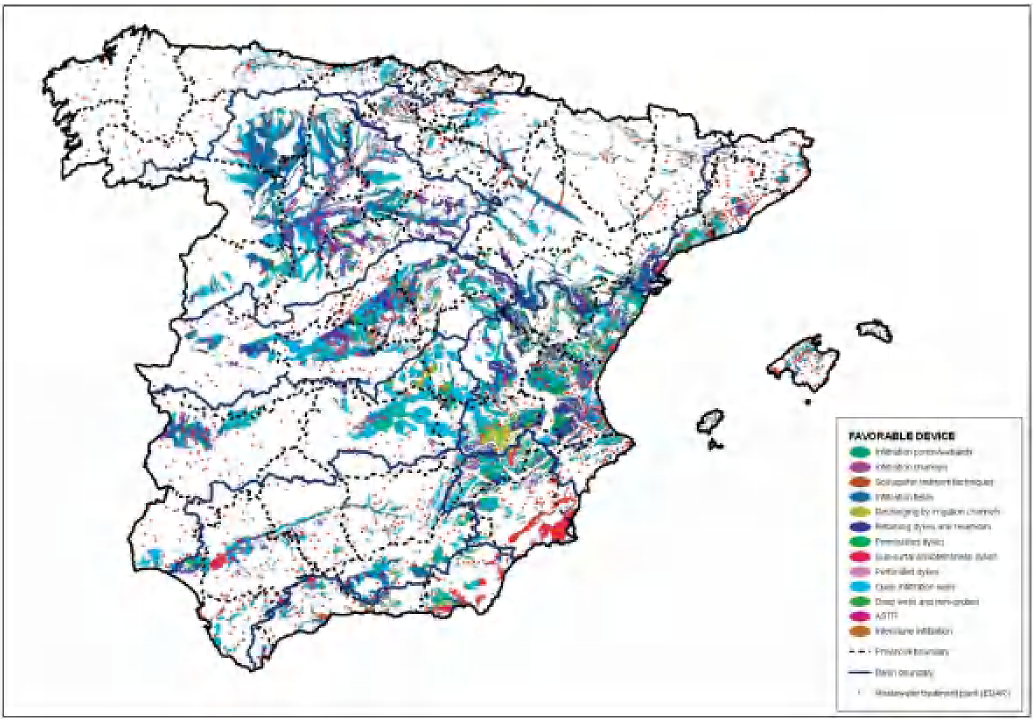
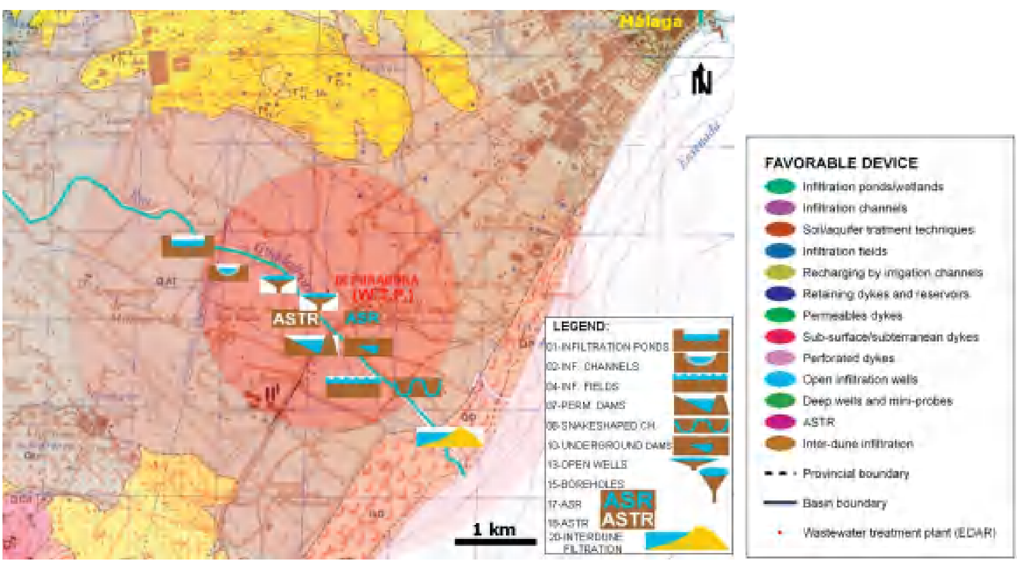


Figure 5. "HydroGeoportal" predicting suitable areas to apply a MAR technique, notably in the Lower Guadalhorce aquifer (Malaga, Spain). The map displays the proposed location of MAR devices obtained through the exposed grades/weights system.



3.3. Economic Studies for MAR Activities Implementation Based on the Origin of the Water and Its Incorporation into "Hydrogeoportal" Map Viewer

An economic study was developed based on the investment ratio or the cost of the device in relation to the recovered water. The ratios for superficial MAR devices are approximately 1/5 of the ratio of the dams, whereas the ratio for ASR is similar to the dams ratio.

The referred study provides two alternatives for decision-making according to the origin of the sources of water, either of fluvial origin or sewage waters.

Table 4 shows the estimation process of the cost intervals. Column 3 differentiates six types according to either the origin of the water or the context in which each device is intended to be implemented. The five distinct classes are as follows: devices in river areas (wells, ponds and canals), dams and dikes in either surface or underground alluvial terrain, urban sustainable drainage systems, drilled wells less than 50 m deep and deep boreholes (deeper than 50 m).

The first alternative diverts running water from a river, channeling the water to an adequate aquifer (underground storage). This technique has several advantages including minimal occupation of the surface, less evaporation, preserved water quality, and the relatively low costs for the storage. For example, from the first row, using a river as a source of intake has a potential cost per action (investment ratio) of close to € 0.20/m^3 for an 8 km conduction pipe and the artificial recharge is performed using channels, infiltration ponds and wells. The cost for each activity is estimated to be close to 1.2 M€. Exploitation and maintenance costs have been estimated at € 0.01 m^3/year (real data taken from budgets of building projects performed by the company that the authors work for, in DINA-MAR, 2010 [7]).

The other considered alternative is the direct injection of reclaimed water during managed aquifer recharge (files 5 and 6) using deep injection boreholes and wells. These injection sites are generally located in the vicinity of sewage treatment plants. The water must be tertiary treated, osmotized and inserted into the aquifers. The flow availability is more regular than in the previous alternative. This study considered flows between 50 and 80 l/s to be recharged through 50 m depth wells. Flows exceeding 100 l/s require boreholes approximately 500 m in depth (average values). This technique does not require special water surpluses and can be used for numerous purposes such as irrigation, combating marine intrusion, environmental practices, and industrial supply. The unit cost of investment is € 0.23/m^3 (50 m) and € 0.58/m^3 (500 m) (tertiary treatment was not considered). An average estimated cost for a 50 m building project is 172,500 €, and 580,000 € is estimated for a borehole 500 m depth plus additional MAR facilities. The estimated costs of conservation per year are € 0.13/m^3 (50 m) and € 0.15/m^3 (500 m).

The premises considered were the variability of the available flow (100 to 1000 l/s) and the possibility of applying this technique in approximately 16% of the Spanish territory (excluding the Canary Islands). This investigation also considered that the projects must be subject to concessions and require detailed suitability and feasibility studies.

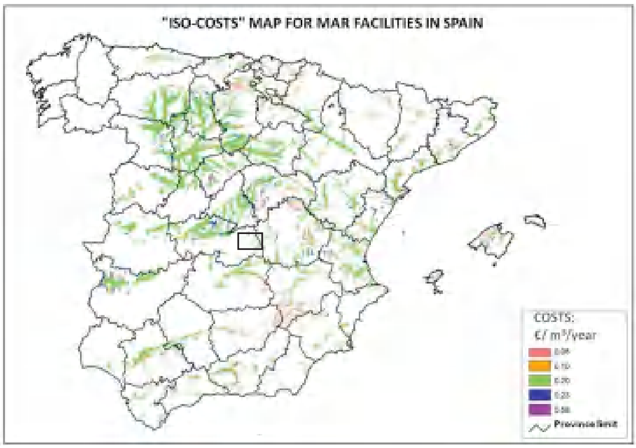
The standards for water quality are ambitious in Spain; therefore, the costs may be lower for countries with less rigorous regulations.

Table 4. The averaged economic index prior to connection with inventoried devices and "MAR zones" in the "HydroGeoportal DINA-MAR" iso-costs layer. The top numbers are specified in Figure 2 (inventory). 1/0 indicates applies/not applies.

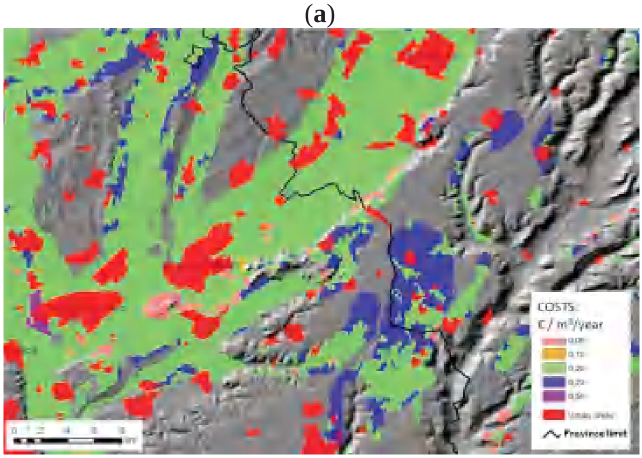
Mar techniques and devices				**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
				Dispersion					**Channels**						**Wells**							**Filtration**			**Rain**	**Suds**	
	cases 1	code	weight	infiltration ponds/wetlands	channels and infiltration ditches	ridges/ soil and aquifer treatment techniques	infiltration fields (flood and controlled spreading)	accidental recharge by irrigation return	reservoir dams and dams	permeable dams	levees	riverbed scarification	sub-surface/underground dams	drilled dams	qanats (underground gallerys)	open infiltration wells	deep wells and boreholes	boreholes	sinkholes, collapses	asr	astr	river bank filtration (rbf)	interdune filtration	underground irrigation	rainwater harvesting in unproductive	accidental recharge pipes and sewer system	sustainable urban drainage systems
Economic index (average inversion)	euros/m3/year	fluvial	0.20	1	1	1	1	1	0	0	1	1	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0
		river dams	0.10	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		buried dikes in rivers	0.22	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
		suds (urban)	0.08	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	1	1	0
		wwtp <50 l/s	0.23	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
		wwtp >50 l/s	0.58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	

Using the maps of potential “MAR Zones” for Managed Aquifer Recharge in Spain Iberian Peninsula and Balearic Islands (in [8]) as the starting point, a new specific mapping is proposed using the total expected costs for each zone (€/m^3) that depended on the most appropriate device for each case. The result is a novel map (Figure 6).

Figure 6. (**a**) Choroplethic map of “iso-costs” for the best MAR facilities in each “MAR Zone” for Spanish Peninsula and Balearic Islands; (**b**) Detailed view for the East of Madrid province (square in Figure 6a). These results are available at DINA-MAR [8].



(**a**)



(**b**)

Classes:

- € 0.08 /m^3. Urban (SUDS) /forestry runoff capture;
- € 0.10 /m^3 Surface devices from river origin;
- € 0.20 /m^3 MAR from buried dikes in rivers;
- € 0.23 /m^3 Wells and boreholes with an injection capacity below 50 l/s;
- € 0.58 /m^3 Boreholes with an injection capacity exceeding 50 l/s.

This novel mapping provides valuable guidance for future development of MAR projects. Water managers and practitioners are anticipated to be able to utilize these innovative results.

4. Conclusions and Comments

Results show that 16% of the 500,000 km^2 area studied using GIS has potential for MAR using a range of techniques adapted to the local situation. In these areas MAR is rather cheap in comparison to surface water storage techniques. The net savings in capital costs if MAR was practiced instead of dams is about 75% for superficial facilities (ponds and channels), about 50% for medium deep wells and 27% for deep boreholes.

Detailed calculations are necessary to support the results and justify future actions. Calculations may be inaccurate, and the resulting figures may cause water managers to consider opportunity costs prior to decision making.

Regarding legality, reviewing current legislation would be desirable (despite the associated difficulty of this goal) because often regulations "fall behind" technological advances. Additionally, the new charges and expenses caused by the economic crisis, some of which may take the form of higher taxes in some communities, have reduced the interest of private investors to undertake MAR projects.

The further understanding of the economics of MAR and an evaluation of the environmental and social effects are necessary. Additionally, the involvement of industry (e.g., agro-industries, desalination agents, waste water treatment agents, and golf courses) in MAR is crucial.

The work presented here could be applied in other countries with appropriate modifications. One aspect to consider in calculations of the "MAR zones" is that the terrain of other countries could vary from the conditions in Spain. The terrain type determines the surface runoff (e.g., plains, plateaus, and moors) and the groundwater flow. Additionally, applying and understanding MAR techniques in heavily deforested areas is desirable according to the results in Figures 2 and 4.

New designs may encompass as many "low cost" devices (example in Figure 7) as possible according to necessities.

Figure 7. Example of a "very low cost" domestic MAR device in Madrid.

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Author Contributions

The authors participated in different stages during the "Hydro-geoportal" production. Enrique Fernández and María A. San Miguel developed the application and coordinated the different stages. Rodrigo Calero calculated the cost and value of the different options for real-building work budgets. Fernando Sánchez provided the IT input for the GIS to be incorporated into a map viewer and studied its compatibility with the EU INSPIRE Directive.

Conflicts of Interest

The authors declare no conflict of interest.

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A System Dynamics Model to Conserve Arid Region Water Resources through Aquifer Storage and Recovery in Conjunction with a Dam

Amir Niazi, Shiv O. Prasher, Jan Adamowski and Tom Gleeson

Abstract: Groundwater depletion poses a significant threat in arid and semi-arid areas where rivers are usually ephemeral and groundwater is the major source of water. The present study investigated whether an effective water resources management strategy, capable of minimizing evaporative water losses and groundwater depletion while providing water for expanded agricultural activities, can be achieved through aquifer storage and recovery (ASR) implemented in conjunction with water storage in an ephemeral river. A regional development modeling framework, including both ASR and a dam design developed through system dynamics modeling, was validated using a case study for the Sirik region of Iran. The system dynamics model of groundwater flow and the comprehensive system dynamics model developed in this study showed that ASR was a beneficial strategy for the region's farmers and the groundwater system, since the rate of groundwater depletion declined significantly (from 14.5 meters per 40 years to three meters over the same period). Furthermore, evaporation from the reservoir decreased by 50 million cubic meters over the simulation period. It was concluded that the proposed system dynamics model is an effective tool in helping to conserve water resources and reduce depletion in arid regions and semi-arid areas.

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1. Introduction

Groundwater extraction has enabled significant social development and economic growth, enhanced food security and alleviated drought in many of the world's farming regions [1]. However, if groundwater abstraction exceeds groundwater recharge or decreased baseflow, persistent groundwater depletion or overexploitation problems can occur [2,3]. Groundwater depletion is a significant threat in arid and semi-arid areas, where rivers are usually ephemeral and groundwater is the primary source of water. Consequently, in many arid countries, dams are built on ephemeral rivers to provide farmers with an expanded and reliable source of water. However, the major disadvantages of dams in arid regions are the high evaporation loss from reservoirs and water quality degradation.

An alternative to constructing dams is recharge enhancement [4], a technique used to increase groundwater availability. One well-known recharge enhancement technique is the engineered system of aquifer storage and recovery (ASR), whereby surface water is moved to aquifers via injection wells and serves to bolster groundwater resources. This water can later be recovered for reuse by conventional pumping. The technique was first implemented in 1957 to inject potable water into saline aquifers [5,6].

Given increasing water demand, stresses on supply and wet *versus* dry season water imbalances, managed aquifer recharge (MAR) techniques, including ASR, are likely to become an important component of water projects in arid and semiarid regions [7]. Aquifers offer significant opportunities for underground water storage, reducing the need of high-cost surface reservoirs and storage tanks. Applying MAR techniques can also act to restore a depleted aquifer's functionality [8]. Moreover, MAR can improve agricultural water security, thus improving the livelihood of farmers and providing economic, social and environmental benefits.

In terms of economic benefits, MAR has direct, as well as indirect financial benefits. The costs involved in MAR projects depend on several variables, including location, land prices, method of recharge, geological conditions, design of the entire holistic system, construction costs and initial water quality [9,10]. For two such projects in Australia, the costs of recharge per million liters were 625 USD and 2,000 USD [5,11]. In addition, MAR increases agricultural productivity, which, in turn, improves farmers' livelihood and provides direct benefits, not only at the economic level, but also at the social and cultural levels. A cost benefit analysis developed for a case study in southwest Iran found a 1:1.32 ratio of project investments to agricultural profits, with an estimated payback period of three years [12].

In basins approaching full development of water resources, optimal beneficial use can be achieved by conjunctive use, which involves coordinated and planned operation of both surface water and groundwater development. The concept of conjunctive use of surface water and groundwater is based on surface reservoir impounding stream-flow, which is then transferred at an optimum rate to groundwater storage. Surface storage in reservoirs behind dams supplies most of the annual water requirements, while groundwater storage can be retained primarily for cyclic storage to cover years of subnormal precipitation [13].

There are some successful examples of conjunctive water resources management around the world, such as the elaborate institutional arrangements for conjunctive use and groundwater management in southern California that have been in place since the 1950s [14]. Kern Water Bank (KWB) in California is another successful example. The KWB stores excess water supplies that are available when rainfall or runoff is plentiful by recharging that water through shallow ponds into an aquifer. The stored water is then recovered in times of need by pumping it out with wells [15]. In some cases, treated sewage effluent has been used as the source of water. For example, sewage reclaimed water from an advanced treatment facility is recharged in the wells of the hydraulic barrier constructed to protect the Los Angeles coastal aquifer from seawater intrusion in southern California. Similarly, in the Dan region in Israel, treated sewage effluent from the metropolitan area of Tel Aviv is recharged in sand dunes and then subsequently pumped for various uses [16].

The objective of this study was to determine if ASR, in conjunction with water storage on an ephemeral river, can be an effective water resource management strategy, minimizing evaporative water losses and groundwater depletion rates, while providing water for expanded agricultural activities. The provided framework, based on system dynamics modeling, consists of a dam, recharge wells, extraction wells and water conveyance units, which can be considered as a "Comprehensive Conjunctive Use System" [13]. A modeling framework based on system dynamics modeling was applied to a regional development plan, including both ASR and a dam, and validated through a case study undertaken in the Sirik region of Iran. Given its semi-arid climate and lack of regular surface water, the agricultural production in the Sirik region is heavily dependent on groundwater. Unsustainable groundwater extractions, leading to a declining groundwater table, have threatened both agriculture and local ecosystems. This has led to proposals to build the Merk dam, which would increase the water supply and thereby allow more farms to be irrigated. The effects on groundwater levels of four different ASR schemes were modeled, and in order to assess their respective financial, social and environmental feasibility, each scheme was subjected to a cost/benefit analysis. This analysis considered economic factors, the quantity of water available for environmental flows, the quantity of water to be released from spillways, as well as the social acceptability.

2. System Dynamics Modeling in ASR Using a Surface Water Reservoir

Sustainable water resources management requires a decision-support approach that accounts for dynamic connections between social and ecological systems, integrates stakeholder deliberation with scientific analysis, incorporates diverse stakeholders' knowledge and fosters relationships among stakeholders that can accommodate changing information and changing social and environmental conditions [17]. A system dynamics modeling (SDM) approach has the unique ability to model participatory and stakeholder analysis in water resources and ecological studies [17–21].

Within the few scientific publications that address the application of a system dynamics approach to groundwater issues, groundwater systems are either oversimplified or considered solely as a reservoir. Moreover, in these studies, modeling practices differ substantially from those employed in conventional mathematical groundwater modeling [21–24]. Although such oversimplification (e.g., ignoring the spatial variability of groundwater systems) decreases model runtime, it also decreases model accuracy [24].

Modeling a reservoir's functions and linking it to an aquifer system while considering various socio-economic factors would constitute a comprehensive and integrated modeling approach. However, at present, there is no comprehensive integrated modeling software that can be used in addressing water resource management problems. On the other hand, system dynamics modeling software packages are flexible and integrated modeling tools, which can be applied to any problem, including participatory modeling and economic analysis. Conventional models, such as MIKE-BASIN (developed by DHI, which is an extension of ArcGIS for integrated water resources management and planning), WEAP (Water Evaluation And Planning system, which is a Windows based decision support system for integrated water resources management and policy analysis) and OASIS (a software program that simulates the routing of water through a water resources system), are all limited to water resources applications [25]. In the proposed groundwater modeling approach described in this paper, a modified spatial system dynamics (MSSD) approach was combined with reservoir function modeling.

Typically, a SDM (system dynamics model) project comprises the following stages: problem definition, system conceptualization, model formulation, model evaluation/testing, policy analysis and implementation [20,26–29]. It is therefore important to determine all system components and their mutual relationships in advance. Table 1 portrays the basic elements that can be found in all system dynamics models and describes each system component.

Table 1. Basic components of system dynamics models.

Symbol	Name	Definition
	Arrow	Shows a directional relationship between two variables.
	Rate	Rate (or flow variable), also called a flow variable, represents change per unit time of a state variable; the cloud mark at the end or the beginning of the rate represents a sink or a source, respectively. These cloud marks can be replaced by a level, in which case, the rate will cause subtraction or accumulation at each time step.
Level	Level or Stock	Also called accumulation, stock or state, it represents accumulation.
Auxiliary variable	Auxiliary variable	Supporting variables that are constant.

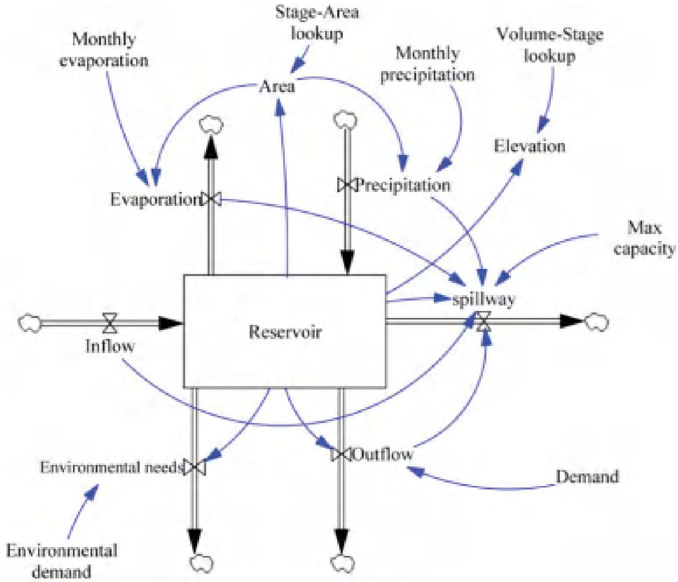
System Dynamics Model Conceptualization and Formulation

The system dynamics model in this study was developed using VENSIM [30] software. The model consists of two key segments, the reservoir model and the groundwater model. The ASR was modeled as a connection between these two segments. By taking into account the relevant components of the surface reservoir, the surface water reservoir segment of the model was the first to be built (Figure 1). This segment included a single level (reservoir), representing the volume of water in the reservoir at each time increment:

$$\text{Reservoir} = \text{Inflow} + \text{Precipitation} - \text{Environmental needs} - \text{Outflow} - \text{Evaporation} - \text{Spillway discharge} \quad (1)$$

Precipitation and inflow are the model's two inputs. Precipitation represents the amount of water directly contributed to the reservoir by precipitation and is a function of the monthly precipitation rate and the expanse of water the reservoir represents. This rate was calculated by multiplying monthly precipitation by the reservoir's surface area. Inflow is the river's discharge into the reservoir. The inflow was calculated based on historical hydrological data for the river, imported through the "get Excel" data function in VENSIM.

Figure 1. System dynamics model of the surface water reservoir segment.



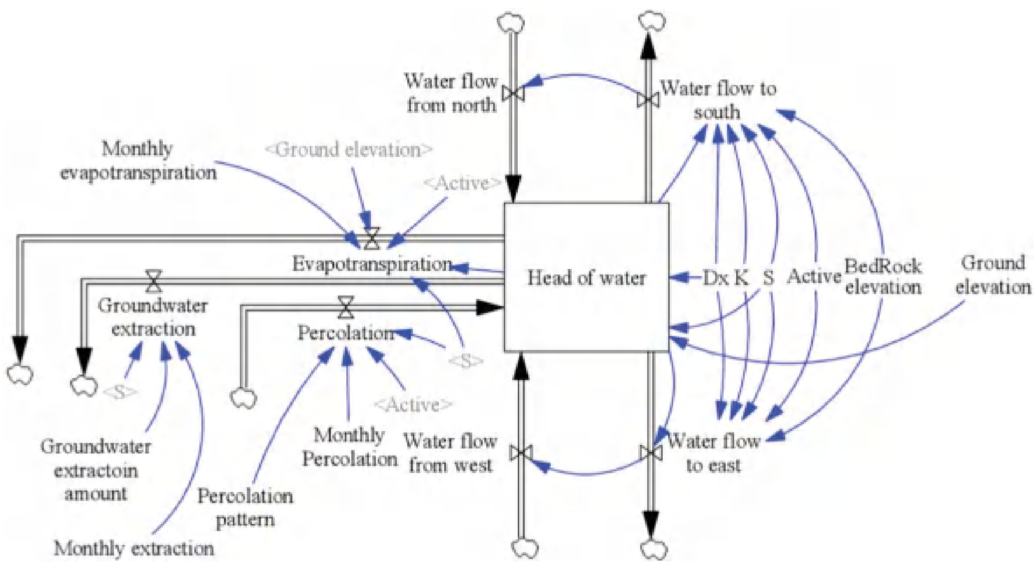
Evaporation, Environmental needs, outflow and spillway discharge represent the model's outputs. Evaporation, the volume of water evaporated from the reservoir surface at each time step, is a function of monthly evaporation and the reservoir's surface area. This volume was calculated by multiplying monthly evaporation by the reservoir's surface area. Monthly evaporation was derived from historical evaporation data for the study area and was introduced to the model by using the "get Excel" data function. At each time step, the reservoir surface area was taken from a volume-stage-area chart for the reservoir. Environmental needs and outflow were derived based on the allocated environmental needs and the irrigation water demand, respectively. Spillway discharge represents the excess water at each time step that exits the reservoir. Spillway discharge is a function of evaporation, precipitation, inflow, environmental needs, outflow, reservoir and the maximum (Max) capacity of the reservoir:

$$\begin{array}{l}\text{If (Inflow} - \text{Evaporation} - \text{Outflow} + \text{Precipitation} + \text{Reservoir)} > \text{Max capacity, then Spillway} > 0) \\ \text{If (Inflow} - \text{Evaporation} - \text{Outflow} + \text{Precipitation} + \text{Reservoir)} < \text{Max capacity, then Spillway} = 0)\end{array} \quad (2)$$

The groundwater modeling portion of the model was developed according to the spatial system dynamics (SSD) concept of a grid-based interaction of spatially-distributed system dynamics modules [28]. The SSD methodology has been used extensively in ecological modeling [31,32] and combines the powers of temporal and spatial analysis, achieved through systems dynamics and geographic information systems (GIS), respectively. This system was later used to model groundwater flow through compartmental spatial system dynamics (CSSD) [24]. Such a framework was intended to address issues related to groundwater and surface reservoir management.

The "stuck" head of water within the system dynamics model's groundwater modeling segment is presented in Figure 2 and represents the head of water in each cell in the discretized aquifer domain. Each cell has flow toward four adjacent cells, located to its north, south, east or west. The head of water is a function of water flow from or toward the cell, water extraction from the cell, along with direct evapotranspiration and percolation. The water flow is calculated based on Darcy's law. The head of water in the aquifer domain must be calculated based on the "subscript" function in VENSIM. The volume of water having entered or exited from the level is transformed into the head of water by dividing it by the area of the cell and the storage coefficient of the aquifer media. As square-shaped cells are used in this framework to simplify the modeling exercise, the cell area was the square of one side of the cell.

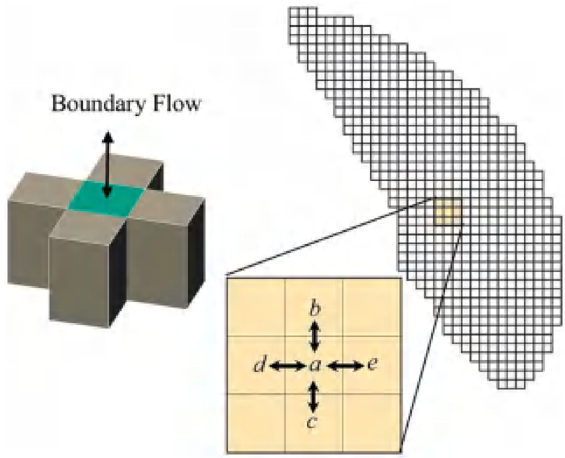
Figure 2. System dynamics model of the groundwater-modeling segment. Representing the active or inactive cells in the modeling domain, "active" is an auxiliary variable, which can also serve to define aquifer boundary conditions; S represents aquifer specific yield; Dx represents the length of one side of the cell; and K is the hydraulic conductivity of each cell in the aquifer.



There were seven rates in this segment: water flow to south, water flow to east, water flow from the north, water flow from the west, percolation, evapotranspiration and groundwater extraction. Water flow toward or from adjacent cells were calculated in the first four rates of the last statement, and the three remaining rates account for the boundary flow from the top of the aquifer. Technically, water flow is calculated in two rates: water flow to the south and water flow to the east. Water flow from the west and water flow from the north are water flow to the east and water flow to the south of the previous cell. Based on Darcy's law, water flow is a function of the media's hydraulic conductivity, the head of the water in two adjacent cells and the length of the cell.

The occurrence of direct evapotranspiration from groundwater is a function of ground elevation, head of water and the region's monthly evapotranspiration rate. If the head of water reaches within a certain distance of the ground surface, direct evapotranspiration can occur. This distance varies according to the aquifer media. Groundwater extraction and percolation are introduced to the model according to their monthly rates and pattern in the aquifer domain. In the groundwater modeling approach presented in this paper, the mass conservation concept was applied in each cell of the discretized aquifer (Figure 3).

Figure 3. Aquifer discretization and groundwater modeling paradigm in the system dynamics model.



The change in storage in cell *a* is equal to the sum of the flow into *a* minus the sum of flow out of *a* to adjacent cells:

$$\frac{ds_A}{dt} = Q_{ab} + Q_{ac} + Q_{ad} + Q_{ae} + Q_{aB} \tag{3}$$

Where,

$\frac{ds_A}{dt}$	is the change in storage through time in cell *a* ($L^3 \cdot T^{-1}$);
$Q_{ab}, Q_{ac}, Q_{ad}, Q_{ae}$	is the flow into *a* from *b*, *c*, *d* and *e*, respectively, ($L^3 \cdot T^{-1}$); and
Q_{aB}	is the sum of boundary flows to cell *a* ($L^3 \cdot T^{-1}$).

All flows are positive for flow into *a* and negative for flow out. Boundary flows are flow terms entering or leaving cell *a*, such as evaporation, evapotranspiration, natural recharge, artificial recharge and groundwater extraction. Ground water flow between two cells, Q_{ab}, can be described using Darcy's law:

$$Q_{ab} = \frac{(T_a + T_b)}{2} \cdot \Delta x \cdot \frac{(h_a - h_b)}{\Delta x} = \frac{(T_a + T_b)}{2} \cdot (h_a - h_b) \tag{4}$$

where,

h_a	is the head of water in cell *a* (L);
h_b	is the head of water in cell *b* (L);
T_a	is the transmissivity of cell *a* ($L^2 \cdot T^{-1}$);
T_b	is the transmissivity of cell *b* ($L^2 \cdot T^{-1}$); and
Δx	is the discrete distance used in the model (L).

By substituting Equation (4) and analogous terms for cells *b*, *c* and *d*, Equation (3) can be written as:

$$\frac{ds_a}{dt} = \frac{(T_a + T_b)}{2} \cdot (h_a - h_b) + \frac{(T_a + T_c)}{2} \cdot (h_a - h_c) + \frac{(T_a + T_d)}{2} \cdot (h_a - h_d) + \frac{(T_a + T_e)}{2} \cdot (h_a - h_e) + Q_{aB} \quad (5)$$

Using a finite time step approximation for storage change, adding superscript notation to specify time and converting to matrix form for all possible generic ground water cells, Equation (4) can be rewritten to solve for storage in aquifer cell *i* at time *t* + 1 as a function of storage and head values at time *t*:

$$S_i^{t+1} = S_i^t + \Delta t \left[\sum_{j=1}^{4} (Q_{ij}^t) + Q_{iB}^t \right] \quad (6)$$

where,

Q_{ij}^t is the flow in or out of cell *i* from four adjacent cells ($L^3 \cdot T^{-1}$);

Q_{iB}^t is the boundary flow ($L^3 \cdot T^{-1}$);

S_i^t is the storage of cell *i* at time *t* ($L^3 \cdot T^{-1}$);

S_i^{t+1} is the storage of cell *i* at time *t* + 1 ($L^3 \cdot T^{-1}$); and

Δt is the simulation time step (T).

This is a forward difference explicit solution for calculating groundwater heads in one time step from head values at the previous time step. Aquifer storage (S_i) is related to aquifer head using the relationship between storage and head in an unconfined aquifer:

$$S_i = (h_i - Z_{bed}) \cdot \Delta x^2 \cdot S_y \quad (7)$$

where,

S_y is the specific yield of the aquifer ;

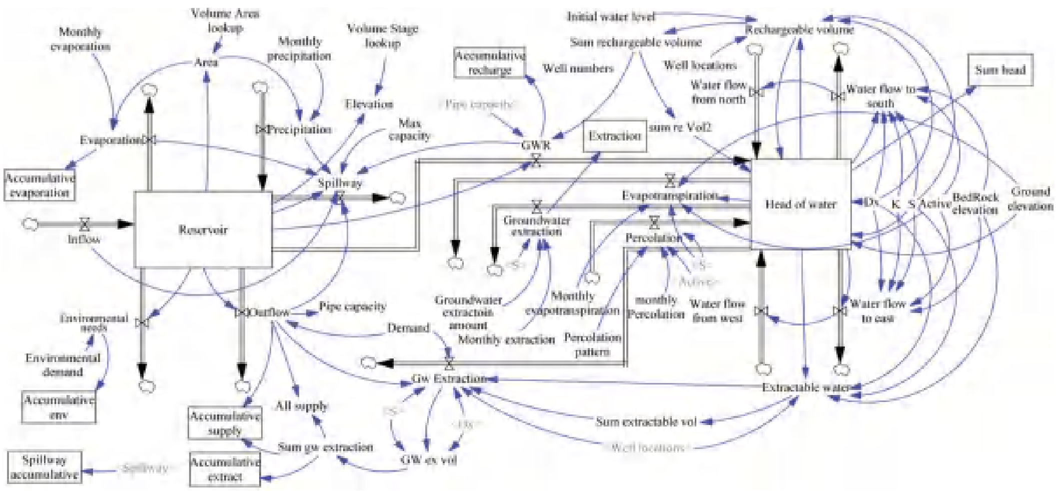
Z_{bed} is the bedrock elevation (L).

Because the forward difference explicit formulation calculates the future state based on the present state, the system of equations can be unstable if the time step is too long relative to the spatial scale and the rate of the movement of water between cells. Therefore, a small time step (such as 0.8 days, as was used in this study) must be used to prevent such a problem.

Having developed a surface water reservoir model and a groundwater model in the system dynamics environment, an ASR segment was added. This can be turned on/off automatically, as needed, in order to quantify the impacts of using ASR for the recharge or extraction of water from the aquifer. In the combined model, as illustrated in Figure 4, the left segment of the system represents the relevant components of the reservoir, while those on the right model groundwater in the aquifer based on the principles explained above.

The connection between the reservoir and the groundwater system is the groundwater recharge rate (GWR), fixed by the rate of water injection determined by the ASR approach. This rate is dependent on the availability of water in the reservoir, the pipeline capacity and the volume of rechargeable water in the groundwater system. As the purpose of the wells is to replenish depleted water, not to raise the water table above its original level, the rechargeable volume is based on the difference between the historical initial level and the actual level of the groundwater table in the cells containing ASR wells.

Figure 4. System dynamics model components.



3. Study Area

3.1. Local Setting

The Sirik region, situated between 26°22' N and 26°43' N lat. and between 57°4' and 57°46' E long., houses an aquifer occupying 65 km^2 on the southern edge of Hormuzgan Province, Iran. The Sirik region is semi-arid with mild winters ($\overline{T} = 22.3$°C) and hot summers ($\overline{T} = 34.1$°C). Average humidity ranges from 32.9% in the spring to a maximum of 71.9% in the winter. Mean annual temperature and precipitation are 28.2 °C and 190 mm, respectively, with the most rainfall occurring between October and December. The region has a population of approximately 11,667 people (2010), most of whom are engaged in agricultural production. The total amount of farmed land currently stands at ~1000 ha, with a mixture of vegetables, palm trees and citrus plantations. These crops were used in the modeling of the dam's water resources and were selected based on their acceptance by farmers, as well as their production values. Agriculture is the main source of groundwater extraction, with total pumping amounting to 7.2×10^6 m^3·y^{-1}. This pumping caused an average decline in groundwater levels of roughly 7 m between 2000 and 2010. It is also important to note that the region's "river" is dry for most part of the year and only experiences flow during flash flood events. Flora and fauna, especially in the southern parts of the region, are more dependent on groundwater discharge than surface water availability. This strong dependency of plants on groundwater is mostly attributable to the fact that in the southern portion of the region, in the absence of surface water, groundwater is near the ground level and thereby available to plants.

The model developed in this study was for the Merk River watershed in the Sirik region; the dam, and the aquifer boundary locations are shown in Figure 5. This watershed drains 745 square kilometers, and the maximum elevation of the watershed is 1950 m above sea level

(MASL), while the minimum elevation is 50 MASL. Daily discharge of the Merk River at the Garaik hydrometric station has been measured from 2006 to 2010. The location of the hydrometric station is also shown in Figure 5. Since the measurement's time span was not sufficient for modeling the reservoir, the monthly time series of discharge was constructed for 40 years (1970–2010) by multivariate statistical analysis from nearby hydrometric stations. These analyses and data were derived from the feasibility study of the dam [33]. Subsequently, this monthly time series was used as the input flow to the reservoir model; the time series is shown in Figure 6.

Figure 5. Location of the dam's watershed, watershed boundary, aquifer boundary and the Garaik hydrometric station.

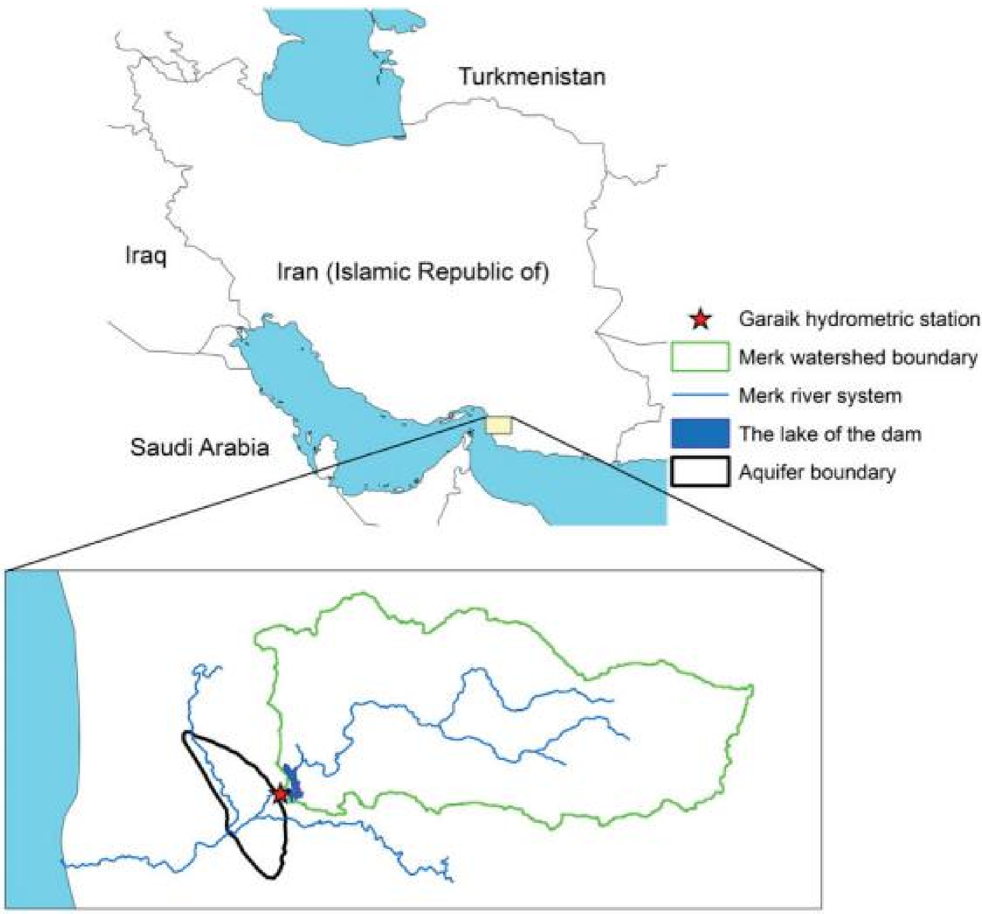
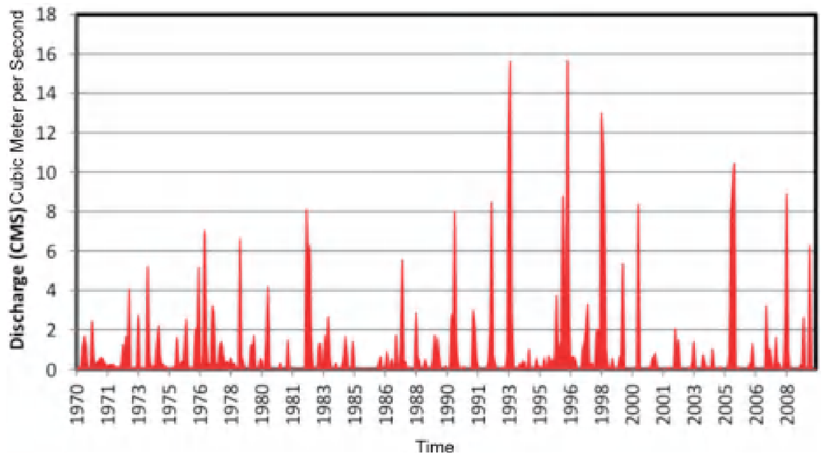


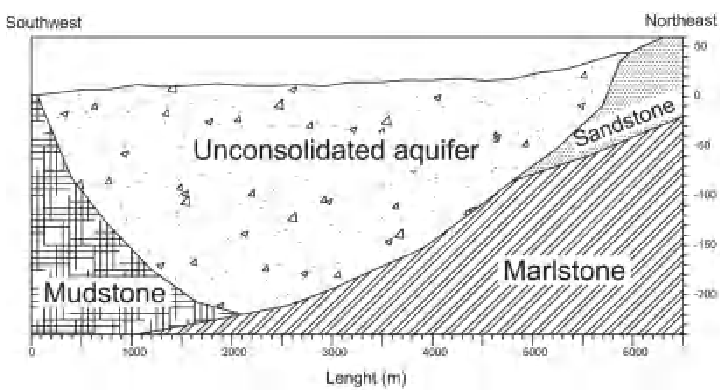
Figure 6. Time series of discharge at Garaik hydrometric station.

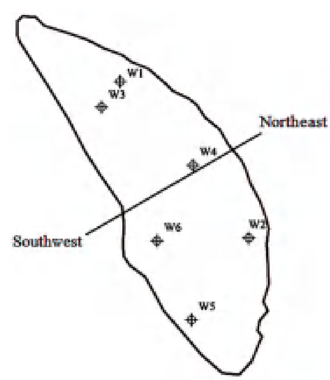


3.2. Hydrogeology of the Aquifer

The primary aquifer in this region is an unconfined and unconsolidated aquifer consisting of quaternary valley terrace deposits and river alluvial deposits (Figure 7a). The piezometric map of the region suggests that there is seepage from the northern sandstone to the aquifer. The bedrock is mostly middle Miocene marl with inter-bedded siltstone and sandstone. In the south, the aquifer is bounded by low permeable mudstone.

Figure 7. (**a**) Northeast to southwest cross-section of the Merk aquifer; (**b**) location of wells where pumping tests were conducted and the geological cross-section.





(**a**) (**b**)

Aquifer hydraulic properties were derived from six pumping tests using the AQTESOLV program with the Neuman method [34]. Figure 7b shows the location of these wells, while Table 2 provides their hydraulic properties and depths. This data was used in the modeling process and adjusted during the calibration process.

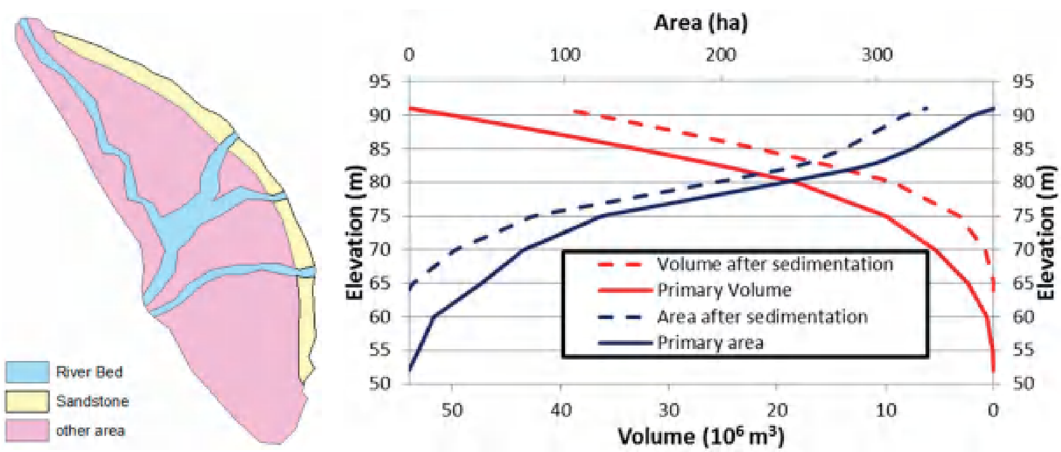
Table 2. Hydraulic conductivity and specific storage of different regions of the aquifer.

Well name	Well depth (m)	Hydraulic conductivity ($m^2 \cdot s^{-1}$)	Specific yield
W1	50	8.4×10^{-5}	0.05
W2	40	8.7×10^{-5}	0.06
W3	70	1.1×10^{-6}	0.08
W4	70	1.3×10^{-6}	0.011
W5	60	5.6×10^{-6}	0.011
W6	90	4.7×10^{-6}	0.014

Based on the different soil types and land uses, three recharge zones were assigned in the plain (Figure 8a). Most recharge is due to seepage from sandstone to the aquifer, with some recharge from riverbeds and precipitation. The preliminary estimation of recharge was based on an estimation of water balance components and then adjusted during the model calibration.

Since 2000, 10 observation wells have been installed and water elevation recorded on a monthly basis. This data served in calibrating and validating the groundwater model.

Figure 8. (**a**) Different recharge zones in the aquifer; (**b**) elevation-area-volume graph of Merk dam reservoir before and after sedimentation.



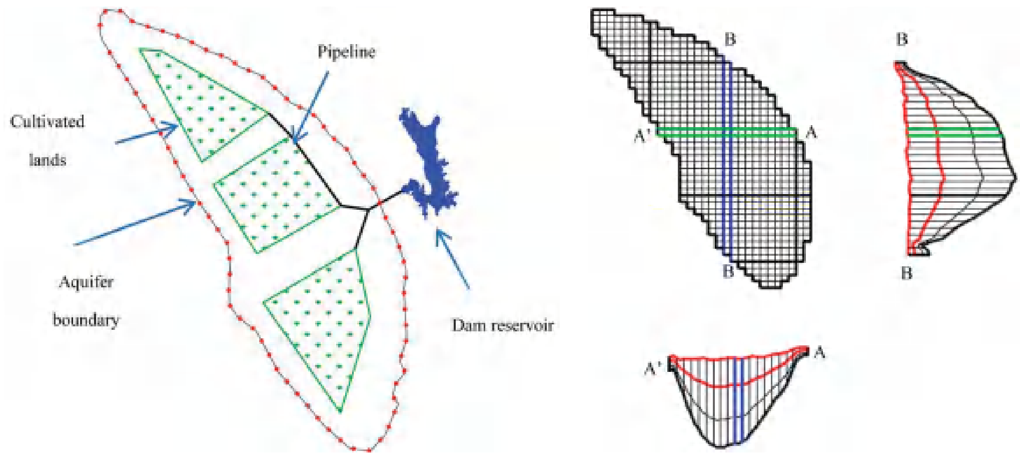
(**a**) (**b**)

3.3. Dam/Reservoir Characteristics

As proposed and if constructed, the Merk dam would be an earth-filled dam with a clay core. The normal elevation would be 91 m above mean sea level (AMSL), and the capacity of the reservoir after maximum sedimentation would be 40×10^6 m^3. The source of water to fill the reservoir would be the Merk River. The river's mean annual stream flow is 25.9×10^6 m^3. An elevation-area-volume chart of this dam (Figure 8b) was used to estimate the rate of evaporation from the reservoir in the system dynamics model developed in our study. This information was derived from a feasibility study report on the Merk dam approved by the Iranian Ministry of Energy [33]. The water supplied from the dam would be conveyed through a pipeline to agricultural areas.

According to dam design reports, the mean irrigation demand of the dam's command areas would be 8013 $m^3 \cdot ha^{-1} \cdot y^{-1}$, oscillating between 2860 and 12,710 $m^3 \cdot ha^{-1} \cdot y^{-1}$. Figure 9a presents a schematic view of the dam, aquifer and agricultural lands [33].

Figure 9. (**a**) Schematic view of the proposed system, consisting of the dam, agricultural areas within the aquifer boundaries and a pipeline to convey water from the dam to agricultural areas; (**b**) discretization of the aquifer system and its side views.



(**a**) (**b**)

Under Iranian governmental regulations [33], a certain percentage of a river's average natural flow must be allowed to remain flowing throughout the river course. This percentage is 10% during the wet seasons and 30% during the dry seasons. Consequently, this amount of water was considered the minimum environmental requirement of the river in the model.

4. Methodology

A conceptual model of the region's groundwater flow was initially developed, then translated to computational form through the use of MODFLOW [35] software. The conceptual model was developed based on information presented in the section "Hydrogeology of the Aquifer". The aquifer was discretized to 45 × 35 cells, with each cell representing an area of 350 m × 350 m (Figure 9b).

The model was calibrated and run using hydrogeological data and aquifer characteristics (Table 2) collected from 2000 to 2005 by regional hydrological experts. The model was then validated using similarly obtained data for the period of 2006 to 2010 using the RMSE performance index. Once the groundwater flow had been modeled using MODFLOW, the information gained was used to build a system dynamics model of the aquifer (Figure 2).

The system dynamics groundwater model was subsequently evaluated against the MODFLOW results. In the next stage, four different ASR implementation scenarios were developed and tested using the comprehensive system dynamics model. The system dynamics model as mentioned formerly has the ability to model concurrently the dam, groundwater system and ASR. Lastly, an economic analysis was undertaken to evaluate each of the different scenarios.

4.1. Scenarios

To assess the best approach to optimize the expanse of land to be converted to new farmland while maintaining appropriate environmental flows from the dam, as well as manageable spillway flows, along with a sustainable groundwater balance, four scenarios were evaluated using the system dynamics model. In all scenarios, the government's goal of adding 1000 ha of new agricultural land was respected. These lands will be referred to as "additional command areas" from now on. In order to gauge its potential economic impact, two different dam heights, resulting in initial reservoir volumes of 20×10^6 m^3 or 40×10^6 m^3, were compared in Scenarios 2_{20}, 2_{40}, 3_{20}, 3_{40}, 4_{20} and 4_{40}, respectively. In the baseline scenario, 1, only the taller dam/larger reservoir option was modeled, and this scenario was represented as 1_{40}.

Scenario 1: baseline scenario, in which the dam's effects on the water table are modeled as the dam's implementation is currently proposed (without any inclusion of an ASR approach). Water trapped in the reservoir flows to farmers' fields (old and new) through a constructed irrigation network.

Scenario 2: 40 new injection wells are constructed throughout the region, from which reservoir water is pumped under high pressure into the aquifer. Farmers continue to make use of their existing boreholes for extraction, while also using the injection wells as pumps during recovery periods.

Scenario 3: 40 new high-pressure injection wells are constructed while existing boreholes are shut down, forcing farmers to rely upon the stored water from the new sites. In this scenario, the existing agricultural lands, which were irrigated by farmers' wells, will be rehabilitated. The rehabilitation of the existing lands will add some costs into the project, but on the other hand, will increase the irrigation efficiency and productivity of the farms that will result in more benefit for the project.

Scenario 4: no new high-pressure injection wells are constructed; rather, water from the reservoir flows via gravity into existing borehole wells spread-out across the current 1000 ha of agricultural land. All additional new land is watered directly from the reservoir through a constructed irrigation network.

4.2. Economic Analysis

For economic analysis, a cost/benefit of investment approach was applied, where the net present value of an investment was calculated by using a discount rate and a series of future payments (negative values) and incomes (positive values). Incomes were based on net economic gains of agricultural activities, valued at 3,556 USD ha^{-1}·y^{-1}, based on average prices of cultivated crops in the region [33]. The cost components of the economic analysis are listed in Table 3.

