MANAGING AQUIFER RECHARGE

A Showcase for Resilience and Sustainability

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SHORT SUMMARY

Creating profound economic benefits and ensuring environmental sustainability

Innovative solutions are vital to tackle challenges to water security and climate resilience. This book presents 28 real-life examples of Managed Aquifer Recharge (MAR) from around the world, where, at village to state level, people have collaborated to improve quantity and quality of water supplies and buffer them against drought and emergencies. The diverse cases inspire an improved understanding of groundwater systems and showcase their capability to store additional water to meet critical human needs for water and food, and to purify water relying on passive treatment.

The case studies give irrefutable evidence that water resources can be sustained, groundwater storage increased, environmental flows in streams enhanced, and seawater intrusion prevented, while passively "treating" water to improve its quality with natural processes. These MAR schemes, often in operation over many years, have demonstrated a level of success that has gained public support. The lessons learned deserve to be shared widely, given the prevalence of the problems solved.

28 Managed Aquifer Recharge case studies reveal

50%

reduction in costs compared with conventional alternatives

MAR has been proven to produce a wealth of benefits from integrated management of a wide range of conventional and un-conventional water resources, paving the way for global adoption to achieve sustainable development goals for water.

"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

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A Showcase for Resilience and Sustainability

Editors:

Yan Zheng, Andrew Ross, Karen Villholth and Peter Dillon

2021

Preface

Groundwater is the earth's foundational water resource that supplies streams and wells, and hence drinking water and food for the majority of people on the planet. It buffers water supplies during drought and climate change and can give the purest safest natural drinking water. However, as a hidden resource its effective management needs vision and understanding, and particularly its connections with all forms of surface water. Enhancing groundwater recharge will become an increasingly valuable adjunct to approach groundwater extraction in order to continue to have durable supplies. Thousands of examples of managing aquifer recharge can be found but few are documented in such a way to give a clear picture of the sustainability and economics of such supplies. Hence this book was produced as a significant product of a chain of activity that goes back 20 years.

The start of the Millennium was a time of bold vision and renewed urgency to address perennial grand challenges, including in water supply, food and pollution through innovative integrated responses. The International Association of Hydrogeologists established a Commission on Managing Aquifer Recharge to explore promising emerging water management techniques with soundly based science, and inform planners, implementers and regulators so that projects to enhance recharge would be sustainable and have real impact on those challenges. The UNESCO Intergovernmental Hydrological Programme in one of its many initiatives, hosted a meeting of leaders of global organisations in Paris 25-26 April 2002 on "Management of Aquifer Recharge". Out of that meeting was born the shared strategic intent to coordinate progress on this topic through the IAH Commission on Managing Aquifer Recharge. This has remained a focus of activity and collaboration ever since, including through a series of working groups to advance knowledge and its dissemination on technical, governance, economic and sustainability aspects of MAR.

Case studies provide a compressed and practical form of learning, not only about what has been done at local level, but how and why in the context of the pre-existing situation, and the consequences of the intervention. This book showcases 28 diverse exemplary MAR schemes from around the world documented by those directly involved with implementation to give readers insight. The volunteers who provided these case studies enabled a consistent assessment of sustainability and economic benefits.

UNESCO and IAH are pleased to have initiated this production, with support also from the Groundwater Solutions Initiative for Policy and Practice (GRIPP), as a milestone contribution to IHP-VIII: Water Security: Responses to Local, Regional, and Global Challenges.

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Organisations that jointly initiated this book

UNESCO Intergovernmental Hydrological Programme

UNESCO IHP recognizes the importance of managed aquifer recharge as a means of buffering against climate change and drought. Groundwater is vital and in the 8th IHP phase (2014-2021) Theme (2) "Groundwater in a changing environment", contains a Focal Area "Addressing strategies for management of aquifer recharge". UNESCO IHP has been active in developing and applying methods to assess impacts of MAR on water availability and quality, social and economic resilience and local ecosystems. Evaluating sustainability and the costs and benefits of MAR are important components. This book is one of the outcomes of the collaborative work between UNESCO, IAH and GRIPP. More information on UNESCO IHP's activities is given at the IHP web site: https://en.unesco.org/themes/water-security/hydrology

International Association of Hydrogeologists Commission on Managing Aquifer Recharge

Established by IAH in 2001 with encouragement from UNESCO to coordinate international effort, the MAR Commission aims that MAR is used to expand and secure water supplies and improve water quality in ways that are appropriate, environmentally sustainable, technically viable, economical, and socially desirable. This is achieved by: increasing awareness of MAR; disseminating results of research and practical experience; facilitating international exchange of information; informing policy development; and facilitating joint projects of international value. This collaborative book is a fitting example. The IAH-MAR web sites in English, Spanish and Chinese contain more free resources, an introduction to working groups and communities of practice, an email list open to all, and information on upcoming symposia on MAR: https://recharge.iah.org/; http://www.dina-mar.es/; http://china-mar.ujn.edu.cn/index1.htm

Groundwater Solutions Initiative for Policy and Practice

Established in 2016, GRIPP is a global initiative of more than 30 partners, including UNESCO IHP, IAH and IGRAC. Coordinated by the International Water Management Institute (IWMI), it aims to support sustainable groundwater management for livelihoods, food security, climate resilience and economic growth through creating long-term partnerships, sharing and scaling up transferable solutions, filling in knowledge gaps, and advocating for policy focus and investment in groundwater. It builds, inter alia, on the Global Groundwater Governance Project and the expertise of GRIPP partners in co-developing informed solutions in developing countries in collaboration with local, national, regional and global players. MAR is one of a number of core "solutions" promoted by GRIPP. For more information, see the GRIPP web site: http://gripp.iwmi.org

Acknowledgements

The co-editors are grateful to the many contributors who went to enormous efforts to provide information in a format that enabled synthesis and increased the value of each case study. We wish to acknowledge the many organizations that initiated and operated these MAR schemes and were willing to share their stories for the global benefit. We thank IAH and GRIPP for supporting the concept of documenting these case studies and particularly their environmental and social sustainability indicators and their economic costs and benefits. As an UNESCO Intern, Ms. Paulina Ramírez Quevedo greatly assisted the production of this book, in coordination with Mr. Mahmoud Radwan and Dr. Aurélien Dumont (Groundwater Systems and Settlements Section). IAH has played a significant role by establishing a Commission on Managing Aquifer Recharge whose working groups triggered this publication. We also acknowledge the catalytic role of GRIPP in identifying managed aquifer recharge as a solution in advancing improvements in groundwater policy and practice. This book is a testament to the concerted efforts of many people from around the world who have enthusiastically supported the basic concept that MAR can be of huge local benefit and with broader recognition of its benefits that it can play a much larger role globally in efficiently enhancing and securing water resources and improving water quality.

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* corresponding author

Executive Summary

Population growth, urbanization, and climate change will increase and intensify the demand for water and the need to buffer against variability in its availability. At the same time, surface water storage reliability will decrease, while the need to protect the quality of water resources and water-dependent ecosystems will increase in importance. Groundwater systems around the world presently supply 30% of household water needs and 40% of irrigation and are better buffered than surface water. However, already around 25% of groundwater use is unsustainable and groundwater use is growing at 5% each year. There is a clear need to identify innovative and integrated solutions to tackle these intertwined challenges to water security and climate resilience.

This book offers hope. It puts on a pedestal 28 real-life examples where, at village to state level, people have collaborated concertedly to manage their water resources to improve quantity and quality of supplies, while buffering against drought and emergencies. The cases show that precedent is no prerequisite, and are offered to help inspire leaders, and assure followers that people at ground level who develop an understanding of their groundwater can adapt and design workable solutions to sustainably meet their needs.

The common thread for these case studies, managed aquifer recharge (MAR), follows the basic principle of intentionally replenishing aquifers to stabilize water storage and improve water quality. This can be done in a myriad of ways that respect other uses of water or harness otherwise wasted water. The enthusiasm for MAR schemes and their popularity and success are enhanced by significant auxiliary benefits such as in protecting against seawater intrusion, improving environmental flows, banking water for drought relief and purifying water through natural processes.

The 28 accounts of how the case studies evolved from concept to implementation, and the experiences and impacts of those actions are reported first-hand by the implementers and operators. Many projects are long-lived, illustrating their feasibility and competency. Many have continued to evolve as needs or conditions changed. While they are all exemplary cases of the state-of the art of MAR, each one has been evaluated for its environmental and social sustainability using a basic qualitative technique specifically developed for this book in order to further evaluate their strengths and sustainability. Furthermore, the cases underwent a benefit-cost assessment, to understand their relative economic benefits and their costs relative to alternative solutions.

Three of the nine sustainability indicators evaluated relate to factors beyond the control of the project implementers reporting the cases. While they were clearly in place in some cases, their shortcomings in a number of cases suggest that sustainability of MAR, and the groundwater resource or drinking water supplies to which it contributes, would be enhanced if groundwater allocation plans and groundwater quality protection policies were implemented, and groundwater quality monitoring capabilities and public consultation procedures were established. The finding that effective MAR projects exist in places without supporting governance and scientific arrangements in place, suggests that these are not prerequisites for MAR, but that investments in MAR would be more secure if such measures were in place.