Table 3. Potential costs involved in the aquifer storage and recovery (ASR) project in Sirik, Iran.

Economic Components	Value	Unit
Irrigation network	6,500	USD ha^{-1}
Installation of each injection well	50,000	USD per well
Building dam with 40×10^6 m^3 reservoir	22,239,000	USD
Building dam with 20×10^6 m^3 reservoir	9,850,000	USD
Modifying an existing well	15,000	USD
Dam lifetime	50	Years
Cost of operation and maintenance of dam	2	% of building cost per year

Table 3. *Cont.*

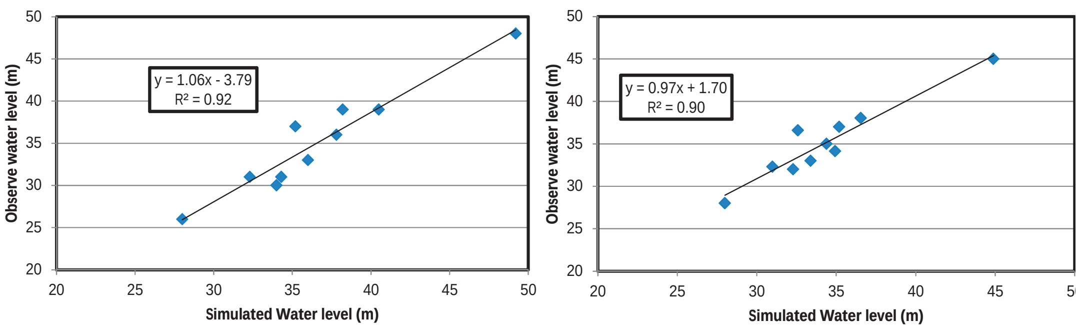
Economic Components	Value	Unit
Cost of operation and maintenance of irrigation network	5	% of building cost per year
Construction duration	2	Years
Education of farmers towards using ASR in scenario 4	200,000	USD
Interest rate	7	Percent
Engineering services	8	% of construction cost
Averaged agricultural gains	3,556	USD ha^{-1}

5. Results

5.1. Results of Aquifer Model Implemented with MODFLOW

Modelmate software and UCODE were used to calibrate MODFLOW. Recharge, hydraulic conductivity and specific yield were introduced as parameters to Modelmate. The model results were then compared with the head measurement in 10 observation wells across the aquifer. The calibration coefficient was 0.92 in the calibration stage (Figure 10a). For validation, correlation coefficients (R^2) reached 0.90. The root mean square error (RMSE) at the end of calibration and evaluation of the model was around one meter (Figure 11b). The results show that the conceptual groundwater model is capable of capturing the major processes in the groundwater system in the aquifer.

Figure 10. (**a**) Simulated water table *vs.* observed water table for the calibration period. (**b**) Simulated water table *vs.* observed water table for the validation period.



(**a**) (**b**)

5.2. Comparison of VENSIM/MODFLOW Results

In this stage, all calibrated data were transferred to the VENSIM software, and this model was run without considering the effect of the dam and ASR system on the aquifer for a period of 10 years to examine whether the groundwater model component of the system dynamics model had the ability to model the groundwater system effectively. Results showed an $R^2 = 0.95$ between the MODFLOW and VENSIM models and an RMSE < 1 m (Figure 11). In Figure 12, the results of the simulation of Scenario 1 and 4 at maximum reservoir capacity are presented.

Figure 11. Correlation between MODFLOW results and VENSIM results.

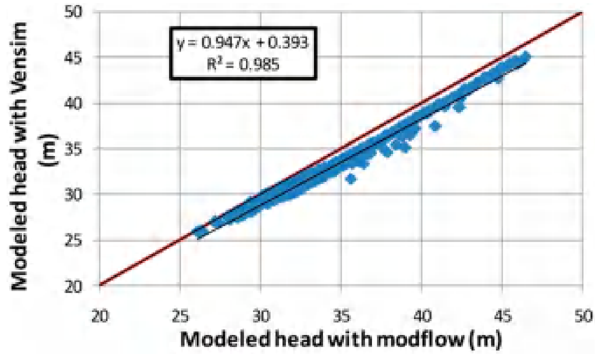
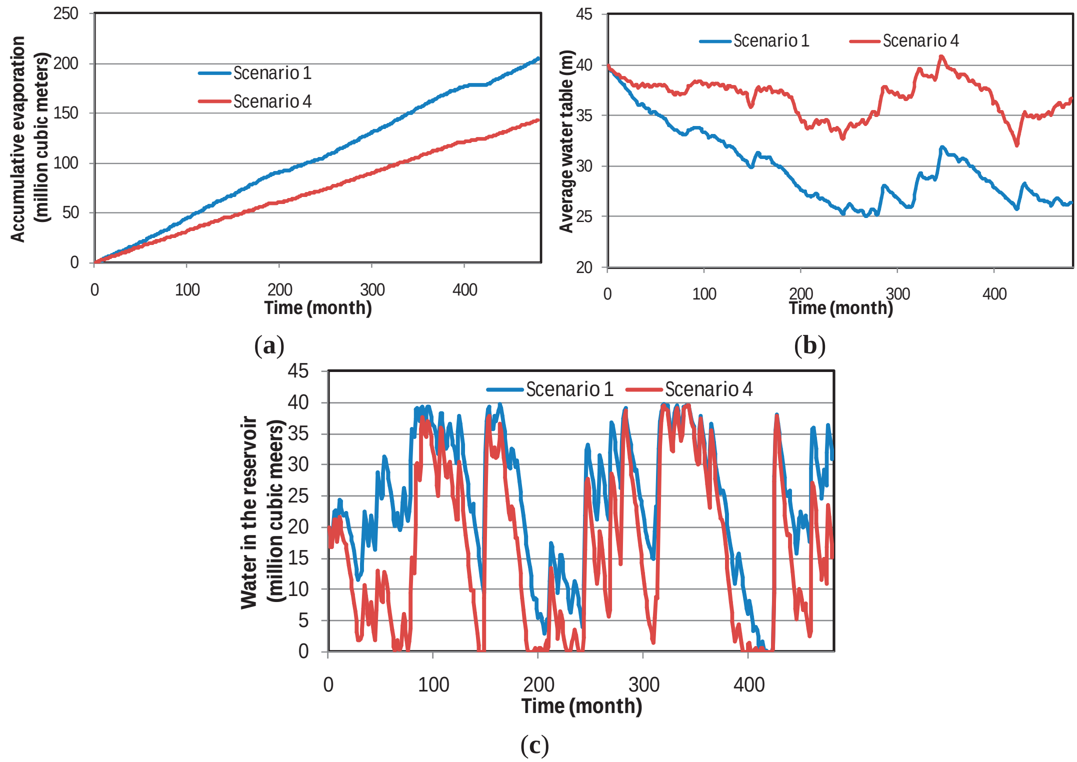


Figure 12. Models results for Scenarios 1 and 4: (**a**) accumulative evaporation; (**b**) average water table of the aquifer: and (**c**) water storage in the reservoir.



5.3. System Dynamics and Economic Analysis Results

The results of the modeling with system dynamics and economic analysis are shown in Table 4. All scenarios had the same amount of inflow, as this was generated by the floodwaters captured by the reservoir (Table 4). Water lost to evaporation (10^6 m^3) varied greatly amongst the scenarios, with 205.1 lost under the "business as usual" scenario (1), 100.1 and 156.9 under Scenarios 2 and 2_{40}, 71.7 and 118.2 under Scenarios 3_{20} and 3_{40} and 98.6 and 153.5 under Scenarios 4_{20} and 4_{40}. Environmental flow (10^6 m^3) from the dam varied, from 153.4 under Scenario 1_{40}, to 130.7 and 144.5 under Scenarios 2_{20} and 2_{40}, 117.0 and 130.3 under Scenarios 3_{20} and 3_{40} and 129.9 and 143.6 under Scenarios 4_{20} and 4_{30}. Spillway flow from the dam (10^6 m^3) also varied, from a high of 423.6 under Scenario 1_{40}, to 342.0 and 227.3 under Scenarios 2_{20} and 2_{40}, 290.9 and 186.0 under Scenarios 3_{20} and 3_{40} and 340.5 and 222.7 under Scenarios 4_{20} and 4_{40}.

The average drawdown of the water table varied from a high of 14.5 m under Scenario 1_{40}, to 5.4 m and 3.2 m under Scenarios 2_{20} and 2_{40}, 2.4 m and 0.9 m under Scenarios 3_{20} and 3_{40} and 5.3 m and 3.0 m under Scenarios 4_{20} and 4_{40}. The total costs of implementation varied, from a low of \$37,296,000 under Scenario 1_{40} (the basic cost of the dam and irrigation network), to \$41,258,000 and \$40,112,000 under Scenarios 2_{20} and 2_{40} (the costs of the dam, irrigation network, 40 new injection wells, as well as the price of pumped water), \$55,983,000 and \$51,082,000 for Scenarios 3_{20} and 3_{40} (the cost of the dam, irrigation network, 40 new injection wells, as well as the price of pumped water) and, finally, \$41,597,000 and \$37,407,000 for Scenarios 4_{20} and 4_{40} (the cost of the dam, irrigation network and modifications to existing boreholes).

Table 4. Water supply and economic analysis of scenarios after 40 years of simulation. Note that for Scenarios 2, 3 and 4, each scenario compared two dam heights resulting in initial reservoir volumes of 20×10^6 m^3 or 40×10^6 m^3.

		Scenario 1	Scenario 2		Scenario 3		Scenario 4	
Initial reservoir volume (10^6 m^3)		40	20	40	20	40	20	40
Inflow (10^6 m^3)		1,036.5	1,036.5	1,036.5	1,036.5	1,036.5	1,036.5	1,036.5
Environmental flow (10^6 m^3)		153.4	130.7	144.5	117.0	130.3	129.9	143.6
Agriculture (10^6 m^3)		313.4	251.7	284.9	373.4	464.1	249.9	282.7
Command area (additional) (ha)		1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0	1,000.0
Improved command area (ha)		0.0	0.0	0.0	1,000.0	1,000.0	0.0	0.0
Existing area (no change) (ha)		1,000.0	1,000.0	1,000.0	0.0	0.0	1,000.0	1,000.0
Evaporation (10^6 m^3)		205.1	100.1	156.9	71.7	118.2	98.6	153.5
Spillway (10^6 m^3)		423.6	342.0	227.3	290.9	186.0	340.5	222.7
Unregulated water (10^6 m^3)		577.0	472.7	371.8	407.8	316.2	470.4	366.2
Pumping (10^6 m^3)		0.0	67.9	34.6	265.77	175.1	69.7	36.9
Injection (10^6 m^3)		0.0	215.6	227.7	227.7	151.7	221.2	238.9
Average water table's elevation	Start (m)	39.9	39.9	39.9	39.9	39.9	39.9	39.9
	End (m)	25.4	34.6	36.8	37.6	39.1	34.6	37.0
Average drawdown (m)		14.5	5.4	3.2	2.4	0.9	5.3	3.0
Normal elevation of dam (m)		91	85	91	85	91	85	91
Benefit (USD)		49,075,000	49,075,000	49,075,000	56,436,000	56,437,000	49,075,000	49,075,000
Cost (USD)		37,296,000	41,258,000	40,112,000	55,983,000	51,083,000	41,597,000	37,407,000
B/C		1.32	1.19	1.22	1.01	1.10	1.18	1.31
B-C (USD)		11,779,000	7,817,000	8,964,000	454,000	5,354,000	7,478,000	11,669,000

6. Discussion

6.1. Consequences of "Business as Usual"

From a water management perspective, the proposed standard reservoir and dam system planned for the Sirik region is poorly thought out, given the significant quantity of water lost to evaporation (about 25% more than any other scenario). Furthermore, continued extraction of groundwater with no plan to replenish the aquifer would lead to a water table level drawdown of 14.5 m over the next 40 years, a case that would not only greatly increase the difficulty and cost of pumping water for agriculture and endangering people's livelihoods, but also threaten local wildlife that depend on shallow groundwater levels in the southwest portion of the Sirik region. It is thus suggested that a new paradigm of groundwater management be adopted in the region that makes use of ASR to prevent losses through evaporation and slows the rate of groundwater drawdown.

6.2. Scenario Selection Based on Cost/Benefit Analysis

To decide the most appropriate scenario for the development of Sirik, we rely on a variety of criteria to determine which scenario provides the best return on investment. The first is the cost/benefit analysis, which takes into account the total costs (C) of a scenario, weighed against the expected financial benefits (B) from expanded agricultural production in the region. The two scenarios that provide the greatest return on investment are Scenario 1_{40} and Scenario 4_{40}; however, return on investment is not the only criterion for acceptability. Scenario 3_{40} provides the greatest reduction in drawdown over 40 years, at 0.9 m, compared to 3.0 m for Scenario 4_{40} or 3.2 m for Scenario 2_{40}. However, scenario 3_{40}'s slower rate of drawdown comes at an additional cost of $13,650,000, while only allowing 84.5% of the originally planned environmental flow. Lastly, the need for farmers to shut down their own wells and to rely solely on newly installed high-pressure injection wells poses problems of social acceptability.

Though Scenario 4_{40} has higher rates of evaporation than Scenario 3_{40} and a similar rate of evaporation as Scenario 2_{40}, it remains the most cost-effective scenario, providing for a manageable quantity of spillway flow (that when unmanaged can lead to flooding damage), as well as the highest proportion of the original environmental flow (93.57%). As the southern ecosystem that sustains the region's native flora and fauna depends on a shallow groundwater table, it is justifiable to transfer some water from environmental flow into the aquifer in order to maintain upwelling and springs.

Scenario 3 has more benefits and costs than the other scenarios. As it was formerly explained, in this scenario, the irrigation system in existing farmlands should be rehabilitated, so that there would be a cost associated with the rehabilitation that will be added to the base cost of the project. On the other hand, the modified system will elevate crop production, and as a result, benefits would also increase. However, the cost of the project in this scenario outweighs the benefit; thus, the benefit over the cost of this scenario is less than for the other scenarios.

6.3. Social Acceptability and Sustainability

Scenario 4_{40} is the most socially acceptable and sustainable of the solutions, allowing farmers to keep their own wells on their land and for them to be improved at no cost to the farmer. Unlike Scenarios 2_{40} and 3_{40}, Scenario 4_{40} does not require the installation of complex high-pressure injection and pumping stations, which require technical upkeep and repairs, but instead makes use of improved boreholes on existing plots. Technical and managerial training programs for farmers would be promoted, in order to provide users with the skills to maintain their own systems and manage water use. Through choosing to work through existing social networks and demonstrating willingness to engage, the project could gain local support from the farmers. This type of public engagement and empowerment is a central tenet of the new paradigm of integrated water resources management and sets the groundwork for farmer-led groundwater management.

6.4. Uncertainty Due to Climate Variability and Climate Change

Although the models benefited from 40 years of historical hydro-climatological time series data, climate variability and climate change results in uncertainties concerning the modeling results of all scenarios. Regarding climate variability, different combinations of wet and dry hydro-climatological input parameters of the model (inflow, recharge, evaporation, *etc.*) will affect the results of each scenario. Nevertheless, since the model input parameters are the same in all scenarios, the variation between scenarios will remain relatively similar to the current study, so the deviation would not be substantial. On the other hand, climate change could have a major impact on the results, since it is believed that the input parameters of the model will no longer remain stationary in the future. It is predicted that climate change will cause more severe extreme events (floods and droughts) in this region [36]. In this situation, conjunctive use should be more beneficial than conventional water management schemes. Conjunctive use (Scenarios 2, 3 and 4) under severe drought conditions is more advantageous than merely relying on surface water.

This study introduced a new modeling tool, which also opens a new avenue to assess uncertainties due to climate variability and climate change in future studies. In order to address uncertainty in future studies, different sets of climate variables (precipitation and temperature) should be derived from downscaled climate change models, and then, this climate data can be used in hydrologic models to estimate discharge in the watershed. The output from the hydrological model can subsequently be used as an input to the SD model to build a set of results. The probability distribution function can then be derived from the results of the SD model to assess the uncertainty associated with climate change.

7. Conclusions

The objective of this study was to examine if ASR, in conjunction with water storage on an ephemeral river, could be an effective water resource management strategy that would minimize both water lost to evaporation and the rate of groundwater depletion, while providing water for expanded agricultural activities. It was determined that this approach can significantly improve the sustainability of groundwater supplies. It must be emphasized that the future development of the

Sirik region must include a water management approach of groundwater storage and recovery. In so doing, significant gains can be achieved at a minimal cost. By modeling groundwater flow and whole system dynamics, ASR was shown to be an applicable and beneficial strategy for the well-being of farmers and the region's groundwater system. Without the inclusion of ASR, the region will face grave consequences due to unsustainable exploitation of groundwater. However, through a combination of central technical planning, ASR strategies and farmer engagement and education, the current proposal has the potential to help direct the future development of the region in a sustainable manner.

The system dynamics modeling framework developed and implemented in this study was shown to be very effective. Not only groundwater, but a surface water reservoir was modeled in a single program. This modeling approach can be expanded and used in different areas where a combination of groundwater and surface water are considered as sources of a water supply system. Interconnection technologies, such as ASR, can also be addressed in this modeling approach, something not easily accomplished in other modeling frameworks. Although the groundwater modeling portion of the model was developed for an unconfined aquifer, it is relatively simple, using the same mathematical concepts, to develop such a model for a confined aquifer.

Another advantage of such a modeling approach is that groundwater and surface water reservoirs are completely linked to each other and in each time step; each model is updated with the output of the other model. This mutual relationship enables one to solve the problem with greater accuracy and fewer simplifying assumptions.

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Author Contributions

Amir Niazi conceived the idea of this research, conducted the SD modeling, economical analysis and writing of the manuscript. Shiv Prasher funded the research and provided recommendations, which improved the system dynamics model. Jan Adamowski provided feedback regarding the SD models and modified the manuscript throughout the project. Tom Gleeson helped conceptualize the groundwater system in the study area, as well as the groundwater modeling in the SD models.

Conflicts of Interest

The authors declare no conflict of interest.

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Assessing the Feasibility of Managed Aquifer Recharge for Irrigation under Uncertainty

Muhammad Arshad, Joseph H.A. Guillaume and Andrew Ross

Abstract: Additional storage of water is a potential option to meet future water supply goals. Financial comparisons are needed to improve decision making about whether to store water in surface reservoirs or below ground, using managed aquifer recharge (MAR). In some places, the results of cost-benefit analysis show that MAR is financially superior to surface storage. However, uncertainty often exists as to whether MAR systems will remain operationally effective and profitable in the future, because the profitability of MAR is dependent on many uncertain technical and financial variables. This paper introduces a method to assess the financial feasibility of MAR under uncertainty. We assess such uncertainties by identification of cross-over points in break-even analysis. Cross-over points are the thresholds where MAR and surface storage have equal financial returns. Such thresholds can be interpreted as a set of minimum requirements beyond which an investment in MAR may no longer be worthwhile. Checking that these thresholds are satisfied can improve confidence in decision making. Our suggested approach can also be used to identify areas that may not be suitable for MAR, thereby avoiding expensive hydrogeological and geophysical investigations.

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1. Introduction

Water demand continues to grow in order to maintain food security and drinking water supplies, while supplies remain limited from conventional sources. Future water security is threatened in many places, as most suitable locations for large surface storages have already been used [1] and ground water is often being withdrawn at unsustainable rates [2–4]. Among other options of water supply augmentation, such as water recycling, desalination *etc.*, storing more water underground appears to be a potential solution to achieve future water supply goals. For many water stressed areas, water security and reliability do not necessarily depend on the absolute amount of precipitation, but on the fraction of water that is efficiently retained as storage for future use [5].

Water shortages can be eased by storing surplus water underground during wet periods for later use during dry periods. Managed aquifer recharge (MAR) has been used successfully in several countries for the storage and treatment of water [6–9]. Storage of surplus water in aquifers can help minimize evaporative losses and help irrigators to adjust to surface water variability during droughts, provided that MAR is technically feasible and cost effective. The feasibility of MAR and its comparative cost to other alternatives depend on a number of technical and financial factors, such as infiltration, injection and recovery rates, which are dependent on local hydrogeology [10].

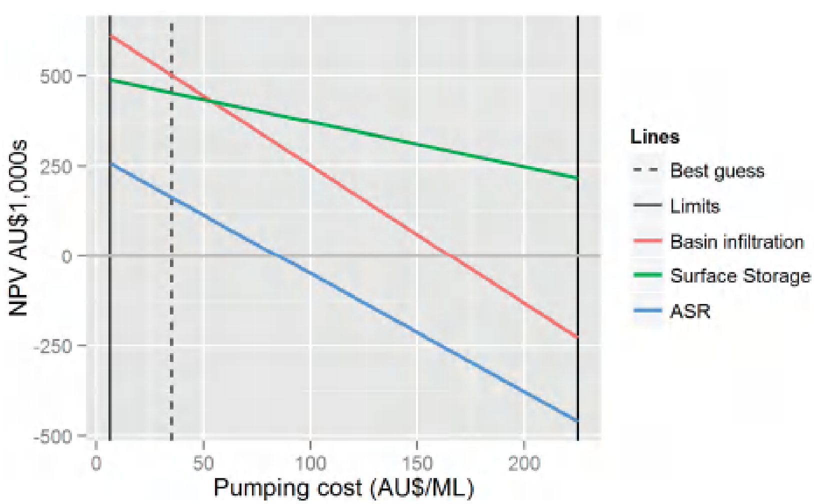
A few studies indicate that MAR can achieve more financial value than surface storage and other alternatives [11,12]. However, uncertainty often exists whether it is more cost effective to store water above ground in surface reservoirs or below ground using managed aquifer recharge [13].

Cost-benefit analysis (CBA) provides a comparison of benefits and costs resulting from a proposed policy or investment [14]. Previous studies undertaking CBA of MAR have assumed hydrogeological factors, such as infiltration, injection and recovery rates, to be known [11,12,15]. Overlooking such uncertainties can result in lower than expected operational efficiency and irrigation returns from MAR [16,17]. For example, future returns from MAR may be affected by increases in groundwater pumping cost or reductions in infiltration rates.

An increase in the turbidity of source water due to hydrological variability can significantly increase the cost of infiltration basin maintenance, adding to the cost of water quality treatment for aquifer storage and recovery (ASR) systems. Maliva [16], in this special issue, highlights that assessing such uncertainty is perhaps the most neglected aspect in the economics of MAR.

The primary focus of this paper is to systematically search for conditions under which the requirements for MAR may not be met and failure might occur. Playing such a devil's advocate role has been shown to improve decision making compared to an exclusively expert-driven approach [18]. The approach used identifies thresholds above which MAR is financially better than surface storage and below which it is not. These thresholds (or cross-over points) describe corresponding values of variables at which the net present value (NPV) from MAR and surface storage become equal. All dollar amounts reported in this study are in Australian dollars. An example of a cross-over point for pumping cost is shown in Figure 1, where basin infiltration (red line) and surface storage (green line) options are compared; and where basin infiltration is initially (dashed vertical line) more profitable than surface storage. A cross-over point between the two compared options is possible when the cost of pumping increases from the best guess value of 35 $/megalitres (ML) to 53.63 $/ML. This increase in the pumping cost will decrease benefits (NPV) from basin infiltration, such that they become equal to the benefits (NPV) obtained from surface storage. However, aquifer storage and recovery (ASR) always result in an inferior NPV regardless of the pumping cost. There is no cross-over point between ASR and the other alternatives.

Figure 1. Illustration of identifying cross-over points for pumping cost when comparing basin infiltration, aquifer storage and recovery (ASR) and surface storage of irrigation water.



At the cross-over point, the decision maker is indifferent to choosing a single option from the two, because their financial returns are equal. In our method, we use computational techniques to identify the cross-over points as values of uncertain variables where the NPV of MAR is exactly equal to the NPV of surface storage of irrigation water. The approach is demonstrated through a case study in a highly developed irrigation region of the lower Namoi catchment in New South Wales, Australia, where irrigation water restrictions motivate the need to consider options to supplement future irrigation supplies, such as MAR.

The suggested approach of identifying cross-over points is beneficial in three ways;

i. It can determine minimum hydrogeological and cost requirements under which MAR can be worthwhile;
ii. It can improve confidence in decision making for MAR investment, by enabling the assessment of conditions that are unfavourable to MAR compared to surface water storage;
iii. It can substantially lower the cost of geophysical and hydrogeological investigations by targeting only areas that satisfy the minimum requirements, as MAR investigations and trials are shown to be time and resource expensive.

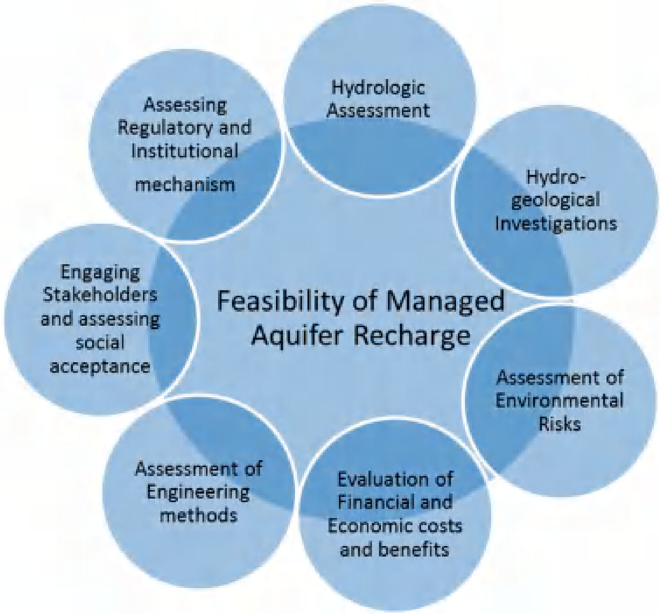
The next section provides an overview of the literature on the feasibility of MAR with a focus on the technical, financial and uncertainty considerations. Section 3 ("Methods") describes the model and tool used to explore cross-over points. In Section 4, an illustrative study in the lower Namoi catchment evaluates the irrigation-related costs and benefits of storing flood water in aquifers compared to surface storages. The analysis of cross-over points in Section 5 provides a discussion of how cross-over points are reached when only a single variable changes, as well as when many variables interact.

2. Related Work: Feasibility of Managed Aquifer Recharge

Assessing the feasibility of MAR requires the integration of many types of data and information from many disciplines (Figure 2). Although carrying out a comprehensive feasibility assessment is essential, the first step in establishing an MAR scheme requires assessing the feasibility of technical and financial factors, to provide a basis for other investigations to proceed.

An overview of the basic requirements and feasibility guidelines for managed aquifer recharge (MAR) is available in [10] and GHD and AGT [19].

Figure 2. A framework for the feasibility of managed aquifer recharge: adapted from GHD and AGT [19], Dillon *et al.* [10] and Rawluk *et al.* [20].



2.1. Technical Considerations

Key technical requirements for MAR include hydrogeological assessment of the target aquifer, the availability of surplus surface water and the means to convey it underground. Relevant hydrogeological factors include aquifer storage size, permeability, infiltration, injection and recovery rates and connections with other aquifers [21,22]. High infiltration rates lower the cost of underground storage; for example, a basin infiltration system with high infiltration rates will require a smaller pond area and can be cheaper to construct and maintain than a pond with low infiltration rates.

There are two main types of MAR methods: basin infiltration and aquifer storage and recovery (ASR), each favourable to different hydrogeological conditions. Basin infiltration is suitable to recharge shallow unconfined aquifers with minimal or no treatment of the recharge water. The methods include deep, large diameter isolated wells, infiltration ponds, infiltration galleries, induced bank filtration, leaky and recharge dams and redirecting floodwaters over the wider landscape to supplement areal recharge [7,9]. Some basin infiltration methods require large surface areas and permeable soils to be effective [21,23].

ASR involves the injection and recovery of water using wells; this has the advantage of targeting a desired aquifer for recharge. Thus, zones of saline water or clay layers can be bypassed. However, ASR systems are costly because of the need for bore well construction and water treatment prior to recharging, and if clogging occurs, they are costly to repair. Passive borehole recharge (under gravity) requires limited mechanical assistance, but the infiltration rate is relatively low.

Water injection using pumps can greatly improve the rate of aquifer recharge [24,25]; however, the pumps require constant maintenance and are costly to run. The risk of clogging of the surface or well with fine sediments is common to both MAR methods. Solutions to this issue include stabilization of recharge water through settling ponds and treatment of water before recharge.

2.2. Financial Considerations

When the focus is on estimating the total economic benefits of recharge to a region instead of an individual, the benefits of aquifer storage become complex, as this needs to include public good, socio-economic and environmental benefits to a region, which are more difficult to assess and quantify. Maliva [16] in this special issue provides a greater review of the methods and techniques for assessing total benefits from MAR. With a known target volume of storage and recovery, it is easier to quantify the financial benefits, since the goal is the recovery of the stored water, and the volumes recovered accrue to an identifiable person or water utility for a particular use. The financial feasibility of MAR can then be studied in comparison to other water supply and storage alternatives, including surface storage.

The local situation dictates the costs of MAR options, and large variations may occur between localities [10]. For a fair comparison, it is essential to analyse the benefits and costs of MAR and surface storage in the same location, because the comparison of benefits and costs is complicated by the wide range of biophysical, socio-economic and regulatory conditions in which MAR occurs. There is little published analysis of the economic and financial benefits of MAR. From the few published studies, Ross and Arshad [26] compiled and reported the benefits and costs of surface storage and MAR at multiple locations, showing that the costs and returns of MAR options vary substantially.

2.3. Uncertainty Considerations

A number of methods have been used to address uncertainty in cost-benefit analysis. Sensitivity analysis simulates the impact of changes in financial behaviour, such as the change in NPV of an investment due to a change in an input variable, and identifies variables that are of greater concern [27]. Probabilistic analysis provides the combined effect of variables' variability on the financial behaviour [17]. Possibility theory assumes that all values within a certain range are possible, with the exact value being treated as unknown [27].

We focus on cross-over points as one possible means of addressing uncertainty in the cost-benefit analysis of MAR. Identification of cross-over points relies solely on the relationship between variables, such that it requires minimal understanding of the uncertainty of variables. The idea of a cross-over point is sufficiently simple that it has a number of widely used variations; it is also known as a break-even point or switch-over point. However, the term break-even in economics specifically applies to the volume of sales at which profit is zero as revenues cover total cost and is therefore used as a tool to calculate the margin of safety of a single investment [28], rather than comparing alternatives. The concept of a cross-over point is fairly simple with only one or two variables, but the complexity increases in the analysis and interpretation of results as the number of input variables increases [29].

3. Methods

The analyses in this paper are carried out in two steps; in the first step, financial analysis compares the net present value of farm benefits to identify the best among the considered options. In the second step, the break-even analysis of cross-over points is carried out; this involves finding values of variables that will provide exactly the same financial returns from the two compared options. The variables were chosen based on an examination of literature concerning the financial feasibility of MAR. Identifying cross-over points allows the user to understand the minimum conditions required for success and allows measures to be taken to ensure they do not occur.

Financial analysis evaluates whether investment in MAR is worthwhile. Analyses of cross-over points help understand the circumstances when MAR is worthwhile. At the most basic level, MAR is worthwhile when net irrigation returns of MAR exceed those of alternatives. In our example, benefits are determined by the agricultural value of the additional water provided, by saving it from non-productive evaporation. This has been referred to as a "vapour shift" [30] from non-productive evaporation to agriculturally-valuable crop transpiration. Costs are composed of additional pumping to recover recharged water and MAR method-specific capital and ongoing costs of implementation during the life of the project.

To enable the break-even analysis, the financial analysis is programmed as a function in R [31]. As a general purpose statistical programming language, R offers a suite of optimization methods, as well as providing tools for visualization and the means to include a user interface. To identify cross-over points of single variables, other variables are set to fixed values, and the R function *uniroot* [32] is used to identify the value of the variable where the difference in NPV between the two compared options is zero (*i.e.*, $\Delta NPV(\Theta) = 0$), meaning that the two options have equal NPV. To identify cross-over points involving many variables, we use optimization to identify a cross-over point (*i.e.*, a point Θ where $\Delta NPV(\Theta) = 0$) that is closest to the best guess, in the sense of minimizing the maximum of the distances for each variable, expressed in relative terms using user-defined bounds ($\max_i|\Theta_i-\Theta_{best,i}|/|\Theta_{bound,i}-\Theta_{best,i}|$). This is one possible criterion for selecting cross-over points of concern. Other criteria, including probabilistic ones, would be possible and would usually raise different cross-over points for discussion. The code for the analysis is available online [33]. The cross-over points generated are assessed by comparing them to maximum and minimum values of variables that a decision maker thinks might be possible due to physical, climate or policy change over the analysis period. The resulting judgment of a cross-over point is not perfect and is based on the best available knowledge of the decision maker for each variable.

4. The Study Area: Lower Namoi

In many parts of Australia, overdraft of aquifers is resulting in falling groundwater levels in the shallow, unconfined systems and decreasing groundwater pressures in the deep confined and semi-confined systems [34]. In response to the groundwater overdraft, the New South Wales (NSW) government has reduced current groundwater entitlements in its stressed aquifer systems [35]. For the lower Namoi catchment, a highly developed cotton irrigation district in NSW, this cutback translates to a reduction of 21 gigalitres (GL)/year in groundwater entitlements for irrigation by 2015 and beyond. Groundwater in the Namoi River catchment supports an irrigation industry worth in excess of $380 million per annum [36]. All irrigation water is stored and routed from surface storages before application to the field. On-farm water storages within the lower Namoi range from conventional single-cell to advanced multi-cell farm dams. The typical Namoi valley farm holds enough water in storage to complete one full year of irrigation. Conservative estimates suggest that the total capacity of on-farm storages in the cotton industry could be on the order of 3150 gigalitres (GL). Evaporative losses from these surface storages are significant. On average, from surface water storages, evaporative losses range from 1200 to 1800 mm/year [37], which constitute 35% to 50% losses from surface water storage volumes.

To tackle the problem of reduced allocation and evaporative losses, improving water use efficiency at the farm level is an obvious option. This will include installing drip irrigation systems, lining water courses and further improving the design of surface storages to minimize evaporative and seepage losses. Improving water use efficiency needs to be a stepwise approach. Another potential option to reduce evaporative losses is to store water underground in aquifers using managed aquifer recharge. Recently, several studies have highlighted the potential of a regional-scale MAR project in the lower Namoi. Arshad *et al.* [38] indicated that a significant volume of water could be available from large floods for MAR while still satisfying environmental flow and ecological requirements. Similarly, Rawluk *et al.* [20] showed a high level of social acceptability for an MAR project in the study area.

4.1. The Analytical Framework for Financial Analysis

The study undertakes an analysis to estimate irrigation-related costs and benefits for a typical irrigation farm in the lower Namoi. The analysis considers a cotton irrigation farm, which has three different scenarios for the storage of flood water: surface storage in farm dams, aquifer storage using basin infiltration and ASR using existing wells. All of the surface water allocations, including flood water, is stored in farm dams before application to the fields. Owing to limited water availability, less than 20% of the available land is irrigated, and irrigated land in each year is variable. Irrigated cotton Bt (*Bacillus thuringiensis*) and faba bean *(Vicia faba L)* are the sustainable summer and winter rotations that provide the highest net income per megalitre (ML) of irrigation water applied [39]. It is assumed in the analysis that all required irrigation infrastructure, such as surface storage and the irrigation water delivery network, are already built for the entire irrigation land, as this is a common practice in the study area. The annual irrigation water allocation from all sources for an average cotton farm in the lower Namoi is approximately 1350 ML. However, in this analysis, we only consider and report irrigation costs and returns of 200 ML of flood water, which is only 25% of recent statutory flood water allocations in the study area. The analysis assumes 40% evaporative losses, taking into account current estimates in the study area [37].

Storage and recovery of water underground will require new infrastructure and additional costs, as reported in Section 4.3. Farm economic data, such as the variable cost of farm inputs, cotton prices and gross margins from irrigated and dryland, are adopted from Powell and Scott [39]. The analysis only considers farm-related costs and revenue and does not monetize any socio-economic or environmental cost or revenue that may occur as a result of a change in the water storage option.

4.2. Infiltration and Injection Rates That Can be Possible in Lower Namoi

Infiltration and injection rates can highly affect the usefulness of any aquifer recharge and storage facility. Bouwer [40] provides typical infiltration rates for surface infiltration systems in the range from 0.3 to 3 m per day (m/day) with relatively clean and low turbidity river water. For systems that are operated year-round, long-term infiltration rates vary from 30 m/year to 500 m/year, depending on soil type, water quality and climate. In the lower Namoi, the infiltration rate of 0.2 m/day is considered to be likely achieved in many locations.

ASR can achieve injection rates from 0.5 to 8 megalitres per day (ML/day) per borehole (1 megalitre = 1000 cubic meter = 0.8107 acre foot). In the absence of accurate well injection rates based on field monitoring, Pyne [41] observed that injection rates increased with increasing aquifer transmissivities. For the lower Namoi, Williams *et al.* [42] reported that the alluvial aquifers that are primarily tapped for irrigation extraction are associated with the semi-confined Gunnedah and Cubbaroo formations and have transmissivities in the range of 1000–2000 square meters per day (m^2 day^{-1}). The yields from bores tapping these aquifers vary up to 250 litres per second in the Gunnedah Formation at depths of 60–90 m and in the deep Cubbaroo Formation at depths of 80–120 m. The shallow Narrabri Formation has transmissivities less than 250 m^2 day^{-1}. For this study, an assumed injection rate of 25 L per second (2.2 ML/day) is considered likely for an ASR well.

4.3. Estimation of Costs and Benefits

Cost estimates of aquifer recharge are scarce and can vary considerably with location. Itemized costs for this study were estimated by combining current market rates of earthworks, services and materials for water infrastructure projects in Australia and were adjusted to the local situation in the lower Namoi. Cost estimates were also compared with published data and technical reports of Khan *et al.* [12], Dillon *et al.* [10] and Pyne [13].

Capital costs of basin infiltration were estimated by assuming an infiltration rate of 0.2 m/day and calculating the required land area to achieve 2 ML of recharge per day. The target volume of harvested flood water of 200 ML would, on average, appear in four or more events in a flood year. An infiltration pond with a surface area of 1 ha and an infiltration rate of 0.2 m/day would recharge 50 ML of floodwater in a single cycle of 25 days. The size of the basin here has therefore been designed to operate only for 100 days, in 4 cycles of 25 days each, allowing rest and maintenance. The analysis assumed 40% evaporative losses from surface storage and a 5% MAR loss rate. The MAR loss rate is the percent of water lost during aquifer recharge and recovery from basin infiltration and ASR and can be expressed as:

$$\text{MAR loss rate} = \left(1 - \frac{\text{groundwater volume recovered}}{\text{Initial water volume used for storage}}\right)\%$$

In the base case, surface storage of flood water, the costs considered are the cost of harvesting 200 ML of flood water and the cost of farm dam annual maintenance. The capital cost of basin infiltration includes the cost of earth works and pipes. Ongoing costs include operation and maintenance of water harvesting and recovery and the cost of basin annual maintenance. An existing bore is assumed to be available for recovery after basin infiltration or for injection and recovery in ASR. The capital cost of an ASR facility on existing farms with a bore primarily includes installing a coagulation and filtration pre-treatment facility. Ongoing operation and maintenance costs for ASR include well maintenance, flood water harvesting, water treatment and water recovery. The analysis assumed a 30-year lifespan for surface storage and basin infiltration and 20 years for ASR, with a 7% uniform discount rate for all options. All capital cost estimates are exclusive of land value. Table 1 summarizes the levelised costs of 200 ML of flood water with each water storage option. Levelised costs are annual unit costs obtained by amortising capital cost components over their expected working life, adding the annual operation, maintenance and management cost and dividing by the annual volume of supply, as defined in Dillon *et al.* [10].

Table 1. Levelised costs ($/ML) of surface storage and MAR methods in lower Namoi. Adapted from Dillon and Arshad [43]. ASR, aquifer storage and recovery; ML, megalitre.

Cost component	Surface storage	Basin infiltration	ASR using existing well
Annual cost of capital items ($/ML)	0.0	32.2	26.0
Annual cost of operation, maintenance and management ($/ML)	22.5	90.5	221.8
Total annual cost ($/ML)	22.5	122.7	247.7

Note: Totals may not match due to rounding.

With the additional water saved through MAR, farmers in our example have the choice to irrigate additional land with cotton, faba bean or some combination of the two crops that yields the highest returns. Value brought by the MAR water under each option is estimated from the useable volume of flood water, after evaporative and recovery losses, times the gross margin per ML of mixed cropping of cotton and faba bean on equal land areas. On average, for a typical lower Namoi irrigation farm, the average gross margins for cotton and faba bean are estimated as 310 $/ML and 435 $/ML, respectively. It is assumed that cotton and faba bean are planted on the same land area, as they are summer and winter crops, respectively. Allocating the water accordingly yields an average gross margin of 342.3 $/ML and a net margin of 230 $/ML after subtracting overhead costs. In the analysis, we assume that additional irrigation with the saved water is not going to increase the overhead cost, as the farm size is large enough (1200 ha) and irrigated land cropped each year is variable depending on water availability. In this analysis, we use gross margins as the irrigation returns, which is the total revenue minus the variable cost of production. Table 2 presents the value of crop that can be grown with the useable volume in each case.

Table 2. Irrigation benefits: value of the crop under each water storage option. Adapted from Powell and Scott [39] and Arshad *et al.* [44].

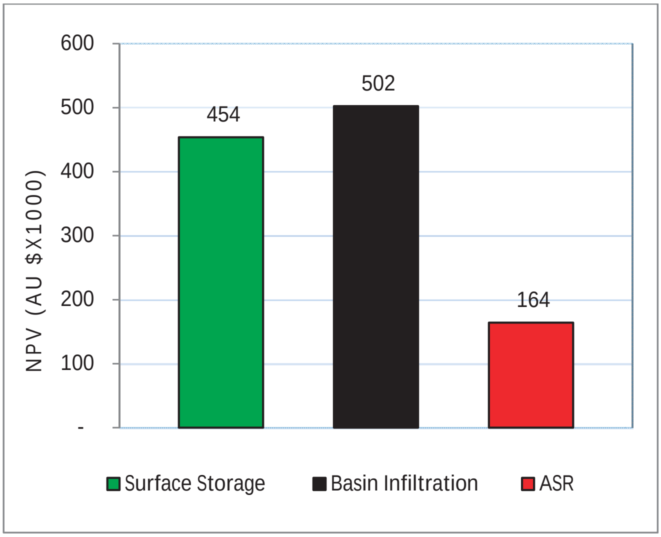
Project component	Surface storage	Basin infiltration	ASR using existing well
Initial volume taken from flooding river ML	200	200	200
Useable volume (after losses) (ML)	120	190	190
Gross value of crop ($/ML)	342.3	342.3	342.3
Irrigation benefits: value of the crop that can be grown with the useable volume in each case ($) (available water times gross margins $/ML)	41,070.6	65,028.4	65,028.4

Note: Totals may not match due to rounding.

4.4. Results of Financial Cost-Benefit Analysis

A long-term trajectory of the difference of the discounted benefits and discounted costs of the three water storage options is expressed in Figure 3 as net present value using the fixed data in Table 2.

Figure 3. Net present value (NPV) of surface storage, basin infiltration and aquifer storage and recovery options.



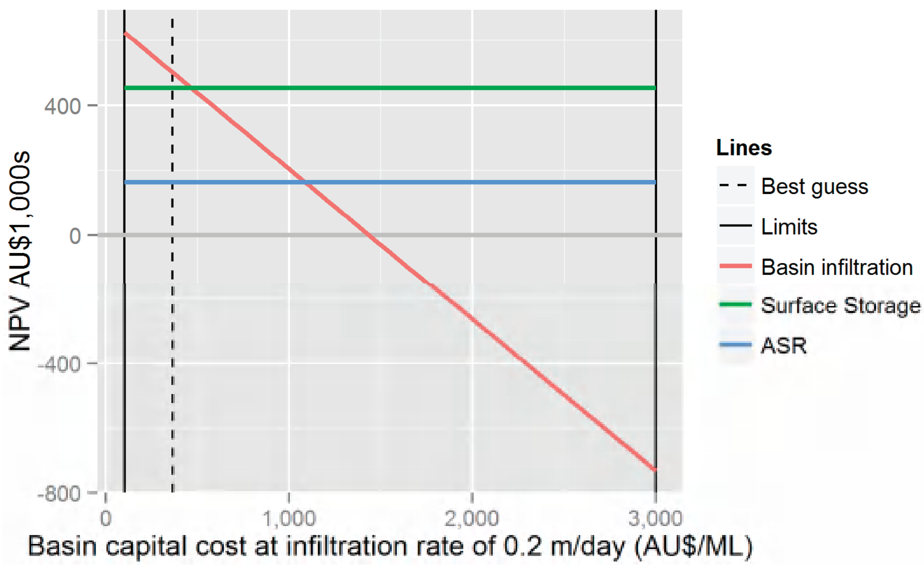
The results show that MAR using the basin infiltration method will yield 11% more value than surface storage of irrigation water. ASR using existing wells appears to be uneconomical, with 64% less value than surface storage, mainly due to the high capital and water treatment costs required for an ASR system.

The cost and additional value of basin infiltration is highly dependent on the infiltration rates; as infiltration rates increase, the capital costs decrease, and the value of saved water increases. Conversely, as infiltration rates decrease, the capital cost increases, and the additional value of basin infiltration decreases. With a reduction in the infiltration rates, a cross-over point is reached, where the additional value brought by basin infiltration becomes zero and its NPV is exactly equal to that of surface storage. The following section expands the analysis to explore cross-over points of infiltration rates and other variables.

5. Identification of Cross-Over Points in a Single Variable

In single variable analysis, the aim is to identify how far a single variable needs to change to reach a cross-over point for the two compared options. A cross-over point may not always exist; there might be situations where the cross-over point falls outside the minimum or maximum limits considered for the analysis or when the change in the cost or benefit is in the same direction. Such a situation is noted with the use of the acronym, NA, for not applicable, in the tables and following text. A cross-over point for basin infiltration and surface storage occurs when their NPVs are equal; and similarly, for ASR and surface storage, as well as basin infiltration and ASR. Figure 1 showed the cross-over point for pumping cost. Figure 4 illustrates cross-over points for basin capital cost.

Figure 4. NPV for varying basin capital cost in three water storage scenarios, showing cross-over points at intersections between lines.



A cross-over point between basin infiltration and surface storage is possible when the basin capital cost increases from 363 $/ML to 466.69 $/ML. That increase in the capital cost will equate to the NPV of the two compared options. Similarly, a cross-over point between basin infiltration and ASR is possible when the basin capital cost increases from 363 $/ML to 1085.55 $/ML. No cross-over point is identified between surface storage and ASR (it is NA). The increase in the basin capital cost may result from increases in the price of services and materials or the need to construct a larger pond due to a reduction in infiltration rates. Rather than drawing these curves for every variable, the values of the cross-over points are reported in Table 3 and discussed in the following text.

Table 3 lists cross-over points for 14 variables when each is varied separately. These cross-over points represent the minimum requirements for MAR to be preferred to surface water storage, assuming that the values of other variables listed in the table remain fixed. For example basin infiltration is financially better than surface storage when pumping cost does not exceed 53.63 $/ML or the surface evaporation rate does not fall below 34%, and so on. The variables selected are the most important when undertaking a financial comparison of surface storage with the two MAR options. In the following section, we discuss the basis of how these cross-over points may be reached in reality for each single variable.

Table 3. Single variable cross-over points in three scenarios.

No.	Variable (Unit)	Best Guess (Modelled) Value	Cross-Over Point		
			Surface Storage and Basin Infiltration	Surface Storage and ASR	Basin Infiltration and ASR
1	Pumping cost ($/ML)	35	53.63	NA	NA
2	Surface evaporation rate (%)	40	34	74	NA
3	Basin capital cost ($/ML)	363	466.69	NA	1,085.55
4	Basin infiltration rate (m/day)	0.2	0.16	NA	0.07
5	Basin maintenance rate (% of capital cost)	10	15	NA	NA
6	MAR loss rate (% of target storage volume)	5	11	NA	NA
7	ASR water treatment cost ($/ML)	150	NA	13.25	NA
8	ASR maintenance rate (% of capital cost)	0.07	NA	NA	NA
9	Price of cotton ($/bale)	538	475.64	1,155.22	NA
10	Price of faba bean ($/tonne)	348	229.52	NA	NA
11	Discount rate (%)	7	13	NA	NA
12	Lifespan of surface storage (Year)	30	48.16	5.57	NA
13	Lifespan of basin infiltration (Year)	30	23.51	NA	6.69
14	Lifespan ASR (Year)	20	NA	NA	NA

5.1. Discussion of Single Variables

5.1.1. Pumping Costs and Surface Evaporation Rates

A cross-over point between surface storage and basin infiltration is possible when pumping costs increase by 53% to become 53.63 $/ML; an increase in the cost of pumping will cause an increase in the cost of agricultural production and a decrease in farm benefits (NPV) from basin infiltration. A cross-over point between basin infiltration and ASR is NA, because the rate of increase in pumping cost applies to both aquifer storage options. Similarly, there is no cross-over point between surface storage and ASR, as the lowest possible pumping cost considered in the analysis (6.25 $/ML) will not make ASR financially superior or equal to surface storage.

Low surface evaporation rates will make surface storage financially superior to MAR, as less water will be lost from surface storage, making more water available and resulting in larger benefits. A cross-over point between surface storage and basin infiltration is possible when evaporation rates decrease by 15%, from 40%, to become 34%. For evaporation rates, a cross-over point between surface storage and ASR is possible when evaporation rates increase to 74%, whereas the cross-over point between basin infiltration and ASR is NA.

5.1.2. Basin Capital Cost, Basin Infiltration Rate and Basin Maintenance Rate

An increase in basin capital cost will increase the overall cost and lower the benefits with a concomitant decrease in NPV. For the basin capital cost, a cross-over point between surface storage and basin infiltration is possible when the capital cost of basin infiltration increases from 363 $/ML to 466.69 $/ML.

A decrease in the infiltration rates will recharge less water per unit area of infiltration basin, requiring a large infiltrating pond area with larger capital cost, or with decreased infiltration rates, less water will infiltrate and be stored underground. A cross-over point between surface storage and basin infiltration is possible when infiltration rates drop from 0.2 m/day to 0.16 m/day. Similarly, a cross-over point between basin infiltration and ASR is achieved when infiltration rates drop from 0.2 m/day to 0.07 m/day. An increase in the basin maintenance rates will increase the overall cost of basin infiltration, reducing NPV in comparison to the compared options. A cross-over point between surface storage and basin infiltration is possible when basin maintenance rates increase from 10% to become 15%. The three considered variables do not apply when comparing surface storage and ASR, such that the corresponding cross-over points are NA.

5.1.3. MAR Loss Rate

Increasing the MAR loss rate makes MAR financially less attractive, because it reduces the volume of water recovered and the resulting benefits, though some pumping cost is saved, as less water is recovered with an increase in the MAR loss rate. In other words, a higher MAR loss rate represents a lower recoverability and, therefore, lower useful storage [22,45]. For benefits to be realized, the volume of water that is not recovered from storage must be less than evaporation losses. This applies to both MAR methods when compared to surface storage. A cross-over point between basin infiltration and surface storage is possible when the MAR loss rate reaches 11%. A cross-over point between basin infiltration and ASR is NA.

5.1.4. ASR Water Treatment Cost and ASR Maintenance Rates

A cross-over point for ASR maintenance rate is not possible when ASR is compared with surface storage and basin infiltration. Even its cheapest possible value, when considered alone, does not achieve an NPV equal or superior to basin infiltration and surface storage. The ASR water treatment cost only has a cross-over point if the treatment cost decreases by 91% to 13.25 $/ML. Increases in both variables increase the cost of ASR and, hence, (further) diminish its advantage over the other options.

5.1.5. Price of Cotton and Faba Bean

A decrease in the price of cotton and faba bean will influence the benefits of all three water storage options and lower NPVs for each case. A cross-over point for the price of cotton and the price of faba bean between surface storage and basin infiltration is possible when the price of cotton drops from $538 per bale to $475.64 per bale, and the price of faba bean drops from $348 per tonne to $229.52 per tonne, which are 11% and 34% drops from the best guess values, respectively. A cross-over point for the cotton and faba bean price is possible between surface storage and ASR when the price of cotton rises to $1,155.22 per bale, an increase of 114%. No cross-over point between surface storage and ASR is possible with the highest price considered possible for faba beans.

5.1.6. Discount Rate and Project Lifespan

An increase in the discount rate tends to increase the levelised cost of the two MAR options, in particular through the basin capital cost and the capital cost of establishing an ASR treatment facility. This will result in lower NPVs from the two MAR options. A cross-over point between surface storage and basin infiltration is possible at a discount rate of 13%, while there is no cross-over point between surface storage and ASR. Because ASR is already more expensive than surface storage, a higher discount rate will make ASR even more expensive, while the lowest considered discount rate of 1% will not be able to raise the NPV of ASR to be equal or superior to surface storage. Similarly, a lower discount rate will make basin infiltration more favourable than ASR, so no cross-over point is possible.

Lowering the lifespan of an option increases its levelised cost, such that the NPV of that particular option is lowered. A cross-over point between surface storage and basin infiltration is possible when the lifespan of surface storage increase from 30 years to 48.16 years or the lifespan of the basin infiltration drops from 30 years to become 23.51 years. Similarly, a cross-over point between surface storage and ASR exists when the lifespan of surface storage drops to 5.57 years. A cross-over point between basin infiltration and ASR is possible when the lifespan of the basin infiltration drops to 6.69 years. No cross-over point for the lifespan of ASR is possible when compared with basin infiltration and with surface storage options.

5.2. Changes in Cross-Over Points Due to Interactions between Variables

The values at which cross-over points occur are affected by the values of other variables, so it is important to consider interactions between variables. Every variable that either increases or decreases changes the financial advantage of MAR in comparison to surface storage. We describe the advantage of MAR in terms of change in the position (value) of cross-over points with respect to the best guess. The interaction of two variables can bring a cross-over point closer or further to the best guess. Two variables can interact in a way that they can increase, decrease or balance the effect of each other on the resulting advantage of MAR, depending on whether changes in the variable increase or decrease the financial advantage of MAR.

A cross-over point that moves away from the best guess value indicates increasing financial advantage for MAR. Conversely, when it moves closer to the best guess, the financial advantage decreases. The movement of a cross-over point closer to the best guess reveals situations where the benefits of MAR are reduced and could ultimately have equal benefits to surface storage when the cross-over point coincides with the best guess value.

Figures 5 and 6 illustrate with examples where the advantage of MAR over surface storage changes due to the interaction of variables. This is expressed through changes in the cross-over point of the MAR loss rate.

Given that increased costs reduce the relative benefit of MAR, when costs increase, the cross-over point for the MAR loss rate moves closer to the best guess value (Figure 5). Similarly, lower prices of crops decrease the benefit of MAR, and the cross-over point moves closer to the best guess (middle bar in Figure 6). When costs and prices both increase, the cross-over point can move closer or further from the best guess, depending on the level of change in costs and prices (bottom bar in Figure 6).

Figure 5. Plot of the MAR loss rate when costs increase. An example of a cross-over point moving toward the best guess.

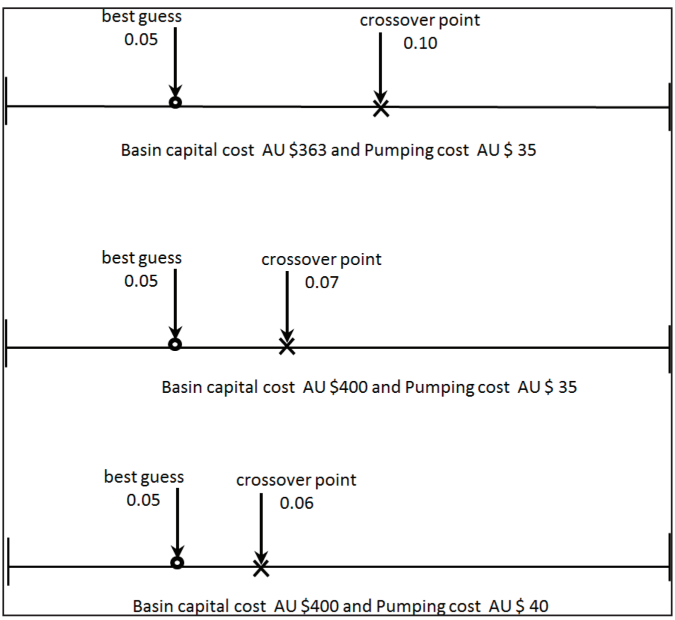
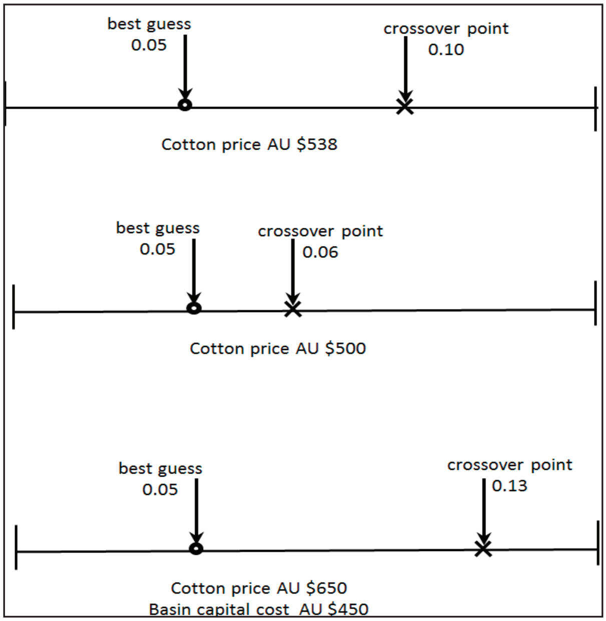


Figure 6. Plot of the MAR lose rate when costs and prices change. An example of the cross-over point changing position when costs and prices both increase.



5.3. Assessing the Risk of Attaining Cross-Over Points

Uncertainty in the financial assessment of MAR can be assessed by evaluating whether the scenarios described by the cross-over points identified are likely to be experienced in reality. If this occurs, then MAR may not be financially attractive. Alternatively, other measures may need to be taken to avoid situations leading to the cross-over point. Note that initial financial analysis suggests that basin infiltration is a favourable investment. As mentioned in the Introduction, the aim of this analysis is therefore to play the devil's advocate, that is to systematically search for reasons that requirements may not be met and that failure might occur.

While cross-over points could be assessed probabilistically, a simple approach is to say that a cross-over point is of greater concern if it is closer to the best guess value. This implies that investment in the MAR infrastructure is at greater risk of not making additional profits than surface storage because the return from MAR becomes closer to that of surface storage. On the other hand, the value of a cross-over point may fall outside the bounds (minimum and maximum limits) that are considered to be of concern, in which case, the analysis suggests that the minimum requirements will be met.

Following this approach, Table 4 shows the cross-over point of greatest concern when surface storage and basin infiltration are compared. The point was identified by simultaneously varying all of the variables and searching for a combination where each variable is closest to the best guess, relative to bounds. The bounds were defined by the authors based on an understanding of the factors influencing the variables, taking into account the expected variability, considering the lack of complete the knowledge of hydrogeological variables and the actions that can be taken to manage these concerns. In interpreting the results, the combination of values is assessed, not just each variable separately, and the reasons for the bounds selected are explained.

Table 4. Cross-over point of greatest concern with basin infiltration *vs.* surface storage, using a subset of variables.

	Variable	Minimum Bound	Maximum Bound	Best Guess	Point of Greatest Concern	Change from Best Guess
1	Pumping cost ($/ML)	6.25	225	35	37.22	2.22
2	Surface evaporation rate (%)	10	100	40	40	0
3	Basin capital cost ($/ML)	100	3,000	363	393.82	30.82
4	Basin infiltration rate (m/day)	0.01	2	0.2	0.2	0
5	Basin maintenance rate (% of capital cost)	1.0	40	10	10	0
6	MAR loss rate (% of target storage volume)	0	85	5	6	1
7	Price of cotton ($/bale)	50	1500	538	532.30	−5.70
8	Price of faba bean ($/tonne)	50	1400	348	344.52	−3.48
9	Discount rate (%)	1	50	7	8	−1
10	Lifespan of surface storage (Year)	2	50	30	30.23	0.23
11	Lifespan of basin infiltration (Year)	2	50	30	29.67	−0.33

Table 4 shows that the values of cross-over points are very close to the best guess and, hence, are of concern. The point of greatest concern describes a scenario of particularly unfavourable conditions, namely when all of the variables interact and change simultaneously. The scenario of greatest concern describes a situation where pumping costs have increased and the prices of cotton and faba bean have decreased. Basin capital cost turns out to be higher than expected, as well as the MAR loss rate. The lifespan of the basin infiltration project is marginally shorter than that of a surface storage project. Other variables remain at their best guess.

Individually, all variables of the scenario appear to be of great concern. However, in reality it is unlikely that all variables change at once and result in the situation described in Table 4. We analyse groups of variables to assess whether or not the generated scenario is possible, what mitigation options might prevent this cross-over point from occurring and what adaptation actions might be taken if it the scenario described by the cross-over point does occur.

5.3.1. Pumping Costs and Surface Evaporative Rates

The cross-over point of this variable is very close to the best guess value and, hence, may be reached. Based on historical trends, energy costs are expected to increase in the future, despite efficiency improvements in pumping technologies. However, the effect of higher pumping costs may be balanced or outweighed if there is an increase in the price of cotton and faba bean in the future. In addition, if farming becomes uneconomical at some stage, it is possible that government might provide subsidies for pumping to maintain agricultural production and preserve the livelihoods of farmers. Using alternate sources of energy, such as wind and solar, can be cheaper mitigation options in the future. High head gravity feed systems can be designed in certain cases to avoid pumping costs [9].

Surface evaporative rates are expected to increase under climate variability and change [46]. Evaporative rates may also be higher for farms where surface storage is shallow and depending on the water colour and turbidity. Higher evaporative rates will favour MAR, so this is unlikely to be a reason not to proceed with MAR. Reducing evaporative losses from surface storage at costs cheaper than those of setting up a basin infiltration system could have been a reason not to proceed with basin infiltration.

5.3.2. Basin Capital Cost, Infiltration Rate and Basin Maintenance Rate

The increase in the basin capital cost seems likely to occur if the investment is delayed, as the cost of labour, construction materials and energy prices for earth moving machinery are expected to rise due to inflation and other economic factors. Similarly, the values of basin infiltration rates and basin maintenance rates exactly coincide with the current best guess estimates, and hence, the two variables are of great concern. The infiltration rate is a function of a number of variables, with water quality a major factor.

A few mitigation options exist to avoid increases in basin capital cost. Field trials and geophysical investigations can help find suitable sites where high infiltration rates can be achieved. Basin maintenance is related to the amount of silt and other suspended and organic matter contained in the floodwater. Basins can be sized to allow rest and maintenance. In the lower Namoi catchment, floodwater already passes through a *de facto* two-stage sediment and silt removal process. Firstly, it is retained in large public dams before release, thereby reducing heavy silt loads; secondly, at the farm level, floodwater is kept in farm dams as temporary storage before recharging begins. The two-step sediment removal process can be advantageous in lowering the cost of basin maintenance.

5.3.3. MAR Loss Rate

In the lower Namoi, more than four decades of groundwater pumping have dropped the water levels, and in many places, rivers and streams (naturally) recharge groundwater [47], such that useful storage exists at a large scale. At the farm scale, while water may not physically stay within a farmer's land and, as such, is not physically stored, the system of surface and groundwater water rights means that injected or infiltrated water could, in principle, be allocated to the farm anyway, in a form of "regulatory storage" [22]. This results in potentially extremely high recovery rates (95%) and low loss rates, as a farmer benefits from contributing water to a common pool rather than being restricted to physically retrieving the water that they recharged. The loss rate determined by regulation could however be affected by a number of broad-scale issues. For example, the MAR loss rate can be of concern for locations where surface water and groundwater connectivity exists and where streams and rivers gain groundwater from aquifers, which is rare in lower Namoi. Low recovery is possible only in aquifers that contain brackish or high salinity water, due to the mixing of fresh recharge water with the native high salinity groundwater. This may occur in some parts of the lower Namoi, particularly areas where drops in groundwater hydraulic heads have resulted in the mixing of saline and freshwater within different layers of aquifers. In areas of excessive groundwater extraction, groundwater hydraulic heads can drop and allow saline water to enter into pumping wells [42], thereby increasing the salinity levels of the recovered water and resulting in less recovery of the volume of freshwater recharged initially.

5.3.4. Price of Cotton and Faba Bean

Cross-over points for the price of cotton and faba bean are not likely to occur, and they are not of greater concern. The future price of cotton is expected to remain stable or increase because of ongoing demand and an established linkage of the Australian cotton industry to overseas markets, where demand exists and can be expected to grow. In the future, with limited irrigation water availability at the global scale, international prices of cotton are expected to rise, rather than decrease. Other cotton producing and competing countries, such as China, Pakistan and Egypt, are likely to become more water stressed in future. Additionally, with world population growth continuing unabated, a higher demand for cotton is expected. The price of faba bean is also expected to increase in the future; however, a drop in the price of faba bean is also possible whenever supply exceeds the local demand. A change in the price of faba bean is not a major concern, because it is a local crop mainly used for cattle and human consumption and has limited potential for export in national and international markets. Faba bean is not a major source of farm revenue, and if at some point, there is an oversupply and a drop in price occurs, faba bean can be replaced with some other high value crop. Any rise in the sale price of both cotton and faba bean would also compensate for increases in pumping costs and other MAR infrastructure costs.

5.3.5. Discount Rate and Lifespan of Projects

A 7% discount rate coincides with the current best guess and is highly likely to occur and is therefore of great concern. Discount rates of more than 7% will make MAR financially unattractive. As this may occur if the cost of borrowing capital is high, farmers may search for financing at lower rates or governments may assist farmers to set up special MAR grants or loans involving the least possible interest rates. Cross-over points for the lifespan of surface storage and basin infiltration almost coincide with the best guess (30 years) and are of great concern. The lifespan of basin infiltration can be enhanced by drying of basins, frequent scarping of accumulated silt layers and controlling weed growth.

6. Conclusions

Break-even analysis of cross-over points is one way of assessing the financial performance of MAR under uncertainty. Cost-benefit analysis of surface storage and MAR helps to compare options in financial terms, but results cannot be relied upon completely without due consideration of uncertainty. Our approach to addressing uncertainty is to undertake a financial cost-benefit analysis by analysing a range of values for influencing variables and to establish thresholds (cross-over points) where financial returns from surface storage and MAR are equal. Once the thresholds are established, mitigation options can be identified and put in place to avoid variables reaching identified thresholds.

The analysis of cross-over points can be undertaken to identify minimum requirements under which MAR can be more advantageous than surface storage, and this was illustrated for the lower Namoi. For this catchment, MAR using basin infiltration can be financially superior to surface storage, but this depends on the selection of a suitable site where a high infiltration rate, low loss rates and other minimum requirements can be achieved. Further exploration of MAR through field trials and geo-physical investigation is suggested in areas of lower Namoi. MAR can be a potential option to achieve future water supply goals, provided that it is technically feasible and more financially viable than surface storage.

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Author Contributions

Muhammad Arshad is the lead author and contributed in developing the introduction, feasibility of MAR and the text and financial analysis in the case study section. Joseph Guillaume contributed to the text on methods, development of the code for consideration of uncertainty in the cost-benefit analysis of cross-over points. Joseph also produced major graphics for the paper. Andrew Ross contributed to the text on abstract, introduction, conclusion and editing the paper. The analysis of cross-over points was carried out jointly by Muhammad Arshad and Joseph Guillaume.

Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 3

Utilization of MAR for Wastewater Reuse in Arid Regions

Managed Aquifer Recharge (MAR) Economics for Wastewater Reuse in Low Population Wadi Communities, Kingdom of Saudi Arabia

Thomas M. Missimer, Robert G. Maliva, Noreddine Ghaffour, TorOve Leiknes and Gary L. Amy

Abstract: Depletion of water supplies for potable and irrigation use is a major problem in the rural wadi valleys of Saudi Arabia and other areas of the Middle East and North Africa. An economic analysis of supplying these villages with either desalinated seawater or treated wastewater conveyed via a managed aquifer recharge (MAR) system was conducted. In many cases, there are no local sources of water supply of any quality in the wadi valleys. The cost per cubic meter for supplying desalinated water is \$2–5/m^3 plus conveyance cost, and treated wastewater via an MAR system is \$0–0.50/m^3 plus conveyance cost. The wastewater reuse, indirect for potable use and direct use for irrigation, can have a zero treatment cost because it is discharged to waste in many locations. In fact, the economic loss caused by the wastewater discharge to the marine environment can be greater than the overall amortized cost to construct an MAR system, including conveyance pipelines and the operational costs of reuse in the rural environment. The MAR and associated reuse system can solve the rural water supply problem in the wadi valleys and reduce the economic losses caused by marine pollution, particularly coral reef destruction.

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1. Introduction

Hundreds of small villages and farms exist in wadi (ephemeral streams) valleys throughout the Kingdom of Saudi Arabia (KSA). For centuries, these agrarian communities relied upon shallow groundwater resources to supply potable and irrigation water demands [1]. Anthropogenic impacts, including over-pumping and contamination, have combined to deplete or render unusable the groundwater in shallow alluvial aquifers underlying the wadis [1–3]. Because of the low population density, generally small contribution of crop production to the national economy, and the arid nature of the climate, there are quite limited options available to supply the necessary water to maintain these populations. Nevertheless, rural communities are considered an important part of the cultural heritage of the Kingdom, and finding a solution to their water challenges is a priority. While the KSA is a wealthy country and has technically feasible options to replace the depleted water supplies for these rural communities, such options are even more limited in other, less prosperous countries in the Middle East–North Africa (MENA) region [4].

Four potential methods of providing a comprehensive and reliable water-supply solution are currently being assessed in the KSA. These options include: (1) the construction of seawater reverse osmosis (SWRO) desalination plants and conveyance of this water from the coastline to the end users via pipelines; (2) desalination of brackish groundwater by reverse osmosis (RO), where brackish-water aquifers are available; (3) construction of wadi dams to trap seasonal stormwater discharges and conveyance of the water to the users via pipelines (treated or untreated); and (4) conveyance of treated domestic wastewater to the users via pipeline with subsequent storage and treatment in the underlying aquifer system using aquifer recharge and recovery (ARR) systems. ARR is a form of managed aquifer recharge (MAR) that takes advantage of natural contaminant attenuation processes to improve water quality. ARR systems have an element of treatment along with the conventional storage functions of aquifer storage and recovery (ASR) systems. Use of cistern water capture and other water harvesting methods have been considered, but are insufficiently robust to meet water supply requirements, especially under future global climate change scenarios.

A more detailed analysis of the region shows that the western part of KSA bounding the Red Sea does not contain significant brackish water aquifers that could produce sustainable quantities of water to become a reliable source of water supply. Also, the construction of wadi dams and development of water supplies is based on storm events that have a very uneven frequency and with global climate change, could become more intense and less frequent [5]. Therefore, only two of the four options (seawater desalination and wastewater reuse with ARR) are technically viable as far as potentially providing sustainable water supplies. The feasibility of the two technically viable options depends upon both costs and social acceptance. It should be noted that if all of the supply options were to be found unfeasible, the population living in the small communities and farms would be forced to leave their lands and move into densely populated urban areas, therefore exacerbating existing water supply and social issues in the region.

It is the purpose of this paper to assess the relative economics of two potential sustainable water supply options for these small communities and farms; use of seawater desalination *versus* use of treated domestic wastewater with ARR storage and treatment for both irrigation and indirect use. This assessment is conducted using unit costs for many of the variables, because there is considerable variation in the transport distances from the sea or sources of treated domestic wastewater to water users and corresponding spatial variation in water demands.

2. Background and Methods

2.1. Description of the Rural Wadi Communities and Farms

Rural communities and small farms are quite common in the wadi valleys of the KSA as well as in many other areas of the MENA region (Figure 1). For centuries, these small communities and farms have been dependent on shallow groundwater for supplies. In the past, there was sufficient recharge to the underlying alluvial aquifer system to maintain the sustainability of the water supply. Aquifer water levels fluctuated seasonally between 1 and 3 m below surface in the early part of the 1900s, depending upon rainfall accumulation and the occurrences of periodic drought conditions [6]. However, in the modern era, population growth and expansion of agricultural activities has caused depletion of the groundwater resources of wadi alluvial aquifers with water levels commonly dropping 20 to 30 m below surface in many areas and causing complete aquifer dewatering in some wadi systems [2] (Figure 2).

Figure 1. Large-diameter abandoned well at the center and a dead date palm plantation in western Wadi Qidayd, Saudi Arabia. Aquifer depletion has caused the large-scale failure of small farms and abandonment of some villages as shown by the dead date palms.

The wadi channels in which the villages and farms lie are moderate to low sloped features that contain alluvial sediments and are periodically flooded to variable degrees. A large number of large diameter wells are used to supply groundwater where it is still available. Many of the wells have been abandoned because of resource depletion or contamination with saline water and/or nitrates. Entire conventional treatment facilities have been abandoned (Figure 3). In areas where groundwater depletion has occurred, the only method of obtaining potable and irrigation water is to purchase it from suppliers and have it hauled by tank truck to fill onsite storage tanks. At Wadi Qidayd, the cost for treated water is \$1.60–1.87/m^3 and for untreated water \$0.27–0.40/m^3. The source of the truck-transported water is often local wells, the use of which contributes to further aquifer depletion. Use of the wadi aquifers for water supply at current rates is not sustainable. The lack of effective rainfall and associated recharge in the lower part of the Wadi Qidayd basin for the past several years has caused the shutdown of several local water suppliers due to dry wells.

Figure 2. Two-meter diameter well showing the water level at about 20 m below surface in Wadi Qidayd, western Saudi Arabia.

Figure 3. Abandoned municipal well that served a village water treatment facility.

2.2. Estimation of Wastewater Treatment Costs

Wastewater treatment costs have been estimated from the literature for primarily conventional treatment technologies that will provide a relatively high degree of purity to allow indirect potable use. The technologies evaluated are discharge lagoons/oxidation ponds with natural infiltration (LAG), conventional trickling filters, conventional activated sludge (CAS) with nutrient removal (*i.e.*, secondary treatment) as nitrates can adversely impact drinking water quality, assessing CAS as conventional aeration tanks or oxidation ditches (CAS-OxD), advanced treatment using an integrated membrane bioreactor system (MBR), and conventional activated sludge followed by tertiary filtration (CAS-TF). The final polishing of the treated domestic wastewater is assumed to be aquifer treatment, whereby the treated wastewater is placed into the alluvial aquifer using wells and the extraction for potable use is from wells located down-gradient. It is known that some refractory trace organic compounds will not be removed from the wastewater and further treatment may be required at extraction points closer to larger population centers. Although there are some public concerns regarding possible impacts of these compounds on human health, there are currently no drinking water standards established for them [7]. The available evidence suggests that exposure to trace concentrations of pharmaceuticals (at concentrations found in treated wastewater and water) is unlikely to cause health effects [8,9].

Capital and operating costs for the various wastewater treatment technologies are comparatively developed, which are then systematically compared to seawater desalination costs.

2.3. Estimation Methods for Desalination Costs

Compilation and analysis of desalination costs have been published recently [10] based on past and recently collected cost data. The costs estimated for seawater desalination are focused on SWRO because it is the least costly of the large-scale desalination methods currently being used in the KSA and can be designed and constructed at a variety of capacities. Thermal desalination systems are quite difficult to design, construct, and operate at small capacities, especially in consideration of the rather small water use requirements in some wadi systems. Low-capacity, renewable-energy driven systems, such as solar stills cannot be used because of the lack of any local supply of water, saline or fresh.

SWRO costs are developed for a range of capacities. There is an economy of scale that generally causes larger-capacity SWRO systems to operate at lower costs compared to small capacities. However, many of the wadi communities are widely separated from large population centers and would require the development of comparatively low capacity SWRO systems. It would be less expensive to construct and operate a small scale SWRO plant to serve a number of small communities, than to pipe treated water a great distance from the very large-capacity desalination plants located near major population centers [11].

2.4. Estimation of Conveyance Costs

The cost of conveyance is based on design and construction of the pipelines using a standard diameter high-density polyethylene pipe (HDPE). The pipe would be buried primarily within the wadi channels at the proper location and depth to avoid damage during flow events. The burial depth is estimated to average 1 m below grade. The two pipe diameters considered are OD 1100 mm and OD 630 mm. The strength grade of the HDPE pipe is 16 BAR PE 100. These large-diameter pipeline sizes are used with the assumption that there will be off-takers of water along the trunk lines and reduced diameter pipelines would serve the most distal farms and villages.

It is assumed that a pumping station will be required for each 40 km of pipeline. The average elevation change is estimated to be about 70 m and head losses due to pipe friction limit the overall head loss to no greater than 120 m. Electrical requirements are estimated based on the friction head loss for the two pipe diameters plus the elevation head required.

Costs of the pipeline design and construction and the pumping stations are estimated based on conversations held with contractors in KSA (Jeddah city) and consulting engineers in the United States that have Middle East region experience. Engineering design and construction observation costs for the pipeline and pumping stations are estimated as about 15% of the total construction cost based on KSA practices.

2.5. Estimation Methods for Treated Water by ARR/MAR Systems

ARR/MAR costs are estimated based on the construction of both large (2 m) and smaller (0.5 m) wells using local drilling contractors. The injection of the water is designed to use the line pressure from the pipeline and is essentially either a gravity feed system or a low pressure injection system. The down-gradient recovery well pump costs and electrical use are based on an average lift of 25 m using electric turbine pumps. A few different pumping rates were used based on the well types and desired capacities.

It should be noted that there are hundreds (or thousands) of abandoned or seldom-used, large-diameter wells located throughout the wadis of western KSA. Wherever possible, existing wells would be used. In some cases, the wells would have to be rehabilitated or repaired. Also, these abandoned wells were commonly located adjacent to the villages and farms where the water would be used.

2.6. Water Treatment

Water recovered from the ARR/MAR treatment systems for potable use is of generally high quality. It is assumed that the only post-recovery treatment would be disinfection using chlorine.

Water from the system used for agricultural purposes would not be treated. Some farms may choose to install storage tanks to allow higher irrigation rates during the nighttime. This would ameliorate any supply and demand imbalances and would keep the pipeline costs lower (smaller diameter pipes).

Most houses and public buildings in the wadi communities are equipped with storage tanks, which would allow a lower amount of system common storage to be used for ARR/MAR recovered and treated water. Therefore, only relatively small capacity storage tanks are used for the village supply systems. Distribution piping system costs are not included in these estimates because of the large differences in demand for population centers ranging from a few families to perhaps 3000 people. Currently, many villages are not equipped with distribution systems, particularly the smaller population centers where water is trucked to the users. This practice may remain after system installation, but the quality of water would be truly potable.

3. Results and Discussion

3.1. Seawater Desalination Treatment Costs

The KSA is the world's largest user of desalinated seawater, accounting for about 18% of the total global capacity [12]. The most used desalination technology in the KSA is multi-stage flash (MSF) distillation which is very energy intensive accounting for up to 70% of the desalination costs, and these plants are expensive to maintain [13]. In recent years, the KSA has begun to use large scale SWRO, but most commonly in hybrid facilities containing electric generation, MSF, and SWRO [14]. In addition, many standalone SWRO and brackish water reverse osmosis (BWRO) plants, with capacities ranging between 50 m^3/d and 17,500 m^3/d, have been installed by the private sector [12]. On the other hand, multi-effect distillation (MED) is being used to replace the MSF process in other sites in the KSA, mainly with enhanced performance using thermal vapor compression (TVC) in a hybrid MED-TVC configuration (Table 1). It is difficult to ascertain the true cost of seawater desalination in the KSA because all utilities are subsidized by the government, and, commonly, freshwater is provided at vey low cost to the consumer [10]. Also, there are virtually no legal restrictions on water use and legal guidelines on reclaimed water use in the KSA.

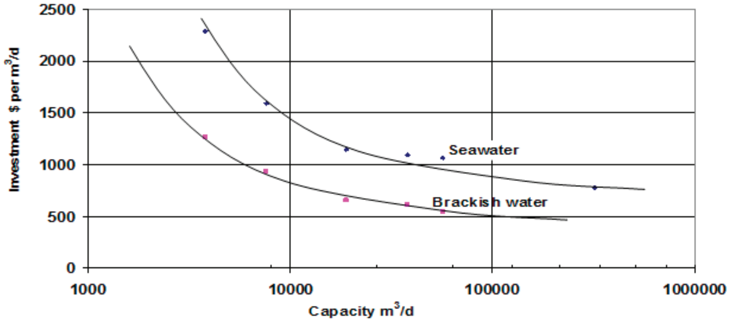
Table 1. Water cost of different thermal desalination projects in Kingdom of Saudi Arabia (KSA), including subsidies (Global Water Intelligence/Water Desalination Report (GWI/WDR), 2009–2014).

Site	Capacity (m^3/d)	Capital Cost (USD)	Total Water Cost ($\$/m^3$)
Shoaiba MSF	880,000 and 900 MW	$2.4B	0.95
Marafiq multi-effect distillation–thermal vapor compression (MED-TVC)	800,000	$3.4B	0.83
Rabigh MED-TVC	2@5000	-	1.15

Some water cost estimates can be made for the various seawater desalination facilities based upon energy consumption for the different technologies being used. These costs are truly scale dependent based on the capacity of the treatment facilities (e.g., large capacity facilities generally produce water at a generally lower unit cost compared to small facilities) [15] (Figure 4). Within the KSA, thermal desalination costs, including subsidies, range between $0.83 and $1.5/$m^3$ depending on the technology used, age of the facility, and the plant capacity. Hybrid water desalination facilities costs depend strongly on the hybrid configuration used along with the capacity. The total water cost produced by a MSF-SWRO hybrid system is 5%–10% less compared to MSF standalone plants [16]. On the other hand, SWRO facilities (standalone) produce freshwater at a cost ranging from $0.5 to $1.5/$m^3$, depending on several parameters, such as feed water salinity, requested product quality (includes post-treatment), and electrical energy, land and labors costs. Water cost of some thermal desalination plants in the KSA is presented in Table 1.

Another important factor affecting desalination water cost for rural communities is the distance of the end users from the coast or from large population centers that are served by high-capacity desalination facilities. In wadi communities located within a 50–100 km radius of a major desalination facility, the actual freshwater production cost would be the same as for the city residents, but the additional cost would be for transmission. In remote communities, the design, construction, and operation of standalone SWRO or BWRO facilities with a moderate to low capacity would likely be required and their costs might be very competitive with long water transfer from coastal desalination plants [11]. However, the feed water sources to supply these local plants within the wadi areas are not sustainable and therefore, would not be a reliable water supply. Overall desalination costs could be quite high from these facilities, located near the user (if possible) or at the shoreline, with a probable range from $1.25–5/$m^3$.

Figure 4. Investment cost/m^3 for seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) systems. Note the reduction as the capacity increases.



Installation of small-scale innovative desalination processes at the shoreline, powered with solar energy, may produce water at a lower cost and would require less maintenance and chemical use [17]. Low-energy processes, such as membrane distillation, could be the best solution for communities living in rural areas. Also, each village would be responsible for providing water storage and a distribution system where the population density permits doing so. Existing systems depend upon trucking water from a well (if available) and conveying the water to storage tanks located at each home or cluster of homes. This system also has a cost.

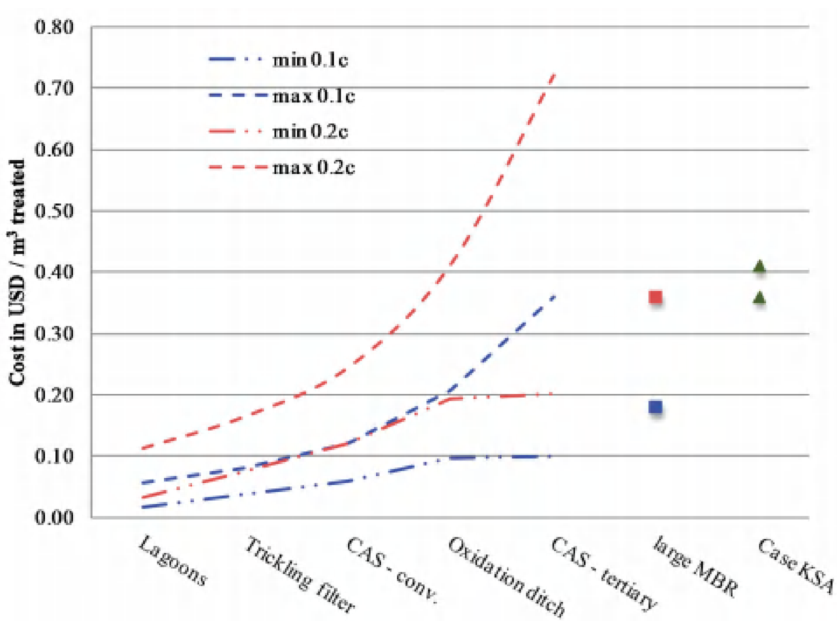
3.2. Domestic Wastewater Treatment Costs

Wastewater treatment plants naturally vary in capacity as a function of the community being serviced as well as the underlying infrastructure approach used (e.g., individual households *versus* decentralized/satellite designs and large centralized technologies). There is also an economy of scale that generally causes larger-capacity treatment plants to operate at lower costs compared to small capacity plants. For smaller communities (e.g., villages and farms) the operating costs for a treatment system will therefore fall in the higher range of cost estimates. In addition, the type of treatment technology selected will impact both capital and operating costs. A complicating factor in such an assessment is the difference in both regional and local parameters, such as land cost (*i.e.*, impact of plant footprint), and the unit cost for energy.

In rural communities there is a tendency to choose low-technology solutions which typically require a lot of space (on the assumption that land costs are minimal) and which will require a minimum of skilled-labor maintenance. However, for a water reclamation and reuse strategy, there is a move to more advanced treatment systems to ensure reliable, safe, and high water quality as defined by the end use. In this cost estimate, representative treatment technologies, which can be defined as low to high technology solutions, have been included in the comparison. These include ponds and lagoons, trickling filters, variations of conventional activated sludge (CAS) (e.g., secondary treatment/oxidation ditches), tertiary treatment of secondary effluent (e.g., membrane filtration/advanced oxidation), and membrane bioreactor technology (MBR) as an alternative advanced tertiary treatment system. A direct comparison of capital costs for these technologies is not straight forward, although studies in the literature can be found showing that high technology options are cost competitive to low technology alternatives [18–21].

In most studies assessing operating costs for various treatment technologies, energy is highlighted as a key parameter for defining the operating costs, typically in the range of 40%–60% of total costs [18,19]. The specific energy consumption for wastewater treatment is reported in the range of 0.4–1.0 kWh/m^3 of treated water [19,21,22]. Breaking this down to commonly used technologies in terms of sophistication of the treatment plant gives the ranges or 0.08–0.28 kWh/m^3 for lagoons, 0.19–0.41 kWh/m^3 for trickling filter plants, 0.33–0.61 kWh/m^3 for conventional activated sludge, and 0.48–1.03 kWh/m^3 for oxidation ditches and tertiary treatment. Membrane bioreactors are perceived as being energy intensive, however recent case studies comparing average energy requirements for tertiary treatment based on conventional activated sludge compared to MBR have shown that a relatively large MBR plant consumes 0.9 kWh/m^3 compared to a range of 0.5–1.8 kWh/m^3 for the tertiary conventional activated sludge options [18,20,23–28]. On the assumption that energy costs on average are 50% of the total operating costs, energy can be estimated at 0.01–0.210/kWh/m^3, an estimate for a lower and upper range of operating costs for various wastewater treatment technologies can be compared. The results are shown in Figure 5.

Figure 5. Estimated cost/m^3 for wastewater treatment using different technologies.



For the low technology options (e.g., lagoons, trickling filters) the treatment costs will range between \$0.05–0.20/m^3 depending on the criteria chosen, however, it is debatable whether the water quality achieved is well suited for reuse. Conventional activated sludge is a more appropriate technology with respect to treated water quality and design options resulting in costs ranging between \$0.10–0.50/m^3. It is interesting to note that conventional activated sludge designed as an oxidation ditch can be relatively higher in O&M costs, as exemplified by the example of case studies in the KSA [26,27]. Treatment of wastewater to a high quality suitable for reuse can be achieved by conventional activated sludge followed by advanced tertiary treatment, estimated at a cost ranging from $0.10–0.70/m^3 based on a series of assumptions. For this level of treatment, MBR technology is shown to be more efficient with estimated costs of less than $0.40/m^3 [23,24]. In recent research conducted on advanced treatment of wastewater by MBR technology, it was shown to be very competitive an as alternative to desalination options [23,24]. With respect to rural populations having to rely on desalination as a reliable water source, it is apparent for the simple estimations shown above that advanced treatment of wastewater for both non-potable and indirect-potable reuse is a viable and sustainable option.

3.3. Conveyance Cost

The cost to convey water from the treatment plant to the end user is quite significant, especially in the isolated rural environment. Conveyance cost can be broken down into capital and operating costs. Capital costs include the pipeline engineering and construction, the cost of the pumping stations, and some undefined costs of conveyance, such as construction of pipelines crossing roads and municipal infrastructure at large facilities. The operating costs include the electrical costs and are mostly for electricity to run the pumps. Any additional costs associated with the operation of ASR wells are considered to be minor within the overall assessment.

Wadi valley pipeline engineering design and construction are relatively simple, but require consideration of periodic flooding within the wadi channels and potential erosion of the main channel area. The soils are predominantly sands and gravels and are easy to excavate. The preferred pipeline material can be HDPE. The strength of the pipe should be 16 BAR PE 100 to prevent any damage due to movement during earthquakes and by trucks or other farm equipment. The cost for materials and installation of HDPE pipe in the wadi valleys of Saudi Arabia is given in Table 2. The hydraulic gradient from the shoreline to the heads of the wadi valleys is not very steep and the overall elevation rise is likely not more than 70 m over a distance of about 40 km. Pumping station costs were obtained for a variety of facilities ranging in capacity from 5000 to 40,000 m^3/d. The cost for such facilities in western Saudi Arabia is roughly $500,000/5000 m^3/day of capacity (Table 2). A preliminary assessment shows that a single pumping station can be used to transmit this range of capacities between 40 and 60 km, assuming that the overall head loss is no greater than 120 m.

Only two relatively large diameter pipe sizes are listed in the table. Since wadi systems contain a series of local farms and village occurring along a linear geometry or with a series of branches, these pipeline diameters would be used as trunk lines and could be reduced in diameter from proximal to distal users. For cost estimation purposes, the larger diameters should be used because the cost of construction will likely be nearly the same for the next lower set of pipe diameters.

The electrical use for operation of the pumping stations to convey the water from the source to the use area is dependent on the required capacity (Table 2). The kilowatt-hours of electricity per day are also given in Table 2. The subsidies used in Saudi Arabia make the determination of real electric costs quite difficult to estimate, but the real cost likely ranges from $0.05–0.15/kw-h. An estimated cost range to convey the water 40 km is $0.45–1.50/m^3.

Since the key aspect of this research is the comparison of costs between use of desalinated water and reuse of highly treated domestic wastewater indirectly via an MAR system for potable supply and directly for irrigation use, the cost of conveyance of the water will be the same for either option. It can be calculated from the data given in the tables. If the water is conveyed from great distance, the cost of desalinated water delivery will be roughly doubled. The multiplier will be even greater for conveyance of highly treated wastewater because of its lower treatment cost.

Table 2. Estimated cost for construction of high-density polyethylene pipe (HDPE) pipelines in wadi systems.

Cost Item	**Cost/km**	
1100 mm outside diameter HDPE pipe (rated 16 Bar PE 100)	$7,000	
630 mm outside diameter HDPE pipe (rated 16 Bar PE 100)	$3,000	
Construction cost (wadi sediments, 1 m burial depth, with fittings)		
For 1100 mm pipe	$107,000	
Construction cost (wadi sediments, 1 m burial depth, with fittings)		
For 1100 mm pipe	$80,000	
HDPE Pipeline Diameter (rated 16 Bar PE 100)	Cost/km Total [1]	
1100 mm outside diameter	$114,000	
630 mm outside diameter	$83,000	
Pumping Station (m^3/day) (total head required = 100 m)	CAPEX	OPEX (kw-h/day) [1,2]
5,000	$500,000	38,000
10,000	$1,000,000	76,000
20,000	$2,000,000	152,000
30,000	$3,000,000	228,000
40,000	$4,000,000	304,000

Notes: [1] The assumed total dynamic head is estimated to be 122 m; [2] Real cost of electric power in the KSA is estimated to range from $0.05–0.15/kw-h.

3.4. Cultural and Religious Issues Involving Wastewater Reuse

A major challenge for indirect potable reuse projects is obtaining public acceptance. Public perception issues associated with reuse of reclaimed water were reviewed by Maliva and Missimer [2]. In general, public acceptance of the reuse of reclaimed water increases with increasing “distance” or isolation from the treated wastewater. There is generally a high level of acceptance for projects with no human exposure and a much lesser support for projects with direct human contact.

The passage of water through a natural environment, such as an aquifer, also reduces its “taint” of being wastewater. Public acceptance also depends upon the recognition by the effected population of the severity of the water shortage and confidence in the agency or organization that will implement the project. Reuse of reclaimed water and even indirect potable reuse are not contrary to Islamic Law. The Council of Leading Islamic Scholars in Saudi Arabia issued a fatwa in 1978, stating that reclaimed water can be used for ablution and drinking if it is sufficiently and appropriately treated to ensure good health, but recommended avoiding use of treated wastewater for drinking purposes to avoid health problems and also in consideration of the negative public sentiment about this water. If drinking is to be avoided, it is to be merely for reasons of public health and safety, not due to any ramifications of Islamic Law [29].

Wastewater is already being recharged to some wadi alluvial aquifers downstream of wastewater treatment plants and through on-site disposal systems, so the introduction of the more controlled upgraded wastewater treatment/ARR could, in some instances would, result in improved water quality. Nevertheless, obtaining local public support will be a critical feasibility issue, which will need to start with a public education campaign. A lack of knowledge on issues such as wastewater quality, health risks, and for farmers, impacts on soils and crops often leads to a negative perception of wastewater reuse.

3.5. Cost for ARR (MAR) Construction and Operation

In most cases, the number of abandoned, large-diameter wells would be sufficient to meet the need for existing small villages and farms, at least for the upgradient injection well or wells for each site. At locations where an additional well is required to recover the injected water, the construction cost for a well ranges from $5000 to 20,000 depending on the depth and diameter of the well. The recovery pump would be a diesel-powered vertical turbine pump with a head lift maximum of 50 m. Typical pumps used in the wadi systems cost about $7500. The cost of fuel to power the pumps is subsidized and is about $0.25/L. Therefore, the operational cost of a small ARR system for a village is <$0.05/m^3. The treatment cost and conveyance of the source water is greater than this cost.

3.6. Indirect Reuse and Irrigation Use Using MAR Treatment of Domestic Wastewater for Wadi Communities in the KSA: Special Circumstances

The economic analyses developed in this research suggest that the use of treated domestic wastewater combined with ARR polishing for indirect potable use is the most economical solution to meet the rural water supply requirements, but it is still costly. However, there are extenuating circumstances that greatly affect the economics of water reuse which include the current practice of disposal of the treated or untreated wastewater and its adverse environmental effects on the marine environment and some inland aquifer water quality.

Only about 10% of the wastewater generated in the KSA is reused in a beneficial manner. Partial treatment and discharge to tidal water or into channels transmitting into the desert with no users are not economically beneficial. Therefore, a real cost comparison between use of desalinated water and wastewater should consider that there is zero cost for treatment of the wastewater if it is being discharged to waste. In fact, environmental damage caused by inappropriate wastewater disposal practices produces a negative economic impact, which must be considered in this analysis.

Wastewater discharges to tide adversely affect the fringing reef of the Red Sea as occurs in all coral reef ecosystems [30–32], which in turn, adversely affects fisheries and the potential recreational aspects of the reef ecosystem. Coral reef ecosystems provide a diverse variety of goods and services to humanity [33,34]. Goods and services of all natural systems of the Earth affect the human economy and well-being [35]. Anthropogenic impacts on coral reefs have a direct economic impact on the recreational value of reefs that can be measured [36]. Economic assessments by Cesar [37] and Berg *et al.* [38] found that losses to coral reef tourism caused by the destruction of 1 km^2 of reef ranged between $27,900 and $100,800 USD and $5500 and $368,000 USD, respectively. A loss of $40 million USD over a 10-year period was estimated by Hodgson and Dixon [39] for tourism and fisheries declines in a coastal area of the Philippines. While the Red Sea of KSA does not have a well-developed ecotourism industry, it is greatly dependent on the fisheries, which may generate an event larger overall economic impact.

There is a negative cost impact on the disposal of each 1 m^3 of wastewater discharged to tidal water in the vicinity of a coral reef system. This cost depends on the concentration of nutrients within the wastewater, the degree of treatment for removal of solids and organic carbon, the proximity of the discharge to the reef, and the nearshore current patterns. A crude estimate of this cost range is $0.05–0.20 USD/$m^3$ for the economic losses associated with marine pollution. The range of loss associated with discharge to wadi aquifers and contamination of groundwater cannot really be estimated for areas where there is no significant water use.

3.7. Long-Term Sustainability of Seawater Desalination to Meet Rural Water Demands: Subsidies

In any economic analysis, the issue of sustainability must be raised within the context of the water supply options being assessed. Based on the economic return of the relatively small population and the farms within the wadi valleys, the cost of supplying desalinated seawater to these areas would have to be subsidized by the government to bring economic viability to the residents and farmers. This issue raises questions concerning the long-term viability of a fully subsidized water supply within the context of the Saudi Arabian economy. However, there may be some mitigating economic issues with regard to food security which cannot be evaluated within the context of this research.

Electricity, fuel, and utilities are all nearly fully subsidized in KSA. The root of economic prosperity in the KSA is the income received from the international sale of petroleum [40]. In 2009, 25% of the petroleum produced in the KSA was consumed domestically and with population growth, this percentage will likely continue to rise [41]. This means that as domestic petroleum consumption rises, the petroleum available for export sale declines, and overall revenue income will decline with time. Also, the rate of domestic energy consumption in the KSA is greater than the United States. Declining revenue raises the question whether significant water use that provides little or no economic return can be maintained.

All other subsidies, including water supply and wastewater treatment are also subsidized to a nearly full degree. However, water and wastewater tariffs are being assessed to a limited degree in an attempt to recover some costs of providing utility service to the public and industry. There has been considerable push-back by the general population and industry that have grown comfortable with free utility services. Ramady [40] suggests that continuation of subsidies is a great challenge that is part of greater economic reform, which will be required in the future. Krane [41] has suggested that most economists believe that continued maintenance of utility subsidies threatens the stability of the Saudi Arabian economy. Therefore, the long-term economic sustainability of providing desalinated water to small villages and farms for drinking and irrigation water is debatable and questionable. This suggests that choosing the low cost water supply alternative, despite religious and cultural questions, may be the only viable long-term water supply option.

4. Conclusions

There are limited options to supply water to the rural villages and farms located in western Saudi Arabia as well as other such communities located in similar global arid lands areas. A comparison of actual treatment costs between providing desalinated seawater for potable and irrigation uses to use of highly treated domestic wastewater with MAR polishing show a difference of nearly 300%. The overall cost of SWRO treatment with conveyance of the water over a distance of 40 km ranges from \$1.70–6.50/m^3. Treatment cost of domestic wastewater ranges from \$0.10–0.80/m^3. Conveyance cost for a distance of 40 km ranges from \$0.45–1.50/m^3. The use of local ARR systems using existing wells and a new well with a new pump is about \$0.05/m^3. Therefore, the water reuse system including treatment, conveyance and the ARR final treatment and operation ranges from \$0.6–2.35/m^3. If it is assumed that the treatment cost of the wastewater is zero, because it is currently not used or is discharged to waste, then the cost range declines to \$0.5–1.55/m^3.

The costs developed herein are rather specific to the western Saudi Arabia region, but can be estimated for any region based on the cost per kw-h for power consumption and correction for local electric rates. Construction costs vary greatly worldwide, but when these costs are amortized over a period of 20 years or greater, the impact on the cost per cubic meter to the consumer is minimal. This is particularly evident in regions where long conveyance of any source water is required.

Use of MAR for storage and polishing treatment of highly treated domestic wastewater is a significant method to minimize cost to supply safe drinking and irrigation water to rural areas in arid lands. Such systems need to be explored for use in areas where wastewater is being discharged with no economic benefit and alternative sources of water are extremely expensive.

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Authors Contributions

Thomas Missimer was the lead author and contributed the text including the introduction, the text on MAR/ARR, conveyance cost, and the special circumstances that impact wastewater reuse costs. Robert Maliva contributed the text on public acceptance of treated wastewater reuse and some of the MAR/ARR text. Noreddine Ghaffour contributed the economics of seawater desalination. TorOve Leiknes contributed the economics of wastewater treatment as applied to arid lands and reuse. Gary Amy provided some of the wastewater reuse text and edited the overall paper based on his wastewater reuse experience.

Conflicts of Interest

The authors declare no conflict of interest.

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Impact Assessment and Multicriteria Decision Analysis of Alternative Managed Aquifer Recharge Strategies Based on Treated Wastewater in Northern Gaza

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Abstract: For better planning of a managed aquifer recharge (MAR) project, the most promising strategies should analyze the environmental impact, socio-economic efficiency, and their contribution to the existing or future water resource conditions in the region. The challenge of such studies is to combine and quantify a wide range of criteria from the environment and society. This necessity leads to an integrated concept and analysis. This paper outlines an integrated approach considering environmental, health, social and economic aspects to support in the decision-making process to implement a managed aquifer recharge project as a potential response to water resource problems. In order to demonstrate the approach in detail, this paper analysed several water resources management strategies based on MAR implementation, by using treated wastewater in the Northern Gaza Strip and the potential impacts of the strategies on groundwater resources, agriculture, environment, health, economy and society. Based on the Palestinian water policy (Year 2005–2025) on wastewater reuse, three MAR strategies were developed in close cooperation with the local decision makers. The strategies were compared with a base line strategy referred to as the so-called "Do Nothing Approach". The results of the study show that MAR project implementation with treated wastewater at a maximum rate, considered together with sustainable development of groundwater, is the best and most robust strategy amongst those analyzed. The analysis shows the defined MAR strategies contribute to water resources development and environmental protection or improvement including an existing eutrophic lake. The integrated approach used in this paper may be applicable not only to MAR project implementation but also to other water resources and environmental development projects.

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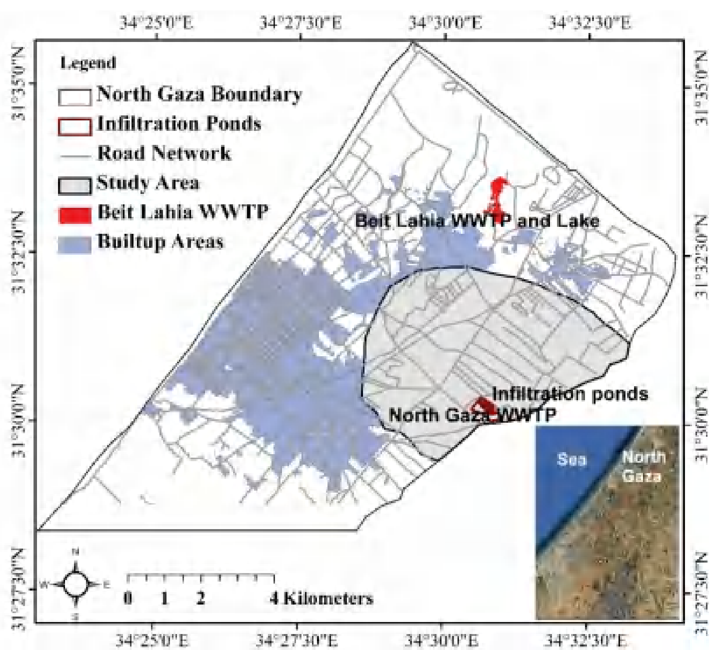
1. Introduction

Nowadays, managed aquifer recharge (MAR) is considered as an integral part of integrated water resources management (IWRM). Like the IWRM concept, the interaction of MAR with other sectors of the water resources system, society, and natural processes is inherently strong [1]. Several researchers e.g., [2,3] mentioned that like other IWRM projects, the most promising MAR strategy should study the environmental impact, socio-economic efficiency, and their contribution to the existing or future water resources problem in the region [3]. Proper investigation and planning of MAR projects is important for successful application and can lead to significant risk reduction (e.g., environmental, health) and overall project cost reduction by potentially reducing uncertainties during project implementation. Again, proper planning requires impartiality and transparency in the evaluation of MAR options, considering explicit assessment of feasibility and cost-effectiveness [4]. Up until now, very few research studies have performed an extensive integrated study that consider the potential impacts on the environment, health, economy and society due to MAR project implementation and which select the best project option after intensive impact assessment [5].

The Gaza Strip, located on the eastern coast of the Mediterranean Sea, is a region facing severe water resources problems [6]. Due to the hot and dry climate, little surface water is available. Water supply relies mostly on groundwater resources located in the Northern Coastal Aquifer of Gaza [7]. The Beit Lahia Wastewater Treatment Plant (BLWWTP), located at Northern Gaza Strip, has been dysfunctional for some time now and is creating severe environmental, socio-economic and agricultural impacts for the public health and the environment [8,9]. A detailed description of the water resources problem at the North Gaza strip is given in Section 4.1. A three-phase 20-year project involving the construction of a new WWTP, called the North Gaza Wastewater Treatment Plant (NGWWTP), is planned to be located further to the south near the Israeli border (see Figure 1) [10]. The new wastewater treatment plant will involve MAR of effluents [11]. The Palestinian Water Authority (PWA), along with international support, decided to use practical, already established MAR technologies such as infiltration ponds with Soil-Aquifer Treatment (SAT) to replenish the coastal aquifer in order to meet the continually rising demand of water for domestic, industrial, and agricultural use in this water-parched region [12–14]. Decision support is required to identify the best MAR project option to implement in the study area.

Figure 1. Study area map showing the wastewater treatment plants. Data source [9]. Inset picture from Google Earth.