Where MAR schemes were implemented concurrently with demand management they materially contributed to recovery of over-drafted aquifers. However, MAR alone could not reverse groundwater level declines but did help supplement local supplies. This suggests huge opportunities for governments to transition over-exploited aquifers to more sustainable groundwater supplies by applying MAR to complement demand management for the benefit of local communities. It could be asked "why should governments invest in MAR systems unless groundwater users agree to water sharing plans leading to sustainable systems? Otherwise there is no assurance that MAR can meet the objective of sustaining groundwater supplies in the long-term." The same argument inhibits private investment in MAR in such systems. In systems where demand management is in place, public and private investments are used to expand water supplies, and public investments to enhance water security.

The evolution of MAR has progressed in several cases as far as the formation of government water banking and trading entities, in the context of water allocation plans. These encourage private investment in MAR to guarantee that existing and future water demands are met through the earning of entitlements by banking natural and/or highly treated recycled water in aquifers.

Ten case studies use recycled water from sewage treatment plants, industrial wastewater, treated urban stormwater or desalinated water as stable sources of water for MAR to provide water for drinking or other uses. Evening out imbalances between supply and demand using aquifers can greatly increase the efficiency of investment in water recycling. Advances in treatment methods are improving the quality of recycled water and reducing costs, creating new opportunities for MAR to enhance and secure water supplies with water that would otherwise be wasted or pollute streams, aquifers and estuaries. This is supported by groundwater protection policies to help protect human health and the environment.

At present, there is only one nationwide rigorous risk-based MAR guideline for protecting health and environment, the Australian Guidelines. These require investigations on the quality of water to be recharged, and on groundwater quality and aquifer mineralogy to determine an appropriate level of treatment for water to be recharged that takes account of biogeochemical reactions occurring in aquifers when new water sources are introduced. At one case study, such guidelines have enabled urban stormwater to be injected to freshen a brackish aquifer to make it suitable for safe irrigation water supplies. At several other sites, recharge with recycled waters is being used to inhibit saline intrusion into coastal aquifers and thereby prolonging and sustaining freshwater supplies.

One environmental sustainability indicator is the change in environmental flow that protects downstream users and ecosystems identified in a catchment water management plan. In some case studies in low- to middle-income countries, such as India, greatly expanding investments in MAR using in-channel modification are focused on increasing food security with limited regard for flow downstream. Catchment water management plans either do not exist or fail to consider environmental flows, and this is particularly important for downstream communities and ecosystems in years of below average runoff. MAR investments when aligned with water management plans would maximize beneficial impacts over the whole catchment. In several other cases a primary role of the MAR intervention is to restore or enhance base flow for ecological conservation.

Another sustainability indicator, energy intensity for recharge and recovery of water (in units of kilowatt hours per cubic meter of recovered water), revealed a strong contrast between case studies that depended on treatment and pumping requirements. Operating and maintenance costs were evaluated for most cases but embodied energy in engineered systems were mostly excluded as this information was rarely recorded. Possibilities for greater use of renewable energy should be considered more routinely for future projects.

An economic assessment was undertaken for all case studies, for which data were available. This included common ways of evaluating costs and benefits of each project and thereby to determine benefit to cost ratio (BCR). In most cases, levelised costs were calculated. Levelised cost of a water supply project is defined as the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply provided by the MAR scheme. Costs were calculated in local monetary units using a standardized project life and discount rate. Costs were then converted to year 2016 values using a GDP deflator, and to US dollars. The standardization of levelised costs in 2016 US$ enables comparison of the cost of water from heterogeneous MAR projects, and comparison of the benefits and costs of MAR projects with alternative solutions. The volume-weighted mean levelised cost of three riverbank filtration schemes was US\$0.10/m^3, of eleven schemes recharging natural water by infiltration or wells US\$0.16/m^3 and for six schemes recharging recycled water by infiltration or wells US\$0.75/m^3.

To assess the cost of three MAR case studies developed for drought and emergency supplies, where volumes and years of use are highly variable, the method used for costing was to divide the capital cost in US dollars by the daily amount recoverable from storage. The cost ranged from US\$730/m^3/day to US\$980/m^3/day.

In the absence of market prices, the value of benefits of MAR schemes were taken as the avoided cost of the cheapest alternative supply or treatment, or net value of production using recharged water (e.g. farm production). Resulting volume-weighted average benefit-cost ratios (BCRs) for ten schemes using natural water and for four schemes using recycled water both exceeded two. This excluded some bank filtration schemes that had very high but unquantified BCRs, as alternatives were considered so expensive or impractical that they had not been costed.

Water banking to increase security and resilience of water supplies has very significant social and environmental benefits that are not accounted for in the benefit-cost analysis above. Further analysis of these benefits would provide additional comparative evidence to guide investment in MAR and water resources management policies that seek to buffer against shortfalls by giving incentives for MAR and water banking.

The information yielded from experience of the 28 diverse case studies provides irrefutable evidence that MAR has helped communities overcome water challenges, prepare for the future, increase safety of water supplies and enhance ecosystems. This has generally been achieved at less than half the cost of conventional alternatives. These case studies are a source of confidence and inspiration for individuals, communities, enterprises and governments to investigate their groundwater systems and systematically and sustainably implement MAR to harness a wealth of benefits from integrated management of a wide range of water resources, with the subsurface providing a critical storage component.

Section I. Synthesis


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How to cite chapters or case studies (example):

Artimo, A., Puurunen, O. and Saraperä, S. 2021. *Case Study 2: Managed Aquifer Recharge for Drinking Water Supply, Turku Region, Southwestern Finland*. pp. 92-99 in Zheng, Y., Ross, A., Villholth, K.G. and Dillon, P. (eds.), 2021. *Managing Aquifer Recharge: A Showcase for Resilience and Sustainability.* Paris, UNESCO.

Chapter 1: Introduction

1.1. Background and rationale

> *Managed aquifer recharge is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. It is not a method for waste disposal.*

Managed aquifer recharge describes a wide range of methods to store water in aquifers or to induce recharge by river bank filtration to improve water quality. In a changing climate and with increased need for food and water by growing populations, increasing water storage will be necessary for secure supplies. Aquifers have been traditional secure water storages in semi-arid and arid areas. However, they have been heavily exploited creating room for storing more water in the short term, but are not a viable option for long-term storage unless additional extraction is prevented. More dams are an alternative, but with longer residence times and higher evaporation rates, adding modular subsurface storage to augment surface storage is a proven more efficient use of land and economic resources.

However, challenges related to MAR, such as the need for investigations on aquifer storage capacity and efficiency to enable siting and design of projects together with water quality evaluation and environmental impact assessment, have been seen as barriers to implementation. The need to manage surface water and groundwater quantity and quality requires cooperation amongst government agencies. The policy dimensions are simple for short term storage, but water banking for drought relief requires agreed water sharing plans and honoring of water entitlements, and community engagement for this may take time. Social, economic and environmental success of MAR is assured by following best practice. The case studies in this book, reveal that these challenges can be met and MAR can pay great dividends. Projects are presented as factual summaries, not as a sales document for one class of water management solutions. They vary in environmental and economic performance according to local circumstances including governance arrangements. Examples range from the rudimentary to highly sophisticated, and demonstrate the value of fit-for-purpose MAR to local communities up to whole of state or basin scale. Section I of this book synthesizes the learnings from the whole collection of case studies.

Section II of this book presents 28 cases of successful MAR projects with a range of objectives using diverse sources of water, recharge methods and aquifer types. All were subject to a newly devised common environmental and social sustainability assessment. Where practical the costs and benefits of MAR projects were also evaluated using established economic frameworks. The document is intended to help water resources managers and potential users of MAR to gain insight into examples of MAR that are both relevant to their own situation and demonstrably sustainable and economic. The evolution of projects from concept to realization, is conveyed in each case study to help readers become aware of some of the processes for initiating successful projects. Precedent is not a prerequisite for MAR, as proven by many of these case studies, however these early adopters stories may give encouragement to not only adapt, but also to initiate new creative approaches using MAR to achieve societal goals for resilient secure and safe water supplies, to support people, agriculture, industry and environment.

1.2. Objectives

In short, the objectives of this book are to:

Provide and showcase a set of exemplary long-term sustainable MAR schemes from around the world, in a form that is accessible and useful for water suppliers, water resources planners and managers, farming collectives, and environmental managers

Develop and apply a set of pioneering environmental and social sustainability indicators that would be useful in a basic checklist for those planning, investing in or regulating new MAR projects to help ensure sustainability in future.

Apply conventional economic assessment of the costs and benefits of MAR as many case studies as practical to provide planners and proponents of new MAR projects an indicator of likely costs of MAR projects and simple procedures to determine economic viability.

1.3. Precis of Case Studies

Salient and distinguishing features of each of the 28 case studies are given here in the same sequence as the case studies are presented in Section II. This is intended to aid the understanding of the following synthesis chapters in Section I. Obviously a much more complete understanding can be gleaned by reading the case studies themselves. It is expected that the characterization of case studies given in the next synthesis chapter will help readers to identify those case studies that are most relevant to their reasons for reading this book.

1. **Ahmed – Khulna-Bangladesh.** Pond water and roof rainwater is sand-filtered and injected into a brackish aquifer to freshen it for village household water supplies. Local women have formed a committee to maintain and manage each operation and collect small fees to cover operation and basic maintenance, including manual filter backwash. There is also a water users group. Water is recovered by hand pump, retaining social interaction and minimizing waste. Water volumes are small, unit costs including capital are high, but cheaper, using much less energy, and more sustainable than the alternative, reverse osmosis.
2. **Artimo – Turku-Finland.** This is an exceptional case that has been founded on thorough hydrogeological and water quality investigations to improve drinking water security and quality for 300,000 people by pretreating river water brought from 100km away by coagulation filtration and then recharging an aquifer via infiltration basins to buffer the water storage and provide additional water treatment before recovery, chlorination and distribution. The system is extensively monitored and managed to ensure compliance with environmental and health regulations.
3. **Chávez – San Luis Rio Colorado-Mexico.** Water recycled to agriculture with soil aquifer treatment replaced disposal to the riverbed which polluted the river and groundwater. The Soil Aquifer Treatment system improves water quality making it fit for use for irrigation, solving two problems at once-pollution and water supply. It has operated for more than 10 years with maintenance to manage clogging.
4. **Dashora – Rajasthan-India.** In spite of billions of US$ of investment in recharge structures in India, monitoring their hydraulic and economic performance has been very sparse. These four check dams monitored by farmers have revealed

the economic benefits for sustaining irrigation supplies, with benefit cost ratio exceeding 4. They also reveal that periodic desilting needs to avoid subsurface compaction. There is a finite capacity for expansion of check dams without adversely affecting flows downstream, especially in dry years. Linking investment in check dams with a community's willingness to maintain them and to participate in water budgeting would be an important step towards sustainable use, and to set this in the context of whole of catchment watershed management, in order to maximize and make fairer the regional benefits of these interventions.

5. **De los Cobos – Geneva-Switzerland.** This site has recharged the Genevese trans-boundary aquifer shared by Switzerland and France for more than 40 years. It gives robustness to water resources, and agreements have been flexible over the years to accommodate all needs. Recharge capacity cannot be fully utilized due to frequent high turbidity in source water in Arve River. Control systems shut recharge when water quality is poor. Costs are significantly lower than the alternative - enhanced treatment of surface water.
6. **Elkayam – Shafdan-Israel.** Water recycling via infiltration of treated waste water has occurred for more than 40 years and has expanded to 135Mm^3/yr using 110 Ha SAT ponds (average hydraulic loading of 120m/yr, infiltration rate ~1m/d) for recovery for irrigation 100km away delivered by third line to the Negev. This has turned a waste into a resource, and a governance arrangement established with monitoring (75 wells) and committees to evaluate results and plan next stages has ensured supply of good quality irrigation water with acceptable and desirable environmental impacts, and minimal energy use 0.62 KWh/m^3 water to improve water quality.
7. **Fernández Escalante – Castilla-León-Spain.** Agreed access to a share of seasonal excess surface water in Cega River has been negotiated by a consortium of farmers who recharge this to the Los Arenales aquifer where it now contributes about 24% of the water they extract for horticultural irrigation. This has reversed a decline in groundwater levels, stabilized production and employment, and enhanced the environment through wetland preservation. They use infiltration basins, canals and pits to infiltrate water to the aquifer. Very low energy use is needed. Negotiations for an expansion of MAR are being resisted due to competition with other uses of river water.
8. **Grischek – Hosterwitz-Germany.** A riverbank filtration system has been operating successfully for more than 100 years to supply drinking water to Dresden. This provides a very low energy natural treatment for water, supplemented with infiltration basins as part of post-treatment. Sections of the water plant adjacent Elbe Rivera were submerged during occasional floods, and although there is evidence that water quality is well protected, ultrafiltration has been trialled as a supplementary treatment. This worked most efficiently drawing bank filtrate rather than water directly from the river. Trials of unclogging of infiltration basins have been undertaken on this site and experimentation is proceeding. Measures to protect the river and groundwater catchment are needed so that reliance can continue on these low cost and low energy natural treatment systems.

9. **Higginson – Perth-Australia.** It took 12 years from the time of concept development to government approval and investment in aquifer injection of advanced treated recycled water into the aquifers used for drinking water supplies for Perth. The nature of the risks and the potential for political or social division and the importance of having an effective solution demanded time for the execution of investigations and conduct of a 3-year trial. This allowed very significant and focused data acquisition, rigorous evaluation of results, establishment of process controls and operational experience, and time for dissemination and digestion of information, regulatory consent and public approval. Like the trial, the operating project has transparent reporting to the public of any incidents and enjoys overwhelming confidence of the residents of Perth. Its rigorous risk management plan demonstrates state of the art of management of potable reuse via aquifers.

10. **Hutchinson – Orange County-USA.** Established in 1936 in response to severe overdraft and saline intrusion into coastal aquifers, Orange County Water District protected the groundwater basin by harvesting water from the Santa Ana River and recharging it via infiltration basins. The annual infiltration from this source is 148 Mm^3/yr, which together with natural recharge of 123 Mm^3/yr and about 100 Mm^3/yr from other MAR balances the 370 Mm^3/yr extraction. Considerable research and investigations have improved infiltration rates and demonstrated water quality protection. These works are supported by a replenishment assessment that OCWD charges all groundwater users. This MAR option is demonstrably cheaper and more energy efficient than alternatives.

11. **Jadhav – Baramati-India.** Recharge structures in ephemeral streams were first constructed in a concerted program in 1968 to combat declining groundwater levels, drought and crop failure. This was a highly effective partnership of government, community and NGOs, and the practice proliferated. In recent years attention has turned to desilting of these recharge structures, to maintain their function. This is regarded as effective, but lack of monitoring has prevented quantitative evaluation of performance and there has been no evaluation of water quality impacts, nor any catchment water management plans in place to maximize benefits of investments.

12. **Jones – North London-UK.** Trials commencing in the 1950s led to establishment of a water banking scheme in North London in 1995. This has helped secure London's water supply using drinking water, when available, to replenish storage in the Chalk and Basal Sand aquifers to support natural recovery following abstraction. This can meet 6% of the city's supply in drought years, at a cost substantially less than other alternative supply options by making efficient use of existing infrastructure. Potential water quality concerns were evaluated, tests conducted, found to be well managed, allowing significant expansion of the scheme over time. The regulatory arrangements have been comprehensive, requiring demonstration of the absence of significant hydro-environmental impact and setting out management rules. Thames Water customers have been informed of the MAR system and its drought benefits.

13. **Murray – Windhoek-Namibia**. A system of injection wells to recharge a fractured rock aquifer has recovered a depleted groundwater storage and is banking water for future drought water supplies. Capacity is being expanded and the system provides buffering storage that will reduce the costs of alternative water supplies if eventually needed without the evaporative losses that surface storage would incur.

Regulations have been put in place to protect the stored water from pollution by preventing future urban development in the storage area. An agreement between main institutions is in process that will assure continued effective operation of the system.

14. **Naumann – Salisbury-Australia.** There are multi-dimensional benefits in urban stormwater harvesting via aquifer storage and recovery in a brackish aquifer. A local government body was able to conceive the benefits of reduced flooding, improved urban amenity, enhanced ecological heath of streams and coastal waters, expanded opportunities for recreation and reversal of urban heating effects under increased urbanization. The combination of benefits gave significant benefit cost ratios, exceeding those for water supply substitutes and increased security of supply alone. This gave confidence for investment, and for local government commencing an innovative wholly owned subsidiary 'Salisbury Water' to build capabilities and implement projects. This has a risk management plan for stormwater to non-potable supplies that is internationally unique. It has expanded to a network of sites connected to a distribution system for non-potable supplies.
15. **Pavelic – Uttar Pradesh-India.** This is a pilot study that shows promise for large scale floodwater harvesting during the monsoon season via village ponds to help offset decline in groundwater levels and secure irrigation supplies. The task would be easier to accomplish if there were water resources management plans in place to restore groundwater storages, secure irrigation supplies, and mitigate flooding. There would also need to be plans in place to protect groundwater resources used for drinking water supplies, helping with siting recharge operations and giving appropriate treatment where needed to protect public health. Finally there needs to be a process for village level ownership and participation in planning and implementation of such schemes to ensure there is capability to maintain and sustain these systems. Modelling suggests that if scaled up there would be considerable potential benefit for such a system to increase water security, food production and at very large scale, to also mitigate floods.
16. **Picot – Colbeaux –Normandy-France.** Soil aquifer treatment is used as a polishing step before discharge of secondary treated effluent to sea in an area where shellfish are commercially grown and in an estuary known for tourism. There is a monitoring plan to assess nutrients and micro-pollutants in the discharge from the sewage plant and in groundwater near the intermittently operated infiltration basins, and this has been agreed with national and local regulators and representatives of local government and the shellfish industry. This involves public annual reporting and reporting of any exceptions beyond the standards. The recharge operation also deters saline intrusion.
17. **Powers – Central Platte River-USA.** Intentional diversions from Central Platte River to irrigation canals in the non-irrigation season are used to increase groundwater storage and consequently secure irrigation supplies as well as enhance baseflows in the hydraulically-connected river during the dry season to support endangered bird species. A sophisticated nested arrangement between state government, local government and canal operators assures all irrigators of their water rights while also meeting environmental obligations. Costs of the recharge operations are borne by the property owners through local government entities.