In order to support the decision makers to plan the MAR project, this paper focuses on the impact assessment for several strategies for the implementation and operation of MAR in the Northern Gaza Strip. The strategies were quantitatively analyzed based on their potential impacts on agriculture, environment, health, society, and the economy. Finally, all strategies were compared to each other and ranked according to their ability to promote water resources development at the Northern Gaza Strip. In addition, this paper also describes the optimal MAR strategy of the candidates considered to sustain water resources and groundwater-dependent environment of Northern Gaza.

2. Study Area

With an area of 365 km^2 and a population of roughly 1.6 million [9], the Gaza Strip is located on the southwestern part of historical Palestine at the Mediterranean Coast on the edge of the Sinai Peninsula. Precipitation varies between 200 and 400 mm/year, with an average of ca. 300 mm/year [6,15], and temperatures are generally high, ranging between 29 and 9 °C throughout most of the year [16], while 97% of water used in Northern Gaza comes from the Northern Coastal Aquifer [7]. In this study, a part of North Gaza was selected for analysis and comparison of MAR strategies (Figure 1), which is referred to in this paper as the “study area”. The study area was delineated based on the boundary selection process using a groundwater flow and transport model. This model simulates the spreading of infiltration water at the new infiltration ponds, which commenced at the beginning of 2008 and will continue until 2040.

Geology and Hydrogeology of the Study Area

According to [17], the Gaza strip is underlain by a series of geological formations from the Mesozoic to the Quaternary. The two main formations are called Tertiary formation and Quaternary formation. The Tertiary formation, a 1200 m thick layer, is composed mainly of Saqiya formation and it consists of clay, marl and shale [14,18,19]. The 160 m thick Quaternary deposits covers the Pliocene Saqiya formation. The overlying Pleistocene deposits “Lower Quaternary” consists of (1) Marine Kurkur Formation (10–100 m thick on the coast); (2) Continental Kurkur Formation (maximum thickness is about 100 m with often-calcareous cement, and Quaternary Deposits. The sand loess and gravel beds formation is considered the main formation of the Gaza strip [17]. A general geological cross section of the coastal plain can be found in a number of sources [17,20–22] and therefore is not included in this paper.

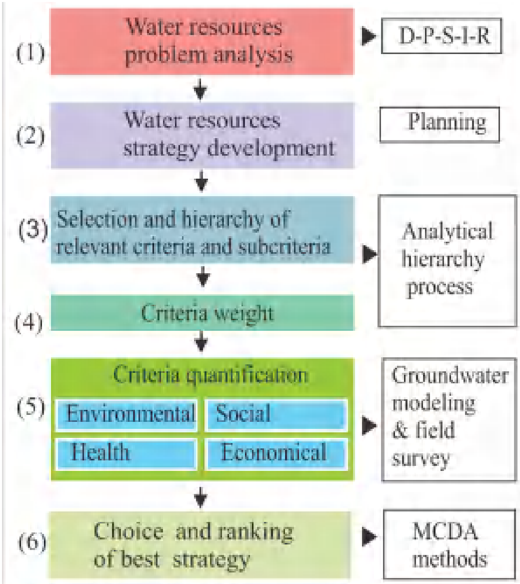
The North Gaza aquifer is a part of the Coastal aquifer that extends north to south from Haifa to the Sinai Coast. The highly permeable shallow vadose zone is mostly sand and gravel [23]. Larger and more consistent clay layers at the coast and extending 2–5 km inland, divide the Coastal Aquifer into several confined permeable layers [23]. The hydraulic connection between groundwater in the different subaquifers and the sea is not well investigated [17]. Beyond this distance, to the east, the Kurkar Group comprises the unconfined aquifer [18,23]. The average thickness of the aquifer at the coast is 150–200 m [23], whereas at the eastern border with Israel, the average thickness varies between 40 and 50 m [18]. The low-permeability Saqiya Formation of tertiary age constitutes the base of the aquifer. The 1 km thick Saqiya Formation is composed of clay, shale and marl [18]. The transmissivity of the Gaza aquifer ranges between 700 and 5000 m^2/d, corresponding hydraulic conductivity ranges between 20 and 80 m/d. Specific yield and Specific storativity values are 0.1–0.3 and 1×10^{-4} per meter [19,24].

Rainfall is the main recharge component for the shallow aquifer unit in the study area. Aish *et al.*, (2009) [20] estimated that the average annual recharge of the Gaza strip is 108 mm/year (39–40 Mm^3/year). Around 1016 agricultural wells pump ca. 50 Mm^3/year and 45 urban supply wells abstract approximately 42 Mm^3/year. Irrigation return flow is considered as 30 Mm^3/year [18]. In the Gaza strip, the groundwater abstraction from the drinking water wells constitute more than 50% of the net withdrawal [25]. In the northern part of Gaza, groundwater levels range from about 2 m above MSL at the eastern border with Israel to mean sea level along the shore [18]. A steep groundwater level gradient is seen at the southern part of the Gaza strip. The coastal aquifer possesses 5000 Mm^3 storage of groundwater of variable quality of which 30% is fresh [26,27]. In North Gaza, the GWL in the centre of the area is lower than the other parts of the area. So, in this part of the coastal aquifer, the main groundwater flow direction is towards the centre of North Gaza [28]. Besides the water quantity shortage, groundwater quality related problems, especially chloride and nitrate contamination, have been mentioned by several researchers e.g., [18,19,29]. The existing monitoring network in the Gaza strip observes groundwater level, and measures nitrate and chloride concentrations. The network is not suitable for monitoring sea water intrusion [18].

3. Methodology

An integrated approach was formulated in order to select the best strategy for MAR implementation. The approach is integrated in the sense that the study considered the impacts of possible MAR strategies on several sectors such as environment, health, economy and society. The sequential steps to select the best rank MAR strategy, a structured and sequential work flow was prepared, as shown in Figure 2. In general, the entire process involves three main steps to identify the best ranked MAR strategy: (a) water resources system analysis and strategy development (b) strategy ranking: criteria selection, impact assessment and criteria quantification, and (c) Multicriteria decision analysis (MCDA).

Figure 2. Overall methodology of the study.



The main objective of water resources system analysis (step-1) is to identify the main water resources drivers and pressures, and the potential responses to solve the impacts. Causal chain analysis using the Driver (D), Pressure (P), State (S), Impact (I) and Response (R), in short DPSIR, methodology [30,31] can be used at this step. Based on the pertaining water resources problem and the potential responses, water resources strategies are developed (step-2). The strategies should comply with the national water policy. In the third step of strategy ranking, relevant environmental, health, social and economic characteristics are selected. Each characteristic is defined as a criterion. The next step involves the decomposition of the ultimate goal into a hierarchy of several levels, following the principle of Analytical Hierarchy Process (AHP). The bottom level is the most specific criteria and the middle levels are more general criteria and can be called the "main criteria". The criteria in the lowest level are related to the main criteria in the middle levels. All levels combined is the goal of the study—the best strategy for MAR implementation, and is positioned at the top of the hierarchy. The next step in the strategy ranking procedure is assigning values of relative importance for each criterion at all levels, which is done by assigning a weight to each criterion. The criteria under each main criterion are compared amongst themselves and a weight is assigned to each one (step-4). The main criteria are also weighted in this way. The next step (step-5) is to quantify the relevant criteria, which is the main focus of the present study. A number of techniques, such as groundwater modelling, GIS and field surveys are available to quantify scores for the criteria. The quantification procedure depends on the type of criterion. After quantifying all criteria, an evaluation matrix is prepared at this step which is one of the principle components for ranking of alternatives. The final step (step-6), strategy comparison and ranking analysis, encompasses two multi-criteria analysis techniques: Weighted Linear

Combination (WLC) and PROMETHEE II (Preference Ranking Organisation MeTHod for Enrichment Evaluations) method.

The role of AHP, mentioned earlier, was to construct the hierarchy and to estimate the relative weight by pairwise comparison, after getting the preference information from the researchers, decision makers and stakeholders. Additionally, the role of WLC and PROMETHEE is to rank the alternatives.

4. Water Resources Problem Analysis and Strategy Development

4.1. Water Resources Problem Analysis (Step-1)

With the aim to analyse the existing water resources problems of the study area, causal chain analysis using the DPSIR method was used. The DPSIR concept has been developed for describing interactions between society and the environment [31,32], starting from the assumption that there is an interaction between the two. The water resources problems of North Gaza were analyzed, decomposed, and structured in this method in order to find the potential response of the problem. In brief, the water resources system of North Gaza is affected by two main drivers: population and urbanization. These drivers cause certain pressures on groundwater exploitation, wastewater status, land-use change, salinization, *etc.* The causal chain analysis of surface water is negligible as there are no surface water resources in the area. The DPSIR analysis has identified four potential responses to the current water resources problem. Each response can be considered and studied independently as well as in combination. In this paper, we considered MAR as a potential response due to the following reasons: (1) the poverty level in Gaza is high and many cannot afford the costs of advanced water treatment or desalination (considered as innovative technology) [33]; (2) Treated wastewater reuse will complement the existing water resources and will improve the water supply for agriculture; (3) Use of reclaimed water for agriculture would make fresh groundwater available for domestic and industrial use. In this study, MAR is seen not only as a contribution for a solution to the water supply and groundwater quality issue, but also as a solution to the problematic effluent lake, located at Beit Lahia, as the use of the new infiltration pond would help to rehabilitate the old infiltration lake.

4.2. Water Resources Strategy Development (Step-2)

Based on the water resources problem analysis and considering the water resources management plans for the years 2005–2025 [2,5,9,10], the following four MAR strategies were established in this study (Table 1).

The water management strategies based on MAR presented in Table 1 consider three phases in terms of wastewater resources development at the case study area. Strategy No.1 (Sc-1) represents the strategies if nothing has been changed with respect to the existing water resources structure and no further planning is being considered. Strategy No.2 (Sc-2) is linked to the first phase. This phase considers the diversion of the water from the BLWWTP to the newly constructed infiltration basin, which is located close to the foreseen position of the new North Gaza Wastewater Treatment Plant (NGWWTP) at the Israeli border. The diversion of water will be accomplished via a pressurized pipeline and the effluents will then infiltrate into the aquifer. Strategy No.3 (Sc-3) considers the strategies if the diverted water will be treated in the NGWWTP and then infiltrated into the aquifer. The effluent quality is higher than that of the water used for infiltration in Sc-2. In Phase 3, the NGWWTP is designed to increase the treatment capacity of around 24 Mm^3 per year in 2025. It indicates in Sc-3, the effluent water quality is better than that in Sc-2. Strategy No.4 (Sc-4) considers infiltration of this extra volume of treated water to the aquifer. Sc-2, Sc-3, and Sc-4 are considered as MAR management strategies.

Table 1. MAR management strategies towards the development of water resources at the Northern Gaza Strip.

Strategy No.	Plan for Water Resources Development	Scenario	MAR Volume (Mm^3) in Year 2040	Chloride/Nitrate Concentration in Recharge Water (mg/L)
Sc-1	Do Nothing	No MAR	0	557–887/20–107 *
Sc-2	Phase 1: Infiltration ponds and pipeline construction	Use the water from the BLWTTP	13	250/19–43
Sc-3	Phase 2: Construction of the NGWWTP	Infiltration of better quality water from the new treatment plant	13	250/7.5–17
Sc-4	Phase 3: Extension of the NGWWTP	Infiltration of better quality water and increase in infiltration volume from the new treatment plant.	23.7	250/7.5–17

Note: * in natural recharge.

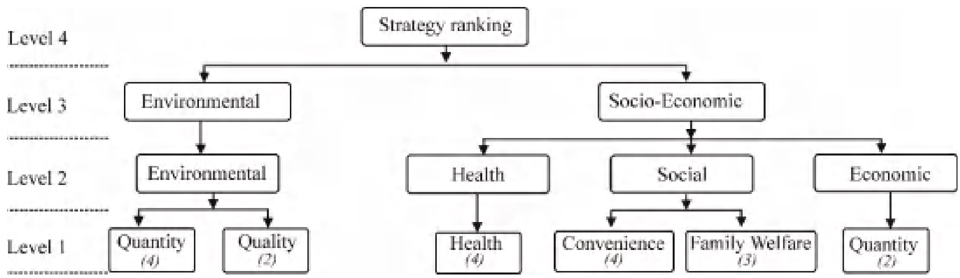
5. Criteria Selection and Quantification Procedure

5.1. Criteria Selection (Step-3)

A wide range of indicators are considered for the selection of criteria. The criteria were derived from the identified sectors of impact and emphasis was given to the availability of information to quantify the criteria. A total of 19 most representative decision criteria were selected in close cooperation with Palestinian researchers and authorities as well as further relevant stakeholders and were discussed with other international experts in related fields. Among the 19 criteria, six criteria represent environment considerations. They consider groundwater level, chloride and nitrate concentration averaged year 2005–2040 and also in year 2040 alone. Four health criteria consider chloride and nitrate concentration at the domestic wells average 2005–2040 and also in year 2040 alone. Seven social criteria consider people’s acceptance, convenience, satisfaction with the water quality and quantity, employment and willingness to pay. Affordability to pay and net cost-benefit analysis were considered as economic criteria.

Figure 3 shows the four-level hierarchical structure of the categories and criteria. AHP was used at this step. The AHP, proposed by [34], is a multicriteria analysis technique that enables the explicit ranking of tangible and intangible factors against each other for the purpose of decision-making or conflict resolution. It combines qualitative and quantitative approaches [35].

Figure 3. Criteria selection and hierarchy. Italic numbers indicate the number of criteria associated to each item at the fourth level.



Nineteen criteria were grouped into four main criteria groups such as environmental, health, social and economic. At the third level of the hierarchy, social, health, and economic criteria were grouped as "socio-economic" criteria. Socio-economic criteria and environmental criteria group combines the ranking of the strategies.

5.2. Criteria Weighting (Step-4)

The relevant importance of each criterion was defined in close cooperation with local scientists, decision makers and stakeholders. A participatory process was undertaken among the local stakeholders and experts. The participatory process includes scientific meetings, questionnaire surveys and workshops. Judgments of international experts were considered along with the weights from local experts and stakeholders. The pairwise comparison method, originally proposed by [34], was used to transfer the linguistic importance to numeric value and relative weights were estimated. The net cost and groundwater quantity were considered to be the most important criteria. All categories at level 2 and level 3 were considered as being equally important for MAR planning and management.

5.3. Criteria Quantification (Step-5)

The selected criteria were quantified using several state-of-art analysis techniques such as groundwater flow and transport models, field surveys, economic models, *etc*.

5.3.1. Quantification of Environmental Criteria (Criteria 1 to 6)

The selected environmental criteria refer to the groundwater quality and quantity status. These criteria were quantified by using groundwater-modelling techniques. A groundwater flow and transport model, developed in this case study using VISUAL MODFLOW (version 4.3, SWS, Vancouver, BC, Canada, 2009) and its integrated modules, was used to quantify the six environmental criteria in this study. The detailed description of the flow model set up and model parameters together with calibration plot can be found in [28]. The transport parameters such as longitudinal and vertical transverse dispersivity were initially assigned values of 4 m and 1 m, respectively (according to [36]). Bulk density of water was considered as 1000 kg/m^3. For Sc-2 and

Sc-3, the infiltration starts in 2008 with 9.7 Mm^3 of treated water and with an increase of infiltration by 0.08 Mm^3 per year until 2012 and afterwards the infiltration volume remains 13 Mm^3 until 2040. For Sc-4, the infiltration starts in 2008 with 9.7 Mm^3 of treated water and with an increase of infiltration by 0.08 Mm^3 per year until 2040. During the analysis and quantification of all the strategies, the current water withdrawal for agriculture was assumed to be constant. Domestic water demand was assumed to increase (based on population growth), according to the estimated demand increase. The model was run until year 2040. Simulation results flow and transport modelling from years 2005–2040 were used to estimate Criteria 01, Criteria 03 and Criteria 05. Simulation results from flow and transport modelling at the end of year 2040 were used to quantify Criteria 02, Criteria 04 and Criteria 06.

5.3.2. Quantification of Health Criteria (Criteria 7–10)

The four health-related criteria refer to the water quality status at the domestic water supply wells. Average chloride and nitrate concentration were considered at the places where the domestic wells are situated (Criteria 07 and Criteria 08). Criteria 09 and Criteria 10 were quantified by considering the average concentration of chloride and nitrate in the waters of the study area aquifer. The developed groundwater flow and transport model was also used to quantify the health criteria for the analysis. The water quality in the domestic wells depends on the quality of infiltrated water, quality of native groundwater and the seasons (winter and summer). These three aspects were considered in the model.

5.4. Model Simulation for the Health Criteria Quantification for the Strategies

5.4.1. Chloride

Chloride was modelled as a conservative parameter and hence, no sorption or kinetic reaction was considered. The initial concentration, ranges between 40 and 2200 mg/L, of chloride was taken from the trend analysis in [37], considering the data from the years 1984–1998 [37,38]. The chloride concentration of the infiltrated water was considered to be the same as that in the wastewater lake at BLWWTP. The chloride concentration used in the model and during the entire modelling period was 559–857 mg/L for years 2004–2007 and 250 mg/L for years 2008–2040 in all strategies except Sc-1 [9]. For Sc-1, the base condition was maintained. The base condition considers the chloride concentration used in the simulation model from year 2000 to year 2003. The effect of chloride concentration changes as the volume of infiltrated water changes in different scenarios.

5.4.2. Nitrate

For nitrate simulation, equilibrium controlled linear isotherm was considered and no kinetic reaction was considered. Similar to chloride, the initial concentration, ranges between 5 and 370 mg/L, of nitrate was taken from the trend analysis from [37] and considered is the data from 1984 to 1998. The nitrate quality of the infiltrated water was calculated based on the quality of the infiltrated water, the infiltration process, and seasonal climatic conditions (after [37,38]) and where dilution and denitrification have been assumed to be the main processes for nitrate reduction in the model simulation. For Sc-1, a base condition was maintained throughout the entire simulation period. A base condition maintains the nitrate source, considering the same land use utilized in the simulation model 2000–2003. The nitrate concentration for Sc-2 used in the model and during the entire modelling period was 20–107 mg/L for years 2004–2007 and 19–43 mg/L for years 2008–2040. The nitrate concentration for Sc-3 and Sc-4 used in the model and during the entire modelling period was 20–107 mg/L, 19–43 mg/L and 7.5–17 mg/L for the period of 2004–2007, 2008–2011, and 2012–2040, respectively.

5.4.3. Quantification of Social Criteria (Criteria 11 and 17)

A questionnaire survey was performed by the Palestinian Hydrology Group to get the social aspect of the MAR strategies [33]. The questionnaire was prepared in such a way that it includes criteria that would measure the anticipated level of convenience, perceptions on willingness to use the recharged water for different purposes and the fees that the user would be willing to pay for the supply and the expected level of satisfaction from the quantity and quality of water supplied from each option. A total of 76 questionnaires were filled out by the locals in the area [33]. The number of questionnaire was decided based on statistical analysis and population residing at the study area.

5.4.4. Quantification of Economic Criteria (Criteria 18 and 19)

In the present study, two economic criteria were considered. Affordability to pay (criteria 18) was quantified using the surveyed data. Criterion 19 considers the net present cost and benefit of the four strategies implementation. For net present cost and benefit estimation, the following factors were considered (after [37]):

- The infiltration starts in 2008 with 9.7 Mm^3 of treated water and with an increase of infiltration by 0.08 Mm^3 per year according to the strategies.
- The estimated operation & maintenance (O & M) cost (water transfer, pumping of water, cleaning of infiltration basin *etc.*) for MAR is \$0.14/m^3.
- The cost of abstracting recharged water by wells is \$0.11/m^3.
- The cost of the land (80,000 m^2) for the infiltration basin is \$100,000 and was considered at the beginning of 2005, as the ponds were planned to be constructed in this year.
- The cost of construction of the nine infiltration ponds and water-pumping infrastructure is \$4,000,000 and was considered in the estimation at the beginning of 2005.
- The opportunity cost will be represented mainly by the land that will be used to construct the infiltration basins. Since the area is an agricultural area and the net return per 1000 m^2 (1 dunam) from various agricultural products (mainly vegetables and citrus) per year is \$562, then the opportunity cost of the land (80,000 m^2) is \$44,960. The lake or the lagoon is planned to close down by year 2018. The area occupied by it is 100,000 m^2. Considering the area will be used for agricultural production, it would produce an annual benefit \$56,200 per year starting from the year 2018.

- The gains from improving water quality is calculated as the cost of desalinating brackish water of 30% of the private well if the MAR is not implemented (Sc-1). The cost of desalinating brackish water is considered as $0.36/m^3.
- The cost of abstracting ground water by wells is $0.11/m^3 due to groundwater lowering in Sc-1 after 2007.
- As a safety measure, $0.01/100 m^3 of recharged water was considered as unforeseen cost due to implementation of MAR.
- The net benefit from the stored water was estimated considering the people's willingness to pay ($0.37/m^3).
- The discount rate to calculate net present value was assumed to be 3% and assumed to be constant over all years of the project.
- No cost for wastewater treatment facilities was considered, as the local authority already considered this cost during the economic feasibility of the NGWWTP [14].

The cost estimation was done using an economic model based on a spreadsheet.

5.5. MCDA Analysis and Ranking of Options

After quantification of all the criteria, the normalized matrix was prepared for multicriteria analysis. The normalization was done using the following formulae:

$$NV = \frac{Max - Value}{Max - Min} \tag{1}$$

Here, NV denotes normalized value, Max and Min indicate the maximum and minimum value among the values to be normalized, respectively. We use Equation 1 to normalize all criteria values.

5.5.1. Criteria Aggregation Methods: Weighted Linear Combination (WLC)

WLC combines the criteria and provides the ranking. WLC is the most simple and commonly used aggregation method in decision analysis [35].

$$S(x_i) = \sum w_j \cdot s_j(x_i) \tag{2}$$

where, w_j is a normalised weight; and $\Sigma w_j = 1$; and $s_j(x_i)$ is the normalised criteria function.

After receiving the criteria weights and preparing the evaluation matrix, the role of WLC is to perform weighted summation for each group of criteria at all levels of the hierarchy until the strategy ranking achieves.

5.5.2. PROMETHEE

PROMETHEE, developed by [39], is a nonparametric outranking method for a finite set of alternatives. The method was later extended by [40,41]. PROMTHEE I gives partial ranking and PROMETHEE II provides a complete ranking of the strategies by using the net flow [42]. The details of the procedure can be found in many sources such as [39,43–45].

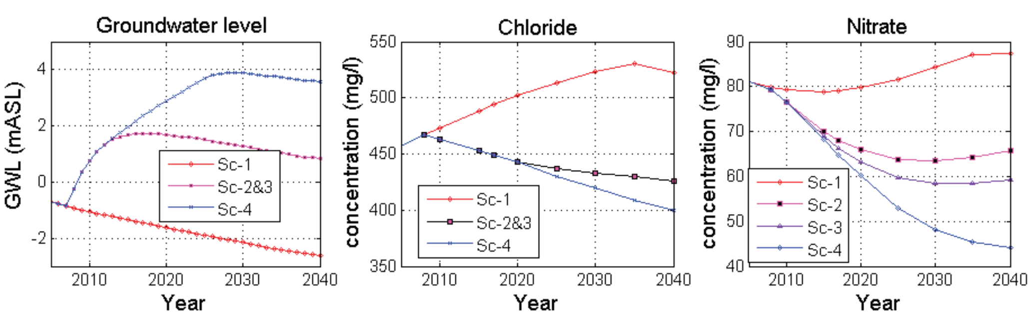
6. Results Analysis

6.1. Environmental Criteria

The simulations show (see Figure 4a) that the maximum average GWL rise in the study area is 6 m by the year 2028 with respect to "Do nothing" (Sc-1). At the end of 2040, the GWLs are estimated to be −2.61 m, 0.81 m, and 3.57 m above sea level (ASL) for Sc-1, Sc-2 & Sc-3, and Sc-4, respectively. 3%–5% of the infiltrated water may flow to Israel each year under the simulation condition of Sc-2 and Sc-3, whereas this outflow was estimated to be 7%–15% per year for Sc-4. The inflow to the study area from the Israeli side will be reduced by 20%, for both Sc-2, Sc-3 and by 30% for Sc-4. Due to the infiltration of treated wastewater, the groundwater level below the infiltration basin would increase and would cause the fresh water flow to be reduced from the Israeli side.

Figure 4b shows the average chloride concentration in the study area for the four strategies. The model results show the average chloride concentrations at the end of 2040 are 522 mg/L, 426 mg/L, and 400 mg/L for Sc-1, Sc-2 & Sc-3, and Sc-4, respectively. Figure 4c shows the average nitrate (expressed as NO_3-N) concentration in the study area for the four strategies. The average nitrate concentrations at the end of 2040 are 82.27 mg/L, 67 mg/L, 59 mg/L, and 44 mg/L for Sc-1, Sc-2, Sc-3, and Sc-4, respectively. Implementation of Sc-4 will therefore provide storage in the aquifer with a maximum value of 23 Mm^3 per year after the full implementation of north Gaza wastewater treatment plant (NGWWTP), Phase 3 (year 2025).

Figure 4. (**a**) Average groundwater level; (**b**) average chloride concentration and (**c**) average nitrate concentration in the study area during year 2005 to year 2040 for the four MAR strategies.

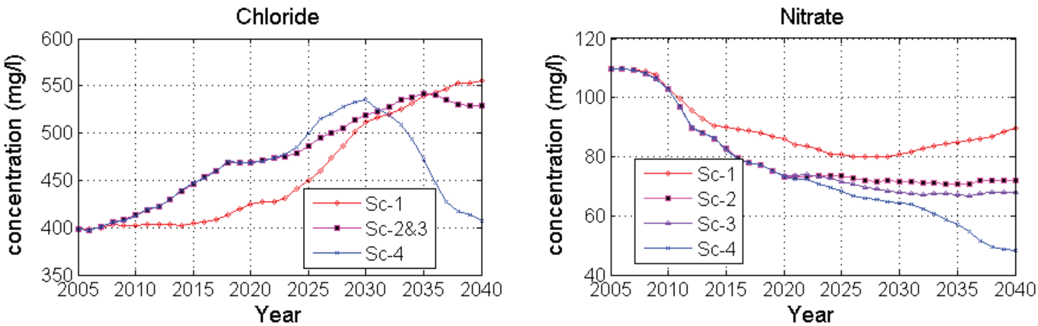


(**a**) (**b**) (**c**)

6.2. Health Criteria

A total of 10 domestic wells are located within the study area. Figure 5a shows the average chloride content of the 10 domestic wells for the four strategies until the year 2040. The average chloride concentrations at the end of 2040 are 555 mg/L, 528 mg/L and 407 mg/L for Sc-1, Sc-2 & 3, and Sc-4, respectively. In the case of Sc-1, the average chloride concentration in all domestic wells increases until the year 2040. In the case of Sc-2 & 3 and Sc-4, the average chloride concentration increases until the year 2035 and 2030, respectively, and then the chloride concentration decreases. Figure 5b shows the average nitrate content of the 10 domestic wells for the four strategies until the year 2040. Minimum nitrate concentration was observed in case of Sc-4. The average nitrate concentrations at the end of 2040 are 90 mg/L, 72 mg/L, 68 mg/L, and 49 mg/L for Sc-1, Sc-2, Sc-3, and Sc-4, respectively.

Figure 5. (**a**) Average chloride concentration; (**b**) Average nitrate concentration in the ten domestic wells for the entire simulation period (year 2005 to year 2040).

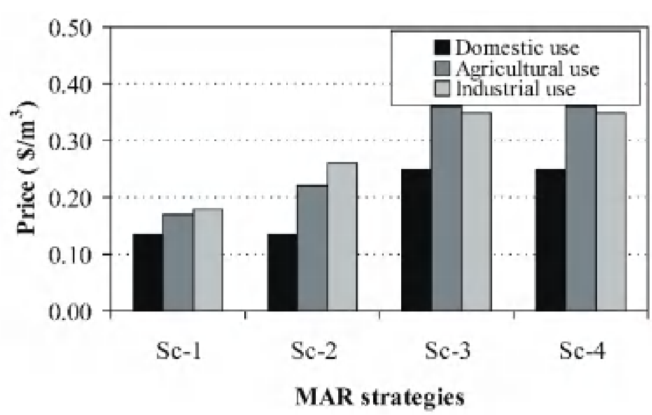


(**a**) (**b**)

6.3. Social Criteria

The survey results indicate that 86% of the respondents agreed to reuse wastewater for agricultural purposes whereas 67% and 42% agreed to reuse wastewater for industrial and domestic purposes, respectively. Results also show that respondents are willing to pay very little for the infiltrated water regardless of use and claim to be able to afford very small fees. The inhabitants are willing to pay a maximum $0.37/m^3 to use wastewater for irrigation (Figure 6). The survey results indicate that the distribution of acceptance and satisfaction of the public is similar throughout the various MAR strategies. In terms of satisfaction with the water quality, perceptions range from being satisfied to fairly satisfied with Sc-3 and Sc-4 having the greatest level of satisfaction.

Figure 6. Willingness to pay of the respondents for the MAR strategies for different usage.

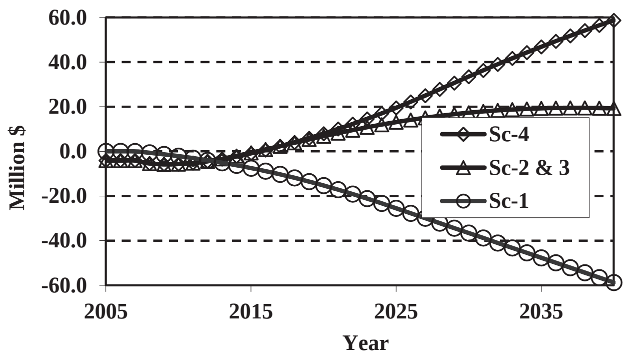


6.4. Economic Criteria

In the study area most of the people depend on agriculture, and many youths and women participate in agricultural activities. The agricultural activities in the study area depend on the groundwater irrigation. Hence, it is important to carefully review the water price (tariffs) for project feasibility. The survey results indicate that the respondents cannot afford to expend more money in order to use the benefit gained due to implementation of Sc-2, Sc-3 and Sc-4.

High investment cost is an important factor that makes a big difference between MAR strategies (Sc-2, Sc-3 and Sc-4) and the "Do nothing approach" (Sc-1). From the net benefit (cost-benefit) estimation (Figure 7), the implementation of a MAR strategy would be beneficial after year 2022 in case of Sc-4 and after year 2024 in case of Sc-2 and 3 (Figure 7). Sc-4 returns the most benefit due to its extended amount of infiltration volume even after year 2012. The net present values of the strategies (years 2005–2040) are $10.2 M for Sc-2 and Sc-3 and $28.4 M for Sc-4 whereas for Sc-1 the value is −$32. 0 M (negative sign indicates net cost). That is, there is a $60.4 M PV net benefit of switching from strategy Sc-1 to Sc-4 or a $42.2 M PV net benefit of switching from Strategy Sc-1 to either Sc-2 or Sc-3.

Figure 7. Net benefit analysis for the four MAR strategies.



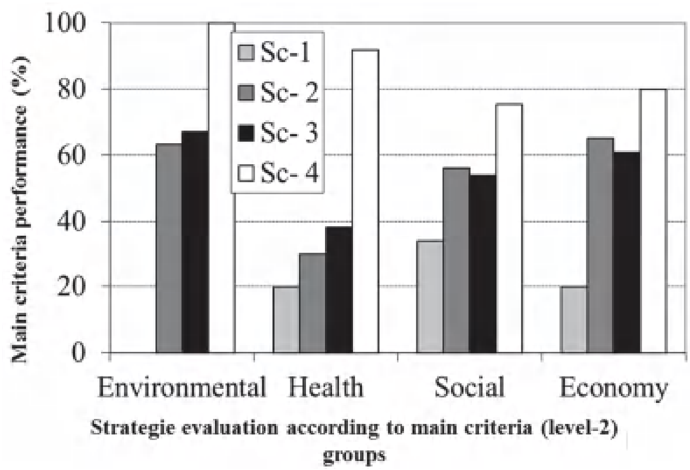
7. Strategy Comparison and Ranking

Figure 8 shows the performance of the four strategies according to the main criteria group (level-2). It is clear from the figure that Sc-4 performs the best in environmental, health and social criteria and Sc-1 performs the worst in these cases. Sc-2 performs better that Sc-3 according to the social and economic criteria but performs worse than Sc-3 for environmental and health criteria. People's affordability, convenience, and acceptance of wastewater seem important for the ranking. The final ranking was achieved after combining the main criteria groups (level-4) and the ranking is Sc-4 > Sc-3 > Sc-2 > Sc-1.

It was found that Sc-4 performs best for all the quantified detailed criteria with the following exceptions; average chloride concentrations in domestic wells over the study period, satisfaction with domestic water quality, willingness to pay and affordability to pay. These deviations are due to temporarily increased salinity of domestic wells in specific locations due to changed flow directions and variable salinity in the aquifer. This also influences criteria for satisfaction with domestic water quality for users of those domestic wells, and willingness to pay. Sc-4 also has the highest capital costs of all options (affecting affordability to pay), although the net benefits are greatest. For these specific criteria, only the "Do Nothing Case" (Sc-1) performs the best, although for other criteria it performs very poorly compared with other options, especially Sc-4.

PROMETHEE I partial ranking also confirms that Sc-4 performs better than the other strategies. No out-ranking relation does exist between Sc-2 and Sc-1; and Sc-1 and Sc-3. PROMETHEE II ranking is similar to that observed using WLC method.

Figure 8. Ranking of the strategies according to main criteria group (level 2) using AHP-WLC combination.



8. Discussion

8.1. Criteria Quantification

8.1.1. Environmental Criteria

The Sc-1 ("Do Nothing Approach") indicates continuous groundwater level mining over time, whereas Sc-4 indicates higher groundwater development than the other three strategies. Similarly, among the four strategies, Sc-4 shows better conditions in terms of inflow from the sea to North Gaza. Infiltration of excess treated wastewater even after 2012 might help Sc-4 to get more environmental benefit. In general, the problem of water flow from the sea will remain under control by the infiltration of all MAR strategies. It is clear from the results that Sc-1 ("Do Nothing Approach") will lead to deterioration of groundwater quality (*i.e.*, chloride and nitrate increase) with time. However, for other strategies, the groundwater quality will improve with time. The long-term effect of groundwater flow might also control the groundwater quality in the study area as the distribution of chloride and nitrate in North Gaza and the nearby Israel border is complex.

From the groundwater model simulation, we delineated a zone of ca. 200 m from the edge of the infiltration basins receiving the infiltrated water with a residence time of ca. six months. Regarding pathogenic bacteria, residence time of more than 6 months is recommended [46]. In the study area, no domestic wells exist within these 200 m.

8.1.2. Health Criteria

The impact of managed aquifer recharge projects on domestic wells is very sensitive to the population living in the area. The simulation result for Sc-4 shows a significant chloride concentration decrease in the study area at the end of the year 2040 in comparison to Sc-1, Sc-2 and Sc-3. By analysing the chloride concentrations in all domestic wells and comparing them with the "Do Nothing" strategy, observations show that the impact on chloride concentrations in all wells will be almost the same. Due to the groundwater flow direction of the infiltrated treated effluent, this would also impact the domestic wells. The increasing trend in the domestic well chloride concentration is due to the higher chloride concentration in the infiltrated water than the native groundwater and groundwater flow direction. In general, the nearby aquifer of the wells and the aquifer beneath the infiltration basin display higher chloride concentration. The infiltrated water would displace this water towards the domestic wells and the chloride concentration rises at the wells. The infiltrated water replaces the worse quality water and chloride concentrations at the wells are expected to decrease with time.

The nitrate concentration at the locations where the domestic wells are located is comparatively higher than the nitrate concentration below the infiltration pond and the nitrate concentration in the infiltrated water. The nitrate concentration in all domestic wells will be slightly improved.

8.1.3. Social Criteria

In general, the inhabitants are willing to pay more if fully treated wastewater is reused. Respondents do not agree to use the infiltrated water for domestic purposes but they have higher acceptance to use this water for agricultural or industrial purposes. The reuse of treated wastewater for irrigated agriculture would save higher quality groundwater water for drinking water supply and subsequently may solve some environmental problems. The health and religious aspects could be a major concern of people of Gaza to reuse wastewater [13]. The study found that the education level, standard of living and the environment might be key issues in order to convince the people of Gaza to reuse wastewater in agriculture.

8.1.4. Economic Criteria

Implementation of Sc-4 would lead to the maximum benefit. Reuse of wastewater would offer the release of corresponding fresh water resources and will help to expand the overall irrigated area by providing more water to irrigate lands. Hence, the livelihood of the residents may improve. Besides the above-mentioned benefits, more indirect benefits may be gained from improving groundwater quality. These are increased safety and the benefits generated from freeing the land that the current effluent lagoon occupies as well as the other subjective benefits related to seawater intrusion. Finally, the MAR project would create many other supported jobs e.g., related to MAR operation and agricultural activities *etc*.

8.2. Strategy Comparison and Ranking

According to the analysis using WLC and PROMETHEE, the same rankings of options were achieved. The comparison of water management options showed that increasing investments in wastewater collection, treatment, and later MAR would result in an improved water management strategy performance with regards to the considered environmental, social, and health criteria. Obvious drawbacks are the investments for infrastructure and their impact on economic feasibility. This should be discussed in greater depth and should be based on comprehensive cost-benefit analysis (CBA) and cost effectiveness that should refer to cost minimization and the related environmental and health benefits, which are fundamental to guarantee the sustainable development of the Gaza Strip.

9. Conclusions and Recommendations

The present study clearly shows the importance of environmental, health, social and economic impact assessment of MAR strategies performing a case study in North Gaza. The integrated approach of combining field campaign, methodological analysis and mathematical modelling has been proven to be effective for a multicriteria decision analysis. In order to increase water supply and to combat water scarcity, water pollution, and health problems at the Northern Gaza Strip, appropriate water resources planning and management measures are urgently required. Reuse of the treated effluent by MAR would strengthen agricultural development and result in increased groundwater availability for domestic and industrial use. The reuse of treated effluent has already been adapted in the national Water Policy for the Gaza Strip [47]. The present study shows that the so-called "Do Nothing Approach" is no real option for Northern Gaza, contributing to further groundwater level decline and groundwater quality deterioration, and increasing health risks for the population of Gaza. The performance analysis of the developed water resources planning and management strategies clearly shows that managed aquifer recharge by infiltration ponds with proper treatment of the effluents is a viable response to the increasing water resources problems of the region. In order to maximize project benefit, optimal pond operation based on practical experiences and regular cleaning of the pond is required to avoid clogging of the pond bed. Application of several MCDA analysis methods probes the robustness of the ranking analysis.

Ten domestic wells will be affected over time due to displacement of relatively low quality groundwater towards the abstraction wells. However, with time, the low quality water will be replaced by the nearby infiltrated water. Special care for water recovery should therefore be planned to protect the existing domestic wells. Another option could be to use the affected domestic wells for agricultural use and use the nearby unaffected wells for domestic water supply. Nevertheless, regular water quality monitoring of abstracted water and efficient recovery wells should be considered. Tremendous effort is required to increase public awareness for wastewater reuse. Adequate water pricing should be made considering the level of income and economic feasibility of the MAR project.

Additional investments should be undertaken for better maintenance and to further extend the wastewater collection network as well as the capacity of the NGWWTP at the Israeli border, accompanying the rapidly increasing wastewater production. Furthermore, managed aquifer recharge contributes to the control of seawater intrusion and groundwater salinity.

Due to the unavailability of scientific data, a variable-density groundwater flow model was not considered in this case study. As the objective of the study is not to quantify salinity intrusion, rather compare different management scenarios, the fresh water flow model is sufficient. In order to investigate the effect of MAR strategies on saline groundwater intrusion into the coastal aquifer, a variable-density groundwater flow model is recommended.

The approach and techniques used in this study can be applicable not only to MAR project implementation but also to other water resource development projects.

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Author Contributions

The text of this article was written by Mohammad Azizur Rahman, Bernd Rusteberg with contributions from Muath Abu Saada, Ayman Rabi and Martin Sauter. Mohammad Azizur Rahman conducted background research on integrated approach for MAR, developed the model and analysed the results. Bernd Rusteberg was involved in method development and coordinated the study. Mohammad Salah Uddin contributed to the model development and result analysis. Muath Abu Saadah provided support to the model development and field data collection. Ayman Rabi involved in coordination of social surveys and contributed to the economic analysis. Martin Sauter provided content review and helped to shape the presentation of our results.

Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 4

Approaches to Stakeholder Engagement and Monitoring

Application of Hydrologic Tools and Monitoring to Support Managed Aquifer Recharge Decision Making in the Upper San Pedro River, Arizona, USA

Laurel J. Lacher, Dale S. Turner, Bruce Gungle, Brooke M. Bushman and Holly E. Richter

Abstract: The San Pedro River originates in Sonora, Mexico, and flows north through Arizona, USA, to its confluence with the Gila River. The 92-km Upper San Pedro River is characterized by interrupted perennial flow, and serves as a vital wildlife corridor through this semiarid to arid region. Over the past century, groundwater pumping in this bi-national basin has depleted baseflows in the river. In 2007, the United States Geological Survey published the most recent groundwater model of the basin. This model served as the basis for predictive simulations, including maps of stream flow capture due to pumping and of stream flow restoration due to managed aquifer recharge. Simulation results show that ramping up near-stream recharge, as needed, to compensate for downward pumping-related stress on the water table, could sustain baseflows in the Upper San Pedro River at or above 2003 levels until the year 2100 with less than 4.7 million cubic meters per year (MCM/yr). Wet-dry mapping of the river over a period of 15 years developed a body of empirical evidence which, when combined with the simulation tools, provided powerful technical support to decision makers struggling to manage aquifer recharge to support baseflows in the river while also accommodating the economic needs of the basin.

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1. Introduction

1.1. Social Context

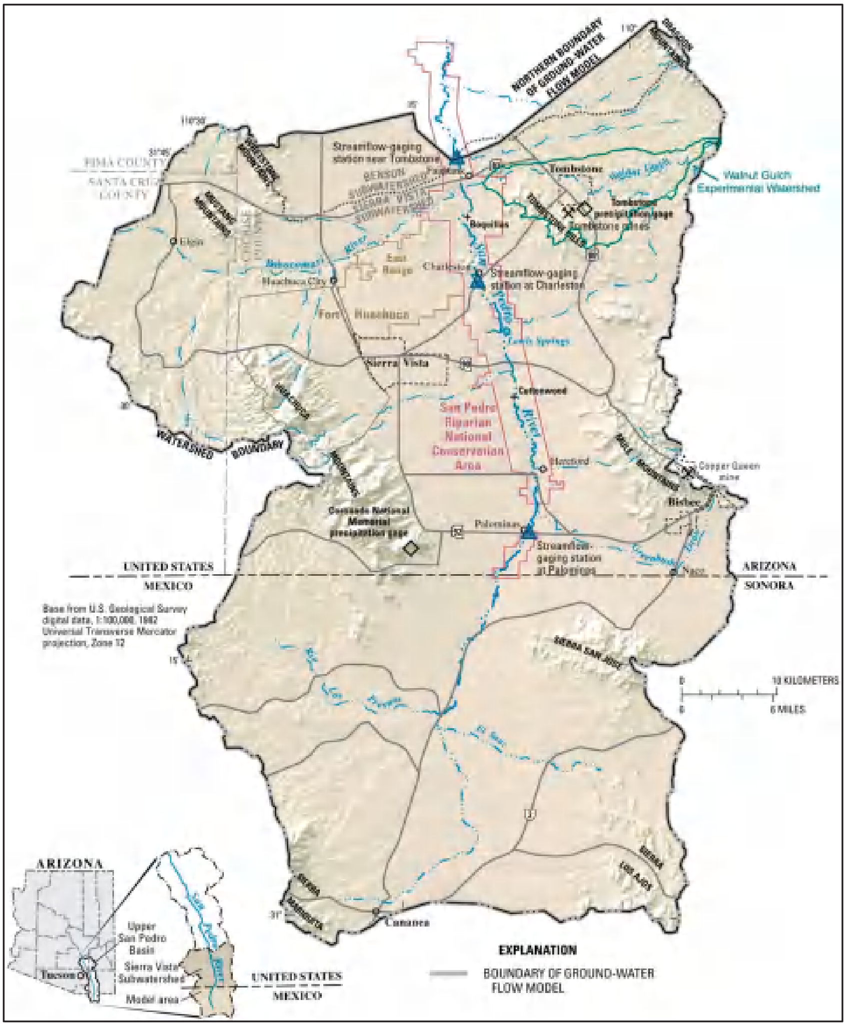
Balancing the social and economic water needs of humans with those of the environment, frequently referred to as sustainable water management, presents a global challenge, especially in arid and semi-arid regions, such as the American Desert Southwest. Understanding that the concept of sustainable water management is subjective, particularly in areas where human groundwater extractions have long exceeded average annual natural recharge, this study focuses on the tension between human demands for groundwater and the groundwater needs of an exceedingly rare perennial river system within the same basin of Southeast Arizona.

We report here on a combination of hydrologic tools and monitoring that are supporting significant progress toward many measures of sustainability on the scale of decades at one important site. The case for developing a regional groundwater recharge network along the Upper San Pedro River is built upon a series of studies and reports funded by the Upper San Pedro Partnership (Partnership), and vetted by its Technical Committee over a period of approximately 15 years. The Partnership is a consortium of 23 agencies and organizations working together to meet the long-term water needs of the Sierra Vista Subwatershed by achieving sustainable yield of the regional aquifer to: (1) preserve the San Pedro Riparian National Conservation Area (SPRNCA); and (2) ensure the long-term viability of Fort Huachuca. The purpose of the Partnership is to coordinate and cooperate in the identification, prioritization and implementation of comprehensive policies and projects to assist in meeting water needs in the Sierra Vista Subwatershed of the Upper San Pedro River Basin. Richter and others [1] provide a more complete discussion of the purpose, methods, and vision encompassed by the Partnership. In addition, recent groundwater modeling efforts have focused stakeholders' collective understanding of the hydrologic system on actionable strategies. Together, this body of work helps identify potential spatial and temporal groundwater recharge targets for mitigating many of the negative environmental, regulatory and economic consequences that may result if groundwater inputs to the San Pedro River diminish as a result of pumping, as predicted by groundwater modeling. Using this information, three of the stakeholders including the U.S. Army Compatible Use Buffer (ACUB) Program, Cochise County, and The Nature Conservancy are collaborating to develop an aquifer protection and recharge network of sites in the San Pedro River basin to protect flows in the river from anticipated pumping-related depletions over the next 50 to 100 years. This interim solution is intended to allow time to develop other longer-term strategies for addressing issues of the accumulated groundwater deficit in the regional aquifer and climate change. Examples of such longer-term strategies could include gradual elimination of consumptive use of groundwater, limitations on new pumping, enhanced utilization of urban runoff, and importation of water from outside the basin. Most of these strategies are controversial and/or expensive, and would require significant political and legal efforts to secure physical water supplies. This approach—using the best available science to implement a relatively uncontroversial and legally available interim solution to preserve baseflows while more difficult long-term solutions are pursued—may serve as a model for other dry-land river basins.

1.2. Study Area

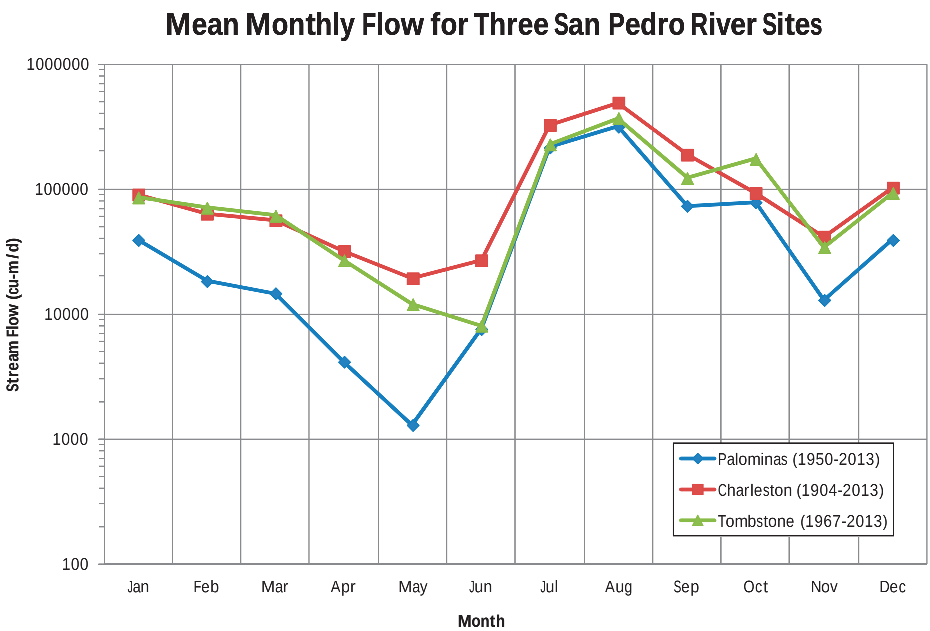
The San Pedro River flows north 279 kilometers (km) from its headwaters in northeastern Sonora, Mexico, to its confluence with the Gila River in southeastern Arizona, U.S.A. This paper focuses on the 2460-km^2 Sierra Vista Subwatershed ("subwatershed") of the Upper San Pedro basin ("basin"), north of the United States-Mexico boundary (Figure 1). This subwatershed area includes about 47 km of the river, most of it within the San Pedro Riparian National Conservation Area (SPRNCA), designated by the United States Congress in 1988 to protect and enhance the riparian area and its aquatic resources [2].

Figure 1. Map of the Upper San Pedro Basin showing the extent of the USGS groundwater flow model [3] and the San Pedro Riparian National Conservation Area. The Sierra Vista subwatershed is the area north of the United States—Mexico boundary.



Elevations within the Sierra Vista subwatershed range from more than 2800 meters (m) above mean sea level in the Huachuca Mountains on the western edge of the basin, to 1052 m at the Tombstone stream-flow gaging station at the north (downstream) end of the subwatershed. Precipitation across the topographically diverse basin ranges from 35 centimeters per year (cm/yr) near Tombstone in the central-north part of the subwatershed to about 76 cm/year in the highest parts of the Huachuca Mountains [4,5]. Like other areas in the desert southwest, precipitation in the study area is predictably bimodal with a summer monsoon season from July through mid-September accounting for about one half, and a winter wet season from December through March that accounts for another one third of the annual precipitation. Occasionally, tropical storms will trigger very large runoff events in October, but otherwise the fall months are typically dry. Stream flow is lowest in May and June, with peak monthly flows occurring during the summer monsoon season (Figure 2). Average monthly minimum flows range from about 1300 cubic meters per day (cu-m/d) at the Palominas stream-flow gaging station in the south (upstream) end of the subwatershed to 19,300 cu-m/d at the Charleston station, and 8100 cu-m/d at the Tombstone station on the north (downstream) end of the study area (Figure 2). Snow melt in the Huachuca Mountains often supports flow in mountain springs and intermittent streams in the spring months of March and April.

Figure 2. Mean monthly stream flow for the three long-term monitoring sites (shown in Figure 1) on the Upper San Pedro River in the Sierra Vista subwatershed for the period of record at each site. The y-axis is plotted on a log scale to highlight the minimum flows in May and June.



Groundwater discharge from the regional basin-fill aquifer supports baseflows in the river and evapotranspiration by near-stream phreatophytes. Groundwater pumping from that same aquifer supplies a human population in the region that is expected to increase by 46% by the year 2050 [6]. Sierra Vista, Arizona, is the largest municipality in the basin with a population of roughly 45,300 [7]. The U.S. Department of Defense installation at Fort Huachuca borders Sierra Vista on the west and north sides and is a major economic force in the basin [8].

Because of its federal designation and its globally significant biodiversity [9], the SPRNCA has been the subject of extensive hydrological and ecological research. One major finding was that stream flow permanence explained most variance in the basal area of two keystone riparian species, Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) [10,11]. As a result, conservation strategies have focused on maintaining or increasing stream flow through reductions in groundwater pumping and managed aquifer recharge at key locations.

1.3. Hydrological Studies in the Basin

1.3.1. General Hydrologic Processes

The Upper San Pedro River is one of the most intensively studied semi-arid stream systems in the world. Estimated ages of the earliest paleo-Indian sites along the banks of the ancestral San Pedro River date back to 11,000 to 13,000 years ago [12,13]. Two Clovis Indian sites have been associated with mammoth kills in the subwatershed, providing some of the earliest dates for human hearths of this culture [13]. The basin has been grazed since the time of the first Spanish explorers in the 1500s [14], and has hosted two major metals mining operations in Tombstone (late 1800s) and Bisbee (1880s–1975), Arizona. In addition, Cananea, Mexico boasts a major copper mine that is currently in active production. The major U.S. Department of Defense Army installation at Fort Huachuca has been in active operation since 1877 and has one of the earliest water rights claims in the basin [15]. More recently, the town of Sierra Vista has grown to include over 45,000 people (including Fort Huachuca). All of these activities have had significant impacts on the landscape and water resources in the basin. Hereford [14] presents a clear description of the land use changes coupled with exceptional periods of flooding near 1900 that led to significant entrenchment and stabilization of the San Pedro River stream channel and dewatering of much of the shallow alluvium of the river channel.