18. **Pyne – Hilton Head Island-USA.** Saline intrusion into a drinking water supply aquifer on an island has led to a deeper brackish Floridan aquifer being used for brackish water desalination supplemented by pipeline supplies from the mainland. As further shallow wells have become salinized, additional mainland piped water has been purchased in winter when cost was low and pipeline capacity available, and injected into the deeper brackish aquifer for recovery from the same well during peak demand in the following summer. After hydrogeological investigations, one year of supply was initially injected into the aquifer to provide a fresh-water buffer zone before regular annual cycles of injection and recovery. Only disinfection is required on recovery. This has provided an economical system to increase and secure water supply without needing to build a desalination plant or duplicate the pipe connection to the mainland to treat and supply water at its peak rate. Aquifer storage recovery (ASR) has been demonstrated over 5 years to be a highly efficient and robust preferred option and is being expanded as further shallow wells salinize.
19. **Rossetto – Serchio River-Italy.** An established riverbank filtration scheme was expanded to now supply 300,000 people following hydrogeological investigations, water quality evaluation and modelling. This gave assurance that the upgraded system, which included a weir to increase groundwater storage, would have acceptable drawdown and that abstracted water would meet drinking water quality requirements. Minimum baseflow requirements were met through reservoir releases. A risk management plan was developed to ensure protection of drinking water supplies. This was developed with the assistance of real time field monitoring with a photospectrometer.
20. **Sandhu – Haridwar-India.** This site has expanded over more than 50 years to demonstrate the value of river bank filtration along the Ganges River to provide very low cost resilient naturally-treated drinking supplies. This was recognized in 2006 when the Department of Drinking Water of the Government of Uttarakhand issued a government order encouraging RBF to be considered by water supply organizations working in that state. The measured and sustained 4 log removal of pathogenic bacteria and >2.5 log removal of turbidity without use of additional costs or energy is highly valued where it is practiced. Further demonstration projects are warranted in many states and countries and would see an enormous increase in appreciation and use of river bank filtration for water supplies in cities built on or near alluvial aquifers.
21. **Seasholes – Arizona-USA** Arizona is the first jurisdiction known to have created an institution, a water bank, whose sole responsibility has been to recharge intermittent excess surface water to aquifers where it is stored to increase the security of future water supplies. Arizona is an arid state with a growing population and historical legacy of falling groundwater storages. The state has extensive highly transmissive unconfined aquifers containing high quality water, deep water tables and permeable soils. It also has an entitlement to take water from the Colorado River and an ability to distribute this through the Central Arizona Project canal. Water banking via managed aquifer recharge has been made possible at a large scale to meet broad water management objectives through a strong regulatory framework, together with public funding and innovative public institutions, such as the Arizona Water Bank.

22. **Shamrukh – Asyut-Egypt.** A bank filtration scheme operated for 14 years as a drinking water supply for a city on the River Nile, and is now a backup supply in case of failure of a new surface water treatment plant. The RBF system gave higher quality supplies than either surface water or native groundwater and had a lower capital and operating cost and lower energy intensity, needing no treatment apart from disinfection required as a risk mitigating measure. It is an attractive option for drinking water supplies where alluvial aquifers are suitable and local groundwater is protected from pollution and over-abstraction.

23. **Shivakoti – Kumamoto-Japan.** This unique MAR project is a payment for ecosystem services scheme (PES) whereby the municipality of Kumomoto on Kyushu, Japan and private companies that rely on groundwater, pay a collective of more than 400 farmers up-gradient to use their rice fields as infiltration basins for up to 3 months each year. They purchase sufficient MAR to gain entitlement to meet their high-valued uses of groundwater and sustain the coastal groundwater resource. This provides 14 Mm^3/yr which is about 13% of municipal water use and is 2.3% of the total recharge to the groundwater system. Independent auditing processes assure the integrity of the system.

24. **Tredoux – Atlantis-South Africa.** In 1980 a bold vision was conceived for a new peri-urban community that would recycle its own stormwater and sewage effluent by using infiltration basins to recharge the unconfined aquifer which was and still is its drinking water source. Through careful design and separation of industrial and domestic wastewater and runoff and even high flow from baseflow of domestic stormwater, a robust system has been operated and periodically upgraded, especially during droughts. Careful protection of the aquifer through land use controls and through risk management plans and practices that include tailored treatment plants, have helped to sustain the system.

25. **Van Houtte – Koksjide-Belgium.** To augment drinking water supplies in 1990 a municipal water supply company performed investigations and obtained approvals to treat wastewater and infiltrate it into sand dunes so that abstraction could be increased. This is carefully controlled and has helped to restore depleted groundwater levels in an area vulnerable to saline intrusion, improved the quality and quantity of the water supply, at a lower cost than alternatives and also led to some improvements in recharge methods to enhance winter recharge rates and reduce the temperature variations in supplied water. The managed aquifer recharge is one of the multiple barriers for ensuring safe water supplies, has public support and has been operating sustainably for more than 15 years.

26. **Wang – Longkou-China.** An underground dam was constructed on a stream flowing on a coastal delta to capture lateral groundwater flow and local rainfall and river infiltration to augment groundwater supplies for irrigation. Groundwater levels rose 8 m and the annual volume available for irrigation increased by more than the holding capacity of the groundwater reservoir created. Within 2 years baseflow began in the stream again. The cost of the additional water is small in comparison with the benefits of the additional irrigation now possible. The method was repeated on 5 other nearby streams. Permit arrangements for similar structures now require a water balance calculation.

27. **Xanke – Wala Dam-Jordan.** The Wala Dam was constructed upstream of the Hidan wellfield to provide detention of flood runoff to increase infiltration and mitigate flooding. Since 2002 it has significantly increased recharge and raised groundwater levels and helped secure municipal water supplies from a karstic aquifer in a semi-arid area. While it has been effective there are evident problems such as siltation in the Wala reservoir, and lapses in implementation of a water quality protection plan for the catchment and aquifer between the dam and the well field. Further improvement in institutional collaboration would be needed to give confidence that a proposed enlargement of the dam will give sustainable benefits for water supply quantity, reliability and quality.

28. **Zuurbier – Dinteloord-Netherlands.** Wastewater from a sugar factory following treatment that involved reverse osmosis was available in winter for use for glasshouse irrigation in summer, and after considering options, was stored via injection and recovery wells in an aquifer that initially contained groundwater that did not meet irrigation quality. A plume of low salinity water was established and could be recovered to meet the growing demand for water. The scheme is owned by the irrigators, so they carry the costs and risks. Agreements have been formed among the organizations needed to sustain and to regulate the operation to enable its successful ongoing operation.

Chapter 2: An overview of features of the Managed Aquifer Recharge Case Studies

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This chapter provides a synthesis of the characteristics of managed aquifer recharge (MAR) practice derived from the collation of 28 exemplary cases spread across almost all inhabited continents. The cases were identified and selected based on an open invitation to practitioners responsible for MAR schemes. The candidates were drafted from the IAH Commission on Managing Aquifer Recharge email list, attendees at the ISMAR10 symposium in May 2019, as well as via the Groundwater Solutions Initiative for Policy and Practice (GRIPP) website on groundwater-based natural infrastructure[1]. The International Groundwater Resources Assessment Centre (IGRAC) MAR Portal[2] also assisted in identifying potential candidate cases from the more than 1200 MAR sites in their global inventory (Stefan and Ansems, 2018) [1]; (IGRAC, 2020) [2]. In order to make a synthesis of the state of the art of MAR, criteria for exemplary MAR cases were promulgated (Appendix I). This is by no means an exhaustive list of exemplary cases, but these were sites where knowledgeable people were willing to invest the effort to document their case studies in such a way that environmental and social indicators and economic costs and benefits could be determined and validated. The 28 MAR cases therefore are a cohort of examples of best practice in MAR from around the world. They vary substantially in their scope, historical development, technology, scale, socio-economic and biophysical and environmental context, as well as water governance arrangements.

2.1. Location of the MAR cases

The 28 MAR cases reported are spread across the globe (Figure 1) and five continents are represented: Africa (3), Asia (9), Australia (2), Europe (9) and North America (5). Although South America is not represented, and for that matter many countries within other continents, this is not an indication that MAR is not practiced in these places, but rather that known cases were not sufficiently documented to perform the sustainability and economic analysis for this book. While not the purpose here, other compilations summarize MAR practices globally (Stefan and Ansems, 2018) [1], and at regional scales: Africa (Ebrahim et al., 2020) [3], Europe (Sprenger et al.), 2017 [4], and Latin America (Valverde et al., 2018) [5]. Further information and locations of most of these can be accessed from the Global MAR Portal (IGRAC, 2020) [2]. It should be noted that the limited number of cases presented here cannot be assumed to be representative of the global cohort of MAR sites.

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[1] https://gripp.iwmi.org/natural-infrastructure/
[2] https://ggis.un-igrac.org/view/marportal

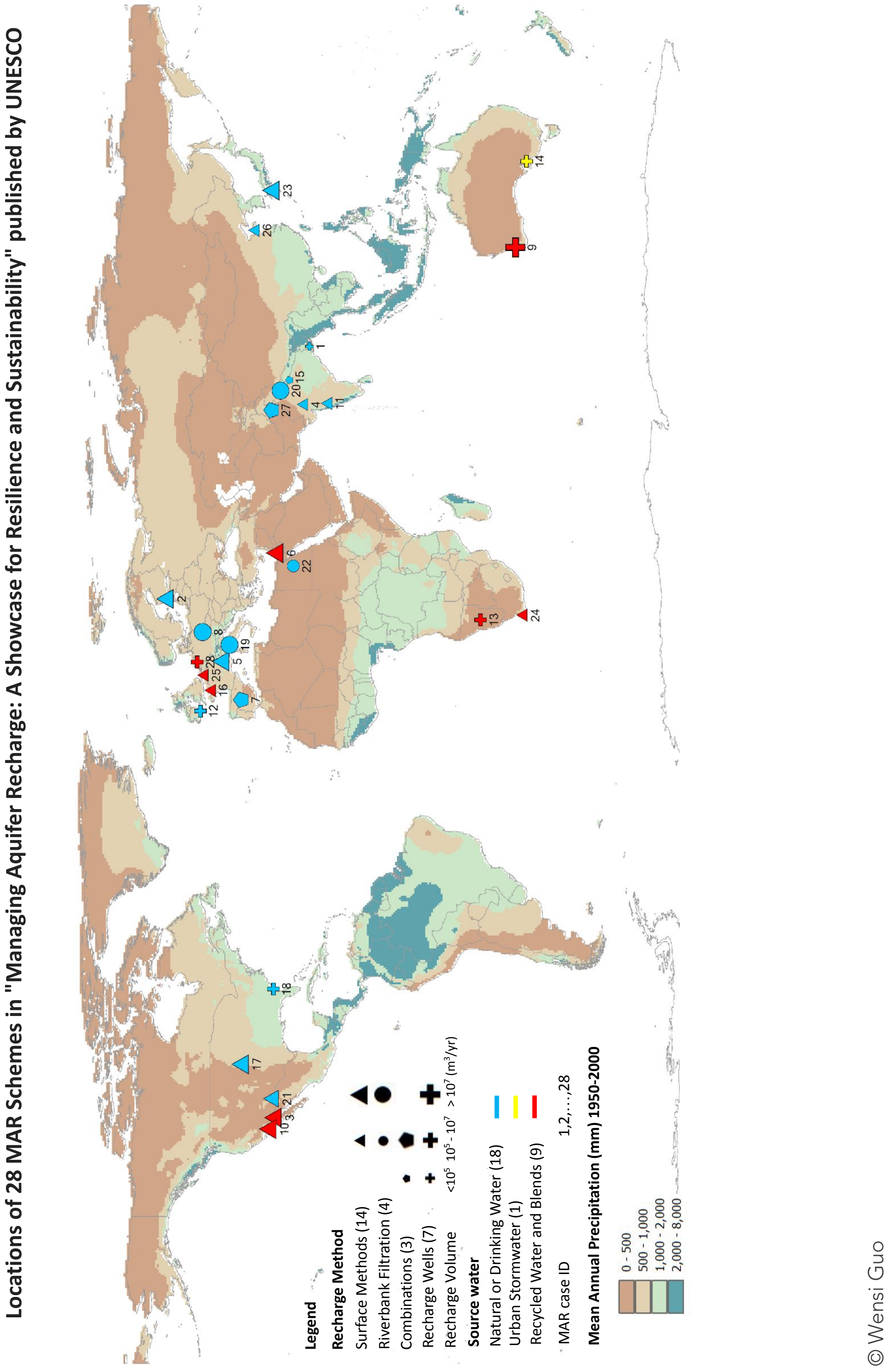

Figure 1.
Location of the 28 MAR schemes. ‘Surface Methods’ include water spreading techniques (infiltration basins, shallow subsurface infiltration, existing reservoirs, and flooded fields), as well as various in-channel modifications. If the source water has a component of reclaimed water, it is classified as ‘Reclaimed Water and Blends’ (map drafted by Wensi Guo).

2.2. Context of the MAR cases

Rainfall at MAR sites and objectives of MAR cases

The MAR cases included in this book are located in both arid and humid areas (average annual rainfall ranging from less than 100 to 2000 mm/yr). The MAR cases in high rainfall areas consistently cover contexts of high population densities, areas with little available land, aquifers afflicted by salinity, and if agriculture is practiced, then mostly intensive irrigated (even greenhouse) cultivated areas (e.g., Shivakoti and Villholth [Japan, 1990 mm/yr], Ahmed *et al*. [Bangladesh, 1700 mm/yr], Pyne *et al*. [east coast of USA, 1280 mm/yr], Sandhu *et al*. [India, 1100 mm/yr] and de los Cobos [France/Switzerland, 950 mm/yr], Zuurbier *et al*. [the Netherlands, 900 mm/yr]).

At the other end of the rainfall scale, in dry areas, it is clear that the drivers for MAR are the high variability and uncertainty of rainfall and the need to secure water availability throughout extended dry and drought periods through capturing and storing of seasonal rainfall and/or more perennially available sources. Hence, in many of these cases, there is a great dependence on source water from more stable supplies, like treated wastewater (here also simply termed reclaimed water), sometimes used exclusively for extensive agriculture (Chávez *et al*. [Mexico, 554 mm/yr], Elkayam *et al*. [Israel, 550 mm/yr], Fernández Escalante and San Sebastián Sauto [Spain, 430 mm/yr]), while in other cases, the main purpose is to secure water supply to large cities (Xanke *et al*. [Jordan, 500 mm/yr], Naumann *et al*. [South Australia, 460 mm/yr], Tredoux *et al*. [South Africa, 445 mm/yr], Murray *et al*. [Namibia, 360 mm/yr], Hutchinson and Woodside [USA, 355 mm/yr], Shamrukh and Abdel-Lah [Egypt, 3 mm/yr]). In the latter set of cases, there is a clear tendency to use a diverse portfolio of source waters to reduce uncertainties of supply, e.g. from surface dams, stormwater, transfer water, reclaimed water and water from large perennial rivers.

In an intermediate rainfall group (approx. 600 -900 mm/yr), the drivers of MAR appear to be the need for water for large population concentrations in bigger cities with good availability of treated wastewater or water from perennial surface water systems (Jones *et al*. [UK, 738 mm/yr], Higginson *et al*. [Western Australia, 733 mm/yr], Artimo *et al*. [Finland, 632 mm/yr], Grischek *et al*. [Germany 592 mm/yr]). Another rationale for MAR in these settings, while not always primary, is to protect the environment, both from seawater intrusion (Picot-Colbeaux *et al*. [France, 807 mm/yr], Van Houtte and Verbauwhede [Belgium, 700 mm/yr], Wang *et al*. [China, 584 mm/yr]), protect coastal shellfish aquaculture from pollution from direct wastewater discharge (Picot-Colbeaux *et al*. [France, 807 mm/yr]), and by enhancing environmental flows and storages (Powers *et al*. [USA, 610 mm/yr]).

Source water

As indicated above, the sources of water used for recharge vary widely between cases (Figure 2). Some schemes use single sources, like "natural water" - i.e. river water, either directly (6 cases) or via bank filtration (4 cases), and pond/reservoir water (2 cases) -, reclaimed water (5 cases), or stormwater (1 case). The remaining ten cases use combinations of the above, including some more exotic sources, like desalinated brackish groundwater from another aquifer (1 case). There is a clear tendency of reclaimed water use being applied in water spreading systems with some level of soil aquifer treatment (SAT), in order to take advantage of the natural additional treatment in the subsurface (e.g., Chávez *et al*. [Mexico], Elkayam *et al*. [Israel], Picot-Colbeaux *et al*. [France], Van Houtte and Verbauwhede [Belgium]).

Table 1.
Characteristics of the MAR case studies

No	Author ref.	Case study location	Country	Annual volume of water re-charged (10^{3}m3/ yr)	MAR type				Aquifer
					In-channel modification	Bank filtration	Water spreading	Recharge wells	Geological formation/ aquifer used for MAR
1	Ahmed et al.	Khulna	Bangladesh	0.64				X	alluvial
2	Artimo et al.	Turku	Finland	22,800			X		esker/ alluvial
3	Chávez et al.	SLRC, Sonora	Mexico	10,500			X		alluvial
4	Dashora et al.	Udaipur, Rajasthan	India	779	X				alluv-hard rock
5	de los Cobos &	Vessy, Geneva	France/ Switz	9,000		X	X		alluvial
6	Elkayam et al.	Shafdan	Israel	130,000			X		calcareous
7	Fernández Escalante	El Carracillo	Spain	2,420	X	X	X		alluvial
8	Grischek et al.	Hosterwitz, Dresden	Germany	24,500		X	X		alluvial
9	Higginson et al.	Perth, WA	Australia	28,000				X	consolidated sed
10	Hutchinson &	Orange County, Cal.	USA	148,000	X		X	X	unconsolidated sed
11	Jadhav et al.	Baramati,Maharash.	India	273	X				alluvial
12	Jones et al.	North London	UK	7,200				X	calcareous
13	Murray et al.	Windhoek, Khomas	Namibia	3,750				X	granite
14	Naumann et al.	Salisbury, SA	Australia	3,000				X	calcareous

type	Source of water			End use of recovered water					
Unconfined, Semi-confined, or Confined aquifer	Natural water	Reclaimed water	Stormwater	Public water supply	Irrigation	Industrial use	Environmental use	Water banking
U - SC	X			X				
U	X			X				
U		X			X			
U	X			X	X			
U	X			X				
U		X			X			
U	X				X		X	
U	X			X				
C		X		X				
U & C	X	X	X	X				
SC	X			X	X			
C	X			X				X
C - SC	X	X		X				X
C			X	X	X	X		

Table 1.
Characteristics of the MAR case studies

No	Author ref.	Case study location	Country	Annual volume of water re-charged (10^{3}m3/ yr)	MAR type				Aquifer
15	Pavelic et al.	Rampur UP	India	44			X	X	alluvial
16	Picot-Colbeau.	Normandy	France	730			X		dune sand
17	Powers et al.	Platte Riv. Nebraska	USA	11,110			X		alluvial
18	Pyne et al.	Hilton Head Is, SC	USA	950				X	calcareous
19	Rossetto et al.	Lucca, Tuscany	Italy	13,600		X			alluvial
20	Sandhu et al.	Haridwar, Uttarakh.	India	15,400		X			alluvial
21	Seasholes & Megdal	Central Arizona	USA	342,000	X		X		alluvial
22	Shamrukh &	Sidfa, Asyut	Egypt	1,533		X			alluvial
23	Shivakoti et al	Kumamoto,Kyushu	Japan	14,000			X		pyroclastic
24	Tredoux et al.	Atlantis, W. Cape	South Africa	6,747			X		sand
25	Van Houtte &	Koksjide, Flanders	Belgium	1,960			X		dune sand
26	Wang et al.	Longkou, Shandong	China	560			X		sand
27	Xanke et al.	Wala Dam	Jordan	6,700			X	X	calcareous
28	Zuurbier et al.	Dinteloord	Netherlands	125				X	unconsolidated sed

type	Source of water			End use of recovered water				
U - SC	X		X	X	X			
U		X					X	
U	X		X		X		X	
SC	X	X		X				X
U	X			X				
U	X			X				
U	X	X		X				X
U - SC	X			X				
C -SC	X			X		X		
U		X	X	X				
U		X		X				
U	X		X		X	X		
U	X		X	X	X			
C		X	X		X			