The Walnut Gulch Experimental Station (Figure 1) was established in the northeast area of the subwatershed by the Research Division of the Soil Conservation Service in 1951, and has been the source of continuous instrument-based hydrologic and rangeland studies since that time [16]. In 1966, Brown and others [17] evaluated the water resources of Fort Huachuca, which lies immediately west and north of the City of Sierra Vista (Figure 1). Brown and Aldridge [18] estimated San Pedro River surface discharge from the international boundary with Mexico to its confluence with the Gila River and inputs to the system from tributary inflow and from mountain-front recharge. Much of the assessment of hydrologic resources in the basin that followed came as a byproduct of the development of groundwater models, including those by Freethey [19], Vionnet and Maddock [20], Corell and others [21], Goode and Maddock [22], and Pool and Dickinson [3].

The Arizona Department of Water Resources (ADWR) evaluated the groundwater resources of the basin in 1990 [23], and then again in 2005 [24], in order to determine whether or not the basin should be classified as an Active Management Area (AMA) under the 1980 Groundwater Management Act of Arizona. The ADWR determined that the basin did not meet the statutory criteria for AMA designation [23,24], but much of the research that was conducted as part of that assessment remains highly relevant. Pool and Coes [25] described the state of the knowledge of hydrogeology of the subwatershed. As part of that work, an extensive monitoring program was initiated in the subwatershed that included geophysical surveys, ephemeral stream flow monitoring, installation or refurbishment of a number of stream gaging stations, aquifer storage monitoring using microgravity techniques, and basin-wide water level monitoring. Much of this monitoring program continues today.

In support of the conservation mission of the SPRNCA, Section 321 of the Defense Authorization Act of 2004 [26] revised how the federal Endangered Species Act applies to the Fort Huachuca Military Reservation and directed the Partnership to "...restore and maintain the sustainable yield of the regional aquifer [of the Sierra Vista Subwatershed] by and after September 30, 2011." It also required annual progress reports on these efforts, which were produced for most calendar years from 2002 through 2011 (see [27], for example).

The Partnership sponsored several research reports during this time, which provided the scientific basis for development of the U.S. Geological Survey (USGS) groundwater model by Pool and Dickinson [3]. These studies include Coes and Pool's [28] assessment of ephemeral-stream channel and basin-floor infiltration and recharge, Gungle's [29] analysis of the timing and duration of ephemeral stream flow in the subwatershed, and Leenhouts and others' [30] analysis of the hydrology, vegetation-hydrologic relationships, and evapotranspiration requirements and plant-water sources in the SPRNCA. Leenhouts and others [30] established additional streamflow and groundwater monitoring in the subwatershed, including streamflow stage and permanence data, near-stream alluvial aquifer groundwater and vertical gradient monitoring, and a continuous meteorological and eddy covariance monitoring station for measurement of evapotranspiration in the SPRNCA.

A statistical analysis of the trends in streamflow in the San Pedro River was also published in 2006 by Thomas and Pool [5]. Leake, Pool and Leenhouts [31] used Pool and Dickinson's [3] five-layer groundwater model of the basin to conduct a capture and recharge analysis that mapped the effects of pumping and recharge across the subwatershed on groundwater discharge to the SPRNCA. Kennedy and Gungle [32] analyzed baseflow discharge from the subwatershed at the USGS gaging station near Tombstone, Arizona, at the north end of the subwatershed. Most recently, Lacher [33] updated the Pool and Dickinson [3] groundwater flow model to include recent changes in pumping and artificial recharge in the subwatershed, and simulated the projected effects of population growth-driven increases in pumping on groundwater levels and baseflow through 2105.

1.3.2. Managed Aquifer Recharge

In 2006, Stantec [34] developed a Flood Control Urban Runoff Plan for Cochise County that evaluated the size, placement, and efficacy of 30 existing and proposed stormwater detention basins on the west side of the subwatershed functioning as de facto recharge basins. As part of this study, GeoSystems Analysis [35] used a detailed precipitation-recharge-stormwater runoff regression model, based on the U.S. Department of Agriculture's Automated Geospatial Watershed Assessment Tool [36] for the urbanized Coyote Wash watershed in Sierra Vista to estimate the cost, recharge volume, and urban-enhanced runoff for that watershed and several others on the west side of the San Pedro River within the subwatershed. GeoSystems Analysis previously developed the stormwater regression model used for the Upper San Pedro Partnership and Cochise County based on detailed AGWA stormwater modeling results for the Coyote Wash watershed located in the City of Sierra Vista [37].

Predictive groundwater modeling [33] indicates that within the next 100 years, two regional cones of depression will merge and reduce groundwater flow from the regional aquifer to the San Pedro and Babocomari (a major tributary to the San Pedro) rivers (Figure 3). These simulations incorporate pumping increases over time that reflect U.S. Census growth rates [5,6] and maintain constant natural recharge and evapotranspiration at 2003 levels (as published in the USGS groundwater model [2]) for the entire 21st century. Figure 4a maps the west-east transect A-A' for the simulated groundwater-level profiles shown in Figure 4b. This transect goes through the Sierra Vista-Fort Huachuca cone of depression, and illustrates how simulated groundwater levels at the groundwater divide between the cone of depression and the river have already declined by 17% since pre-development conditions in 1902 and are predicted to double that level of decline, to 35%, by the year 2100. These reductions in groundwater levels produce commensurate percent reductions in groundwater gradient (change in head divided by distance) as measured from the same point on the groundwater divide to the river. While gradients directly under the river are not yet showing the same degree of impacts as those farther west, the ultimate outcome of these simulated changes would be greater baseflow losses in some losing reaches, smaller gains in some gaining reaches, and possibly the conversion of some reaches from gaining to losing. The resulting groundwater-driven reduction in baseflow and shallow groundwater would likely impair the dependent riparian systems [33].

Figure 3. Simulated drawdown (m) in the primary regional aquifer of the basin (**a**) in 2000; (**b**) in 2050; and (**c**) in 2100 [33].

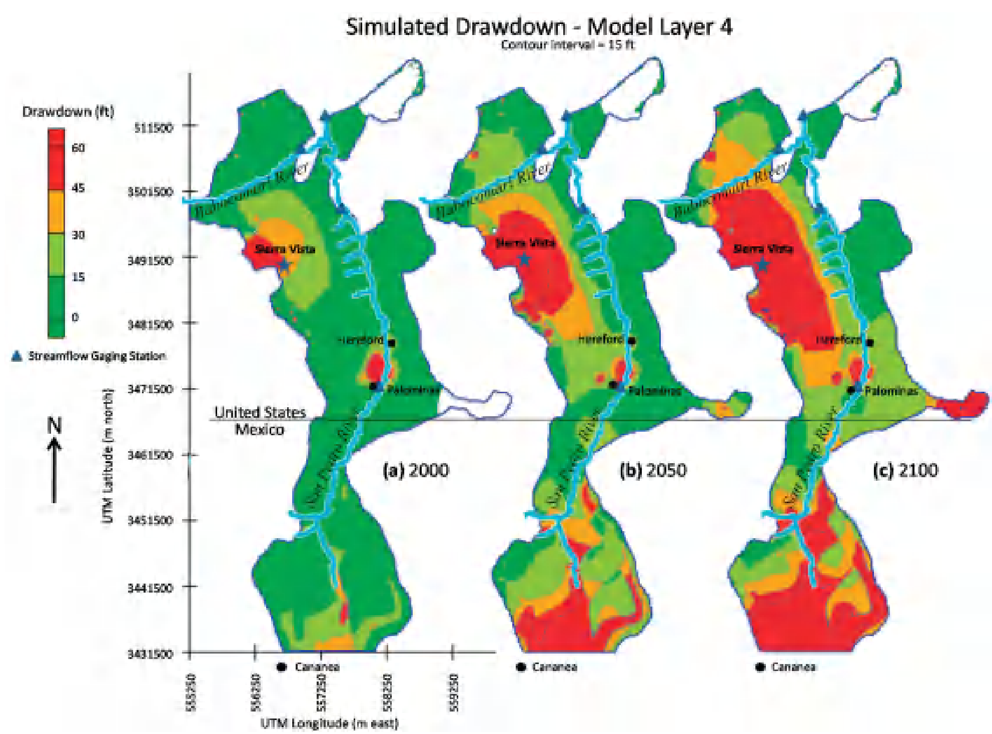
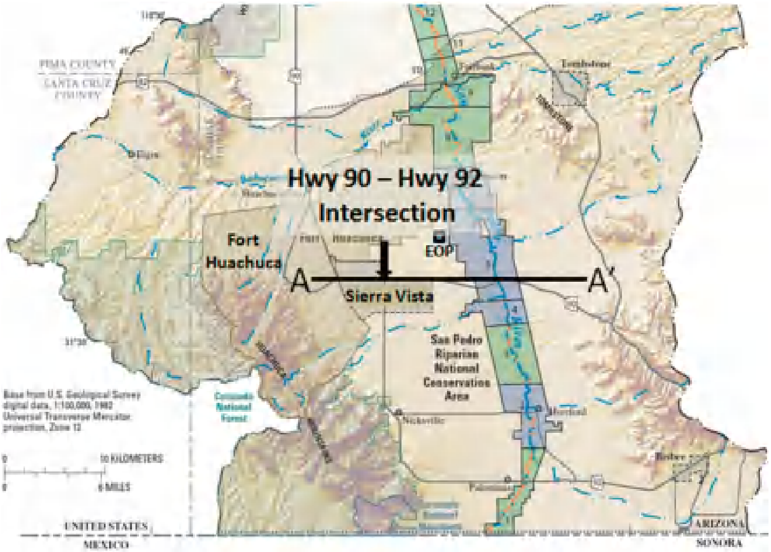
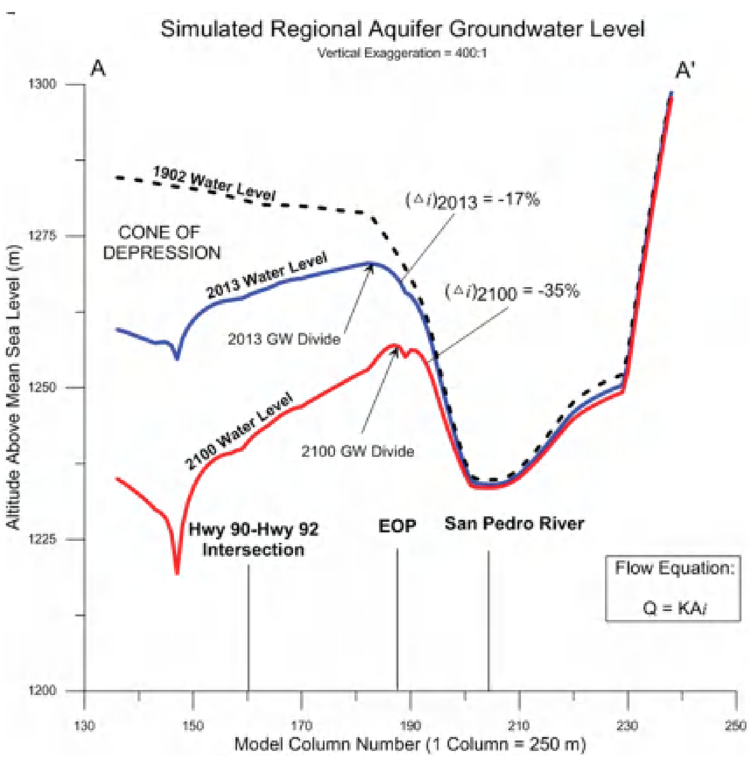


Figure 4. (**a**) Cross-section A-A' in the center of the Sierra Vista subwatershed (adapted from Stromberg and others [10]; (**b**) Simulated groundwater-level profiles in 1902, 2013, and 2100 along the A-A' cross-section showing change in gradient (Δi) from −17% in 2013 to −35% in 2100.



(**a**)



(**b**)

One potential solution to the problem of aquifer storage depletion would entail importation of at least some water from a source outside the basin [38]. However, at this time, importation does not appear likely in the foreseeable future (see companion paper by Richter and others [1]). In lieu of a replacement water supply, water managers and stakeholders in the subwatershed recognize the need for a near- to medium-term (*i.e.*, years to decades) intervention to protect stream baseflows and the associated riparian areas.

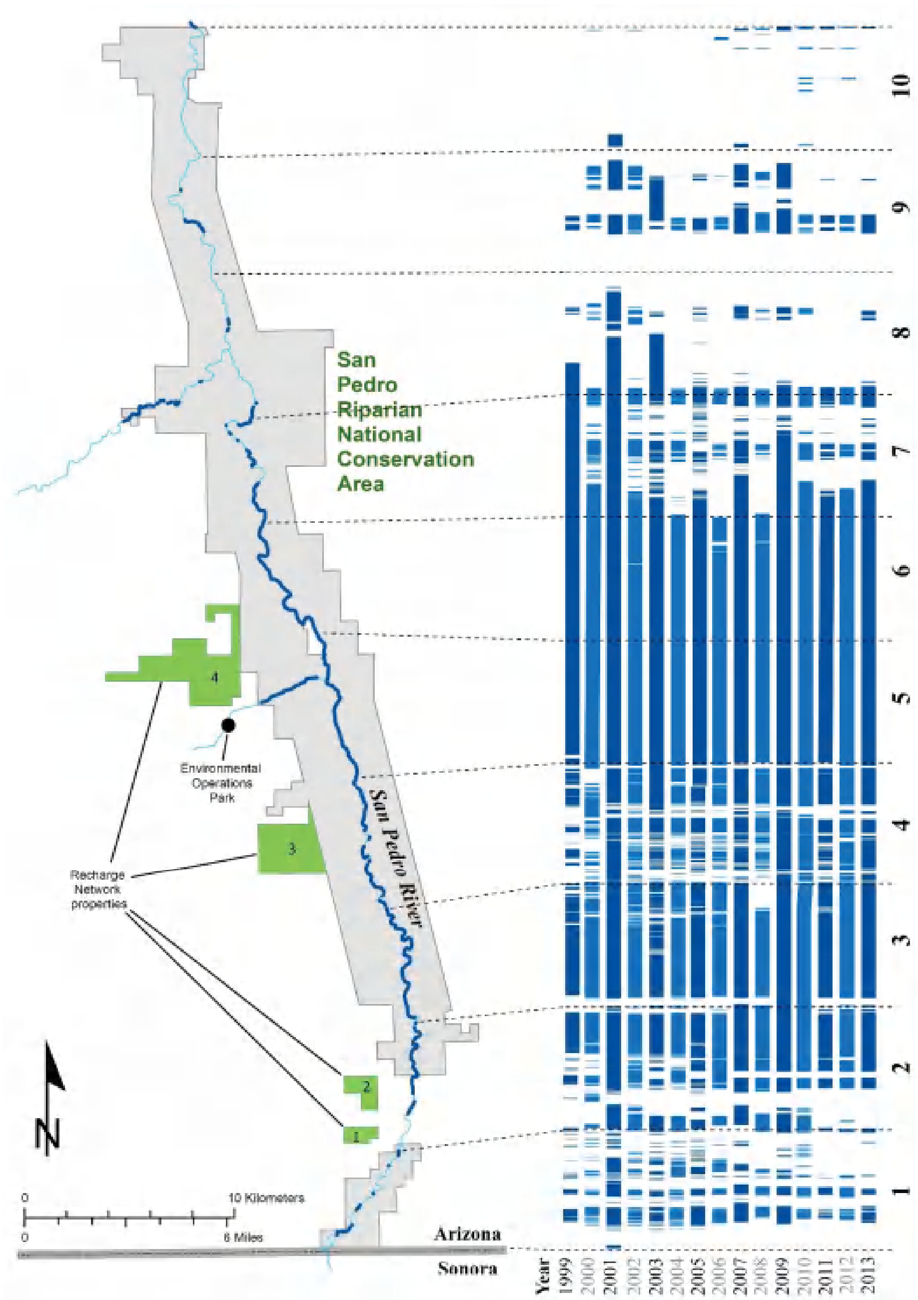
The City of Sierra Vista has more than 10 years of monitoring data from its Environmental Operations Park (EOP) where treated effluent is recharged at a rate of roughly 9100 cubic-meters per day (m^3/d) through artificial wetlands and recharge basins between the City's pumping center and the San Pedro River. This project was designed and constructed to create a groundwater mound to sustain surface water flow and supplement alluvial groundwater levels during low-flow periods [39]. Groundwater modeling that incorporates the EOP recharge data indicates that the project is successfully contributing recharge to both the nearby cone of depression in the regional aquifer and to baseflows in the San Pedro River [33,40]. Further groundwater modeling presented in this study suggests that additional recharge projects designed to utilize enhanced urban runoff, treated effluent or other local supplies near the San Pedro and Babocomari rivers may successfully mitigate anticipated pumping-related baseflow depletions for up to 100 years.

While conservation efforts within the subwatershed have reduced consumptive use of groundwater in the basin, particularly on the Fort Huachuca Army installation, the cumulative storage loss in the regional aquifer within the subwatershed from the past half century of pumping, estimated to exceed 800 MCM (refer to explanation provided in Section 2.3.2) remains a threat to the San Pedro River and its tributaries by intercepting mountain-front recharge and by reducing the groundwater gradient that drives aquifer discharge to the rivers. Because of this storage deficit and the fact that virtually all water use in the subwatershed depends on groundwater, almost any level of continued groundwater use poses an increasing risk of stream and riparian evapotranspiration capture over time.

1.3.3. Streamflow Permanence Monitoring

Direct measurement of baseflow, defined as the portion of streamflow derived from groundwater, is complicated by the effects of prolonged storm and/or snowmelt runoff (which tend to exaggerate baseflow estimates) and evapotranspiration (which reduces apparent baseflow). Acknowledging these complexities, practitioners have found that inter-annual stream-flow permanence in a river system that experiences intermittent drying in some reaches is a useful indicator of both hydrologic and ecological conditions in the San Pedro basin. Using a technique called wet/dry mapping, analysis of surface water presence (strict criteria are used to ensure consistent definition of surface water versus minimal puddles) during the driest time of year (mid June in the San Pedro Basin) reveals areas with high year-to-year variation in the length of surface wetting (Figure 5). By limiting the influence of storm events as much as possible, and assuming no significant changes in the condition of the riparian forest, these variations in wetted length are believed to be the best available physical expression of local groundwater conditions and may provide early warning of ecological changes [41].

Figure 5. Wet/dry results from the San Pedro Riparian National Conservation Area. The heavy river line shows reaches, which were wet in June 2013. Bars on right side represent wet reaches for each year, 1999–2013. Labels on the far right identify the 10 analysis segments, each covering 8.1 km. The four green properties (parcels 1 through 4) on map were recently acquired for groundwater protection and recharge projects. Redrawn from Turner and Richter [41].



Wet/dry mapping, as applied in the San Pedro River basin, uses citizen scientists annually to map the spatial extent of surface water in a river or stream. The method provides a comprehensive snapshot of conditions for the whole river at the same date each year, allowing comparisons of year-to-year variability [41]. Beginning in 1999, staff from The Nature Conservancy and the U.S. Bureau of Land Management coordinated volunteers to map the spatial extent of surface water within the SPRNCA. The exact dates varied slightly, but mapping was conducted during the third weekend of June each year to coincide with the lowest flow before the expected start of the summer rainy season. Through the years, progressively more of the river and its tributaries have been surveyed, increasing to 231 km of the mainstem and 266 km of tributaries in 2013. This paper addresses only the 80 km of mainstem river surveyed through SPRNCA.

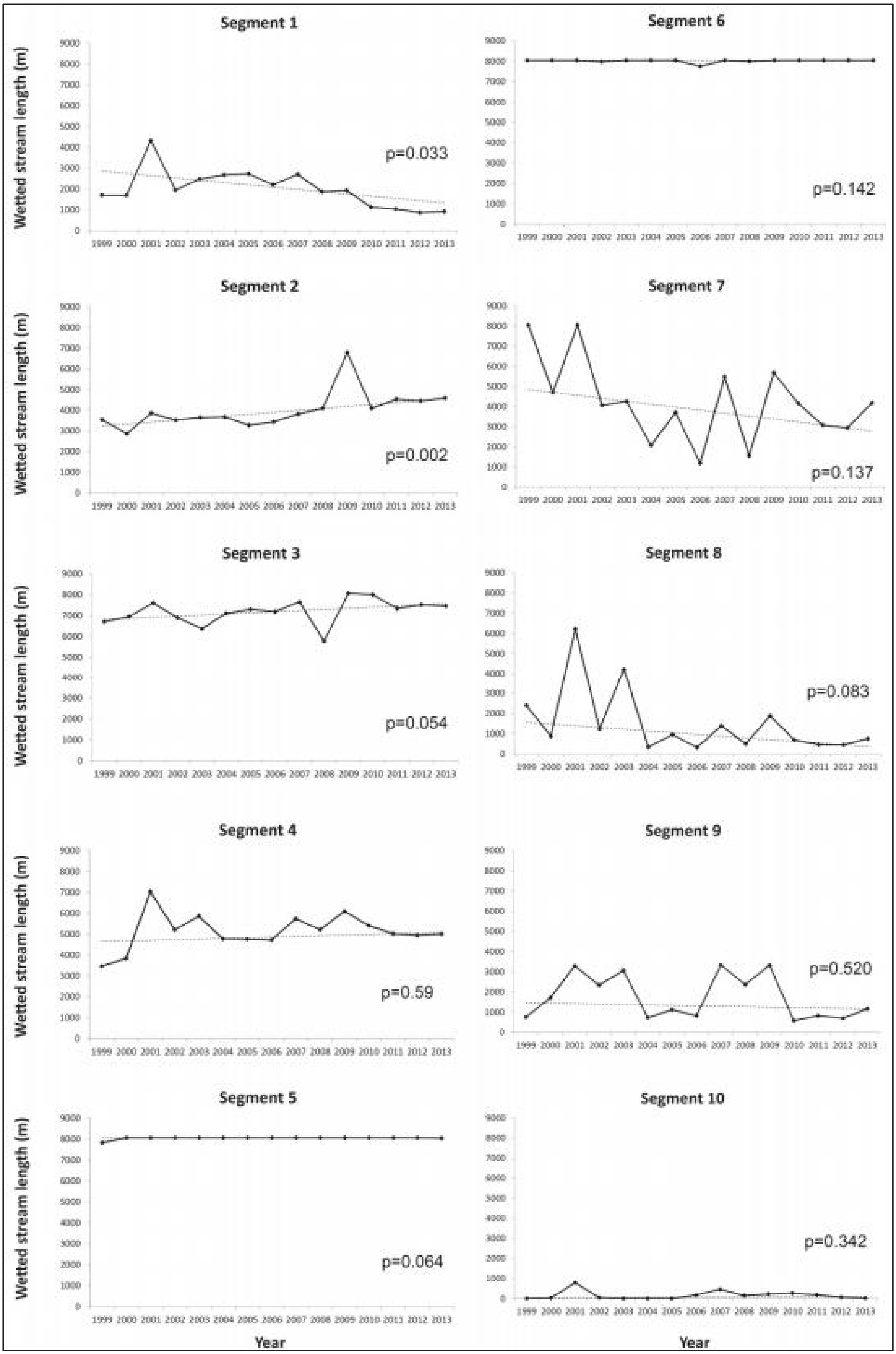
2. Methods

2.1. Wet/Dry Mapping

Surveyors walked predetermined segments of the river, recording the coordinates of beginning and end points of all surface water segments greater than or equal to 9.1 m long using paper data forms and consumer-grade Global Positioning System units. They disregarded any dry gaps less than 9.1 m long in otherwise wet reaches. The resulting point coordinates were imported to a Geographic Information System (ArcGIS, Environmental Systems Research Institute, Redlands, CA, USA), and snapped to the closest points on a linear representation of the river. To identify localized trends, organizers partitioned the SPRNCA into 10 equal segments, 8.1 km long. Segments were analyzed for probability of trend using the Mann-Kendall test. For graphic purposes, we calculated and display the Sen estimate of linear trend (detailed methods are provided by Turner and Richter [41]). Starting in 2007, maps and summary data from the wet/dry surveys have been posted each year to a web site (http://www.azconservation.org) for public distribution.

Results from wet/dry mapping in the SPRNCA (Figure 6), as a whole, show about half the river has permanent surface water with some year-to-year variation but no trends. However, analysis of the smaller segments shows considerable variation Turner and Richter [41]). The southernmost segment, Segment 1, displays a significant downward trend, while Segment 2 trends upward. Most of the other segments have either year-to-year up/down results or a stable condition without trend. The distribution of wet and dry reaches has provided a simple way to prioritize and site conservation actions aimed at reduced groundwater pumping and managed aquifer recharge, as described in Section 3 below. Wet/dry mapping data are also expected to provide a quantitative measure of conservation progress after those strategies are implemented.

Figure 6. Total wetted lengths for the 10 analysis segments in Figure 3. Segment numbers increase from south to north (downstream). Revised from Turner and Richter [41].



2.2. Capture Mapping

2.2.1. Overview of Capture

The Upper San Pedro River's position near the geographic center of an alluvial basin makes it a classic example of basin-fill hydrology. The existence of a major pumping center at Sierra Vista/Fort Huachuca between the primary area of recharge for the subwatershed (the Huachuca Mountains on the western boundary) and the river (Figure 1) also makes the basin a classic case study in groundwater capture. Capture is the increase in recharge to, and (or) decrease in discharge from, a basin that eventually occurs as a result of groundwater pumping. Theis [42] first addressed the consequences of groundwater pumping from a previously undeveloped system in 1940:

> *"Under natural conditions…previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system, and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge, or by loss of storage in the aquifer, or by a combination of these."*

Lohman and others [43] further clarified the definition of capture from Theis' description:

> *"The decrease in discharge plus the increase in recharge is termed capture."*

This definition of capture may be written as:

$$\boldsymbol{Capture} = \Delta\boldsymbol{R} + \Delta\boldsymbol{D} \tag{1}$$

where $\boldsymbol{\Delta R}$ and $\boldsymbol{\Delta D}$ equal the increase in recharge and the decrease in discharge, respectively.

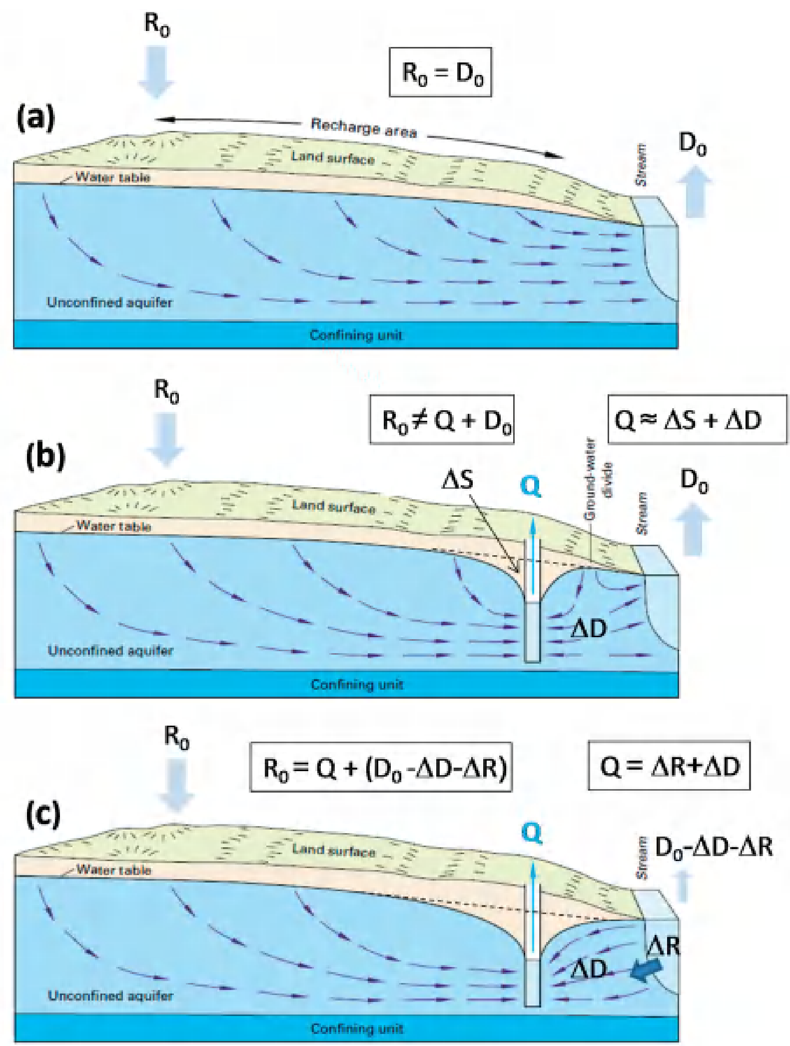
In the Upper San Pedro basin, as in many basins in the southwest deserts of the United States, aquifer storage is plentiful as a result of recharge over thousands of years of depositional history, but potential sources of capture are limited primarily to reductions in riparian ET, reductions of groundwater discharge to streams (baseflow), and direct capture of streamflow. The numerical partitioning of extracted groundwater into its constituent sources through a water-budget process is a common and fraught practice in many water-short areas of the United States. Bredehoft, Papodopulos, and Cooper [44] attributed this practice to "perhaps the most common misconception in groundwater hydrology" which is "that a water budget of an area determines the magnitude of possible groundwater development." Under this line of reasoning, many water managers have concluded that all water entering the system as natural recharge is available for extraction without long-term deleterious effects. Brown [45] addressed the problem with this argument through an example of a well whose cone of depression eventually expands to intersect a stream in which he demonstrated that,

> *"…the rate at which the hydrologic system reaches a new steady state depends on the rate at which the natural discharge [in his example to a stream] can be captured by the cone of depression."*

Figure 7 illustrates the evolution of a groundwater system which receives natural recharge (through precipitation) at a fixed and limited rate, $\boldsymbol{R_0}$, and discharges to a stream as baseflow at a rate of D_0. In Figure 7a, the system is in equilibrium prior to any significant groundwater development. In this natural state of equilibrium (roughly prior to 1940 in the Upper San Pedro basin [3]) recharge equals discharge (Equation (2)):

$$R_0 = D_0 \tag{2}$$

Figure 7. (**a**) Groundwater discharging to stream under equilibrium conditions; (**b**) Pumping at rate Q from a well intercepting groundwater that would have discharged to the stream under equilibrium conditions; Q is roughly equal to the rate of change in aquifer storage (ΔS) plus reduced groundwater discharge to the stream (ΔS); (**c**) Pumping at the same rate (Q) under a new equilibrium condition. Now, pumping is reducing groundwater discharge to the stream (ΔD) and inducing recharge directly from the stream (ΔR), and aquifer storage depletion ceases (ΔS = 0). Adapted from Winter and others ([46], Box C, p. 15) and from Heath ([47], p. 33).



In Figure 7b, pumping at a rate of $\boldsymbol{Q}$ is superimposed on the system, producing a rapid rate of change in aquifer storage near the well ($\Delta\boldsymbol{S}$) and intercepting some groundwater that would otherwise have discharged to the river ($\Delta\boldsymbol{D}$), but having no immediate effect on discharge to the stream ($\boldsymbol{D_0}$) due to the persistence of a groundwater "high" between the well and the river. At this point, pumping is roughly equivalent to the rate of change in aquifer storage plus the reduction in groundwater discharge to the stream (Equation (3)).

$$\boldsymbol{Q} = \Delta\boldsymbol{S} + \Delta\boldsymbol{D} \tag{3}$$

and recharge and discharge are no longer in balance (Equation (4)):

$$\boldsymbol{R_0} \neq \boldsymbol{Q} + \boldsymbol{D_0} \tag{4}$$

After some time (Figure 7c), the cone of depression intercepts the stream and reverses the gradient of the groundwater so that it now flows toward the well from all directions, directly capturing streamflow. Even though the pumping rate ($\boldsymbol{Q}$) remains constant, recharge from precipitation also remains fixed at $\boldsymbol{R_0}$, so the only sources of water for extraction come reduced groundwater discharge to the stream, capture (increased recharge) from the stream, itself, and possibly some additional aquifer storage. A new equilibrium is achieved when aquifer storage is no longer being depleted ($\Delta\boldsymbol{S} = \boldsymbol{0}$) and pumping is balanced by the capture of stream flow and decreased discharge to the stream (Equation (5)):

$$\boldsymbol{R_0} = \boldsymbol{Q} + (\boldsymbol{D_0} - \Delta\boldsymbol{D} - \Delta\boldsymbol{R}) \tag{5}$$

or,

$$\boldsymbol{Q} = \Delta\boldsymbol{R} + \Delta\boldsymbol{D} \tag{6}$$

Lohman [48] identified another potential source of capture not expressly described above. He referred to it as "salvaged rejected recharge from precipitation." This potential source of capture would comprise a new source of recharge ($\Delta\boldsymbol{R}$) as described in Equations (1) and (6). In the case of a large alluvial basin like the San Pedro, where much of the shallow alluvial aquifer is separated by a thick sequence of confining materials from the underlying regional aquifer, this source of potential capture would derive from the occasional replenishment of the shallow alluvial aquifer during runoff from one or more very large precipitation events. Runoff exceeding 25M cu-m/d occurs roughly every 5 to 6 years at the Palominas station (Figure 1), so any excess alluvial aquifer storage opened up by groundwater pumping could capture flood flows that would otherwise have been rejected and remained in the stream.

For the period 2000 to 2009, Kennedy and Gungle [32] found that alluvial aquifer storage changes that govern baseflow measured at the Tombstone stream-flow gaging station (near the far downstream end of the study area (Figure 1)) were a function of upstream riparian ET and summer precipitation. Although they did not identify groundwater pumping as a clear source of baseflow decline in that reach over that short period, they do caution that, "[c]ontinued regional groundwater pumping will, however, eventually lead to a decline in the contribution of regional groundwater to base flow." This contrast between the interannual scale of fluctuations in alluvial aquifer storage and the multi-decadal scale of changes in regional aquifer discharge is highly significant for long-term water management planning. Our study focuses on these longer-term regional aquifer changes, but acknowledges the importance in improving our understanding of the linkages between sources of capture at different temporal and spatial scales.

Groundwater simulations [3,33] indicate that the Upper San Pedro basin is transitioning between the second and third scenarios illustrated in Figure 7. Of course, streamflow is not the only potential source of capture in most groundwater basins, and may not be available at all, as in basins where the streambed has lost connectivity with the underlying aquifer. Other potential sources of capture include riparian evapotranspiration, groundwater inflow from boundary sources, and groundwater outflow from the basin. Because groundwater and surface water systems operate on such different time scales, stresses on a groundwater system may not manifest as baseflow depletions for many years. Unfortunately, "in many circumstances the dynamics of the groundwater system are such that long periods of time are necessary before any kind of an equilibrium condition can develop. In some circumstances the system response is so slow that [groundwater] mining will continue well beyond any reasonable planning period" ([44], p. 55–57). The goal of the study described in this paper is to anticipate the future impacts of 20th and 21st century pumping on the San Pedro River and to develop a strategy to mitigate those effects as they occur.

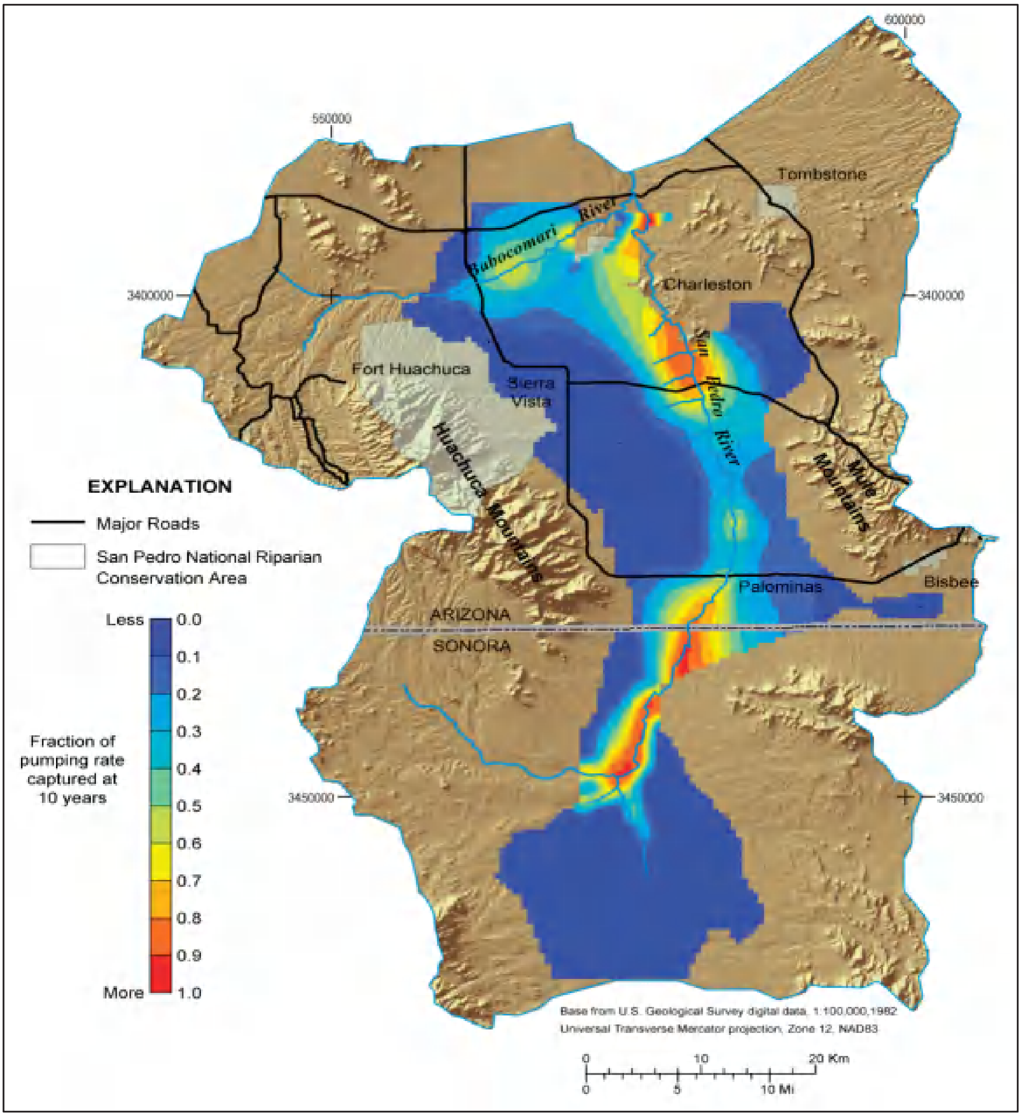
2.2.2. Development of Capture Map

Leake and others [31,48] developed a unique tool that utilizes the Pool and Dickinson [3] regional groundwater flow model to assess simulated pumping-induced capture of streamflow, spring discharge, and riparian ET across the model domain in response to a unit pumping stress at every location in the model, and presents the results as a map overlay with colored contours representing the amount of capture, as a fraction of the pumping rate, after pumping for a specified amount of time (Figure 8). Leake and others [49] provide detailed steps for developing a capture map using a groundwater model. Alternatively, capture for a given location can be calculated as the pumping time needed to reach a depletion-dominated supply (the time at which capture begins to provide greater than 50% of total groundwater pumped). A typical time scale for a basin in the American Southwest might be 0 to 100 years [50]. Capture map development can also be run in reverse, providing estimates of the total increase in streamflow, riparian evapotranspiration, and spring flow, as a fraction of recharge rate, after recharging at a unit rate for a specified amount of time [51]. The two are not necessarily the inverse of each other. Leake and others [31] calculated stream and riparian area capture resulting from pumping in the lower basin fill primary aquifer (layer 4 of the 5-layer groundwater model [3]) in the Upper San Pedro basin. They used the same method to calculate response in the stream/riparian area from recharge applied to the top-most layer of the model that overlies the extent of layer 4 (layers 1, 2, or 4).

2.2.3. Use of Capture Map in the San Pedro Basin

Richter and others [1] discuss the evolution of the capture map concept and its use in policy development within the basin. While the capture map does not replace groundwater modeling, it is a simple, intuitive tool that permits the layman to gain a better understanding of the degree of connectivity between the groundwater system and the river. Policy makers and stakeholders embraced the capture map in the San Pedro basin as a guide for various preliminary decisions on community development and ecological restoration.

Figure 8. Computed capture (as a percentage of pumping rate) of streamflow, riparian evapotranspiration, and spring flow that would result for withdrawal of water from model layer 4 at a constant rate for 10 years. The color at any location represents the fraction of the withdrawal rate by a well at that location that can be accounted for as changes in outflow from and or inflow to the aquifer for model boundaries representing streams, riparian vegetation, and springs. Redrawn from Leake and others [31].



2.2.4. Advantages/Disadvantages and Limitations of the Tool

Capture maps highlight where pumping will have the greatest impact on a water resource (such as a river) within a specified period of time, and thus make an excellent preliminary planning tool for water managers, commercial and residential developers, and conservationists who can benefit from reducing the immediate impacts of groundwater pumping. The similarly constructed recharge map provides similar planning benefits, offering the planner an initial overview of the most advantageous sites for storm-water, treated effluent, or other recharge facilities.

Despite the value of capture maps for communicating some complex hydrologic concepts to lay audiences, details about specific volumes and rates of capture for specific sources/sinks in the basin cannot be extrapolated directly from this tool. Capture maps, based on linear superposition, reflect the assumption of constant hydrologic properties of the aquifer, assuming that pumping causes no non-linear behavior in the hydrologic system. This limitation, and the fact that each cell of the model is stressed in isolation to make the map, means that capture maps cannot replace the use of a full groundwater model for examining the cumulative impacts of various stresses and sinks that change over time or that cause nonlinearities in hydrologic properties or boundary conditions.

2.3. Near-Stream Recharge Simulations

2.3.1. Description of Model

Simulations in this study used the most recent and most sophisticated groundwater flow model of the Upper San Pedro Basin available [3]. Although the model area includes all of the 4500-km^2 basin of which 40% is in Mexico, this study focuses on the Sierra Vista subwatershed within the United States (Figure 1). This MODFLOW-2000 [52] model is based on a uniform 250 m × 250 m grid spacing oriented north-south in alignment with the basin. The stream is represented by the Stream Package [53], hydraulic flow is modeled with the Layer Property Flow (LPF) package, and riparian evapotranspiration is modeled with the Evapotranspiration (EVT) Package of MODFLOW-2000. The two-season model reflects the seasonal significance of evapotranspiration in the riparian zones along the San Pedro and its tributaries. The cool season extends from mid October to mid March, and the warm season runs from mid March through mid October [3].

As with all groundwater models, this model has several limitations. Most significantly, it does not simulate flood flows, which are known to contribute significant recharge to the alluvial aquifer near the center of the basin as well as along some ephemeral tributaries to the mainstem of the San Pedro River. This seasonal "topping off" of the shallow alluvial aquifer may support baseflows in the river through one or more dry seasons, and is an important component of the riparian system. While this shortcoming means that the model tends to underestimate true baseflow (regional aquifer plus shallow alluvial aquifer contributions), it does not preclude the model as a useful tool for analyzing the effects of pumping on the regional aquifer's contribution to baseflow. For this reason, the term "baseflow" in this study refers strictly to that component of total baseflow that derives from the regional aquifer where most of the pumping in the basin occurs.

Figure 9 illustrates the conceptualized hydrogeologic cross section (upstream view) of the subwatershed and shows how the model layers correspond to that conceptualization. The model structure includes five layers in a stacked-bowl configuration representing sediment accumulation in the structural depression between two bounding mountain ranges, as is typical of the Basin and Range province of the western United States [3]. Only model layer 5 is found throughout the entire region (Figure 10).

Figure 9. Conceptualized cross section of basin showing model layers. Adapted from Figure 3 in Pool and Dickinson [3]).

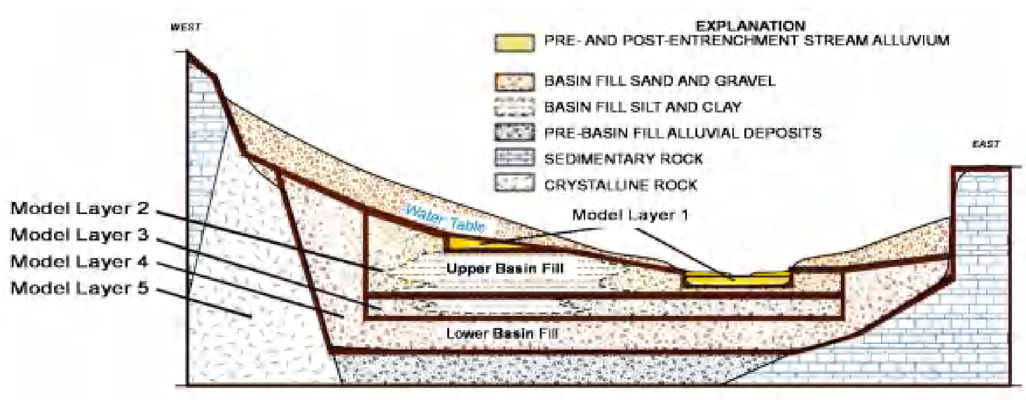
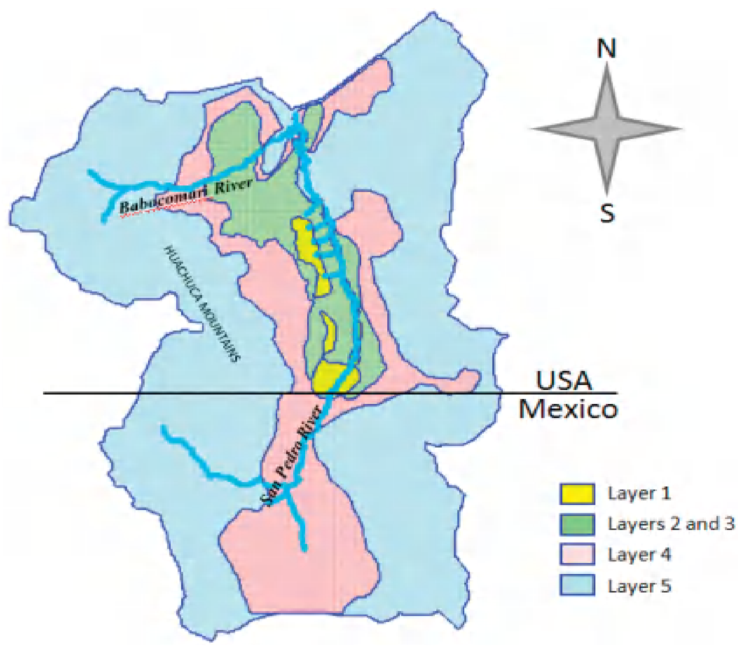


Figure 10. Model layers [2] in plan view with San Pedro River intersecting various layers. Light blue line represents river location but does not necessarily signify perennial flow.

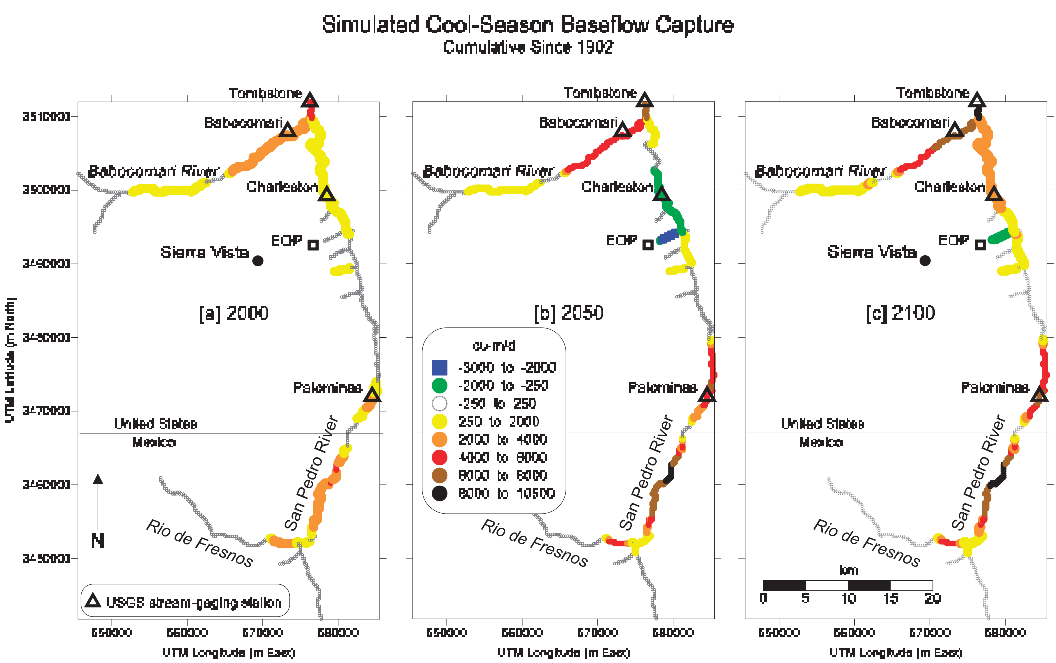


2.3.2. Use of Model in Water Resources Assessments

Initial groundwater modeling efforts by Pool and Dickinson [3] simulated transient groundwater levels and baseflows in the basin resulting from 20th-century (1902–2003) pumping and changes in riparian evapotranspiration associated with climate and evolving geomorphology of the stream channel [14]. These simulations reflected the development of a major cone of depression under the Sierra Vista/Fort Huachuca population center on the west side of the river, and a smaller area of groundwater depletion very close to the river near the communities of Palominas and Hereford, where agricultural pumping occurred for many decades (Figure 3a). The effects of groundwater use in Mexico also manifest as an irregular cone of depression progressing northward from the south edge of the regional aquifer.

Simulations by Lacher [33] built on the work of Pool and Dickinson [3] and projected pumping through the 21st century based on population projections developed by the Arizona Department of Commerce [54] and TischlerBise [55], and calculating the total drawdown (Figure 3) and change in baseflow over the 1902–2100 period (Figure 11). These simulations predicted widespread increases in aquifer storage depletion across the western side of the basin during the 21st century (Figure 3b,c). They also quantified projected declines in baseflow in the basin over the next 100 years due to pumping and evapotranspiration, as well projected increases in baseflow until about 2050 resulting from the recharge facility at the City of Sierra Vista's Environmental Operations Park (EOP) (Figure 11b).

Figure 11. Simulated baseflow capture from 1902 to: (**a**) 2000; (**b**) 2050; and (**c**) 2100. Capture is cumulative [33] and measured in cu-m/d. EOP indicates location of Sierra Vista's Environmental Operations Park wastewater recharge facility.



Water budget calculations and groundwater simulations suggest that cumulative total groundwater depletion is presently on the order of 800 MCM in the subwatershed with annual net storage loss over the last decade on the order of 5 to 7 MCM [56,57]. Policy makers in the subwatershed have considered the feasibility of importing water at a maximum rate of roughly 37 MCM/yr [38]. However, even that most optimistic rate of importation would require nearly 25 years to bring the subwatershed's cumulative water budget back into balance. In the meantime, ongoing pumping-induced baseflow capture would continue to depress the groundwater gradient between the pumping centers and the river (Figure 4) further reducing baseflows.

2.3.3. Near-Stream Simulated Recharge Site Selection

Although artificial recharge of urban-enhanced runoff through detention basins has long been considered a viable option for mitigating impacts of groundwater pumping, the basins have previously been designed to target the active cone of depression in the Sierra Vista/Fort Huachuca area [34] rather than the river. The concept of simulating targeted near-stream recharge arose from the process of quantifying the pumping-induced capture of baseflow (*i.e.*, a reduction of groundwater discharge from the regional aquifer to the river) over time using the regional groundwater flow model [33]. With simulated current baseflow capture for the entire basin and projections of aquifer storage and baseflow capture trends over the next century, near-stream recharge was identified as a potential mechanism for addressing projected baseflow "deficits" (declines from 2003 (end of transient model calibration period) baseline values) in targeted areas of the basin.

Taken together, the suite of hydrologic tools pointed to sections of the San Pedro River where greater protection was warranted and where meaningful impacts—such as converting an intermittent stream reach into perennial reach—could be made. Simulations with the groundwater model [58] suggested that developing a distributed, strategically located network of recharge projects near select river reaches might result in groundwater mounding that would effectively compensate for baseflow capture, thus, protecting baseflow and the riparian vegetation community from the anticipated effects of pumping for several decades or more.

2.3.4. Application of Recharge Models

A small core team of technical experts within the Upper San Pedro Partnership Technical Committee selected three trial sites for simulating hypothetical recharge near the river: (1) Palominas; (2) Garden Canyon; and (3) Babocomari (Figure 12). The site selection process was informed by both simple geography (upper, middle, and lower part of the subwatershed) and current and projected baseflow capture in the river system. Simulated recharge at each trial site consisted of surface recharge over four 250 m × 250 m model cells (0.25 km^2) for the period 2012–2111. For each of the three trial sites shown in Figure 12, the recharge simulation investigation involved increasing recharge, as needed, to prevent any decline in baseflow below baseline (2003) levels downstream of the site over the simulation period while also preventing simulated surface flooding at the trial site.

Starting with 0.62 MCM/yr, simulated recharge at each site was incrementally increased, and baseflow response tested, until baseflow downstream of each site remained at or above 2003 levels for the 100-year simulation period. Figure 13 shows simulated change in the cool season (October–March) baseflow from 2003 (end of the transient calibration period) conditions in the years 2030, 2050, 2070, and 2111. As the decreasing cool (blue and green) colors in the northern half of the subwatershed over time indicate, baseflows are predicted to fall below 2003 levels in all of the mainstem San Pedro River and on the Babocomari by 2111. Recharge at the Sierra Vista EOP successfully maintains simulated baseflows in the mainstem above 2003 levels until at least 2070, but the impacts of pumping (deepening and widening cone of depression) overwhelm the recharge benefits by about the turn of the century.