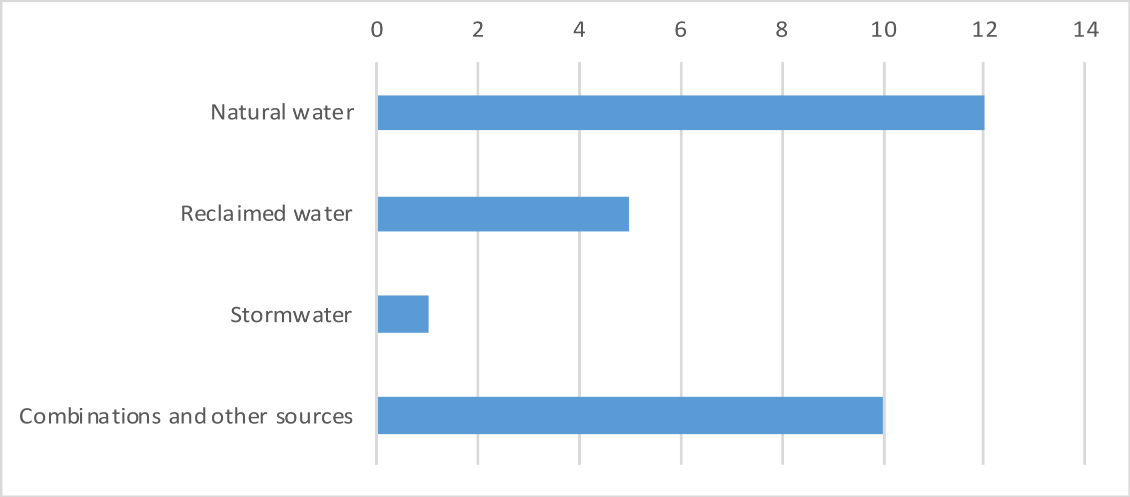

Figure 2.
Distribution of MAR cases across different sources of water. Source: Own elaboration

Using reclaimed water for MAR (solely or partly) is quite widespread (9 cases, 32%) and will likely increase in importance in the future, and likely independent of aridity. Reclaimed water is also used indirectly in some of the bank filtration schemes, especially in Europe, where treated wastewater is discharged to rivers and then later drawn into wells along the banks (e.g. Grischek *et al.* [Germany]).

Type of aquifer

MAR feasibility also depends on the subsurface conditions. Nineteen of the MAR cases recharge unconsolidated sedimentary unconfined aquifers, whereas implementation in fractured formations is not as well represented. This is partly due to generally lower recharge and recovery rates and diminished storage capacity compared to primary porosity aquifers, and also due to difficulty in characterizing fractured systems and hence designing functioning MAR schemes (Tuinhof and Heederik, 2002) [6]. However, the only two cases of the cohort (Dashora *et al.* [India], Murray *et al.* [Namibia]) in fractured hardrock systems have proven very efficient, which indicates that these aquifers should not be excluded in consideration for MAR. There are also cases of MAR target aquifers in consolidated formations, like sandstone/siltstone/shale (Elkayam *et al.* [Israel], Higginson *et al.* [Australia]), volcanic pyroclastic (Shivakoti and Villholth [Japan]), and limestone aquifers (Jones *et al.* [UK], Naumann *et al.* [Australia], Pyne *et al.* [USA], Xanke *et al.* [Jordan]). The latter could be (partially) karstified/fractured systems providing similar challenges as the hard rock aquifers. Unconfined systems (16) outnumbered confined (4) and semi-confined or variably confined across the individual sites (8) (Figure 3). However, there is a tendency to use confined aquifers for the MAR-based public water supply schemes for urban centres (Higginson *et al.* [Australia], Jones *et al.* [UK], Murray *et al.* [Namibia], Shivakoti and Villholth [Japan]), in part due to superior groundwater quality protection. For MAR systems in unconfined aquifers used for drinking water supplies, land use planning and aquifer protection are essential to ensure adequate groundwater quality over the long term.

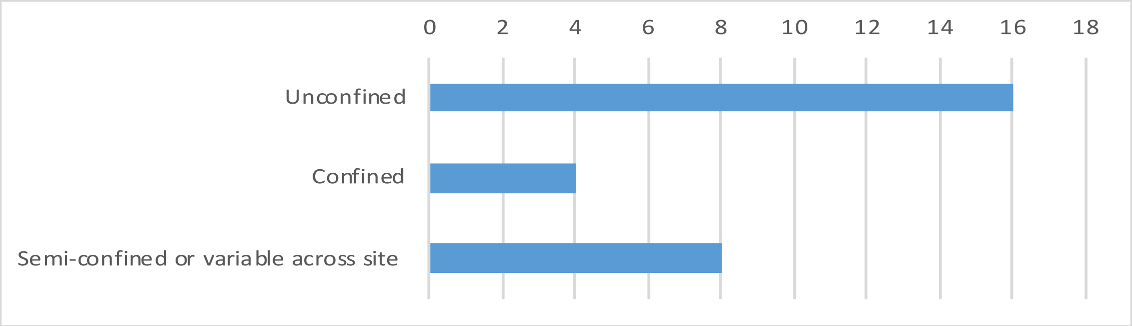

Figure 3.
Distribution of cases according to confinement of recharged aquifer.
Source: Own elaboration

2.3. Type of recharge method

MAR encompasses a range of recharge methods, and the four main categories are: in-channel modification, bank filtration, water spreading, and recharge wells. Hence, this book, excludes other incidental causes of increased recharge, such as land clearing, soil conservation, terracing and contour bunding, where the main purpose is to enhance agricultural production, erosion protection or flood mitigation.

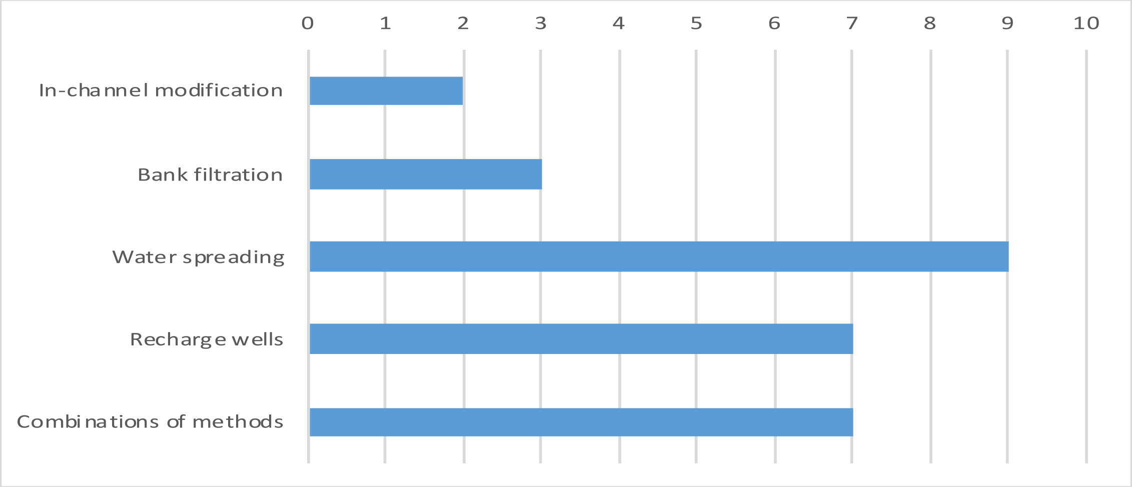

Figure 4.
Distribution of MAR cases across different types governed by the recharge technique.
Source: Own elaboration

The distribution of MAR cases across the different techniques is shown in Figure 4. In-channel modifications, such as check dams and percolation tanks on ephemeral streams (Dashora *et al*., Jadhav *et al*., [India]), increase recharge in the vicinity to sustain irrigation and drinking water supplies. Wang *et al*. [China] use subsurface dams beneath a streambed to sustain water supplies and increase baseflow. In-channel modifications in Santa Anna River (Hutchinson and Woodside [USA]) evolved into infiltration basins (water spreading) within and beyond the channel. Infiltration basins on permeable soil over unconfined aquifers have been used to harvest natural surface water when available in Arizona (Seasholes and Megdal [USA]) and via channels and basins (Fernández Escalante and San Sebastián Sauto, [Spain]) and for polishing treatment of drinking water (Artimo *et al*., [Finland]). Other forms of infiltration, such as through buried slotted pipes, called infiltration galleries, are used for water treatment and storage where land is precious (de los Cobos and Luyet [Switzerland]). When recycled water is used as the water source in infiltration basins, intermittent wetting and drying of basins has been found to improve the water quality reaching the aquifer (Tredoux *et al*. [South Africa]).

Riverbank filtration, the practice of pumping from an alluvial aquifer to induce recharge from a near-by stream and improve the quality of water produced for drinking water supplies is reported in four case studies (Grischek *et al*. [Germany], Rossetto *et al*. [Italy], Sandhu *et al*. [India], and Shamrukh and Abdel-Lah [Egypt]).

Wells may be used to inject water into unconfined or confined aquifers and there are eleven applications presented. In two of these, treated reclaimed water is injected into aquifers that supply drinking water for cities (Higginson *et al*. [Australia] and Murray *et al*. [Namibia]). Some cases are combinations of infiltration basins and wells (Fernández Escalante and San Sebastián Sauto [Spain], Hutchinson and Woodside [USA], Pavelic *et al*. [India], and Xanke *et al*. [Jordan]). For some injection systems, the water is withdrawn from the same well and this has been termed aquifer storage recovery (ASR). This is popular where the ambient groundwater is not fit for the intended use of recovered water and for reducing infrastructure costs. Examples include Ahmed *et al*. [Bangladesh] for village drinking water supplies, Jones *et al*. [UK] and Pyne *et al*. [USA] for resilient city water supplies. ASR is also used for irrigation supplies using urban stormwater (Naumann *et al*. [Australia]), and treated wastewater (Zuurbier *et al*. [the Netherlands]). In general, recharge wells are more common in urban areas, where land is not available for surface spreading methods, and also in all areas, including rural, where confined aquifers make better storage targets than unconfined aquifers (e.g., Ahmed *et al*. [Bangladesh] and Pavelic *et al*. [India]) including due to better protection of groundwater quality.

End use of water

The reported MAR case studies serve a range of end uses and most frequently more than one type of end use (Figure 5). Public water supply was the sole end use for 11 cases, and was one of the uses in 21 of the cases (Table 1). Irrigation is the sole use in three cases (Chávez et al. [Mexico], Elkayam [Israel], and Zuurbier et al. [the Netherlands]) and was among combinations of uses in 11 cases. In one case, (Picot-Colbeaux et al. [France]), ecosystem protection was the sole purpose of the system, and this was one of the primary purposes of another case (Powers et al. [USA]). Not distinguished in Figure 5, because they are among the combinations of end uses, are four cases where water banking was undertaken to provide drought and emergency supplies of various types already mentioned (Ahmed et al. [Bangladesh], Jones et al. [UK], Pyne et al. [USA], and Seasholes and Megdal [USA]). Industrial water use was among the combinations of end uses for three cases (Naumann et al [Australia], Shivakoti et al [Japan], and Wang et al [China]). Thirteen schemes serve multiple purposes.

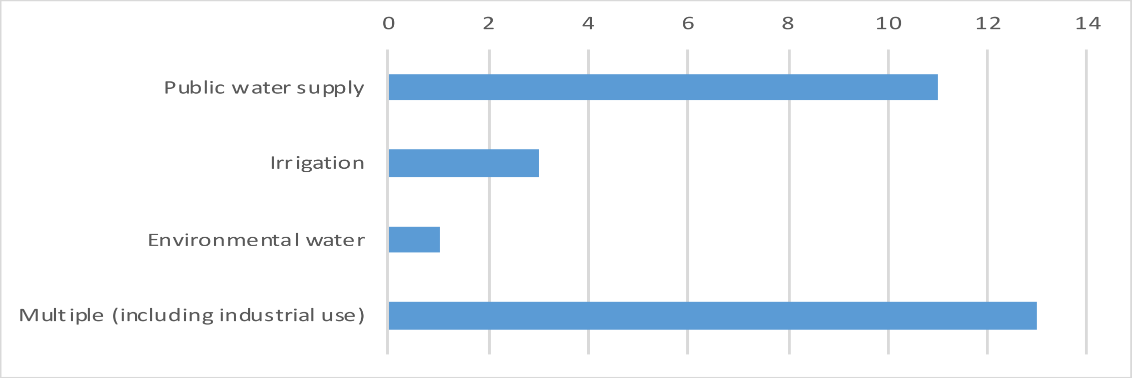

Figure 5.
Distribution of MAR cases according to end use of the water. Source: Own elaboration

2.4. Size of MAR schemes/ annual volume of recharge water

The annual volume of water recharged in the case studies ranges over almost six orders of magnitude, from 640 m^3/yr (Ahmed *et al.* [Bangladesh]) to 342 million m^3/yr (Seasholes and Megdal [USA]), with a median of 3.3 million m^3/yr (Figure 6). The schemes may be grouped into micro, small, medium, and large schemes, each differentiated by two orders of magnitude (Table 2).

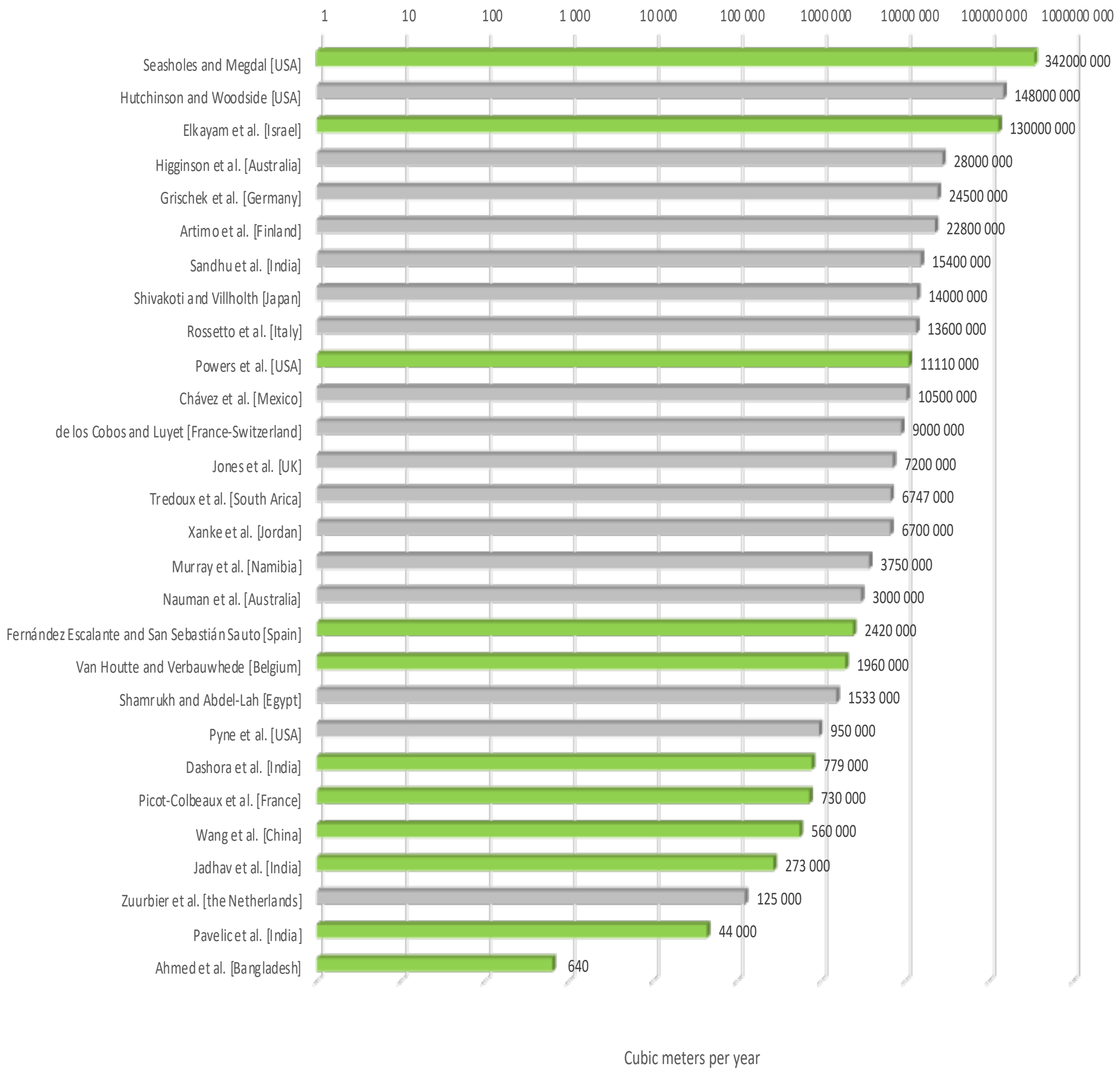

Figure 6.
The 28 MAR schemes in decreasing order of size with respect to recharged water volume (note the logarithmic x-axis). The color indicates whether the schemes are rural/low population density (green) or urban/high population density (grey) systems.
Source: Own elaboration

Table 2.
Distribution of MAR case studies across four size groups. Source: Own elaboration

	Annual recharge volumen (m^3/yr)	Number of cases
Micro schemes	Less than 1000	1
Small schemes	1000 to 100,000	1
Medium schemes	100,000 to 10,000,000	14
Large schemes	Greater than 10,000,000	12

The selection process for case studies in this book only included cases with sufficient monitoring of flows, groundwater levels and water quality. Hence, many micro and small rainwater harvesting and other recharge systems that have been operating for many years went unreported, as they did not monitor and quantify recharge and recovery and verify whether water quality parameters meet the criteria for safe use. In reality, the smallest reported scheme, at 640 m^3/yr (Ahmed *et al.* [Bangladesh]), would be among the largest of the hundreds of thousands of rainwater harvesting schemes in Asia. The classification of schemes shown in Table 2 reflects this large diversity in sizes of MAR schemes globally, and the bias of these case studies towards medium and large schemes that are well-monitored.