Figure 12. Simulated trial recharge sites (Babocomari, Garden Canyon, and Palominas) in the Sierra Vista subbasin. Riparian condition class reaches delineated within the SPRNCA [10]. Adapted from Figure 42 in Stromberg and others [10].

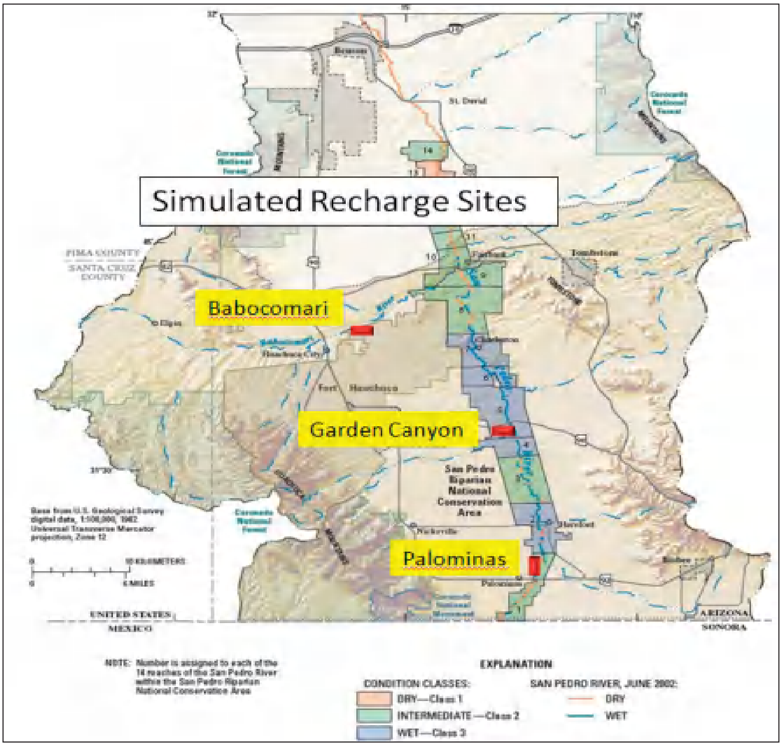
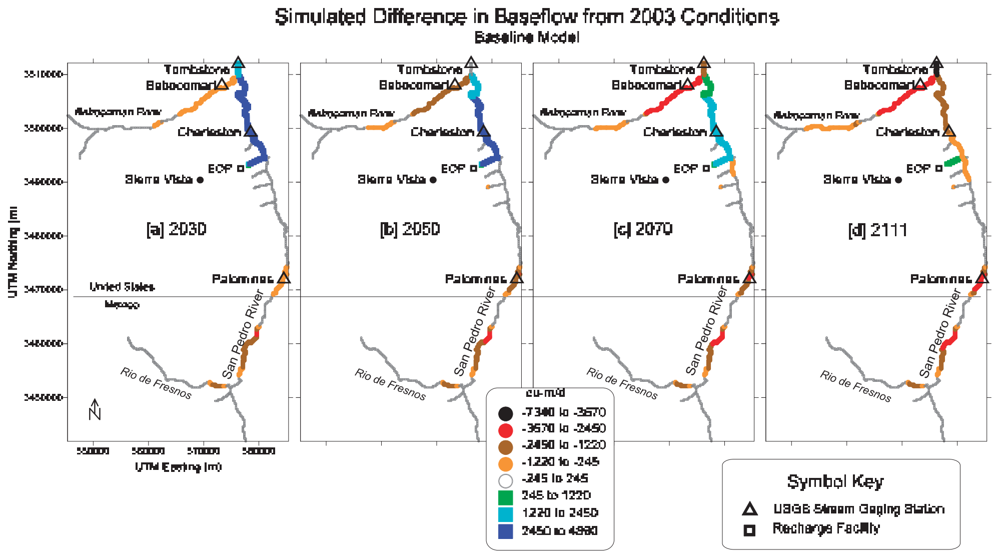


Figure 13. Simulated difference in baseflow (cu-m/d) in basin streams from 2003 conditions in: (**a**) 2030; (**b**) 2050; (**c**) 2070; and (**d**) 2111.



2.3.5. Simulation Results

Hydraulic conductivity, antecedent depth to groundwater, and projected aquifer storage depletion over time controlled the simulated baseflow response to recharge at each of the three trial sites. Since simulated recharge applied at each of the three trial sites was tailored to meet the anticipated baseflow deficit downstream, each site demanded a unique recharge distribution and exhibited a unique response to the simulated recharge. Figure 14 illustrates the recharge rates determined by trial and error as necessary to sustain simulated baseflows at or above 2003 levels in the groundwater model [3] through 2111. While each of the three test sites exhibited a unique response to the simulated recharge rates shown in Figure 14, the Babocomari site exhibited a much higher demand for recharge and a much more pronounced response in the underlying groundwater than the other two sites [58]. For the purpose of illustration, only the Babocomari test site recharge results will be discussed in detail here.

Figure 14. Simulated recharge rates for the Babocomari, Palominas, and Garden Canyon test sites.

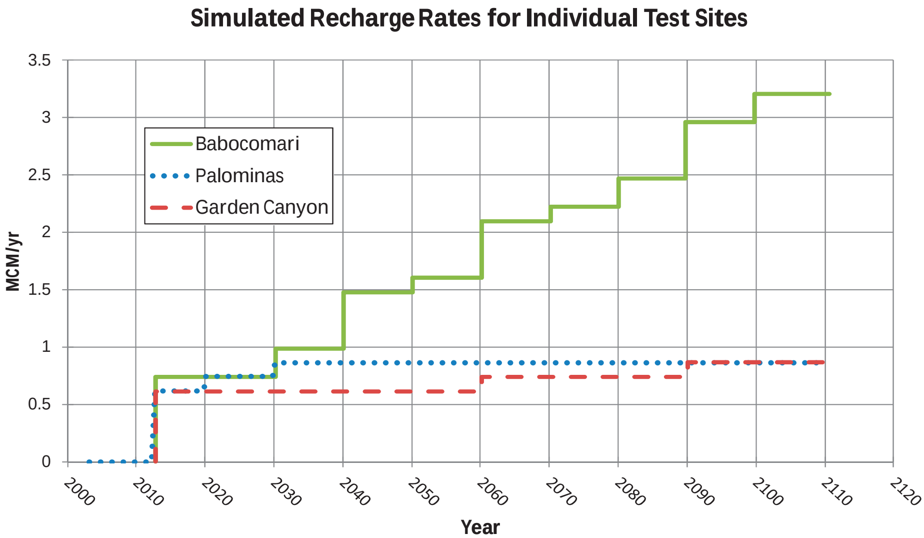
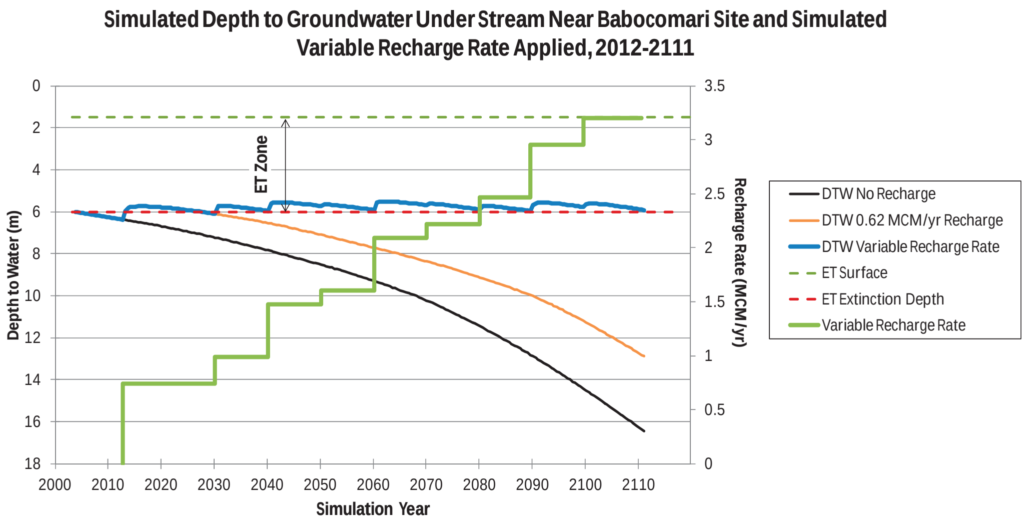


Figure 15 illustrates the groundwater response to recharge at the Babocomari site. The black line represents depth to groundwater (DTW) under the stream adjacent to the recharge site in the baseline model with no simulated recharge at the Babocomari site. The orange line shows DTW in response to a constant rate of 0.62 MCM/yr. recharge, and the blue line shows DTW in the same location under the stream for the varying-recharge scenario illustrated by the green "Variable Recharge Rate" line. In the absence of any intervention (black DTW curve), simulated heads at this site are projected to drop by more than 10 m over the 21st century in response to pumping. However, these simulations suggest that incrementally increasing recharge from an initial rate of 0.74 MCM/yr in 2012 to 3.2 MCM/yr by 2100 would successfully maintain groundwater levels under the river at or slightly above the 2003 level.

The oscillation in the blue DTW curve reflects the fact that the simulated variable recharge increased groundwater levels under the river to a depth between the top of the evapotranspiration (ET) surface (1.5 m below top of aquifer) and the ET extinction depth at 6 m below the top of the aquifer. Thus, groundwater is more accessible to riparian vegetation in the varying-rate recharge scenario than in the baseline case, but baseflows still remain at or above 2003 levels in the area of the stream downstream where baseflow declines are projected under baseline conditions.

Figure 15. Simulated variable recharge rate at the Babocomari site and depth to water (DTW) under stream adjacent to the Babocomari recharge site from 2012 to 2111 for three scenarios: (**a**) no recharge; (**b**) 0.62 MCM constant-rate recharge; and (**c**) variable-rate recharge scenarios [58]. Evapotranspiration (ET) zone occurs between 1.5 and 6 m [3].



2.3.6. Optimization of Recharge Rates

Section 2.3.5 presented the results of simulated varying-rate recharge at each of three trial sites individually along the San Pedro and Babocomari Rivers. One additional simulation combining the three trial recharge sites was run in order to answer the question of whether hydrologic efficiencies might be gained with simultaneous recharge at all three sites [58]. Because the reach of the San Pedro affected by simulated recharge at the Garden Canyon site is downstream of both the Babocomari and Palominas sites, some reduction in the required recharge at the Garden Canyon site was achieved by combining all three trial recharge sites in a single simulation. Figure 16 illustrates the reduced recharge required at the Garden Canyon site to maintain simulated baseflows downstream of that site at 2003 levels when recharge is simulated at the Palominas and Babocomari trial sites concurrently.

Total recharge required to maintain simulated baseflows at 2003 levels downstream of each of the three test sites is shown in Figure 17. The blue curve shows the total recharge required when the three sites are simulated independently of each other, and the green curve shows the total recharge requirement when all three test sites are simulated concurrently. The difference between the curves illustrates the efficiency gained by combining the three recharge test sites. The maximum total recharge rate in the independent simulations is 4.93 MCM/yr (3.35 MCM/yr average over the 2012–2111 period), but that value drops to 4.63 MCM/yr (2.91 MCM/yr average) for the concurrent recharge simulations. The average recharge saved by operating all three sites concurrently is

0.45 MCM/yr. Figure 18 shows the final simulated change in baseflow from 2003 conditions when recharge at the three test sites is optimized for concurrent simulation of the three sites.

Figure 16. Simulated variable recharge rates for the Babocomari, Palominas and Garden Canyon test sites. Simulating recharge at all three sites concurrently allowed a reduction in Garden Canyon recharge relative to the rates for the independent recharge simulations.

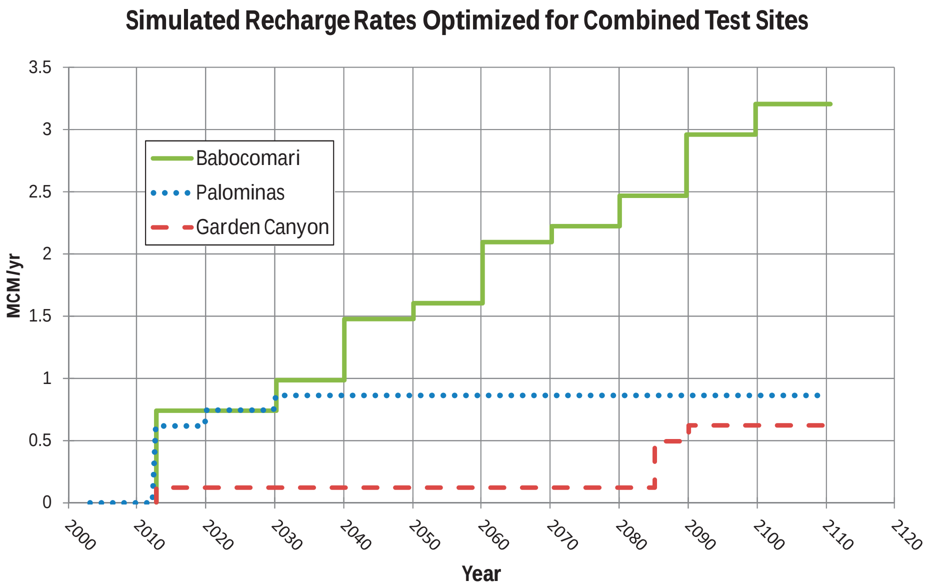


Figure 17. Total simulated recharge at the Babocomari, Palominas, and Garden Canyon test sites required to maintain baseflows downstream of each site at or above 2003 levels when recharge is simulated at each site independently and when all three sites are simulated concurrently.

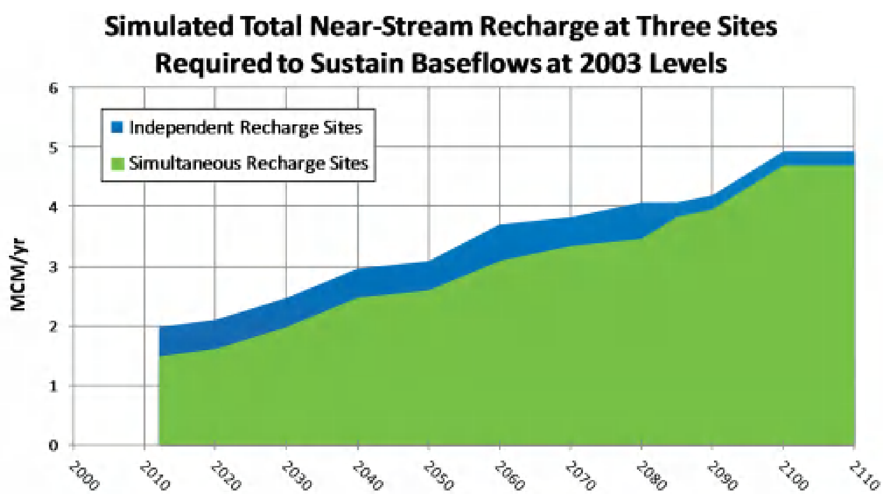
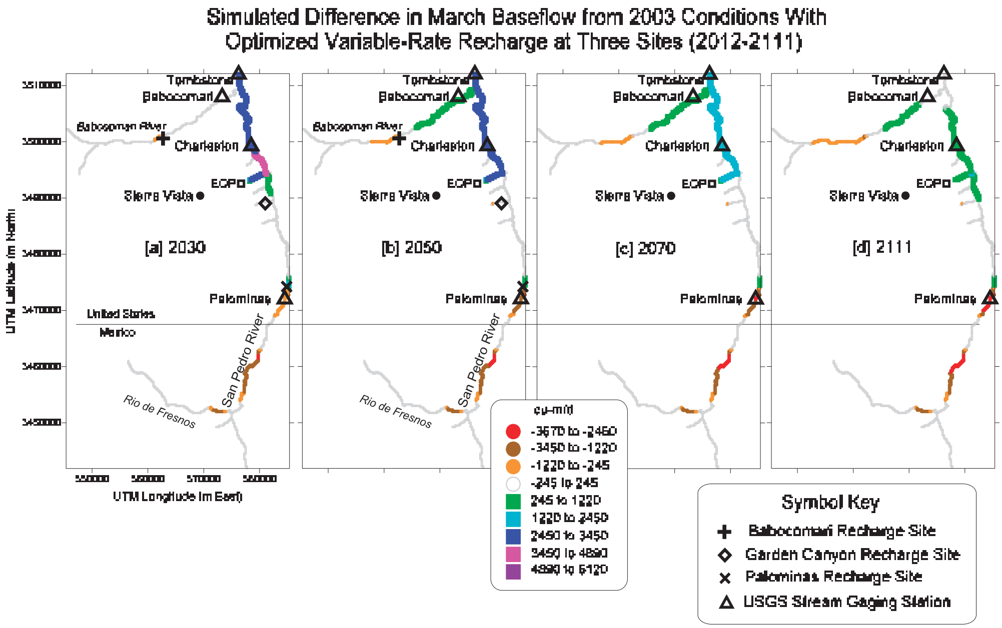


Figure 18. Simulated difference in March baseflow (cu-m/d) from 2003 conditions with optimized variable-rate recharge at three trial recharge sites in: (**a**) 2030; (**b**) 2050; (**c**) 2070; and (**d**) 2111.



2.3.7. Advantages/Disadvantages and Evolution of the Tool

Any perceived bias in the construction of the model, or simple disagreements among stakeholders with the technical modeling approach, can be problematic in terms of how modeling results will be used, if at all. Engagement of stakeholders throughout the model development process is essential for it to be embraced as a useful tool for decision making among varied interests. In this case, the groundwater model [3] was developed in response to wide dissatisfaction with some precursor models of the subwatershed. Richter and others [1] describe the process by which stakeholders were involved in the development of the Pool and Dickinson model [3] and the evolution of trust in the model among technical water resources experts and politicians in the basin.

Several years of experience with the Pool and Dickinson model [3] in developing and communicating results of baseline projections helped pave the way for using it as a tool to evaluate the prospects of near-stream recharge. The model made experimenting with various recharge rates and tracking the resultant changes in baseflow a fairly quick and inexpensive undertaking. While we feel that these simulation efforts successfully conveyed the general concept and potential merits of near-stream recharge to the public and decision makers, significant criticism arose from our choice of an arbitrary initial recharge rate of 0.62 MCM/yr for the hypothetical recharge sites. We viewed the initial near-stream recharge simulations as an exploratory mission to determine how much water would be required to produce the desired effect on baseflows in the San Pedro River, irrespective of the potential feasibility of attaining that quantity of water or distributing it in the locations of interest. As our initial simulation results were presented to stakeholders, many of them questioned the value in simulating recharge with water that is not available and for which no plans to develop were pending. We saw the near-stream modeling process as a “proof-of-concept” effort, but others quickly made the leap to the real difficulties in securing water for recharge. Significant time and energy were expended in efforts to bridge this conceptual gap, and in hindsight, more early effort to clarify the purpose and strategy behind the simulations would have been helpful.

2.3.8. Application of Recharge Simulations to Upper San Pedro Parcels

The primary value in the groundwater modeling efforts undertaken for the three “test sites” described above was in proving the potential benefit of multiple recharge sites near the river. In recent years, the U.S. Army Compatible Use Buffer program, Cochise County, and The Nature Conservancy collaboratively acquired and set aside for conservation purposes four parcels on the west side of the San Pedro River totaling 2226 hectares within the subwatershed (Figure 5). Collectively, these properties make up the physical sites currently under consideration for development of a network of near-stream recharge projects. The groundwater modeling process detailed above for the three hypothetical “test sites” was employed to some extent in the preliminary planning process for parcels 1 and 3 in Figure 5. As projects move from the conceptual phase to the physical site investigation stage, use of the groundwater model is being adapted to suit the project planning needs for the individual sites. While development of a recharge project on parcel 1 was constrained by several factors (parcel size, flood-control objectives, location of high-permeability soils off site), the current planning process for parcel 3 is relatively unconstrained. Modifications to model structure to reflect observed field conditions and refinement of the model grid to allow for more detailed simulation of potential recharge are two of the anticipated outcomes of the next phase of investigation at parcel 3.

3. Results and Discussion

The suite of analytical tools discussed here is being used to inform key decisions necessary to balance groundwater use and maintain San Pedro River flows and associated riparian area ecological health. An extensive collection of hydrological studies and a robust, long-term monitoring program in the San Pedro basin have provided policy makers and stakeholders with important information about the complex relationships between groundwater condition, streamflow, and the ecological integrity of the riparian system within and near the SPRNCA. As a result, most of the stakeholders in the subwatershed understand that much of the San Pedro’s riparian vegetation uses groundwater from the stream alluvium, and that this alluvial aquifer stores water from flood flows, receives groundwater from the regional aquifer, and contributes baseflow to the river during low-flow periods.

The groundwater model used in this study does not incorporate the complex interactions between flood-driven recharge of the shallow alluvium which influences baseflow to varying degrees from year to year, and pumping-induced depletions of the regional aquifer, which take decades to centuries to alter baseflow. While the model’s authors made every effort to exclude storm-flow influences from the baseflow measurements they used in model calibration [3], it is virtually impossible to ensure that any given measured baseflow value represents only regional aquifer groundwater. The implication of this limitation is that the model may slightly overestimate the regional aquifer's contribution to baseflow, which would manifest as overestimated aquifer transmissivity and/or streambed conductance. That outcome, in turn, means that the model would also overestimate the simulated impact of pumping on baseflow until capture reaches its maximum (equilibrium) value. For the purpose of this study, which is to develop strategies for mitigating pumping-related impacts on baseflow, that response would be conservative and acceptable.

The Pool and Dickinson [3] model represents the culmination of years of study and is the best tool currently available for the study area. As discussed by Richter and others [1], using a groundwater model that is accepted by the vast majority of decision makers to perform predictive groundwater modeling has been essential for beginning to make management and project decisions from a common starting point. The modeling has demonstrated that within the next 100 years, two regional cones of depression will enlarge and likely change the nature of the hydrologic connection between the San Pedro River and the regional aquifer, reducing baseflow and impacting the dependent riparian system and thus wildlife populations.

Awareness and acceptance of an impending problem, however, is only the first step in finding a solution. The additional tools of the wet/dry maps and groundwater capture/recharge maps helped to focus management attention on finding both the most vulnerable areas of the system and the most beneficial locations for mitigation efforts. Analysis of wet/dry maps showing surface water presence during the driest time of year and areas with high year-to-year variation in wetted length may be the first physical evidence of changes in local groundwater conditions at the river. While wetted length is not solely controlled by groundwater conditions (it may also be affected by climate), different trends in various reaches of the river may help identify areas at higher risk of future ecological changes. Aligning these low-flow river reaches with the groundwater capture maps provided a rough indication of the rate that recharge in those areas of the aquifer might respond, expressing itself as baseflow in the San Pedro River. The capture maps also suggested the suitability of various locations for recharge that may communicate with the alluvial aquifer and/or the San Pedro River. On-site investigation of actual hydrogeologic conditions and suitability for recharge at a particular location is the first step toward refining a preliminary conceptual model derived from the tools described in this paper.

In the San Pedro basin, the use of these complementary approaches informed the purchase of the most hydrologically sensitive lands near or adjacent to SPRNCA (Figure 5) in order to both defer residential and/or agricultural development and provide the opportunity for near-stream recharge project development. The concept of a strategically located network of recharge projects near these river reaches evolved, in part, from the success of more than a decade of managed aquifer recharge at the City of Sierra Vista Environmental Operations Park in supporting both baseflow and replenishing the deep regional aquifer. We anticipate that recharging urban-enhanced runoff, storm water, and treated effluent near at-risk reaches shown would create groundwater mounds to sustain surface water flow and supplement alluvial groundwater levels during low-flow periods, effectively compensating for the otherwise deleterious impacts of encroaching cones of depression in the regional aquifer on baseflows for the next several decades or more.

4. Conclusions

The application of the study methods presented in this paper and the development of system-specific techniques appear to have great promise for protecting dry-land riparian systems from the impacts of groundwater extraction, surface water diversions, and the extremes of climate change for up to several decades. The ecological, cultural, and economic significance of the San Pedro River has made it one of the most well-studied and understood river systems in the world. The tremendous volume of data and hydrologic tools already developed for this specific system coupled with many years of collaborative partnerships that have matured with the science make the San Pedro basin a very unique policy environment. There is likely no other river system with an identical set of social, political, and ecological circumstances, but the hydrologic analysis tools described in this paper can be used anywhere. The strength of collaborative partnerships and knowledge of which tools they jointly support is key to building a common understanding of the history, goals, and resources at hand to make real progress.

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Author Contributions

The text of this article was written by Laurel J. Lacher, Dale S. Turner, Bruce Gungle, and Brooke M. Bushman, with contributions by Holly E. Richter. Laurel Lacher conducted background research on capture and urban-enhanced runoff, and performed the simulations of near-stream recharge. Bruce Gungle compiled and synthesized water budget data for the Upper San Pedro Partnership and provided the literature review. Dale Turner compiled and synthesized wet/dry mapping data. Brooke Bushman provided coordination of the research efforts in her role as the Upper San Pedro Basin Program Coordinator for The Nature Conservancy. Holly Richter provided content review and helped shape the presentation of our findings.

Conflicts of Interest

The authors declare no conflict of interest.

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Development of a Shared Vision for Groundwater Management to Protect and Sustain Baseflows of the Upper San Pedro River, Arizona, USA

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Abstract: Groundwater pumping along portions of the binational San Pedro River has depleted aquifer storage that supports baseflow in the San Pedro River. A consortium of 23 agencies, business interests, and non-governmental organizations pooled their collective resources to develop the scientific understanding and technical tools required to optimize the management of this complex, interconnected groundwater-surface water system. A paradigm shift occurred as stakeholders first collaboratively developed, and then later applied, several key hydrologic simulation and monitoring tools. Water resources planning and management transitioned from a traditional water budget-based approach to a more strategic and spatially-explicit optimization process. After groundwater modeling results suggested that strategic near-stream recharge could reasonably sustain baseflows at or above 2003 levels until the year 2100, even in the presence of continued groundwater development, a group of collaborators worked for four years to acquire 2250 hectares of land in key locations along 34 kilometers of the river specifically for this purpose. These actions reflect an evolved common vision that considers the multiple water demands of both humans and the riparian ecosystem associated with the San Pedro River.

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1. Introduction

Many aquifers within the United States contain an essential—yet shrinking—supply of water for both people and natural systems. Groundwater resources support the irrigation of crops, drinking water supplies, and industry. Declining groundwater levels strongly affect riparian ecosystems in the semi-arid southwestern United States, where many aquifer systems are characterized by a large volume of water in storage, but a relatively small rate of natural annual recharge and discharge [1]. Because groundwater also supports natural systems such as wetlands, riparian systems, lakes, streams, and rivers, it has become increasingly difficult for water managers in this region to meet both increasing human water demands and the water needs of natural systems under persistent drought conditions [1,2]. In Arizona, perennial streamflows have significantly declined across the state—at least seven river systems could be dewatered over time, and an additional four will experience degradation if actions are not taken to reverse these trends [2]. In other words, it is increasingly difficult to manage groundwater supplies sustainably in either short or long time frames.

Widespread acceptance/adoption of "sustainable yield," which acknowledges long-term impacts of human pumping but tries to balance those impacts with environmental flow needs, represents a paradigm shift in groundwater management from the more common "safe yield" management paradigm that assumes it is acceptable for consumptive human uses of water to equal groundwater inflows. The name "safe yield" implies some level of security in terms of water availability, which by the very definition of the term is not afforded to water dependent natural systems if they are downstream of human water uses. Sustainable yield, on the other hand, more broadly addresses social, economic and environmental aspects of water availability. The methods for estimating sustainable yield, however, remain largely subjective and poorly understood by the general public, decision makers, and even water resources professionals.

This paper provides a regional case study of the Upper San Pedro River Basin of southeastern Arizona where groundwater management has focused for over a decade on the goal of sustainable groundwater yield, and proposes a generic framework for stakeholder engagement in this process, as well as lessons learned. While several questions and challenges persist, and the implementation of key strategies is ongoing, we present the tools and processes that have proven effective to date there. In particular, we offer a clear definition of sustainable use of groundwater, a conceptual framework for collaborative regional efforts to work toward attaining it along with an example of how the framework was applied in the basin, and examples of specific policies and projects that were developed to foster sustainable use there.

2. The Upper San Pedro Basin

The Upper San Pedro Basin lies within the Basin and Range Province of the southwestern United States and is roughly bisected by the international boundary between Mexico and the United States (Figure 1). The basin is bounded on the east, west, and south by mountains that drain to the river near the center of the alluvial valley. The basin contains up to 520 meters of fill accumulated during the late Tertiary and early Pleistocene [3]. Runoff from the mountains recharged the basin fill over millennia, creating a vast aquifer underlying the San Pedro River. Today, dry-season flows in the San Pedro River depend almost entirely on groundwater discharge. In recent years, concern over potential pumping-related depletions of fragile surface water supplies has lent urgency to efforts to integrate the management of these two connected resources.

Figure 1. Map of the Upper San Pedro Basin showing the location of the San Pedro Riparian National Conservation Area managed by the U.S. Bureau of Land Management and the U.S. Army installation at Fort Huachuca within the Sierra Vista Subwatershed, just north of the United States—Mexico international boundary. From [4] (Figure 1).

Despite the fact that Arizona law generally does not recognize the hydrologic connection between groundwater and surface water, collaboration aimed at integrated groundwater-surface water management in the Upper San Pedro basin has been ongoing for decades, both within the United States and, to a lesser extent, between the United States and Mexico. The State of Arizona is in the process of delineating the “subflow zone” of river alluvium adjacent to the San Pedro

River in order to protect senior surface water rights. Management, monitoring and modeling efforts focused on groundwater-surface water interactions in the Sierra Vista Subwatershed (Subwatershed) have supported vital scientific understanding of the physical basin. However, building a shared vision toward such an integrated water management approach along the binational San Pedro River is challenging for many reasons, including: differences in the political structure, economic development, cultural norms and values, water law, and language on either side of the border combined with a highly variable and complex physical system. Browning-Aiken *et al.* [5] laid out some of the processes used for collaborative watershed management of the San Pedro based on the principles of collective action theory, dispute resolution, adaptive management, power dynamics, and sustainability. The complex binational legal constraints pertinent to San Pedro water issues were also described by Browning-Aiken *et al.* [6]. This paper, however, focuses only on activities on the United States side of the border.

Within the United States, Congress created the San Pedro Riparian National Conservation Area (SPRNCA) in 1988 [7], the first Riparian National Conservation Area of its kind in the nation, and charged the U.S. Bureau of Land Management, to manage it "…in a manner that conserves, protects, and enhances the riparian area…" and other resources. This streamside riparian habitat, composed of Fremont cottonwood, Goodding willow, mesquite bosques, and sacaton floodplain grasslands, supports high levels of biodiversity and functions as a migratory bird corridor of hemispheric importance [8]. It includes approximately 64 km of the 279-km river that flows north to eventually join the Gila River, itself a tributary river to the larger Colorado River (Figure 1).

Several miles away from the SPRNCA another national asset, the U.S. Army installation at Fort Huachuca, had its own needs for groundwater to sustain its military mission associated with national security including communications testing. Fort Huachuca represents a major driver for southern Arizona's economy as the largest employer in the region and contributes approximately $2 billion (U.S.) annually to the state's economy [9]. Located between these two federal interests, the residents of the City of Sierra Vista and Cochise County depend upon the same limited groundwater resources as the National Conservation Area and Fort Huachuca.

In terms of the legal and regulatory context, there are no state restrictions on groundwater extraction along the San Pedro River except for pumping from the zone of subflow, typically a narrow band along the river corridor corresponding to fluvially deposited alluvium. In Arizona, the legal priority of surface water rights is governed by the claim filing date: the earlier the filing date, the more senior and defensible the water right. However, a comprehensive adjudication of water rights on the Gila River system has been ongoing for decades, including federal and other water rights claims along the San Pedro, therefore, considerable uncertainty regarding the nature of surface water rights continues to exist. However, there is a clear legal distinction between surface water rights, which can be defended against more junior competing surface claims, and groundwater use, which is almost wholly unregulated in the state outside of specifically designated Active Management Areas.

Arizona law prevents placing any use limitations—or even requiring a water meter—on wells with a maximum pump capacity of 132 liters/min or less [10], even within the state's Active Management Areas. While the Upper San Pedro River Basin is outside of any state groundwater management area, Cochise County is one of only two counties in Arizona that have adopted requirements that subdivisions in the County must obtain a Designation of Water Adequacy. This program, administered by the Arizona Department of Water Resources (ADWR) requires water companies or subdivisions to show proof of a 100-year water supply before development is permitted. A total of twenty-seven privately owned local water utilities that depend upon groundwater supplies are regulated at the state level by the Arizona Corporation Commission and Arizona Department of Environmental Quality and operate in the area. In addition, three public water supply providers operate municipal water utilities.

3. History of Collaborative Water Management in the Basin

A consortium named the Upper San Pedro Partnership (Partnership) was created through a Memorandum of Understanding (MOU) in 1998 in response to the Arizona Department of Water Resources Rural Watershed Initiative. This collaboration also developed, at least partially, in response to a situation where "dueling hydrologists" hired by different factions provided widely varying opinions about the fate of groundwater and the San Pedro River. The Partnership provided a vehicle for local jurisdictions to work together alongside a range of federal and state agencies, as well as with non-governmental organizations and business interests. The organization's purpose is to meet the long-term water needs of both the SPRNCA and the area's residents [11]. According to the Partnerships mission statement, this goal is to be accomplished through the identification, prioritization, and implementation of policies and projects related to groundwater conservation and (or) enhancement [12].

One of the first objectives for the Partnership was to create a collaboratively-developed regional groundwater model on which all interests could agree and then utilize it for decision making. The model, developed by the USGS, was funded through multiple federal agency budgets, with additional supporting studies funded by other some of the other Partnership members. Over the course of the five years it took to build, USGS hydrologists provided a high level of transparency about the structure of the model and the empirical data sources used to calibrate it [8]. Ultimately, this collaborative model building process served to establish a clear context and common understanding of the complexities of the hydrogeology, surface and groundwater systems, human water demands, and riparian vegetation trends and water needs. During this time, the Partnership was also recognized (in 2003) by the U.S. Congress via Public Law 108-136, (Section 321) [13], which charged the Partnership with achieving sustainable yield of the Sierra Vista Subwatershed regional aquifer by 30 September 2011.

The Section 321 legislation also required the U.S. Secretary of the Interior to deliver nine annual reports to Congress on the water management and conservation measures necessary to restore and maintain the sustainable yield of the regional aquifer by and after 30 September 2011. Future federal appropriations to the Partnership were to depend on the Partnership's ability to meet its annual goals for groundwater deficit reduction. On behalf of the Secretary and following Partnership decisions about methods and content, the reports were compiled and written by USGS staff of the Arizona Water Science Center with the assistance of other Partnership members. What the 321 legislation did not provide was a Congressional definition of the term "sustainable yield of the regional aquifer."

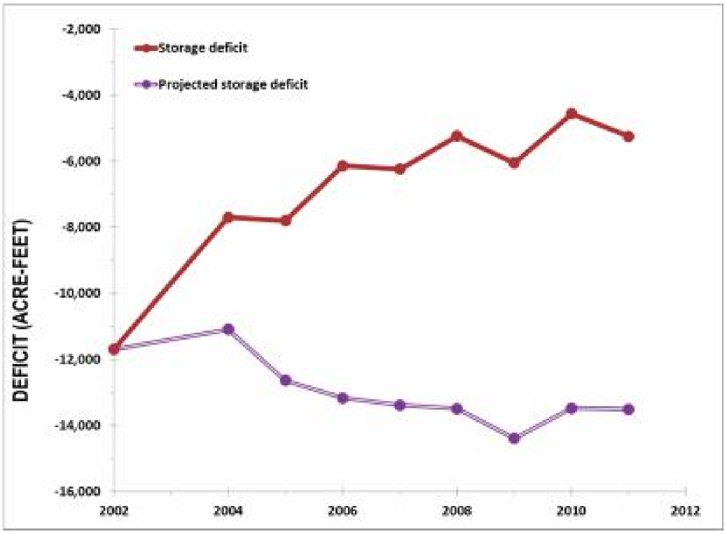
The Partnership chose a definition of sustainable yield based on the competing objectives view of sustainability [14]

> "…managing [groundwater] in a way that can be maintained for an indefinite period of time, without causing unacceptable environmental, economic, or social consequences" [15].

This was operationalized to mean, "…a sustainable level of groundwater pumping for the Sierra Vista subwatershed could be an amount between zero and a level that arrests storage depletion, with the understanding that to call a level of use sustainable (other than zero) will entail some consequences at some point in the future" [16].

Figure 2 summarizes the progress of the 23 member agencies in their collaborative efforts to reduce the groundwater deficit through water conservation, recharge and reuse programs after the Section 321 legislation was enacted.

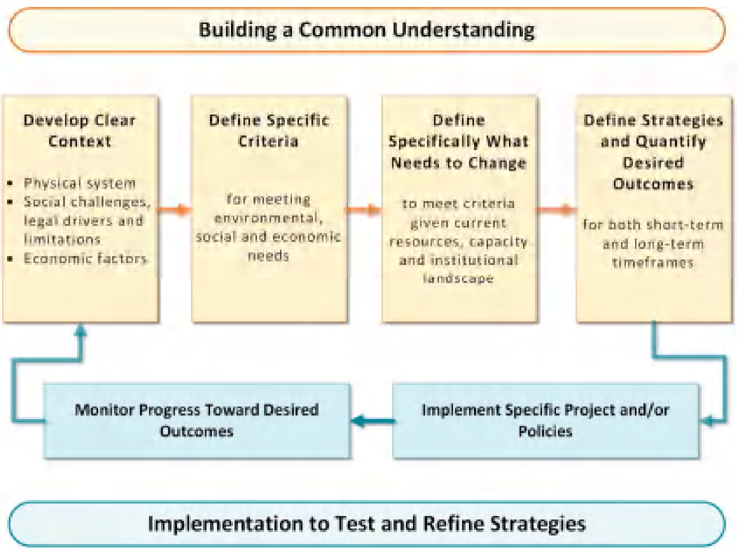
Figure 2. Estimated actual Sierra Vista subwatershed annual storage deficit and projected annual storage deficit that would have occurred had no management, conservation, or incidental yields due to human activity taken place. Incidental yields include increased recharge of runoff due to urbanization. The projected annual storage deficit is based on 2002 pumping rates and actual (not projected) population data from the State of Arizona and the U.S. Census through 2012. Modified from [17].



4. Development of a Shared Vision for Sustainability

Based on the approach used along the Upper San Pedro River, we developed a generic conceptual model (Figure 3) consisting of six components for developing a shared vision for sustainable groundwater management among diverse stakeholders, and for the subsequent implementation of measures to test and refine strategies over time.

Figure 3. Conceptual Model for the Development of a Shared Vision of Sustainability for Integrated Water Management: The process of developing a shared vision of sustainability for regional groundwater management first requires an initial investment in *building a common understanding* of: the context of the water management challenge among stakeholders, the specific criteria for meeting environmental, social and economic needs, the theory of what needs to change to meet these criteria, and lastly, the strategies that will result in the desired outcomes. The subsequent *implementation of projects or policies* will have a better chance of providing multiple benefits and avoiding conflict when preceded by these steps.



Given the physical, economic, and social/legal/political scope and complexity of managing groundwater and surface water at the regional scale, various water managers and stakeholders typically have differing assumptions and opinions regarding management priorities, strategies, and potential outcomes. The development of a shared understanding of these multi-faceted complexities provides an essential foundation upon which to build a more collaborative approach and more robust solutions. This can be critical, especially given that the decisions of certain water managers and/or stakeholders may directly impact, either for benefit or detriment, the interests of others in terms of water availability. However, given the urgency, timing, and often political or legal sensitivities associated with some of these regional water management challenges, the initial investment in building a common understanding among various affected interests is not always made before the execution of plans, or implementation of projects or policies. Other authors have described that the "co-evolution of preferences" takes place through developing shared values and that people ultimately change their demands out of a motivation not just of helping others meet their needs, but because their perceptions and understanding of the issue have also fundamentally changed [18].

Therefore, a process that builds a common understanding of the specific criteria for meeting environmental, social, and environmental water management needs, as well as agreed upon strategies to address these criteria, is crucial to not only avoid subsequent conflict between interests but to build the most effective and robust solutions. In addition, specific desired outcomes for sustainability should be accurately defined, as well as the theory of what specifically needs to change to reach these outcomes with specific timeframes in mind. The strategies and theory of change can subsequently be tested through the collective implementation of projects and/or policies only if adequate monitoring programs are in place to do so at the appropriate spatial and temporal scales (Figure 3).

4.1. Develop a Clear Context

In our experience, the physical complexity of groundwater systems alone can be tremendous, and the simultaneous consideration of social and economic factors can seem insurmountable to stakeholders working together to identify shared solutions for regional water management. One of the key lessons learned from collaboration along the San Pedro was the pivotal step of directly engaging stakeholders early in the process to participate in defining the scope of technical investigations from their own perspectives as decision makers. However, this approach is not intuitive for scientists, who have been trained to approach problems from a purely technical perspective. Decision makers need specific types of information for making high-risk policy, finance, and political decisions. Even if risks are inherent or unavoidable, the ability of scientists to quantify the probability of certain outcomes can be very useful for decision makers to choose between various alternatives. Enabling scientists to understand the specific information most needed by decision makers early in collaborative planning processes is imperative. The subsequent steps in developing a shared vision of sustainability all depend upon getting this initial step of the process right [19].

Developing social and economic criteria related to groundwater management is sometimes hard to definitively quantify or even anticipate in a qualitative sense into the future. However, in the San Pedro example, the fact that the core interests of some of the stakeholders were conceptually defined through the development of even qualitative criteria (such as “Fort Huachuca remains operational unless for reasons unrelated to water”) helped to build a shared understanding and advanced discussions toward a possible solution set. One approach taken by the Partnership was to develop a decision support system (DSS) model based on the USGS groundwater model to help decision makers understand the impacts and cost-effectiveness of different combinations of water-conservation measures and management policies [20,21].

The primary technical tools used along the San Pedro River to explore the physical aspects of regional water management options and to aid in their development are discussed in detail by Lacher *et al.* [22]. While various research, data collection, and monitoring efforts were conducted from 1998 to 2014, the development of a groundwater model acceptable to all stakeholders was the overarching process that united stakeholders around a common understanding of the physical system. As stakeholders began deconstructing the complexities of the system by discussing the individual assumptions that went into that physical model, they recognized the need for improved information on which to base the model, and additional technical studies and/or predictive modeling tools were developed, such as stormwater/runoff models, evapotranspiration models, and riparian health inventories to provide better context regarding pivotal aspects of physical systems. As these types of additional studies strengthened the development of the regional groundwater model over time, it also had a secondary, but very important direct benefit for stakeholders—it improved their own common understanding of the physical system, and the eventual modeling results at the regional scale became more and more intuitive to them as well [20].

A common understanding of the legal, social and economic context of regional groundwater management issues emerged over the years from monthly Partnership meetings, multiple public opinion surveys conducted by various groups with an interest in regional water issues, and contracted studies, as well as through annual production of the "Legal Impediments" portion of the Section 321 reports to Congress. In addition, building an understanding of the relative costs for enhancing water supplies through a detailed assessment of a wide range of strategies proved essential for decision makers. The Partnership conducted a cost/yield study of 74 water management alternatives [23]. This process helped clarify the universe of all stakeholders' preferences and ideas about possible water management solutions and put all these alternatives in a common currency of relative cost and benefit. It also reinforced the concept that no one, or even several, projects could address the existing short- and longer-term water challenges. Instead, based on an increased understanding of the physical system, stakeholders came to realize that an array of long-term demand-reduction measures would be needed along with more immediate aquifer recharge and stream flow protection measures.

4.2. Define Specific Criteria for Meeting Environmental, Social and Economic Needs

For the cost/yield study of water management activities, the Partnership defined seven environmental criteria for sustainability, including two groundwater, three surface water, and two ecological criteria, through a facilitated consensus-driven process (Table 1).

Table 1. The suite of criteria developed by the Upper San Pedro Partnership for sustainable yield.

Environmental needs	Social and economic needs
(1) Groundwater levels in aquifer within the San Pedro Riparian National Conservation Area maintained	(1) Sufficient water quantity for human demands
(2) Regional aquifer storage increased	(2) Fort Huachuca remains operational unless for reasons unrelated to water
(3) Stream baseflow and flood flows in the river are maintained	(3) Cost of living, insomuch as controlled by water, remains within the means of a diverse population
(4) Water quality in the river sustained	(4) Local participation in water management
(5) Springs in the San Pedro Riparian National Conservation Area continue to flow	(5) Water quality maintained
(6) Overall riparian condition maintained	
(7) Riparian habitat and ecologic diversity maintained	

4.2.1. Environmental Criteria

In general, some of the defining environmental criteria commonly associated with sustainable yield include: (1) avoid excessive depletion of surface water and excessive reduction of groundwater discharge to springs, rivers, wetlands, and riparian vegetation (defined as capture); (2) prevent the intrusion of contaminated water to the groundwater system during induced recharge; and (3) avoid irreparable impact to any groundwater-dependent ecosystems, and prevent land subsidence from groundwater withdrawals [24].

Along the San Pedro River, the groundwater-dependent riparian habitat composed of native Fremont cottonwood and Goodding willow forest would experience increased mortality and declining recruitment and give way to invasive, non-native tamarisk if groundwater depths were to fall and persist beyond about 3 m below land surface within the riparian area [25,26]. Loss of surface flow to capture would likewise also result in the loss of wetland herbaceous plants such as rushes, sedges, and bulrush, dependent on continuously moist soils [26]. As the number and length of reaches with perennial surface flow decrease, the number and diversity of aquatic species would decrease as well [27].

Since the environmental consequences of falling groundwater elevations in near-stream locations would include the degradation of the current riparian and aquatic habitats along the San Pedro River [26] affecting species dependent on those habitats as well, *maintenance of groundwater elevations* was clearly a key criterion. However, in consideration of longer term time scales and larger spatial scales, the increase in *storage of the surrounding regional aquifer* was also considered a meaningful criterion for inclusion as well, given its connection and influence on the near-stream alluvial aquifer. *Surface water availability, water quality, and riparian health considerations* were also included as key criteria for environmental sustainability.

4.2.2. Social Criteria and Consequences

Typically, when the social consequences of sustainable groundwater development are discussed, it is in reference to a physical shortage of available and (or) uncontaminated groundwater supply for human use. In general, access to good quality potable groundwater supplies should be equally available to all residents; down-gradient users should have a water right equal to up-gradient users; and groundwater pumping should not damage the existing water rights to spring and surface waters [24].

For the San Pedro, not only was the physical *availability of water to meet human demands* one of the social criteria identified by the Upper San Pedro Partnership, but for them, the ability of the *local communities to influence and control their own destiny in water management decisions* was also a clear priority. The eventual establishment of a regional network of sites owned and operated by County and/or municipal governments for managed aquifer recharge purposes clearly met those criteria.

The recharge of treated wastewater effluent to sustain groundwater is a human health concern expressed by some along the San Pedro River, and *sustaining water quality* was identified as one of the social criteria for overall sustainability. Since 2003, the City of Sierra Vista has recharged approximately 3.1 million cubic meters per year (MCM/yr) of its treated wastewater with the aim of mitigating the effects of long-term groundwater pumping in the Sierra Vista Subwatershed. Water quality monitoring of spring discharge has been conducted near this recharge site and it was found that no constituent concentrations had exceeded any federal standards as of 2009 [28].

4.2.3. Economic Criteria and Consequences

In the United States desert southwest, most water users expect groundwater development to fulfill the water demands for agricultural irrigation, industrial uses, and residential development while maintaining an economically feasible depth to water with regard to pumping and well construction costs [29,30]. For the San Pedro, Fort Huachuca's water use is constrained by federal law, specifically the Endangered Species Act (ESA). Two federally listed endangered species, the Huachuca water umbel (*Lilaeopsis schaffneriana* var. *recurva*), a small semi-aquatic vascular plant that grows in moist soils along the San Pedro River, and the southwestern willow flycatcher (*Empidonax traillii extimus*), a songbird generally associated with permanent water, rely on the surface flow and riparian system of the San Pedro River corridor for habitat. Fort Huachuca and the U.S. Fish and Wildlife Service completed a Biological Opinion in March 2014 addressing these issues for the next 10 years [31]. From the perspective of sustainable groundwater yield, then, the use of groundwater for economic development (*i.e.*, to support the Fort's mission) is constrained by endangered species such as the Huachuca water umbel and southwest willow flycatcher, as reflected in the ESA.

This tension between regulatory mechanisms and economic drivers reverses the normal relationship between water use and economic need. In this case, Fort Huachuca must minimize its water use in order not to cause unacceptable adverse economic impacts to the Subwatershed. Therefore the set of environmental criteria—specifically hydrological—as listed in Table 1 are also direct measures of the reduction of social and economic risks. Thus, the issue of balancing sustainable groundwater use in the Sierra Vista Subwatershed revolves around the environmental needs of the San Pedro Riparian National Conservation Area's aquatic and riparian communities, which are inextricably linked to local economies and the federal military installation that acts as an economic engine across all of southern Arizona.

4.3. Define What Specifically Needs to Change through Strategies and Desired Outcomes

It became clear to San Pedro decision-makers and stakeholders through the process of developing the numerical groundwater model with the USGS, development of a spatially explicit Decision Support System (DSS) model based in the USGS groundwater model, and later working with consulting hydrologists who ran various simulations [22,32,33], that balancing human demands with flows in the river required not only the quantification of current withdrawal rates, but the management of impacts expressing themselves today due to water uses of the past century. In addition, predictive simulations of anticipated changes in groundwater trends over the coming century was essential to inform the decisions we make about current groundwater management. This was a much more complex and multi-dimensional view of the problem and its possible solutions, both spatially and temporally, than simply attempting to balance the current year's groundwater budget deficit. And yet, understanding these complex relationships actually clarified and simplified the necessary strategies and outcomes by setting more realistic expectations about what could be realized in the short-term, as opposed to longer timeframes. For example, a balanced groundwater budget within the Subwatershed might not be accomplishable within the time frames of years to decades, nor would it necessarily ensure that flows would be protected. However, over longer timeframes of centuries a balanced budget will be essential, and there are actions we can begin today that will contribute toward these longer term goals.

Once the regional groundwater model was developed, specialized applications of it were also possible, including development of a regional groundwater capture map (Figure 4) to provide a comprehensive spatial view of pumping and recharge impacts or benefits at any location in the subwatershed [34]. This more-intuitive representation of the system's physical dynamics resonated with decision makers and the public alike, and began to clearly highlight that near-stream locations had higher importance than locations closer to the regional cone of depression in terms of anticipated depletions of the river from pumping.

This understanding helped stakeholders move toward near-stream solutions that could most effectively benefit flows. While not eliminating the need to balance the overall groundwater budget throughout the subwatershed over longer time frames, strategies to sustain and enhance river flows in the short-term needed to center around near-stream locations to have the most impact. Once partners began to focus on the concept of an optimized suite of sites for both aquifer protection and recharge along the river corridor, the model was used to assess sites that could protect the most vulnerable sections of the river. This information was used to identify specific parcels of land that were feasible for acquisition. Some of those were later acquired, and subsequent groundwater modeling efforts used higher-resolution, local-area models to assess specific site and reach recharge characteristics and to simulate more specific recharge scenarios [22].

4.4. Implement Specific Projects and Policies

Member agencies of the Partnership have been implementing a wide array of projects and policies targeted at their collective goal of "the identification, prioritization, and implementation of policies and projects related to groundwater conservation and (or) enhancement" for approximately 15 years. The establishment of a dedicated fiscal agent (the City of Sierra Vista) and ongoing collaborative budget approval processes gave partners an effective way to pool resources and apply funding swiftly to key science and monitoring needs as they developed. These projects included water conservation outreach programs, residential water audits, water fixture rebate programs, construction of stormwater detention basins, and effluent reuse and recharge facilities.

However, as more predictive model simulations were run, an increased focus developed on projects that had the most immediate benefits for flows in the river: those that increased near-stream aquifer recharge. This included land acquisition and conservation easements specifically aimed at the permanent retirement of high-volume pumping over the last two decades. However, given a better understanding of the temporal and spatial dynamics of the groundwater system, Cochise County, The Nature Conservancy and Fort Huachuca recently added a new strategy to near-stream groundwater protection efforts. The addition of multiple aquifer recharge locations became a priority to complement the existing City of Sierra Vista effluent recharge facility that went into operation in 2002. The Nature Conservancy identified available land in areas believed to be the most productive for near-stream recharge, based on the groundwater capture map (Figure 4), wet-dry mapping of surface flows (described below) and other tools [22]. Thanks to funding for land acquisition made available from the U.S. Department of Defense Army Compatible Use Buffer Program, and in combination with drastically-reduced property values due to depressed market conditions in the past several years, the opportunity to acquire land previously slated for development arose at near-stream locations. Between 2011 and 2014, The Nature Conservancy purchased 2056 hectares and Cochise County purchased another 194 hectares of hydrologically sensitive land (Figures 4–6). This network of four properties, totaling over 2250 hectares, and spread along 34 km of the river, far exceeds the amount of land originally envisioned as attainable for managed aquifer recharge purposes.

Figure 4. Groundwater capture mapping shows where managed aquifer recharge offers the greatest benefits for the riparian system within a 50-year timeframe. Dots indicate existing recharge projects. Historically most were constructed as detention basins for downstream flood control with secondary recharge benefits to the larger regional aquifer (over the warmer colors), and more recently to more directly benefit flows in near-stream locations (over the cooler colors). Outlined and numbered near-stream recharge sites are locations where aquifer recharge projects are currently under construction or being investigated as future project locations. Redrawn from [34].

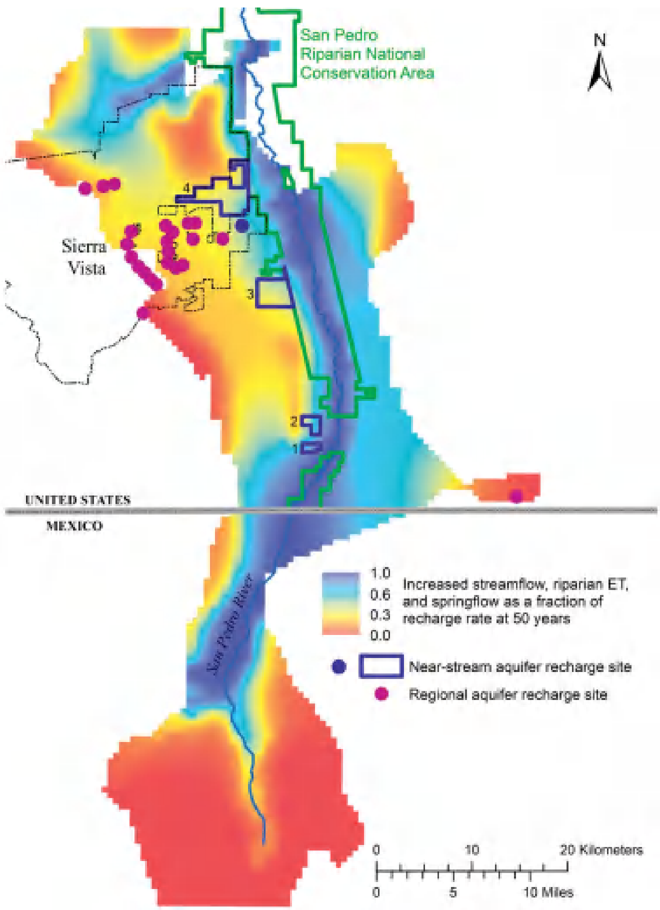


Figure 5. One of a series of in-channel infiltration basins recently constructed at Recharge Site #1 near the San Pedro River where on-site monitoring (e.g., soil-moisture probes, pressure transducers) will be used to quantify the relative performance of the individual structures, within this constructed channel that receives surface run-off from upstream residential areas.

Figure 6. The in-channel basins under construction include infiltration trenches and drywells at Recharge Site #1, within the constructed channel. The channel is perpendicular to the river, and the river's riparian corridor is visible in the background.

After the acquisition of this recharge network, the collaborating partners are conducting site assessments that include hydrogeologic sampling, more-detailed stormwater modeling simulations, and potential source water locations. Ongoing planning by the County and local municipalities will now have additional options for managing both stormwater and effluent, at the places with the most regional benefit for river flows.

4.5. Monitor Progress toward Desired Outcomes

The member agencies of the Upper San Pedro Partnership remain committed to securing continued funding for a broad suite of monitoring activities to evaluate the response of the regional groundwater system to their ongoing project and policy development. The USGS and USDA Agricultural Research Service monitor regional and alluvial aquifer water levels, main-stem, tributary, and low-flow mountain stream gaging, storage change monitoring using micro-gravity methods, and streamflow permanence. The Nature Conservancy, in cooperation with the U.S. Bureau of Land Management, also leads an annual monitoring effort using GPS mapping of surface flows, a technique called wet/dry mapping, to determine the absence or presence of surface flows during the driest time of year (mid June in the San Pedro Basin). This 16-year dataset is used to track year-to-year variability of the length of surface flows, and used to infer changes in alluvial groundwater conditions that may provide early warning of ecological changes [22]. The USGS also continues to monitor water quality at the Charleston gaging station on the San Pedro River as part of the National Water-Quality Assessment program.

The Partnership has recently committed significant funding to a comprehensive, multiple-year analysis of progress toward sustainable groundwater use in the Subwatershed. While that analysis is not yet complete, their previous annual reports to Congress included a suite of eight indicators to measure progress toward sustainable yield, as shown in Table 2. It is important to note how strongly this suite of indicators aligns with the previously defined environmental criteria for sustainability described in Table 1.

Table 2. A suite of eight indicators was used to describe progress toward sustainable yield in the Section 321 reports to Congress that were prepared by the USGS (e.g., [17]). They relate directly to the environmental criteria for sustainability developed by the Partnership.

	Indicators of Sustainable Yield
1.	Regional aquifer water levels
2.	Aquifer storage change measured with micro-gravity
3.	Annual groundwater budget balance
4.	Near-stream vertical gradients
5.	Near-stream alluvial aquifer water levels
6.	Streamflow permanence
7.	Base-flow discharge on San Pedro and Babocomari Rivers
8.	Springs discharge

5. Results and Conclusions

Based on the San Pedro experience, approaches such as the Partnership that directly engage affected policy makers, stakeholder organizations, regulatory agencies, and the scientific community can more effectively implement the necessary projects or policies, than if the partners were addressing the same challenge as individual interests. The involved partners more deeply understand the need for management measures, but are engaged in the actual exploration and development of possible alternatives, and witness the results and progress toward specific desired outcomes through adaptive management over time [35]. This was certainly the case for the Partnership as they first quantified the annual yield from a wide array of member agency water conservation, reuse, and recharge projects, then implemented dozens of them since 1998 [6] (Figure 2).

However, the Upper San Pedro Basin is unique in many ways. The presence of an important federal military installation and a federally protected riparian corridor within the Sierra Vista Subwatershed have brought a level of interest and involvement absent from many other basins with similar hydrogeologic conditions. The federal nexus in water issues has also resulted in significant funding to assess groundwater pumping impacts and to help mitigate those effects. Without Congressional funding for the Partnership and much of the federally-sponsored scientific research that supported development of the groundwater model, the state of the science would likely not have advanced to its current level.

Despite these unique socio-political aspects, the San Pedro Basin represents one of the best examples of riparian corridors remaining in the desert Southwest. The Gila River that drains more than 60% of the state no longer has any undammed perennially flowing segments, and is dry over most of its length. Many of the state's once-flowing, now-dry rivers reflect the impacts of long-term groundwater pumping in the mid to late 20th century. They provide a stark reminder of how directly connected groundwater and surface water resources are for our desert rivers.

5.1. Lessons Learned

Lesson 1: *Engage decision makers and key stakeholders early in the process to define the science and technical tools needed for an integrated water management approach.*

These needs should be tailored explicitly to the existing conceptual models of key stakeholders, and the gaps in understanding, disagreements and/or misperceptions that they hold. This approach strengthens the foundation for shaping meaningful criteria for success, the formation of effective strategies, and the definition of meaningful desired outcomes. The Upper San Pedro provides an example of a stakeholder-driven process where project implementation was driven by an evolving science-based understanding of the system, and additional financial resources and political support were generated over time in response to an enhanced understanding and appreciation of the challenges and opportunities. As stakeholders progressively learned more about the system, they were also in a better position to make the case for generating additional public and private funding to support their efforts.

Lesson 2: *Collaboratively define desired outcomes as specifically as possible both temporally and spatially.*

The process of defining "sustainable yield" for the San Pedro is still underway more than 11 years after Congress mandated its implementation in the Subwatershed. By some measures, such as per-capita water consumption rates and managed aquifer recharge, efforts to mitigate the effects of groundwater pumping have been very successful. However, developing the predictive models to more specifically understand the response of the physical system allowed decision makers to recognize that, while their previous efforts would aid in slowing overall aquifer storage depletion, they would not necessarily protect the river from pumping-induced capture in shorter time frames (years to decades). Later efforts to initiate near-stream recharge arose from a better understanding of both the spatial and temporal aspects of the system, and strengthened the recognition that both short-term and long-term actions and effects were important.

Lesson 3: *Stakeholders with varied interests are more likely to work successfully toward a common goal if they feel that their individual interests are represented, and can actually benefit from the process.*

Challenging economic and legal contexts should not prevent diverse parties from working toward a solution if they perceive that their interests are represented in, and perhaps even benefit from a shared vision with other interests. Even though some objectives may seem to be competing (e.g., preserving reasonable depths to groundwater for water supply wells AND preserving baseflows in the river), finding a common thread among the parties—such as preservation of a vital economic driver for the region—can lead diverse parties to define and accept a mutually beneficial outcome. Once stakeholders recognize what outcomes of a solution might look like (such as baseflow supported by near-stream recharge), they may better reach consensus about how to achieve that proposed solution. For the San Pedro, the acknowledgement of all three aspects of sustainability—economic, social and environmental—helped to build trust, agreement and eventually support among interests. In addition, it opened conversations to the consideration of more specific objectives aimed at both the short- and long-term. The parties acknowledged that preserving flow in the river was the most immediate short-term concern, while also recognizing the need for longer-term efforts to maintain supplies at municipal pumping centers.

Lesson 4: *The importance of effective communication and two-way learning between scientists and decision makers cannot be overstated.*

While scientists and subject experts may recognize specific physical trends and processes in respect to hydrologic systems, other stakeholders may not agree on the nature or even the existence of them. Conversely, water managers and decision makers function within an operating environment that includes many dynamic political, financial, and legal factors that are not clear to scientists. Developing a shared understanding of these challenges as they relate to key water management decisions may take years. How do we help decision makers with little or no technical knowledge of complex groundwater hydrology understand that the pumping of half a century ago will manifest as declines in baseflow over the next half century? Even more problematic is trying to convince them to invest in expensive solutions to a crisis that—if the solution works—will never materialize. Accepting these hydrologic "mysteries" that are taking place in an invisible underground system they will never see requires a considerable leap of faith.

The burden lies with both the scientific community and decision makers to invest the required time and effort communicating and learning about the environmental, social, and economic aspects of regional water management to be able to develop meaningful collaborative strategies together. The development of a set of specific criteria for meeting environmental, social, and economic needs as part of a shared vision of sustainable groundwater management is an essential first step toward the development of that understanding.

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The authors would like to recognize the support of the Upper San Pedro Partnership, and its respective 23 member agencies, over the past 15 years in developing the science and fostering the collaboration required for the progress that has been made toward groundwater sustainability in the Upper San Pedro Basin. The USGS has also made significant contributions toward not only the development of the groundwater model in the basin, but also toward the conceptual understanding of sustainable yield on a broader basis. Lacher Hydrological Consulting has played a pivotal role in running various groundwater model simulations. The Department of Defense Army Compatible Use Buffer (ACUB) Program provided significant funding for the acquisition of land for aquifer recharge sites, and the Walton Family Foundation generously provided private funding for the subsequent design and engineering of initial aquifer recharge facilities. The authors thank David Goodrich and two anonymous reviewers for substantially improving this article.

Author Contributions

The text of this article was written by Holly E. Richter, Bruce Gungle, Laurel J. Lacher, Dale S. Turner and Brooke M. Bushman. Holly E. Richter and Bruce Gungle wrote the bulk of the history of the partnership and development of the shared vision content. Laurel Lacher helped formulate the basic concept of the paper, provided input on the concept of sustainable groundwater use, and assisted with organizing the paper's structure. Dale S. Turner conducted background research on the technical tools, helped hone the sustainable yield concepts, provided content review, and also served as our primary internal editor. Brooke Bushman added current project implementation content, developed several figures and maps, and also provided content review.

Conflicts of Interest

The authors declare no conflict of interest.

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The Role of Transdisciplinary Approach and Community Participation in Village Scale Groundwater Management: Insights from Gujarat and Rajasthan, India

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Abstract: Sustainable use of groundwater is becoming critical in India and requires effective participation from local communities along with technical, social, economic, policy and political inputs. Access to groundwater for farming communities is also an emotional and complex issue as their livelihood and survival depends on it. In this article, we report on transdisciplinary approaches to understanding the issues, challenges and options for improving sustainability of groundwater use in States of Gujarat and Rajasthan, India. In this project, called Managed Aquifer Recharge through Village level Intervention (MARVI), the research is focused on developing a suitable participatory approach and methodology with associated tools that will assist in improving supply and demand management of groundwater. The study was conducted in the Meghraj watershed in Aravalli district, Gujarat, and the Dharta watershed in Udaipur district, Rajasthan, India. The study involved the collection of hydrologic, agronomic and socio-economic data and engagement of local village and school communities through their role in groundwater monitoring, field trials, photovoice activities and education campaigns. The study revealed that availability of relevant and reliable data related to the various aspects of groundwater and developing trust and support between local communities, NGOs and government agencies are the key to moving towards a dialogue to decide on what to do to achieve sustainable use of groundwater. The analysis of long-term water table data indicated considerable fluctuation in groundwater levels from year to year or a net lowering of the water table, but the levels tend to recover during wet years. This provides hope that by improving management of recharge structures and groundwater pumping, we can assist in stabilizing the local water table. Our interventions through *Bhujal Jankaar*s (BJs), (a Hindi word meaning “groundwater informed” volunteers), schools, photovoice workshops and newsletters have resulted in dialogue within the communities about the seriousness of the groundwater issue and ways to explore options for situation improvement. The BJs are now trained to understand how local recharge and discharge patterns are influenced by local rainfall patterns and pumping patterns and they are now becoming local champions of groundwater and an important link between farmers and project team. This study has further strengthened the belief that traditional research approaches to improve the groundwater situation are unlikely to be suitable for complex groundwater issues in the study areas. The experience from the study indicates that a transdisciplinary approach is likely to be more effective in enabling farmers, other village community members and NGOs to work together with researchers and government agencies to understand the groundwater situation and design

interventions that are holistic and have wider ownership. Also, such an approach is expected to deliver longer-term sustainability of groundwater at a regional level.

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1. Introduction

India is the largest user of groundwater in the world with an estimated usage of 230 km^3 per year [1]. Globally, areas under groundwater irrigation are the highest in India (39 million ha), followed by China (19 million ha) and the USA (17 million ha), and at present 204 km^3 y^{-1} of groundwater is pumped annually in India [2]. Several reasons may be attributed to this phenomenon. Access to groundwater increased since the 1970s, when diesel and electric pumps became affordable to most small landholders. The causes of increased groundwater use are also rooted in population growth and economic expansion, and as result the annual groundwater use now probably exceeds the annual rainfall recharge. The notion of groundwater as a private resource, the rights of which are associated with land rights, has led to an exploitative extraction regime [3].

Farmers in semi-arid parts of India use groundwater to save rainfed crops from failure and to increase yields. As it is a relatively cheap and easily accessible water resource for individual farmers, irrespective of their farm size, groundwater is often extracted beyond its natural recharging capacity. With increased use of groundwater, the depth to the water table in many parts are fluctuating considerably during the year and the use of groundwater has risen to a level that groundwater from shallow aquifers is not adequate to meet the rising demand. Hence, groundwater from deeper aquifers is being pumped by the drilling of tube wells. There are also instances where fresh groundwater at shallow depths has been depleted, rendering marginal quality water from deeper layers of the aquifer [4]. The extensive use of groundwater resources by farmers all over the country pumping out water in an unregulated manner creates its own sets of complex management and sustainability issues.

The use of groundwater in agriculture is important in India, as it has enabled farmers to manage deficiencies in monsoonal rainfall, allowed dry-season irrigation, thus contributing to poverty alleviation. For this reason, a range of on-ground works to recharge groundwater are being implemented at the village scale throughout India as a part of the Government of India's "Mahatma Gandhi National Rural Employment Guarantee Act" (MNREGA) to enhance livelihood opportunities while developing a durable asset base. A significant part of the investment through MNREGA is for enhancing long-term, local water security by on-ground structures such as check dams, percolation tanks, surface spreading basins, pits and recharge shafts [5]. The development of on-ground structures to enhance groundwater recharge in India is called "watershed development". It is a long running program of Government of India and has significant hydrologic consequences, in particular, altering the runoff regime in downstream regions and groundwater recharge at local and regional scales.

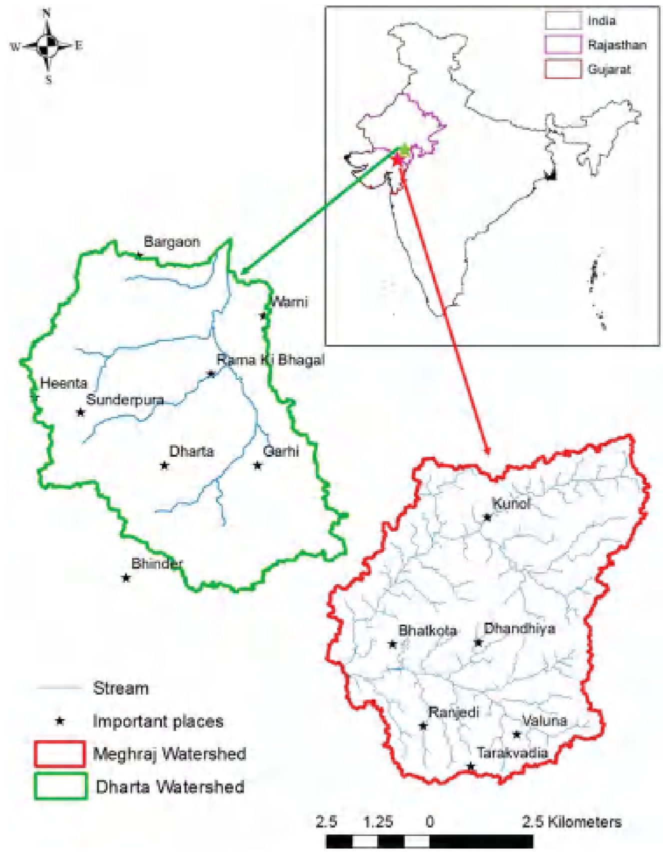
In spite of all the efforts in the past to improve the sustainability groundwater in India, the problem of groundwater management is still severe, particularly in Rajasthan and Gujarat. In this project, called **M**anaged **A**quifer **R**echarge through **V**illage level **I**ntervention (**MARVI**), the research is focused on developing a suitable participatory approach and methodology with associated tools that will assist in improving supply and demand management of groundwater. Another important aspect of the project is education of and engagement with village communities, local NGO and government agencies to facilitate them working together to achieve sustainable groundwater management.

In this article, we report on some key findings from the MARVI project with two main objectives: (i) to show how basic hydrologic information collected by farmers and supplemented with hydrologic, agronomic and socio-economic data collected by the project team is leading to an assessment and understanding of the groundwater storage changes; and (ii) to reveal how this information and engagement activities can be used to empower village communities and other stakeholders to develop and assess their own viable options for groundwater management, including managed aquifer recharge and measures to reduce water demand while sustaining livelihoods.

2. The Study Watersheds

The work reported here was conducted in the Meghraj watershed in Aravalli district, Gujarat, and the Dharta watershed in Udaipur district, Rajasthan, India (Figure 1). Both watersheds have a semi-arid climate, with the average annual rainfall in excess of 600 mm, but more than 90% of this rainfall is received during the monsoon months of June to September. Most farmers in the two watersheds grow maize, black gram, mungbean, guar, soybeans (recently introduced) and vegetables as *Kharif* crops during the rainy season. Wheat, gram and mustard are the main *Rabi* crops grown during the winter season. Farmers who have access to groundwater (and in some instances canal water) grow two crops a year and those who have access to water supplies throughout the year also grow some summer crops such as vegetables and fodder.

Figure 1. The Meghraj and Dharta watersheds. The inset map shows the location of the watersheds in the states of Gujarat and Rajasthan in India.



The occurrence and distribution of rainfall in both the Meghraj and Dharta watersheds are highly uneven in both time and space. *Kharif* crops are mainly dependent on the vagaries of the monsoon and are often at risk of either complete or partial crop failure due to inadequate rainfall, or rainfall not occurring at a critical stage of crop growth. Therefore, the uneven and erratic distribution of rainfall provides a major challenge to growing crops successfully and to sustaining a decent livelihood. When rainfall does not occur at the right time or in the required amount, some supplementary irrigation, also called "life saving irrigation", using rainwater stored on the surface or drawn from the underground aquifer systems can make a huge difference in avoiding crop failure.

A number of *in situ* conservation measures, including farm ponds, percolation ponds and check dams have been constructed in the two watersheds under both the Integrated Watershed Management (IWM) programs and MNREGA. The State Governments of Gujarat and Rajasthan, along with the Central Government have invested significant amounts in these two watersheds in the past, and continue to do so by constructing more of these structures. However, it is not clear how effective these programs are, and what impacts these investments are having on groundwater security. Figures 2 and 3 show the MAR structures in the Meghraj and Dharta watersheds.

Figure 2. Location of MARs in Meghraj.

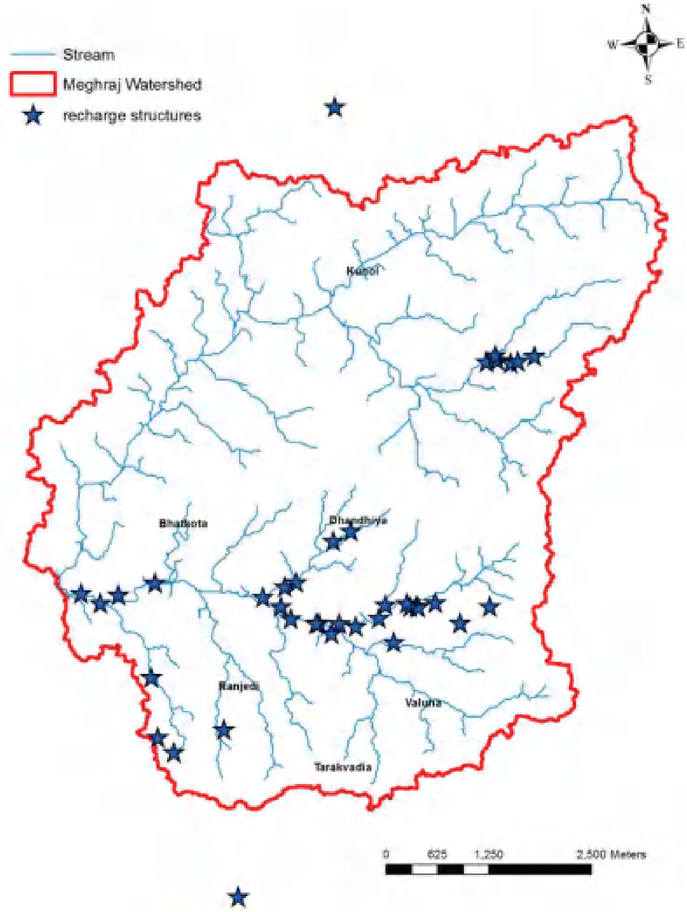
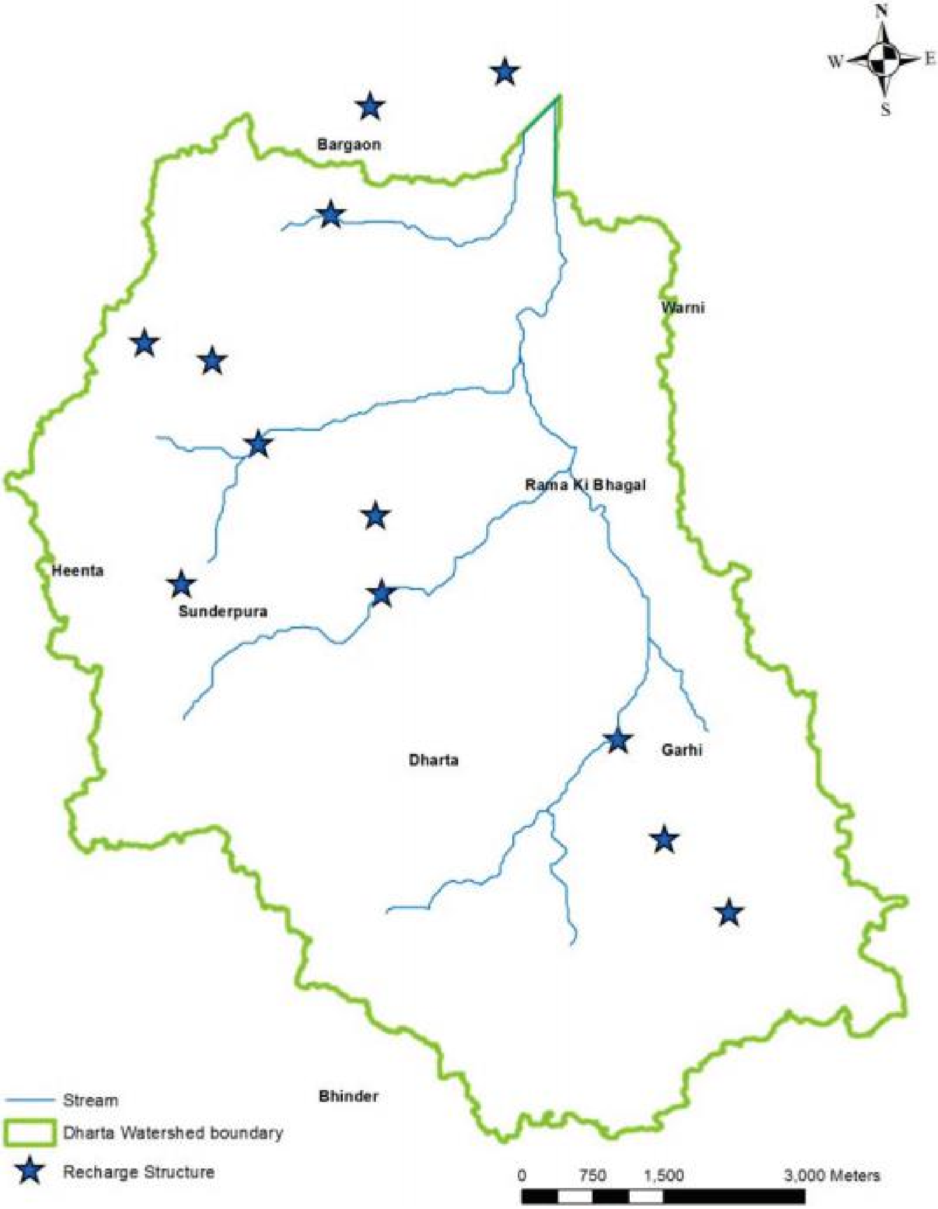


Figure 3. Location of MARs in the Dharta watershed.



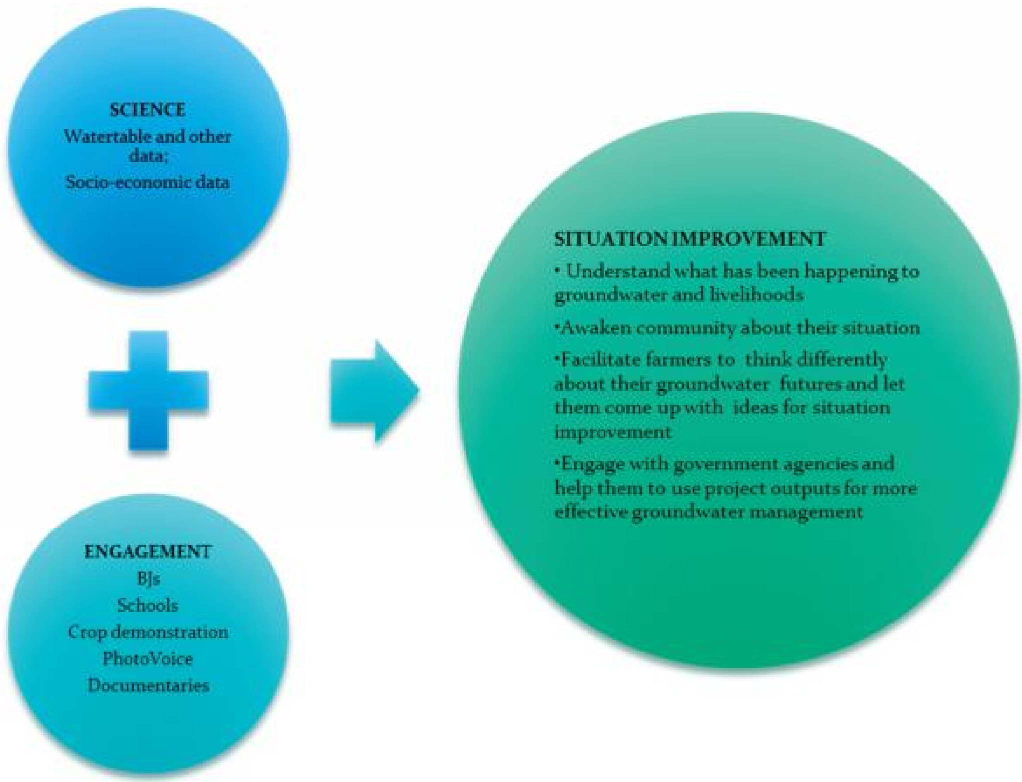
It is important to note that both watersheds are in hard rock aquifer areas. It well known that hard rock aquifers have low porosity and low connectivity and the movement of groundwater occurs through faults, fissures and fractures. Hence they store limited volumes, and when stored water is withdrawn by pumps, the emptied pores are not immediately filled by flows from adjacent areas. As result of low rain-recharge, and low porosity and low connectivity, the depth to water table fluctuates considerably during the year and significant water scarcity is often experienced during summer months or drier years.

Most farmers in the Meghraj watershed belong to a tribal community, while those in the Dharta watershed are from mainstream groups. The farming practices in the two watersheds have not advanced adequately to cope with declining water supplies. For this reason, the physical and socio-economic conditions in the two watersheds provide a diversity of transdisciplinary research opportunities and engagement issues around groundwater recharge and management.

3. Study Approach

The study approach in the MARVI project is underpinned by transdisciplinary research with a main focus at the "village scale" to understand the complex interrelations between rainfall, aquifer recharge, groundwater pumping and livelihood opportunities. We define transdisciplinary research as one in which both researchers from different unrelated disciplines and non-academic participants, such as farmers and other villagers, work together for a common goal and create new knowledge and theory to improve a complex situation. Thus, in this project we recognized the importance of involving local villagers and other stakeholders through this approach during the research process and engaged them in participatory groundwater monitoring and education to explore options for groundwater sustainability. Figure 4 illustrates the application of relevant social and natural sciences research and engagement to improve the field situation.

Figure 4. Study approach in MARVI project.



With an active engagement of local villagers, the project team collected a range of hydrologic, agronomic, economic, social and cultural data at selected clusters of villages over a two-year period. The engagement of villagers and data collected are then employed to understand the current situation and develop bio-physical and socio-economic insights to evaluate the current issues, identify options and strategies, provides a scientific and evidence-based input to enhance watershed development policies.

4. Field Research and Data Analysis

4.1. Participatory Groundwater Monitoring

A desired outcome of the MARVI project would be collective action at village level that is mutually beneficial to all the villagers, and from which other communities could learn. To achieve this, [6] have shown the need to develop Social Capital. This project used participatory approaches to help to develop social capital competences, with training programs aimed at supporting cognitive aspects of this social capital competence. In addition, the project used participatory monitoring for some data collection to also support this development.

Participatory monitoring of the water table was achieved through the engagement of villagers in the two watersheds. A total of nine local villagers, called *Bhujal Jankaars* (BJs)-a Hindi word meaning "Groundwater Informed" volunteers—were recruited in the Meghraj watershed and similarly 25 BJs were selected in the Dharta watershed. The main idea of recruiting BJs into this project was to give local villagers ownership in the project, build their capacity so that they can understand their groundwater issues and eventually help them to become champions of their community for improving the groundwater situation. The BJs were trained in a number of relevant aspects, such as mapping, water table and water quality measurements. They were also exposed to basic hydro-geologic concepts influencing groundwater availability for agricultural use.

The BJs were involved in weekly monitoring of the water table in open wells, 110 wells in the Meghraj watershed and 250 in the Dharta watershed. Prior to the monitoring of wells, all BJ's did a baseline survey with the help of the project team to compile the required information about village wells. The BJs monitored the groundwater changes through the measurement of water level depth from the ground surface on weekly basis and pH and EC on monthly basis. To assist in the reliability of the data collected by BJs, the project staff each week randomly measured the water level depth data in some of the wells using the same method as those of the BJ and crosschecked water level depths with those measured by BJs. This ensured that BJs were collecting the data properly.

4.2. Hydrologic Measurements

Two automatic weather stations, one in each watershed, were installed to collect local weather information for water balance modeling and evaluating the effectiveness of recharge structures on groundwater levels. In addition, six automatic rain gauges were installed in local schools in the Meghraj watershed and five in the Dharta watershed. The purpose of engaging schools in rainfall measurements was to make the school children aware of the water availability in the area and its importance. Some villagers, acting as BJs in the two watersheds, were also given manual rain gauges to monitor rainfall.

A total of five groundwater depth sensors were installed in the Dharta watershed and three in the Meghraj watershed for monitoring water table depth at 15 min intervals. The measurement of water table depth at such a short interval is helpful to analyze rapid changes in water table depth following a pumping event or significant rainfall occurrence. Four water meters in each watershed were installed to measure pumped volume and water productivity for specific crops. Groundwater and soil samples were collected in the watersheds at different times during the study to examine whether they impose limitations for crop production and consequently on the livelihood of people.

The Central Ground Water Board (CGWB), an Indian Government organization, maintains and monitors observation wells across the country. In Gujarat and Rajasthan, CGWB monitors 1197 and 1111 wells, respectively [7]. The data is collected four times, Post-Monsoon (*Rabi*), Pre-Monsoon, Monsoon and Post-Monsoon (*Kharif*), which correspond to January, May, August and November respectively. For the current study, we chose two wells that fall in our study watershed areas. The data was collected from the WRIS website [8] which is maintained by the Indian Space Research Organisation (ISRO) and Central Water Commission (CWC).

4.3. Socio-Economic Survey

Households in the two watersheds that contributed to this study were identified through the first survey step—participatory community assessments. With the help of community leaders and extension workers, a total of 500 households from eleven villages from the Meghraj watershed were randomly selected and interviewed, representing 21%–24% of total village households. Similarly, a total of 300 households were interviewed from five villages in the Dharta watershed, representing 24%–29% of the total village households. Interviewees were either household heads or members who make decisions on behalf of household members.

Social and economic data were collected using a pre-tested questionnaire. Four major aspects were considered: (i) Household's livelihood assets—human, natural, physical, financial and social assets [9]; (ii) household livelihood activities and strategies; (iii) household's perceptions of livelihood determinants, potential future changes, and adaptive intentions; and (iv) farming inputs and outputs. A pilot survey in both watersheds was carried out to finalize the questionnaire before full-scale surveys were conducted.

A separate survey was also conducted to answer research question about women's responsibilities regarding water and gendered perceptions of water use, availability and quality and who collects water. Five villages from Gujarat and Rajasthan were chosen and an average of 10 women, three men and three members of community associations were interviewed from each village. A random sampling method was used. Both surveys mentioned here were translated in Hindi and Gujarati and field investigators underwent a three-day training session conducted by the MARVI research team.

Cluster Analysis was used to identify relatively homogeneous groups of households/farmers based on selected groundwater use characteristics. Because the goal of this cluster analysis is to identify a typology of similar groups of groundwater users, the agglomerative hierarchical clustering method was used in this study.

4.4. Engagement with Schools and Local Communities

Engagement of village communities through a range of activities that involved farmers, school communities and other members of village communities was an important part of the transdisciplinary approach used in this project. Field demonstrations on farmers' fields in the middle and end of the crop seasons were conducted on aspects, such as water requirements and water conservation practices, such as mulching and crop varieties that may be more drought tolerant or may result in improved income for a given water use. School children and teachers were engaged to record daily rainfall. Total weekly, monthly and seasonal values of rainfall were displayed on school noticeboards by students to create awareness about rainfall patterns and amounts and general awareness about water issues in their local areas.

Photovoice workshops were organized in villages and schools in both watersheds. Students and farmers were trained in photography and interestingly, most of them had never touched a camera in their lives. The idea of using a camera to express their ideas was something new and exciting for them and they actively participated in these workshops. They captured photographs regarding their past, present and future thoughts about water resources and groundwater as one of the critical factors of livelihood in village communities.

A newsletter in Hindi, called "MARVI Manthan"—a Hindi word Manthan meaning "deep contemplation"—was launched to share the project findings with village communities. This newsletter is published twice a year to coincide with the beginning of *Rabi* and *Kharif* seasons. The target audiences of this newsletter are farmers, the general community and other stakeholders, and the main purpose of the newsletter is to connect with local communities and pursue a dialogue with farmers for participatory use and management of local groundwater resources.

5. Results

5.1. Understanding the Local Groundwater Situation

The water table fluctuation for the Dharta and Meghraj watersheds, based on the monitoring of the Central Ground Water Board of India, are shown in Figures 5 and 6 respectively. The water table depth trends for the Dharta watershed indicate a depleting of groundwater from January 1994 to November 2000, after which the groundwater level seems to stabilize over the next 14 year period. From the twenty-year analysis, the net rate of groundwater depletion is of the order of 0.18 m per year. However, from the 2005 to 2013 period, the groundwater levels are increasing at the rate of 0.36 m per year. Over the 20-year period, the largest water table fluctuation, *i.e.*, the maximum difference between the lowest and highest groundwater level, was estimated to be 24 m. For the Meghraj watershed, the 18-year time series of groundwater levels show some large fluctuations in the water table but overall the net depletion in groundwater over 18 years seems to be negligible (Figure 6). The largest water table fluctuation for the Meghraj watershed was 8 m for the monitoring period considered.

Figure 5. Central Ground Water Board groundwater head trends for the Dharta watershed from January 1994 to November 2013.

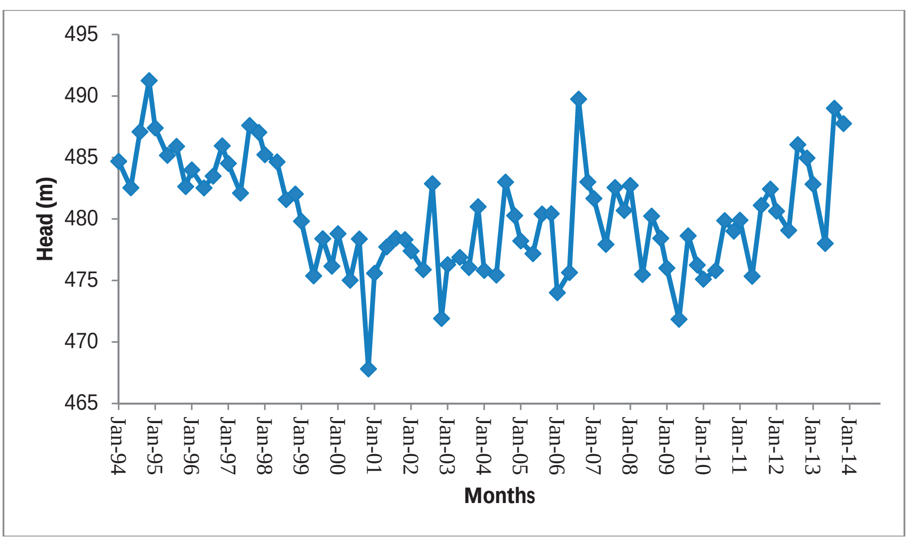
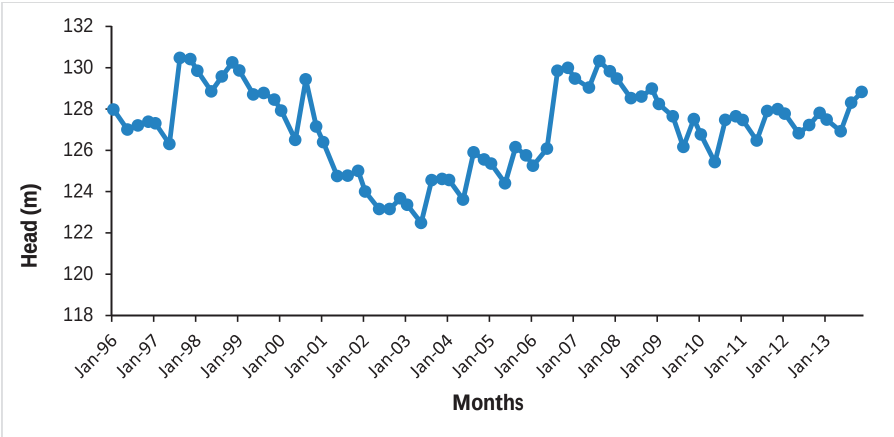


Figure 6. Central Ground Water Board groundwater head trends for the Meghraj watershed from January 2005 to November 2013.



5.2. Bhujal Jankaars

While the BJs were monitoring the water table on a weekly basis, they have also helped to develop good linkages between this project and local communities, creating awareness about the groundwater issues in the two watersheds. The evaluation of the BJ approach so far indicated that BJs interact extensively with their communities as they do their measurement tasks on a weekly basis. They are sharing project outputs that are written in the local language and tailored to the needs of village communities, particularly sharing some observed water table data to indicate the state of groundwater fluctuations in the area.

Discussion with village communities indicates that BJs are now becoming an integral part of the engagement process and data collection activities in the project in both watersheds. There is now an increasing acceptance of BJs in village communities in regards to the source of information about the local rainfall, extent of water table fluctuations and groundwater quality. They have also become an important link between the project team and the village communities for mobilizing farmers for project meetings, field demonstrations and dissemination of research findings from the project.

5.3. Engaging with Local Community

The engagement activities with the farming community through water table monitoring, crop demonstration, work with local schools and targeted workshops have helped to create community awareness about the local groundwater situation and develop a suitable atmosphere for future meaningful dialogue with the community on local groundwater management issues and challenges. Competencies are being built to enhance the social capital of the area, with the aim of facilitating mutually beneficial collective action. The workshops with villagers have indicated that farming and village communities were all deeply concerned about groundwater quality and the rapidly declining groundwater supplies. The community is willing to explore options that will help in improved water availability for irrigation and drinking purposes but are currently more focused on water availability in their individual wells and not appreciating that groundwater needs to be managed at the village and watershed levels and beyond.

The school engagement activities in the project included a poster and painting competition on a range of topics such as drip irrigation, water harvesting, soil testing and climate change. It was observed that the engagement of school children in the project extended the groundwater dialogue with parents and may also result in longer-term benefits. Another important engagement activity was photovoice workshops that involved school communities and villagers and resulted in several hundred photos and the subsequent selection of over 50 photos with text from the participants. Photovoice is essentially a participatory process of collecting information and expressing issues and concerns through photographs, and it can be used to effectively engage different groups and communities in a research project. It can particularly help individuals and communities groups to record and reflect on their ideas and concerns, help them promote critical dialogue and exchange of knowledge about important issues at different levels and reach policymakers for improving situations. Photovoice in this study helped to significantly engage teachers, students and villagers and facilitated them to think about their current groundwater situation and some options they may like to pursue to improve the situation. In particular, through a participatory photography process, the activity helped to explore some basic questions regarding what water means to villagers in the two watersheds. The analysis of photographs and text provided by the participants indicated that women and youth tend to emphasize future and personal responsibility while older male participants focused more on current problems. Unsurprising, the photovoice data indicated that participants saw the lack of water as the overarching problem, alongside specific human behavior and infrastructure problems.

In general, engagement and awareness campaigns aimed at educating the beneficiaries on a potential policy may be more effective, rather than using uninformed preferences based on expert opinion to drive policy decisions for complex natural resources management issues and challenges [10] (Rogers, 2013). In this project, the engagement with the local community and stakeholders has been an important element of transdisciplinary research on complex issue such as groundwater sustainability and will particularly assist in an effective dialogue with village communities, government agencies, including policy makers at the state and national levels, for participatory management of groundwater.

5.4. Socio-Economic Dimension of Groundwater Management

A series of 11 questions in the livelihood survey elicited household attitudes and perceptions concerning the role of MAR, adequacy of groundwater to meet future needs, the influence of extraction of, and on, proximate wells, mechanisms to coordinate aquifer resources, who should pay or be compensated for aquifer remediation and willingness to adjust extraction for future needs.

In this study, it was assumed that the cluster analysis can be used to identify relatively homogeneous groups of households/farmers based on selected groundwater use characteristics. There are numerous ways in which clusters can be formed and the hierarchical clustering is one of the most straightforward methods to use. Hierarchical clustering can be either agglomerative or divisive. Agglomerative hierarchical clustering begins with every case being a cluster unto itself. At successive steps, similar clusters are merged. The algorithm ends with everybody in one huge, but useless, cluster. A divisive clustering starts with one large cluster with all objects in it and gradually broken into smaller sized clusters and ends up with clusters with one object (singleton cluster). Because the goal of this cluster analysis is to form similar groups of groundwater users, the agglomerative hierarchical clustering method is used in this study.

The cluster analysis of the factor scores in this study revealed a four-cluster solution (Table 1). Cluster composition and membership was predicted by eleven groundwater questions specified as x-axis variables. The composition and relative values of the four groundwater management clusters mainly differentiated attitudes regarding the effectiveness of MAR, the willingness to reduce extraction for their children's future use, the role of markets in groundwater management and relative impacts of proximate wells. The four clusters were defined:

- Cluster A-future and market oriented, with a preference for MAR;
- Cluster B-future, non-market oriented with a focus on water use efficiency;
- Cluster C-present non-market orientation; and
- Cluster D-present market orientation.

The present, markets groundwater management (Cluster D) is characterized by a low likelihood of children taking over the farm in the future, does not believe that increasing the depth of the well will have an impact on neighbors, does not consider that MAR is the best way to maintain the well, does not deem that efficient water use is the best way to maintain the well but expects that a MAR scheme operated by a neighbor and self should be compensated. In contrast, the future, markets, MAR groundwater management (Cluster A) is typified by a high likelihood of children taking over the farm, the belief that increasing the depth of the well had an impact on neighbors, judge MAR as the best way to maintain groundwater resources, and believe that a neighbor's groundwater use reduced water in their own well.

Table 1. Response to different questions for different clusters.

Groundwater Attitudinal Questions (Yes/No Response)	Cluster (Proportion Yes Response)			
	GW A	**GW B**	**GW C**	**GW D**
How likely is it that your children will take over your farm in the future?	0.76	0.82	0.58	0.46
Do you think that increasing the depth of your well has had an impact on your neighbours?	0.78	0.51	0.08	0.00
Will the current depth of well/ tubewell be sufficient in the next 5 years for your current cropping pattern?	0.21	0.13	0.11	0.25
Is MAR the best way to maintain your well?	0.76	0.30	0.37	0.01
Is efficient water use the best way to maintain your well?	0.86	0.91	0.50	0.16
Has your neighbour's groundwater use reduced the amount of water in your well?	0.89	0.93	0.04	0.15
Would you be willing to share the water and costs of a recharge scheme with other farmers close to you?	0.96	0.73	0.32	0.86
Would you be willing to reduce the number of watering if it meant that water would be assured for your children?	0.92	0.88	0.44	0.30
If your managed recharge scheme increases the water available for your neighbours, should they compensate you?	0.99	0.08	0.05	0.93

Table 1. *Cont.*

Groundwater Attitudinal Questions (Yes/No Response)	Cluster (Proportion Yes Response)			
	GW A	GW A	GW A	GW A
If your neighbours managed recharge scheme increases the water in your well, should you pay them?	0.99	0.11	0.07	0.96
Would you be willing to adopt a new groundwater management scheme that shared water and costs fairly amongst all irrigators in your village?	1.00	0.99	0.82	1.00

The relative proportions of groundwater management cluster membership of respondents located in the two watersheds vary. About 9% of respondents from Gujarat are assigned membership in Cluster D, and 34% in Cluster A. The Rajasthan respondents are characterized by high proportional membership in Cluster D (55%) and Cluster A (40%). The farmers in Cluster D derive their groundwater information from traditional knowledge (42%), family (20%) and neighbors (19%), while those in Clusters A and B acquire information from family, neighbors and television. However, the farmers in Cluster C only rely on traditional knowledge (26%) and family (22%). As to the level of trust, there is no significant difference among the four clusters.

The cluster analysis indicates that groundwater management perceptions and attitudes influence the willingness and capacity of well owners to adopt specific remediating technological solutions and their compliance with policy incentives. Differentiated perceptions and information sources revealed in the cluster membership and the distribution of clusters in the two watersheds suggests that a suite of targeted technologies and incentives, in contrast to a reliance on single technological solutions and policy instruments, is likely to achieve the highest adoption rates [11]. The analysis provides the basis for designing watershed specific policy instruments and technologies that align with statistically differentiated attitudes and perceptions revealed in the four clusters.

5.5. Groundwater and Gender

Though women are found to be significantly involved in irrigated agriculture in both the Dharta and Meghraj watersheds, the revenue generated from agriculture is entirely controlled by men. This clearly separated intra-household activities according to gender. These activities, however, are not separate from the water users' perspective, and this often impedes women's access to and control over this scarce resource. For instance, men usually have a greater say in water provision for irrigated agricultural production, which in turn influences agencies responsible for infrastructure and determines availability and security of water from the women's perspective. Even production from women's fields and household gardens is often controlled by men to a certain degree, as is the availability of water for non-agricultural tasks. This bias of water allocation and control is even greater in times of water scarcity.

Women were found to be responsible not only for domestic water use but also in the productive uses of water, such as vegetable growing and herding. The women interviewed are almost exclusively responsible for domestic chores and for maintaining hygiene in their households. Most of them commented that water scarcity has a direct impact on their access to water within the household as well as on the time they and their daughters and daughters-in-law have to spend in water collection. This means the time available for other activities in the household and livelihood opportunities becomes limited. In addition, mothers are concerned that their daughters are missing school because they have to help in water collection. A majority of them suggested boosting women representation in groundwater management.

The women interviewed are almost exclusively responsible for domestic chores and for maintaining hygiene in their households. Due to inadequate water being locally available for basic consumption in poorer households, women fetch water from nearby villages, where applicable, walking for more than 30 min and up to one hour per trip. The physical strain of collecting water is doubly compounded during the peak of summer, and women have to wait in long queues at water sources. This shows the precarious situation of women in households and also indicates how women are compelled to shoulder additional burdens for the welfare of their families.

Overall, the analysis of gender related issues of water indicate that for achieving broad livelihood improvement outcomes the needs of water from women's perspective cannot be ignored. Furthermore, the gender aspect of groundwater needs to be considered along with securing sustaining groundwater for crop production.

6. Discussion

6.1. Capacity Building of BJs as Local Champions

The training program of eight modules spread over about six months was aimed to orient the BJs regarding the MARVI project and to build their understanding about geology, hydrology, watershed management and mapping. While it was comparatively easy to develop an understanding of the depletion of surface water resources, the measures used for water harvesting and groundwater issues are quite complex to comprehend, both for the village communities as well as the project research partner field staff. However, in presenting these module inputs it was realized that, despite the difficulties, it was possible to demystify the technical aspects of groundwater management in a language that villagers could understand. It was also recognized that capacity building for the BJs has to be a gradual and continuous process, and one which blends theoretical inputs with practical exercises in their own villages in order to help them grasp these complex issues. Convincing people to work on an action research project that does not give them direct benefits requires a lot of effort. In addition, it was observed that groundwater management is a new concept that is not easily understood by rural communities. Retaining the BJs in the midst of other work opportunities available in and near the villages at a high remuneration was also an issue.

Besides well monitoring, the BJ's were also linked into other key project activities, viz.; village level meetings, field days during and after crop demonstrations and seed and fertilizer distribution. The BJs shared their experiences in a monthly meeting with project community organizers and prepared the plans and strategies for further activities. The BJs also interacted with other village members individually or through various village institutions like farmers' club, *Sujal Samiti* (water co-operative), *Gramsabha* (village council) and the like. In this way, the BJs were working as a communication bridge between the MARVI project team and villagers.

An interesting aspect of BJ involvement in this project was that the information collected by BJs made people in the villages curious about the MARVI project activities and triggered further communication. The location of monitoring wells also helped in spreading information as the wells were widely dispersed and every well owner asked why was the BJ taking readings and what will come out of it? These questions assisted in starting communication with the farmers about the current issues of groundwater scarcity. Some of the BJs became quite capable in preparing charts for displaying current rainfall and well water depth and hung these outside their house so that more people could see the results. Thus, as result of the BJ's involvement in the project most people in the villages came to know that this is a research project, not another project that focus on on-ground construction works, and that the research data which are being collected will be helpful for them in the future.

Given the skills that the BJs have acquired through their training, and subsequent practical experiences, they will be able to continue to contribute towards various development projects being implemented by local NGOs and the Government agencies, both in their own and the adjoining villages. It was observed that there was a dearth of competent human resources available at the village level before the commencement of this MARVI project, but now local villagers have relevant local groundwater knowledge, data collection experience and significant interest to improve their groundwater situation. It would be foolhardy for anybody not to utilize the local knowledge and skills on water and agriculture acquired by these BJs. At least one project partner is now collaborating with the Government of Gujarat to promote and effectively use the BJs to help implement the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), while in Rajasthan the BJs can continue to work with other government funded watershed development projects that are about to commence in the watershed. This is also in line with a recent report by the Planning Commission of India highlighting the need for building strong partnerships and collaborations among a broad spectrum of institutions and community to monitor and implement groundwater management strategies across India [12].

6.2. Managing Complexity of Groundwater Use

Farmers in the two watersheds face significant water shortages and the risk of crop failure even with a slightly abnormal decline or delay in monsoonal rains. Because of advances in drilling technology and its easy access, there has been a massive increase in the drilling of tubewells and deepening of open wells for irrigation. This has motivated farmers to extract groundwater from whatever depth it is available. As a consequence, this phenomenon has changed the idea of equity and sustainability of groundwater use in the two watersheds. Not only is the water table lowering or fluctuating considerably from year to year, which impacts on crop production but, also the quality of groundwater has deteriorated due to pumping from deeper aquifers. For example, in the Dharta watershed, there is some evidence that fluoride levels in groundwater (which is also used for drinking water supplies) for some villages are above the values recommended in the World Health Organization's guidelines [13]. In general, the groundwater situation in the two study watersheds also illustrates what is prevailing in many other parts of the States of Gujarat and Rajasthan and for that matter in many States of India.

Another complex and difficult issue is determining the limits of groundwater available for withdrawal, especially in hard rock aquifers with limited storage capacity. Without mechanisms and sanctions to coordinate individual withdrawals to meet socially agreed sustainable levels, groundwater use represents an open access resource where at the end everyone loses when the groundwater system gets over exploited. Access to and availability of groundwater affects household livelihoods and community well-being and, in some instances in India, it has been reported to have led to farmers taking the extreme step of ending their own lives [14]. Therefore, a proposal to coordinate groundwater use remains a source of conflict between competing farmer interests and is the subject of significant political argument. The flow of groundwater does not recognize boundaries of individual farms, villages or watersheds and the subtractive attribute implies that one farmer's gain through over-pumping incurs a loss of access for others. Therefore, in the current situation it is almost impossible to ensure equity of access among farmers and regulate its use sustainably.

While groundwater recharge of varying amounts occurs during each monsoon season, there has been a net lowering of water tables in many parts of Gujarat and Rajasthan [4]. The consequences are notably manifest during the *Rabi* season. In the absence of institutions, regulations to share the costs and risks of aquifer remediation, individual farmers are unlikely to undertake mitigating actions independently, as they are unlikely to be compensated for the benefits shared by the common pool community. The depth to the water table increases with pumping over a longer time period, and the impact of such pumping usually extends over larger areas. While groundwater recharge of varying amounts occurs during each monsoon season, the real impact of any lowering of the water table is severely felt during drought periods. Once groundwater has been extracted in excess of annual recharge, it is not easy for individual farmers to reverse this situation. It then requires co-operative actions from group of adjoining farmers to see any real impact of local recharge and demand management on the water table situation.

6.3. Challenges of Sharing Groundwater

It is important to recognize that groundwater is an invisible, common property resource that is accessible to anyone who has a well and a pump, or can afford to dig a well and install a pump. The amount of groundwater available in hard rock aquifers with their limited storage capacity is not easy to predict, and hence it is hard to estimate the limit of groundwater pumping. Groundwater use is a good example of "tragedy of the commons" and "survival of the fittest" but at the end everyone loses when the groundwater system is over exploited. Groundwater can affect the livelihood and wellbeing of communities. Therefore, the regulation of groundwater use is a very sensitive issue for farmers and can become a significant political issue if not tackled properly

Common pool resources are characterized by costly exclusion of beneficiaries, a characteristic shared with public goods and rival consumption (or subtractable usage), a characteristic shared with private goods [15]. That is, the withdrawal of additional groundwater by an individual well owner appropriates and subtracts from the total available aquifer volume, reducing the opportunity of other irrigators to make use of the groundwater resource. When joint outcomes depend on multiple actors contributing inputs or actions that are costly and difficult to quantify and there is a lack of policy instruments to restrict usage, incentives exist for individuals to act opportunistically, often appropriating to a level where aggregate overuse occurs. A social dilemma occurs when individuals are tempted by short-term gains to over appropriate the common pool resource, thereby imposing group-shared costs on the common pool community. Additionally the opportunity exists for some individuals to free ride and benefit from the reductions in extraction or increases in recharge committed by other aquifer users. Individual over appropriation will eventually lead to falling water tables, increased pumping costs and lower crop productivity for all farmers.

The solution to the overexploitation of groundwater may well come from adequate licensing to access the resource. In India, the electricity for groundwater pumping is free in a number of states, and as such this has aggravated the problem of overuse groundwater. On the other hand, the State Government of Gujarat in recent years implemented a policy to limit groundwater pumping through limiting hours of electricity supply by constructing a separate power grid for farm sector. While the policy implementation in Gujarat has certainly limited the hours of pumping, this also pointed out that any attempt to deal with the issue of limiting user access to groundwater, in this case limiting the supply of electricity through a separate power grid, does involve some transaction cost of policy. An important outcome of the transdisciplinary research in this study would be to understand the issues and options of groundwater overexploitation from a number of perspectives and design a system of effective control for groundwater access.

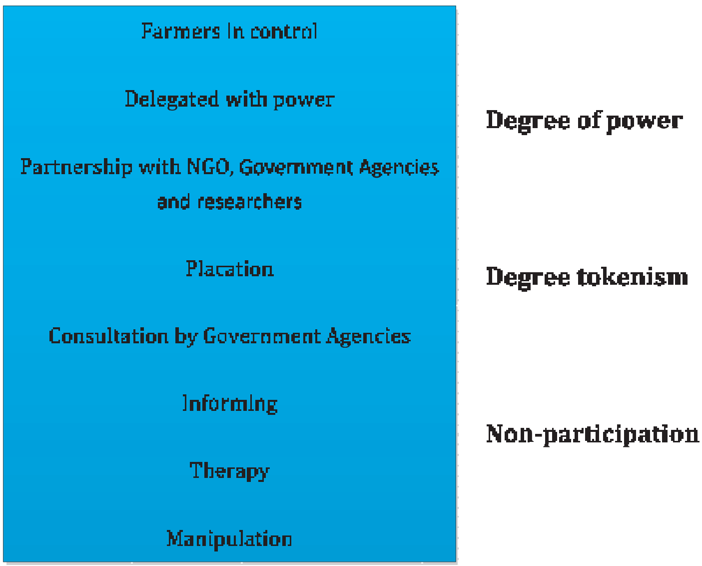
6.4. Making Community Engagement Effective

Groundwater, being a common resource accessible by every member of the community individually, requires a common approach to its management. However, in general, past efforts of community involvement in aquifer management have been shown to be quite inefficient [4]. Therefore, for this study, it was decided to tackle this issue through more effective participation by the village communities involved, and thus community engagement was critically important to the success of the study.

Effective participation is important groundwater management and in general it depends upon commitment rather than coercion and cannot be fully programmed or tightly controlled. Further, it involves resolving issues about the nature of participation in terms of extent and quality, as well as questions about who should participate. Sriskandarajah *et al*. [16] identified key themes in participative projects and included (i) the importance of the scope for genuine participation in decision-making if "community participation" is to be meaningful; (ii) the need to see participation as a continuing process of negotiation and decision-making rather than a once only input into project planning; (iii) the need for clear identification of interested parties as the first step in establishing community based resource management programs; and (iv) the need to recognize and build upon local knowledge and existing local resource management and institutional support practices.

A number of different forms of "Citizen participation" have been identified by Arnstein [17] in the form of a ladder, which moves from very tokenistic forms of participation (manipulation) and progresses to more meaningful forms of involvement (Citizen control), as illustrated in Figure 7. In the context of resource management projects, Sriskandarajah *et al*. [16] also suggested that at the three higher levels, community participation involved local people in making decisions about the management of the resources they used, while at the lower five levels, these decisions were made by bureaucratic "experts", with community members only being involved as either voluntary or paid labor. At the higher order, participation meant that communities either defined the ends themselves, or at least had a substantial input in defining them.

Figure 7. Degree of participation for managing groundwater (adapted from Arnstein, [17]).



Pretty [18] suggested that two overlapping schools of thought and practice have evolved. One views participation as a means to increase efficiency, with the central notion that when people are involved, they are more likely to agree with and support the new development or service. The other view sees participation as a fundamental right, in which the main aim is to initiate mobilization for collective action, empowerment and institution building. In an analysis somewhat similar to that of Arnstein [17], Pretty [18] notes that participation has been used to justify the extension of and control by the state, as well as to build local capacity and self-reliance; it has been used to justify external decisions, as well as to devolve power and decision-making away from external agencies; and it has been used for data collection, as well as for interactive analysis.

In this study we felt the problems Shah [4] had identified were due to participation being at level A, while we would use community engagement to strive to achieve level (B), but also developing local capacity to move to level C (Table 2). It is considered that we have achieved level B participation and that this is continuing to strengthen as the project matures. As research results become available and are shared through the community engagement processes, notably via the BJs, it is hoped that the options for improvement to ensure groundwater sustainability will be taken up and lead to the emergence of level C participation.

Table 2. A selection of the typology of participation: How people participate in development programs and projects (adapted from Pretty [18]).

Participation Level	Participation Type	Description
A	Functional Participation	Participation seen by external agencies as a means to achieve project goals, especially reduced costs. People may participate by forming groups to meet predetermined objectives related to the project. Such involvement may be interactive and involve shared decision-making, but tends to arise only after major decisions have already been made by external agents. At worst, local people may still only be co-opted to serve external goals.
B	Interactive Participation	People participate in joint analysis, development of action plans and formation or strengthening of local institutions. Participation is seen as a right, not just the means to achieve project goals. The process involves interdisciplinary methodologies that seek multiple perspectives and make use of systemic and structured learning processes. As groups take control over local decisions and determine how available resources are used, so they have a stake in maintaining structures or practices.
C	Self-Mobilization	People participate by taking initiatives independently of external institutions to change systems. They develop contacts with external institutions for resources and technical advice they need, but retain control over how resources are used. Self-mobilization can spread if governments and NGOs provide an enabling framework of support. Such self-initiated mobilization may or may not challenge existing distributions of wealth and power.

7. Concluding Remarks

Sustainable groundwater use is a wicked problem and has technical, social, economic, policy and political dimensions. The access to groundwater for the farming communities is also an emotional issue as their livelihood and survival depends on it. Availability of relevant and reliable data related to the various aspects of groundwater and developing trust and support between local communities, NGOs and government agencies are the key to moving towards a dialogue to decide on what to do to achieve sustainable use of groundwater. Technical information on water table fluctuations, groundwater balance modeling, socio-economic and other data and analyses alone will hardly have any impact on over-exploitation of groundwater resources. This study has demonstrated that transdisciplinary research, which involves people who are going to benefit, is more effective in developing a deeper understanding of issues and exploring options to improve the current groundwater situation. In particular, the involvement of local villagers through groundwater monitoring, photovoice techniques and community workshops has been valuable in generating local knowledge and capacity building.

The socio-economic analysis revealed diverse attitudes to farmers' own and neighbors' groundwater responsibilities, mechanisms to coordinate groundwater use, attitudes to MAR, information sources and preferred groundwater and MAR managing agencies. Cluster membership variance highlights three key factors in designing participatory approaches and potential ground water management instruments in the two study sites. First, design principles need to address the diversity of attitudes and motivations observed in the sampled households, by emphasizing the participation of members across the whole cluster typology. Second, a reliance on a single instrument or approach to coordinate aquifer access is unlikely to align with the diverse attitudes observed across clusters, potentially resulting in low compliance rates or antagonizing sustainable groundwater management and MAR efforts. Third, while the transaction costs and resource demands make the tailoring of instruments to correspond with cluster attributes infeasible, community consultation is likely to reveal instrument sequencing as a viable strategy to promote aquifer sustainability. Addressing these three design principles in response to the observed household diversity is likely to enhance the prospects of community participation and improve aquifer recharge and groundwater pumping coordination.

The project has demonstrated that the harnessing of local experience and the indigenous knowledge of villagers has been useful in understanding the real issues of groundwater management, the geology of the area and groundwater use and changes over time. This engagement also helped in creating awareness about the project and sensitizing the community about the concept of groundwater management. The community is well aware that their groundwater is depleting at a fast rate but they were not aware of the technical reasons behind it. Local villagers had the perception that by digging deeper tubewells they would have more water, but they were not examining the issues related to groundwater recharge and water quality management. The regular monitoring of wells by BJs and the subsequent community meetings and the presence of project staff in the two study areas has now prompted the communities to talk among themselves about the future of their groundwater resources and the need to find options for managing and using groundwater more sustainably.

Efforts have been made by various government and NGO’s for the augmentation of the water table, but this has not been enough to ensure long term sustainability. There is a need to awaken the people to take up groundwater recharge and rainwater harvesting and also manage demand and make irrigation more efficient. This is where the local administration must take responsibility and ensure that villagers are fully involved in such schemes. Planning is required at the micro level using participatory approaches to make each village self-sufficient in water.

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Conflicts of Interest

The authors declare no conflict of interest.

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Policy Preferences about Managed Aquifer Recharge for Securing Sustainable Water Supply to Chennai City, India

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Abstract: The objective of this study is to bring out the policy changes with respect to managed aquifer recharge (focusing on infiltration ponds), which in the view of relevant stakeholders may ease the problem of groundwater depletion in the context of Chennai City; Tamil Nadu; India. Groundwater is needed for the drinking water security of Chennai and overexploitation has resulted in depletion and seawater intrusion. Current policies at the municipal; state and national level all support recharge of groundwater and rainwater harvesting to counter groundwater depletion. However, despite such favorable policies, the legal framework and the administrative praxis do not support systematic approaches towards managed aquifer recharge in the periphery of Chennai. The present study confirms this, considering the mandates of governmental key-actors and a survey of the preferences and motives of stakeholder representatives. There are about 25 stakeholder groups with interests in groundwater issues, but they lack a common vision. For example, conflicting interest of stakeholders may hinder implementation of certain types of managed aquifer recharge methods. To overcome this problem, most stakeholders support the idea to establish an authority in the state for licensing groundwater extraction and overseeing managed aquifer recharge.

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1. Introduction

In India, as well as in many other countries (e.g., China [1]), overexploitation of groundwater is a serious problem. It has caused declining groundwater levels, deterioration of water quality, and in coastal regions intrusion of seawater. Such a situation may lead to a race for pumping water for irrigation, which accelerates groundwater depletion and ends in a “tragedy of the commons” [2,3]. This becomes evident by higher energy costs for pumping irrigation water: In India, energy for farmers is subsidized (diesel, electricity) or given free and the escalation of subsidies for agriculture burdens government budgets [4].

To overcome groundwater depletion and the associated costs, governments may support managed aquifer recharge (MAR). MAR is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit, such as rainwater harvesting (RWH), infiltration ponds, or check dams. These are considered in this paper, as they generate water supplies from sources that may otherwise be lost due to runoff [5–8]. MAR also has the aim of preserving or improving groundwater quality. Related groundwater management actions can include substituting alternative water sources for groundwater (the paper considers desalination) and “non-structural policy measures”, by which the paper means demand management to promote water conservation (e.g., by water pricing or state sponsored incentive programs to reduce cropping; [9] is an early example).

The basis of this study is a water supply scenario for Chennai, where overexploitation of groundwater has become a threat to drinking water security [7]: “Chronic water shortages mark the norm in this city.” Thereby, for the state of Tamil Nadu the legal framework provides a favorable atmosphere for groundwater management, making e.g., RWH on roofs mandatory since 2001. Also present water polices of India are favorable, acknowledging MAR as an important tool for sustaining water supplies for all kinds of users [10]. However, MAR involves multiple agencies, which may not always cooperate or share information [11]. At the same time, there are many different stakeholder groups and their interests in groundwater recharge, groundwater use, or quality of groundwater may not be compatible with each other; rather multiple conflicts of interests (e.g., urban *vs.* peri-urban and rural) are to be expected [12,13].

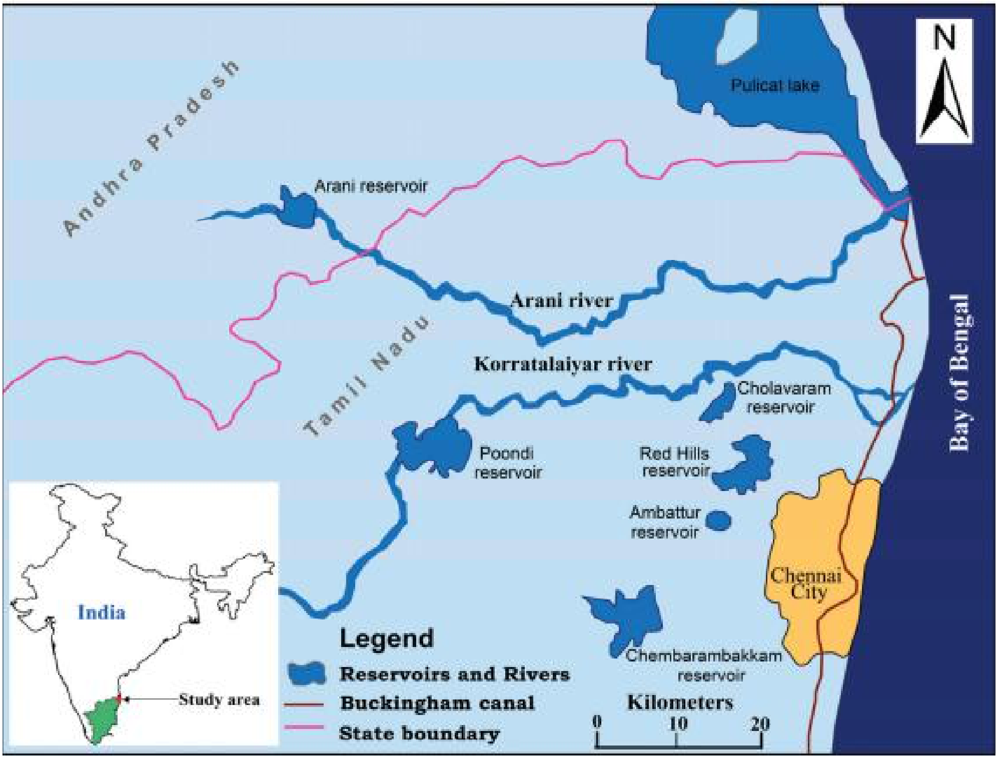
Therefore, the paper focuses on the perception of these stakeholder groups on MAR, considering the broader context of groundwater management. It also asks, which policy changes the stakeholders deem necessary to implement a specific MAR approach, namely the construction of many small infiltration ponds.

2. Background Information: Current Water Supply and Future Options

Chennai City (formerly Madras) is the capital of Tamil Nadu state. With 4.7 million people (2011 census) and an area of 426 km^2 it is the sixth largest city in India. (Official statistics refer to the old boundaries prior to the expansion of city limits in the year 2011.) With a larger metropolitan area of 1189 km^2 and nine million people, it is the fourth largest metropolitan agglomeration in India. The Chennai Metropolitan Water Supply & Sewerage Board (CMWSSB), a statutory body established in 1978, is responsible for water supply and sewerage functions. It operates in the city, only, but is expected to gradually extend its services to the entire metropolitan area.

Over 90% of the water supply of Chennai is covered by water stemming from reservoirs, which are depending on the monsoon rains ([14] and Figure 1). When the reservoirs are empty then the water to the city is mostly met by groundwater to cover the gap in water supply. However, due to exploitation of the groundwater resources (pumping of groundwater for domestic, industrial and agricultural water supply), the contribution of groundwater to the water supply of Chennai has diminished, from a maximum of 25% to around 6% during 2000. At the beginning of the 2013 summer season (March 2013) the share of groundwater was as low as 1% [14]. This indicates over-dependence on all current sources to meet Chennai’s water supply. Further, the decline of the groundwater level has led to the intrusion of seawater in the coastal area.

Figure 1. Reservoirs around Chennai.



Conventional technical approaches to overcome the water shortages during summer were the construction of new reservoirs (e.g., Veeranam Lake Water Supply Project, commissioned in 2004), the increase of the capacity of existing reservoirs, and the provision of desalination plants. The Telugu Ganga Project diverts water from Krishna River in Andhra Pradesh to Chennai. Also, water pricing is practiced; however, in comparison with other cities such as Bangalore and Hyderabad only few households have functioning meters [15].

In addition, MAR has been practiced to replenish the aquifer and to mitigate seawater intrusion. Thereby, MAR was considered for replenishing the local aquifer at acceptable costs in order to "build a credit that can be drawn on in drought" [16]. Indeed, mitigation of seawater intrusion by MAR in the aquifers north of Chennai was observed by [17]. Thereby, in Tamil Nadu State RWH in all buildings is mandatory. Further, there has been a popular movement for the revival of traditional structures, e.g., Oorani for RWH or temple tanks for groundwater recharge. Two other technologies for MAR have been implemented: check-dams and infiltration ponds.

With respect to infiltration ponds there is one pilot study, implemented by Anna University. To be effective, a large number of small ponds would be required and a preliminary survey has shown that around 10,000 percolation ponds are feasible in the Arani and Koratallai river basin north of Chennai. Initial results indicate that approximately 40% of water stored in an infiltration pond may be recharged.

Similar figures about recharge were published for check dams [18]. Their overall storage capacity shall be 31 million m^3, with capacities ranging from 0.2 to 2.87 million m^3. Currently, there are nine dams at Arani River (4.42 million m^3), seven at Kortallai River (3.4 million m^3) and three at Palar River (5.18 million m^3). At Arani and Kortallai Rivers 71% of the planned capacity is implemented. Check dams at Palar River have lower priority, as the city depends only in extreme droughts on water from that river basin, which is at a distance of about 80 km.

Table 1 informs about the costs of recent projects.

Table 1. Capital costs for water supply infrastructure.

Infrastructure	Water Supplied/Recharged (Million m^3/year)	Capital Costs (Million INR)	Unit Costs (INR/m^3)
New surface storage reservoirs (Thervoikandigai-Kannankottai Reservoir)	28.31	3300	117
Increasing storage capacity of existing reservoirs (Cholavaram, Porur, Ayanambakkam & Nemam tanks)	16.08	1300	81
Desalination (Nemmeli plant)	36.50	8712	239
New check dam (Irulipattu check dam)	0.30	62	207
Infiltration pond (Anna University pilot project)	0.000175	0.015	86

Note: Data are drawn from project reports. These values were considered suitable for initiating discussion on stakeholder opinions, but should not be relied on for estimating actual costs of the respective types of infrastructure.

3. Problem and Goal

This paper studies stakeholder perceptions in Chennai about groundwater management. It compares their views about three MAR options (roof top RWH in urban areas, large check dams and small infiltration ponds) with other approaches to overcome the problem of groundwater depletion due to over-exploitation, such as conventional infrastructure solutions (building or enlarging reservoirs), desalination, and non-structural policy instruments (e.g., water pricing). With respect to these options, the paper presents the interests, preferences and motivations of representatives of stakeholders at the national, state, municipal and individual levels, who took part in two workshops.

4. Method

A preliminary study identified the most relevant local stakeholders, in particular the governmental key-actors with interests in groundwater use, recharge, and quality (Table 2). Subsequently, the perceptions and preferences of stakeholder representatives for about six options to secure the future water supply for Chennai were explored, based on two workshops. Stakeholders interested in the topics (first workshop about options to secure water supply for Chennai, second workshop about infiltration ponds) were contacted and invited to participate. Thereby, "stakeholders" at the national, state or municipal levels are government agencies involved in water governance, while at the local and individual level these are groups of persons, companies or organizations in the Chennai area with a concern for groundwater related issues.

Table 2. List of stakeholders.

Stakeholder/Institution	Level	Abbreviation
Government of India, Ministry of Water Resources, Planning Commission	National (Union State)	GoI
Central Pollution Control Board		CPCB
Central Groundwater Board		CGWB
Coastal Aquaculture Authority		CAA
National Green Tribunal		NGT
State Government of Tamil Nadu	Tamil Nadu State	GoTN
Public Works Department		TNPWD
Pollution Control Board		TNPCB
Water Supply & Drainage Board		TNWSDB or TWAD
Town & Country Planning Board		TNTCPB
Hindu Religious & Charitable Endowment Board.		TNHRCE
Water Resources Regulatory Authority (proposed)		TNWRRA
Chennai City Municipal Corporation	Municipality	CCMC
Chennai Metropolitan Development Authority		CMDA
Chennai Metropolitan Water Supply & Sewerage Board		CMWSSB
Food and mining industry	Local non-governmental	Industry
Private water companies		WaterBus
Tanker truck operators		Tanker
Water users associations		WUA
Agriculture sector		Farmers
Peri-urban villages		Peri
Peasants without own land		Workers
Residents of the city		Residents
Organizations of civil society		CSOs
Research centers and universities		Acad

A first workshop was conducted with participants from government and civil society. Also, several members of the project team took part and informed the participants about the present situation (see background information in Section 2).

In particular, respondents were informed about the technical options and costs observed for recent projects (Table 1): Increasing the capacity of existing reservoirs and groundwater recharge by infiltration ponds are most economical. The subsequent plenary discussions focused on the legal situation and on implementation aspects. At the end of the workshop, 25 respondents answered a questionnaire about the opinions concerning different groundwater management approaches, about the relevant criteria to assess these approaches, and about the opinions concerning different policy approaches.

The output of this workshop was used for the subsequent discussion of the legal and policy issues of implementing infiltration ponds in the area surrounding Chennai, mapped in Figure 1.

The project team presented these results at another workshop with representatives from government organizations and civil society. Again, at the end of the workshop 29 questionnaires were answered. (Respondents of the survey at the first workshop did not take part.) In addition to the previous questions about groundwater management approaches and criteria to assess them, a set of questions inquired specifically about infiltration ponds as well as legal and policy issues to implement them.

Participants of the workshops came from stakeholders groups, who could be decisive for MAR implementation. For the government (Table 2 for the abbreviations), these were members of the Chennai branch of CGWB for the central government; from Madras High Court for the jurisdiction, from several government departments (e.g., TNWSDB, Chennai, TNPWD, Chennai) of Tamil Nadu State; and from CMWSSB, Chennai, for the city. From civil society, there were representatives from business (e.g., consultants, advocates), NGOs (e.g., Alacrity Foundation, Chennai, DHAN Foundation, Chennai), and students and scientists from research institutions (e.g., Anna University, Chennai, Tamil Nadu Dr. Ambedkar Law University, Chennai). At both workshops, farmers took part, whose land might be used for MAR structures.

The surveys were conducted in the context of the future water supply needs of Chennai. For the interpretation, it should be recalled that the surveys were not intended to be representative opinion polls for any specific group, and *no concrete decision should be prepared*. Rather, these were explorative studies, where samples of 10–30 respondents suffice [19].

In particular, the sample was not representative for the population at large: 11% were women and the median age was 51, ranging from 20 to 37 for women and 25 to 71 for men. Further, 38% were from government or courts, 15% from research institutions, 19% experts from (other) NGOs, and 27% were farmers, some without education. To ensure their inclusion and to avoid misunderstandings of the questions, members of the project team (they did not take part in the survey) assisted the respondents in filling the questionnaires.

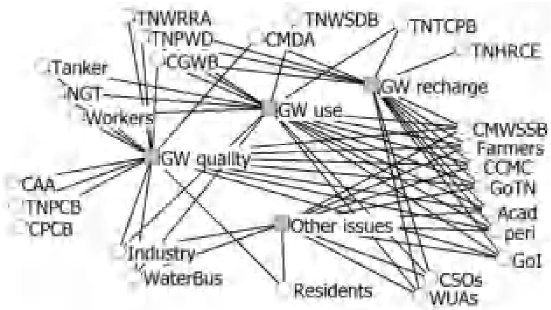
In order to identify explanatory structure, the survey data were processed by methods of pattern recognition, data mining, and social network analysis, using preferably non-parametric tests suitable for small sample sizes. The significance level was uniformly 95% (with the Bonferroni correction for significance of multiple comparisons, e.g., Milton Friedman’s test). For one-sided 95% confidence intervals, Clopper-Pearson method (based on the inverse beta-distribution) was used, as it is conservative (higher confidence than stated as the nominal level). Software used was Microsoft Excel, XL-STAT of Addinsoft for statistical tests and data mining (an add-in to Microsoft Excel) and UCINET 6 of Analytic Technologies for social network analysis. In future decision making and project planning, accommodating and acknowledging stakeholder input and feedback will be important for a successful implementation and these methods may be applied again for such analysis.

5. Results

5.1. Stakeholder Survey

This section lists 25 stakeholders (Table 2) and summarizes their interests in groundwater issues (Figure 2).

Figure 2. Stakeholders and their groundwater-related interests.



Notes: (2-mode network, using UCINET 6): Grey squares are groundwater-related interests; "GW quality" = pollution control of groundwater, "GW use" = extraction of groundwater, "GW recharge" = RWH or other MAR infrastructure, "Other issues" = water saving by the use of recycled water or similar questions. White circles represent stakeholders (abbreviations explained in Table 2), whereby lines connect stakeholders to their interests.

For governmental stakeholders, the interests are defined from the mandate (*i.e.*, laws and policies). For instance, as GoI delegated to the states groundwater responsibilities [20], and as the municipalities are responsible for actual water provision, at all levels of government there is an interest in all groundwater issues. More specialized government institutions have more restricted interests (Figure 2).

For institutional non-governmental local stakeholders (companies, universities, water user associations and other organizations), interests in groundwater issues, also indirect ones (e.g., industry, with direct interest in groundwater extraction, but not necessarily in recharge), were inferred from their business, research or other activities. For instance (with respect to CSOs), media regularly inform the public about the depletion of groundwater and sea water intrusion, and about advantages of groundwater recharge. The same is true for certain NGOs, such as local groups against sale of groundwater in the villages around Chennai [21].

For groups of individual stakeholders (e.g., farmers, peasants, residents), the interests were figured out from their needs.

5.2. Comparing Acceptance for Water Supply Options

The results of this subsection are based on two stakeholder workshops and the subsequent surveys with 54 responses, of which 50 could be used, as all relevant questions were answered.

Stakeholders were asked about the acceptance of six approaches: increasing the capacity of reservoirs (representative of conventional approaches), desalination, non-structural policy instruments (such as water pricing), and MAR through RWH, check dams, and infiltration ponds. The options were chosen, because they were practiced or considered in the political discourse in the context of water saving and recovery, drinking water security, and groundwater recharge. (RWH is mandatory, reservoirs, desalination, and check dams are common, infiltration ponds and water pricing are discussed.) Further, they are typical instruments for different policy and technology approaches, and they operate at different scales.

Respondents were asked to assess the potential of the different options for securing the water supply (very high, high, low, very low) and to rank the options in terms of their individual preferences (from 1 = highest preference to 6 = lowest), using the “1224 competition ranking” (rank function of Microsoft Excel) to handle equals. From these answers, *low acceptance* (–1) of an option for a stakeholder was defined, if it was of low or very low potential and the ranking was five or six, and *high acceptance* (+1) was defined symmetrically (high or very high potential and rank one or two); the other answers were interpreted as *indifference* (0).

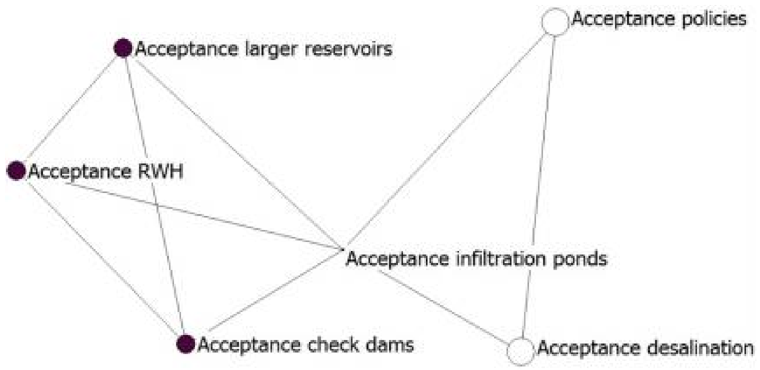
Summarizing the confidence intervals (Table 3), except for desalination plants and non-structural policies with low acceptance for at least ¼ of stakeholders, all other options appeared to be acceptable. Infiltration ponds were neither strongly supported, nor disliked by many.

Table 3. One-sided 95% Clopper-Pearson confidence intervals for acceptance of options.

Option	**High Acceptance**		**Low Acceptance**	
	Lower	***Upper***	***Lower***	***Upper***
RWH	34%	59%	0%	6%
Enlarge Reservoirs	34%	59%	3%	17%
Check Dams	38%	62%	4%	20%
Infiltration Ponds	13%	34%	1%	12%
Desalination	14%	36%	34%	59%
Non-Structural Policies	2%	15%	28%	53%

Comparing also the distribution of the acceptance levels of each two options (Figure 3), desalination and policies had with 95% significance stochastically lower acceptance than RWH, building new check dams or enlarging reservoirs. For infiltration ponds (37 indifferent respondents) there were no significant differences in acceptance to any other option.

Figure 3. Pair-wise tests for differences in acceptance.



Notes: Based on 50 responses, nodes represent options for securing water supply and links indicate, that “there is no 99.7% significant difference by Friedman’s test”, as computed with XL-Stat (correcting significance for 15 pair-wise comparisons). Colors identify two K-cores (clique-like structures) and node size is by closeness (a measure of centrality, which identifies far-off and thus rather different options), as computed with UCINET 6. The positions indicate lower acceptance to the right.

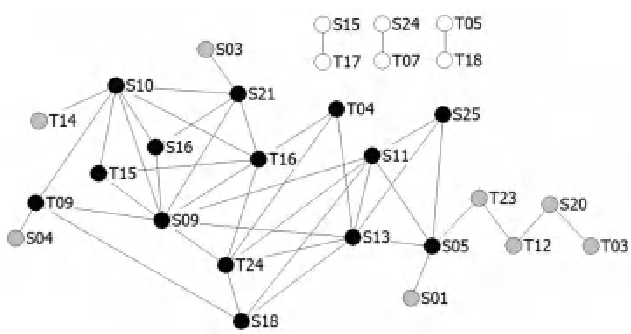
5.3. Stakeholder Motivations

The results of this subsection are based on two stakeholder workshops with 54 respondents.

Again, from 54 responses 50 were used, as they answered all relevant questions. To explore the motivation, respondents were asked to rank key-criteria by importance. As expected, on average human health (water quality) was most important, followed by the impact on the environment, social aspects (equity), impact on economy (costs, development), and practical issues (implementation, readiness of institutions). While between two consecutive criteria (e.g., health and environment) the difference was not significant, the criterion after the next one (e.g., social compared to health) had a stochastically higher (*i.e.*, worse) rank for importance (Friedman's test at 99.5% significance to correct for 10 pair-wise comparisons).

The 50 responses that answered all questions about the ranks of criteria and about the potentials, ranks, and acceptance of options were positively correlated, which indicates some consensus amongst respondents. A cluster analysis based on high correlations identified 22 respondents ("cluster respondents") with similar views (Figure 4). However, it also singled out 28 "non-cluster respondents", of them 22 idiosyncratic (no high correlation to any other response) and six almost idiosyncratic (highly correlated to only one other response). Regression trees (using XL-Stat) characterized the cluster-preferences (see [22] for atypical responses): Typically, 91% of the cluster respondents (20 of 22) had low acceptance for desalination and they ranked health first or second. Non-cluster respondents were expected to be more diverse, but typically, 68% of the non-cluster respondents (19 of 28) were indifferent or positive (high acceptance) about desalination and indifferent or negative (low acceptance) about check dams.

Figure 4. Cluster analysis of respondents to identify consensus.



Notes: Nodes labeled S and T denote participants of the first and second workshops respectively. Based on the preferences for options (potential, rank, and acceptance) and criteria (importance rank), for each pair of responses the correlation coefficient was computed. Links indicate a 99.99% significant positive correlation coefficient of 0.9 or higher between responses (*T*-test, XL-Stat). For the figure, 22 isolated responses were removed (not highly correlated to any other response) and for six (white) nodes there is a link to one other node only. The remaining 22 nodes identify "cluster respondents" with similar views. Within this group, 14 black nodes represent a K-core (a clique like structure), of them 50% farmers, and 8 grey nodes peripheral respondents; they would be disconnected upon removal of a node (computations with UCINET 6).

5.4. Views on Legal Regulations and Policy Instruments for Implementing Infiltration Ponds

The results of this subsection are based on the second workshop.

For Table 4, 24 of 29 respondents answered all relevant questions (five did not). The workshop focused on the stakeholder views concerning the implementation of infiltration ponds, as in the view of the project team building thousands of small infiltration ponds would be an economically viable response to groundwater depletion, where the social group with the largest consumption of groundwater, the farmers, assume responsibility for its recharge.

Table 4 summarizes the views and displays significant differences between cluster and non-cluster respondents. The majority of respondents was critical about water supply, supported “the proposal to construct thousands of infiltration ponds in agricultural areas around Chennai” (interview question), whereby the farmers should take the initiative to implement them, the government should finance a substantial share of the construction costs, and farmers should operate and maintain their infiltration ponds and be responsible for the running costs (*i.e.*, for operation and maintenance). As to the differences between cluster and non-cluster respondents displayed in Table 4, cluster respondents have seen more responsibility in all aspects with the farmers.

For Table 5, the acceptance for instruments that support implementation of infiltration ponds was explored on the basis of 26 responses at the second workshop. (Three of 29 respondents did not answer all respective questions.) Thereby, the acceptance for policies was defined from the answers about the suitability (suitable, rather suitable, rather not suitable, not suitable) and the rank (1 = highest to 5 = lowest preference; respondents could propose as fifth category “other”) of the policy instruments: High acceptance means suitable and rank one or two, low acceptance means not suitable and rank four or five. Table 5 displays the acceptance. (“Other” is not displayed, as only 7 of 26 respondents considered it.) Summarizing, two policy instruments to promote infiltration ponds were acceptable: supporting ponds using public funds and providing information. Thereby, “information” was discussed in a broader context of a (participative) communication strategy, as outlined e.g., by [23]. Making infiltration ponds mandatory for farms with more than one acre (about 4000 m^2) may be contested, with up to 32% opponents (not so much farmers) and up to 56% supporters. Rather not acceptable was fining farmers, who do not have infiltration ponds.

Table 4. One-sided 95% Clopper-Pearson confidence intervals for stakeholder views.

	Question	Approval		*Cluster Difference*
		Lower	**Upper**	
1.	Water Supply: improvements needed	88%	100%	NC > C
2.	Infiltration ponds: want them	71%	97%	No
3.	Policies & laws support infiltration ponds	52%	85%	No
4.	Farmers should drive pond development	32%	68%	NC < C
5.	Government should drive pond development	21%	56%	No
6.	Taxpayer should drive pond development	0%	12%	No
7.	Consumers should drive pond development	3%	29%	No
8.	Others should drive pond development	6%	34%	NC > C
9.	Farmers should pay pond construction	11%	43%	No
10.	Government should pay pond construction	40%	75%	NC > C

Table 4. *Cont.*

	Question	Approval		*Cluster Difference*
		Lower	**Lower**	
11.	Taxpayer should pay pond construction	6%	34%	NC < C
12.	Consumers should pay pond construction	0%	18%	NC < C
13.	Others should pay pond construction	3%	29%	NC > C
14.	Farmers should pay O&M of ponds	44%	79%	NC < C
15.	Government should pay O&M of ponds	6%	34%	NC > C
16.	Taxpayer should pay O&M of ponds	3%	29%	NC < C
17.	Consumers should pay O&M of ponds	0%	18%	NC > C
18.	Others should pay O&M of ponds	3%	29%	NC > C
19.	Farmers should operate ponds	61%	91%	NC < C
20.	Government should operate ponds	3%	29%	NC > C
21.	NGOs should operate ponds	0%	18%	NC > C
22.	Others should operate ponds	0%	18%	NC > C

Notes: Respondents could answer yes/no = ±1, and yes/no with reservations = ±0.5. "Approval" gives one sided 95% confidence intervals for the percent answering yes or yes with reservations. "Cluster difference" informs, if with 99.99% significance (Mann-Whitney test) respondents of one cluster had a stochastically higher/lower approval and different mean approval rates.

Table 5. One-sided 95% Clopper-Pearson confidence intervals for acceptance of policies.

Policy Instrument	High Acceptance		Low Acceptance	
	Lower	**Upper**	**Lower**	**Upper**
Public support for ponds	33%	67%	0%	17%
Information about ponds	26%	60%	0%	17%
Mandatory ponds (farms: 1 + acre)	23%	56%	5%	32%
Fine farmers without a pond	0%	11%	23%	56%

As the questions to identify needs for legal and policy changes were more specialized, respondents of the second workshop skipped certain questions depending on the expertise. (For this set of questions, 7% of 667 entries, *i.e.*, 29 responses to 23 questions, were not answered). The following percentages refer to those respondents that answered the respective questions.

(1) For the question, as to what institution should play an active role in groundwater conservation, most responsibility should rest with the State Government (48% stated that it would be the most important institution), municipal governments (for 48% it was the second most important institution) and farmers (for 33% the third most important group). Further, the State Government had (at 95% significance) stochastically higher priority than the Union Government (for 35% less important than the above actors or civil society/NGOs).

(2) For the question, as to whom governments should hear, when drafting and implementing water policies, farmers (for 68% the most important group to be heard) had with 95% significance a stochastically higher priority than all groups, except civil society (for 44% the second most important group). Surprisingly, courts (for 52% least important of all

groups, except “other”) had with 95% significance a stochastically lower priority than civil society and farmers.

(3) Most respondents (66%) considered the current situation as supportive for infiltration ponds and overall the present groundwater recharge measures in Chennai would be adequate (50%). However, in view of the discussion at the workshop with respect to MAR, 59% answered that the current groundwater law was not adequate (see Section 5.5).

(4) With respect to groundwater-related institutions, 79% wished a law resembling the Tamil Nadu Groundwater Development and Management Act of 2003, which was never notified and finally repealed in 2013 (Groundwater Development and Management Repeal Ordinance). That Act would have foreseen an authority (TNWRRA) for MAR and Madras High Court repeatedly urged the state to notify it [24]. However, only certain aspects of this act were preserved in the form of Government Orders.

(5) Further, 69% would also approve of a law similar to the Model Bill for the Conservation, Protection and Regulation of Groundwater. This draft bill by the National Planning Commission of India is favorable for MAR.

(6) With respect to the characteristic features of these proposals, 78% support the establishment of a state authority responsible for water allocation. If there were such an authority, its agenda should include for 84% the regulation of groundwater extraction and for 79% the stipulation of MAR measures.

(7) Further, for 93% of respondents, a new groundwater law should be effective against encroachers who endanger groundwater. For 86% the legal regulations should be specific for regions with respect to MAR. 90% support stricter pollution control, where the local situation requires this. For 82% land utilization policies should be based on water availability.

5.5. Specific Observations from the Workshop Discussions

Compared to the other options, “non-structural policy instruments” was atypical, as it describes a bundle of policy instruments. In the workshops, the project team explained that this would include e.g., water pricing, banning or licensing of groundwater extraction, enforcing or supporting change to less water demanding crops, enforcing or supporting summer plowing to maintain soil humidity, or merely awareness rising amongst different target groups for issues related to water saving. However, perhaps as water pricing is practiced in Chennai (see Section 2), the discussions focused on “reducing demand by higher drinking water or irrigation water prices”. Thus, for this paper “non-structural policy instruments” de facto means “water pricing and measures supporting it” (e.g., cut of energy subsidies, privatization).

For the other options, no such problems occurred. Further, although respondents of the first workshop added several proposals for mitigating water scarcity, these proposals were conceptually similar to the considered options. Amongst the proposals was metering in apartment complexes and big hotels; control of demand by licensing; to encourage water saving toilets; recycling of grey water for domestic purposes (toilet flush); to simplify water recycling by separating wastewater according to its sources; clearing silt and sand from existing ponds to help sustain groundwater recharge; recharging storm-water and treated wastewater. Other suggestions were interlinking the rivers of Chennai and transporting water from distant sources.

For the criteria, additional questions (at the first workshop only) indicated that in applying the criteria to specific options, respondents lacked a common understanding about the meaning of the criteria. For instance, with respect to health, some approved of desalination, as it provides clean water, while others disapproved, as it does not provide natural water, which they perceived as healthy. Also for RWH, some were concerned about possible contamination, if collected rainwater was used for drinking, while others focused on other domestic uses and were not concerned. Similarly, for reservoirs and to a lesser extent for infiltration ponds, some were concerned about risks due to water contamination and dumping of waste.

In view of these experiences, the second workshop on infiltration ponds elaborated more on these criteria. However, with respect to the preferences there were no significant differences between the workshops, except for RWH: Participants of the second workshop had with 95% significance a stochastically higher acceptance for RWH than those of the first workshop (but at both workshops it was highly accepted). Perhaps, this was due to the focus of the second workshop on infiltration ponds, which are conceptually similar (small decentralized systems) to RWH.

For the legal situation, although by Table 3, RWH had highest support and least opposition, and at both workshops there was substantial criticism. Some stakeholder representatives disapproved of the mandatory implementation of RWH in every building without taking note of the different geological patterns, the different capacity of the ground to hold water, different rainfall patterns and complex groundwater usage. Stakeholder representatives of the second workshop therefore asked that regulations should allow considering the local situation (point 7 in Section 5.4).

These concerns about the consideration of the local situation apply also to the other options: If e.g., laws were requiring all farmers to build infiltration ponds, under certain circumstances such ponds may be meaningless.

Further, stakeholders reported implementation problems, as due to understaffing CMWSSB barely communicates with the public and lacks support from other stakeholders. This in turn results in deficient law enforcement: RWH structures are routinely monitored and maintained only in exceptional cases. Hence, stakeholders asked for more regular monitoring.

Similar implementation problems made current groundwater laws (point 3 in Section 5.4) inadequate: While CMWSSB denies groundwater extraction licenses for commercial purposes, the registration of wells largely failed and unauthorized extraction of groundwater is prevailing throughout the city; the offenders enjoy impunity.

6. Discussion

The stakeholder surveys confirmed the known fact that a substantial fraction of stakeholder representatives was skeptical about desalination plants, which are amongst the most costly options to secure drinking water supply. Such low acceptance for desalination plants is known also from other countries, e.g., Australia [25]. In India cultural issues (also for educated populations, only spring water may be perceived as clean and healthy) aggravate this low acceptance problem.

The observed low acceptance of non-structural policies may be explained by the critical discussion of water pricing and privatization of water services. These policies are perceived critically also in other countries, e.g., Bolivia, where increases of tariffs have stirred violent public protests [26], Ghana and Tanzania [27], or South Africa [28]. There are concerns about environmental justice, as the burdens for the poor could be out of proportion [29].

Also, the high acceptance for RWH was as expected, as RWH is a traditional water supply option supported also by court judgments that repeatedly confirmed the eviction of encroachers from land used for RWH [30]. However, stakeholders had doubts about the efficient functioning of RWH structures.

The conventional approach to secure water supply is building new reservoirs. The stakeholder views on this option were not inquired, as there are limitations to new reservoirs, and to fulfill its water needs, Tamil Nadu state already operates reservoirs outside the state. This causes specific problems, as is illustrated by a recent interstate case at the Supreme Court of India [31]: Tamil Nadu state leases and operates Mullaperiyar dam in Kerala. Kerala was concerned about the earthquake-safety of the dam and enacted a state law to limit the reservoir level. In view of the consequently unmet water needs of Tamil Nadu, in 2014 the Court declared the Kerala state law as unconstitutional.

Increasing the capacity of existing reservoirs was the most economical of the considered solutions and it was generally accepted. However, stakeholders were aware that for reservoirs there is a need for regulations that consider the local situations: Vulnerable water bodies might need a higher protection than guaranteed by the national standards. A notorious example, for 15 years in courts, was the Orathupalayam dam project to use water from Noyyal River for irrigation, where five years after its completion in 1992, heavy water pollution from textile industry forced farmers to give up irrigation [32].

Groundwater recharge by check dams was the second most expensive option, but it was generally accepted and it is widely used. Conflicts about land acquisition plans may hinder the realization of such large scale infrastructure projects. This is exemplified by the delay of the construction of the Thirukandalam check dam [33]. For although landowners benefit substantially from check dams by increased yields [34], farmers fear receiving insufficient compensation for arable land that is used for such projects. Also, the survey confirmed that stakeholders were aware of the need to hear farmers, when formulating water policies (see point 2 in Section 5.4).

In terms of unit costs, infiltration ponds were second best with respect to unit costs. While the acceptance was not as clear as for the other options (see Figure 3), stakeholder representatives at the second workshop (about infiltration ponds) supported the idea to construct thousands of infiltration ponds in the rural areas surrounding Chennai (point 2 in Table 4). Farmers may at first not understand why they should give up arable land and spend money to build such ponds (just to secure the water supply of Chennai). Stakeholder representatives were aware of this problem and they approved the idea that the government should support the farmers in building infiltration ponds (Table 5 and point 10 in Table 4). Later on, the farmers should operate and maintain them without public support (points 14 and 19 in Table 4). Thereby, the implementation of infiltration ponds may also benefit from the observed high acceptance for RWH. Accordingly, infiltration ponds are small structures comparable to RWH structures and farmers will benefit from the aquifer recharge. Media reports [35] further emphasized that farmers may generate additional income from aqua-cultures (with risks for water quality).

Stakeholder representatives at the second workshop were not so critical about existing laws (many are used to apply them in administration and courts) and considered that current laws would support infiltration ponds (point 3 in Table 4).

However, in view of the workshop discussions, the majority, and also the project team, had critical views about the inadequacy of current groundwater laws and regulations (point 3 in Section 5.4). An example for the ineffectiveness of existing laws was the still applied national Easement Act of 1882 vesting owners of land with ownership of groundwater, irrespective of the rights of neighbors or public interests in groundwater preservation. Thereby, the interests of neighbors in water *de facto* have not been framed as legal entitlements or obligations. Further, national agencies (CGWB, CPCB) in charge of the implementation of national policies may not really influence actual decision making, as they tend to approve projects, which receive a “no objection certificate” from state agencies [36]. Yet, the stakeholder representatives considered that the national government should indeed have only a minor role for groundwater conservation, below state governments in importance (point 1 in Section 5.4).

For the specific problem of groundwater extraction, more than 75% of stakeholder representatives acknowledged the need to better regulate it and they supported the idea that a state authority should be in charge of MAR (points 4 and 6 in Section 5.4). Currently, different agencies of the government appear to act in an uncoordinated manner and without an integrated perspective about MAR [11]. For example, the water bodies and channels are not governed by CMWSSB, and neither are the temple tanks, which could serve as MAR structures. Another issue for the workshop was ineffective governance of groundwater, as commercial operators extract it unlawfully throughout the city.

The survey also identified a communication problem, illustrated by the lack of a common understanding of key criteria, such as health. A cluster analysis confirmed this lack of a common vision: While amongst 50 stakeholder representatives, 22 “cluster respondents” with similar preferences could be identified (Figure 3), the other 56% of respondents were almost idiosyncratic and perhaps unfavorable to MAR; e.g., the “typical non-cluster respondent” was indifferent or negative with respect to check dams.

7. Conclusions

Groundwater is an important source of domestic water supply in Chennai during the regular droughts and the peri-urban villages depend completely on groundwater. As agriculture and industry have been overexploiting groundwater, which is evident from the lowering of the water table and the intrusion of seawater, more effective instruments would be needed to control the extraction of groundwater and the use of water.

The paper investigated several feasible approaches, amongst them two MAR options, namely to build large check dams or many small infiltration ponds.

For the considered options, urban RWH is widely accepted and already mandatory, but stakeholders reported ineffective monitoring. Thus, better enforcement could make RWH more effective and better define the impact.

As to non-structural policy instruments, stakeholders identified them with water pricing and did not accept them.

Desalination plants and reverse osmosis of brackish water are too costly solutions to cover the basic demand, and consumers may not accept them.

Building new reservoirs for additional water or building check dams for groundwater recharge are costly, too, and in similar projects conflicts about land acquisition have caused substantial delays.

For the same reason, infiltration ponds could meet resistance, as thousands of ponds would be needed, but there is no legislation that would make them mandatory.

Further, for the implementation of infiltration ponds there is a coordination problem, as it would have not much effect, if only a few farmers would build small infiltration ponds: About 500 ponds would correspond to a small check dam and 10,000 to a large one. Thus, farmers would face costs, the groundwater table might barely rise, and if it rises, then farmers without infiltration ponds would be free-riders that benefit as well.

From these considerations it follows:

- In the short term the most economical solution to secure water supply appears to be the enlargement of existing reservoirs. This solution is also generally accepted.
- In the long term, infiltration ponds, which are the second most economical solution, are an alternative that most stakeholder representatives would accept. However, a coordination problem needs to be resolved.
- All other options are already implemented (RWH; also most planned check dams along Arani and Kortallai Rivers are realized) or significantly more costly or not acceptable for most stakeholders.

To solve the coordination problem, stakeholder representatives support the idea to establish an authority in the state for licensing groundwater extraction and overseeing MAR. Accordingly, the establishment of a state authority responsible for groundwater governance and MAR (TNWRRA) would support the legal and policy measures needed to implement MAR structures. Thus, in this respect, stakeholders basically support the National Water Policies, where such instruments have been proposed. Of course, stakeholders did not envision merely another organization amongst the many existing ones, but wanted to see all groundwater responsibilities amalgamated.

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Author Contributions

All authors are equally responsible for the conception of the paper. The CEMDS team was responsible for the data analysis and legal analyses, the Anna University team for the factual information and all Indian authors for the information acquisition from the workshops.

Conflicts of Interest

The authors declare no conflict of interest.

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