2.5. Beneficiaries

The size of case studies varies considerably, and so does the number of human beneficiaries per scheme. The numbers provided by chapter authors for individual schemes are best estimates as it can be difficult to determine the number of people benefitting, and some benefits may accrue directly, as in provided water supply through public schemes, while others are indirect, as e.g. from improved ecosystem services and associated recreational areas. Benefits may be in terms of extractive and non-extractive values. The best estimate of number of beneficiaries vary from 7 (Zuurbier *et al.* [the Netherlands]) to 6 million (Seasholes and Megdal [USA]), with a median of 168,000.

Environmental benefits

Environmental benefits, ecosystem support and recreational services are critical aims of two of the MAR cases (Powers *et al.* [USA], Picot-Colbeaux *et al.* [France]). Other schemes may also have significant surplus recharge for environmental purposes, while still pursuing extractive benefits (Artimo *et al.* [Finland], Fernández Escalante and San Sebastián Sauto [Spain], Naumann *et al.* [Australia], Tredoux *et al.* [South Africa]). Others focus on a surplus for banking water to create a buffer for drought or emergency supply (Jones *et al.* [UK], Murray *et al.* [Namibia], Pyne *et al.* [USA], Rossetto *et al.* [Italy], Seasholes and Megdal [USA]).

In highly variable water availability settings, banking may occur only in very wet years, while drawdown of the storage prevails in dry years (e.g. Murray *et al.* [Namibia]). Some schemes, have general surplus recharge, but no indicated banking or environmental goals (Ahmed *et al.* [Bangladesh] and de los Cobos and Luyet [France/Switzerland]), while some schemes with no surplus, or even deficit, have environmental benefits. It is possible to achieve both environmental and water supply goals, e.g. if infiltration basins are used for recreational purposes, nature enhancement and habitat and biodiversity support. Some case studies highlight the use of MAR for coastal salinity control (Tredoux *et al.*

[South Africa], Van Houtte and Verbauwhede [Belgium], Wang *et al*. [China], Zuurbier *et al*. [the Netherlands]), which can be partially achieved by making cumulative recharge exceed cumulative abstraction. While a number of schemes mention 'controlling aquifer drawdown' as a goal (both for surplus and no-surplus cases) (Artimo *et al*. [Finland], Hutchinson and Woodside [USA], Rossetto *et al*. [Italy], Sandhu *et al*. [India], Van Houtte and Verbauwhede [Belgium]), only one scheme mentions explicitly the recovery of depleted aquifers as a critical goal, but only in the initial phases (Chávez *et al*. [Mexico]). Hence, MAR in the cases explored do not appear to be applied with a key goal of recovering depleted aquifers.

This is in part due to that our cases represent relatively well-managed systems. Conversely, where groundwater depletion is a major issue, the resources are typically not properly managed and any induced recharge occurring is not sufficient or sufficiently controlled to ensure a reversal of groundwater levels. This is further evidence of the need to integrate MAR into a broader water management strategy. In some places, such as Arizona (Seasholes and Megdal), California (Hutchinson and Woodside), and Western Australia (Higginson *et al.*), risk of depletion is critically considered, and water banking is an important strategy for improving the security of groundwater supplies and helping to buffer future drought.

2.6. Initiation and historical developments of MAR cases

Although small dams in ephemeral streambeds have been in use in India and the Middle East for more than a millennium, a wider variety of MAR schemes were conceptualized in Europe and the USA. The earliest MAR case study reported in this cohort was in Hosterwitz, Dresden, commencing in 1907 (Grischek *et al*. [Germany]). However, the majority (15 in total) of case studies reported here came into place in the 21st century, in parallel with the accelerating global need for water and the associated rate of development of new schemes (Dillon *et al*., 2019) [7] (Figure 7 and Appendix II). The first of the reported schemes in a developing context is the Atlantis scheme from 1980 (Tredoux *et al*. [South Africa]). Hence, there is already experience and evidence reflected in these case studies to demonstrate the long-term viability and usefulness of MAR in different contexts.

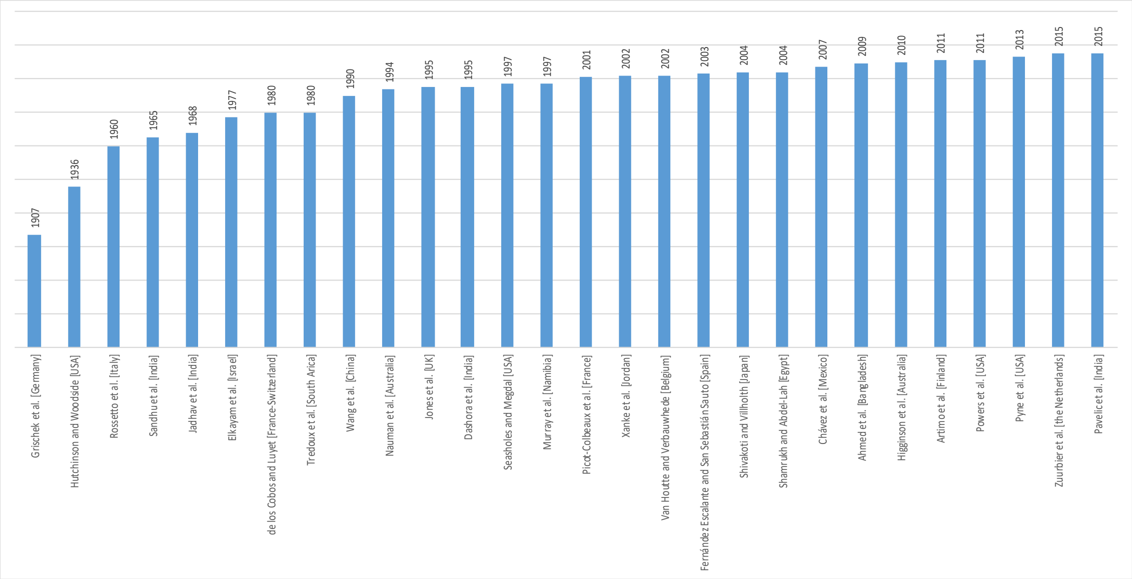

Figure 7.
Commencement year of the MAR schemes.
Source: Own elaboration

Initially, MAR schemes primarily responded to demand for good quality water in growing urban centers. In contrast, the Shafdan scheme (Elkayam *et al*. [Israel]) was an early MAR intervention, from 1977, which demonstrated the successful beneficial reuse of reclaimed water in irrigated agriculture in semi-arid, and water-constrained economies. Funding for schemes have mostly been from public sources or from international financing mechanisms. For some schemes, their successful running and up-to-present viability has been driven by pioneering engineers and hydrologists lending a long-term perseverance to securing the functionality, refinement and expansion of the schemes as demand grew or changed. Both pushing and pulling factors have helped spark MAR implementation. Crises, such as droughts, depletion of water resources, growing water demand outpacing existing supply, and progressively, climate variability, have helped start many schemes (e.g. Higginson *et al*. [Australia], Hutchinson and Woodside [USA], Murray *et al*. [Namibia]). Pulling factors such as favorable policies addressing water resilience, water quality and economic development, backed by financial support, e.g., integrated watershed management programs in India (Sharda *et al*., 2012) [8], have also played a role in developing more water-secure communities (Jadhav *et al*. and Dashora *et al*. [India] since the 1960s and 1990s, respectively).

Many formal schemes have gone through various phases beyond the piloting phase, the most typical related to expansion (e.g. Jones *et al*. [UK], Murray *et al*. [Namibia]), retrofitting to other sources of water (e.g. Hutchinson and Woodside [USA]), better water treatment (e.g. Sandhu *et al*. [India]), and handover to local communities for self-management (Ahmed *et al*. [Bangladesh]). MAR schemes are often amenable to gradual and modular development as needs change or additional water sources for MAR are developed (e.g., Elkayam *et al*. [Israel]). Phased development of MAR is usually advantageous, with each new phase building upon lessons learned in previous phases. Another development seen is that more monitoring of schemes take place with time (e.g., Van Houtte and Verbauwhede [Belgium]), and in this regard helps increasing sustainable management of the schemes. Some schemes may have started through mostly incidental recharge, e.g. through surface discharge of reclaimed water, which now are converting into fully managed schemes, especially driven by the need for acceptable and safe water supplies (Chávez *et al*. [Mexico]). Increasingly, MAR is also seen as a solution to enhance environmental goals, and where multiple goals can be achieved with single systems, this appears to be an added advantage (e.g. Fernández Escalante and San Sebastián Sauto [Spain], Picot-Colbeaux *et al*. [France]).

2.7. Participation and gender aspects

While public participation in establishment or approval of MAR projects is generally more advanced in countries with more mature water resources governance arrangements, there are excellent examples from low-to-middle income countries. One of these (Ahmed et al. [Bangladesh]) involved awareness building activities through village-level meetings of local users on the benefits of safe water and of following a water safety plan in order to build ownership of village-scale programs of MAR to improve quality and availability of water). After community members completed training on operation and maintenance by the project team in 2015, a five-member user committee, consisting entirely of women, took charge of operating and maintaining the system (Figure 8). Users make small monthly payments to cover operation and maintenance costs, with lower income households making smaller payments. Women, who normally take responsibility for fetching water for their household, have strong incentives to support the scheme and take an active role in operation and maintenance, as it provided safe drinking water for their families. This case study has become a national demonstration site, and water supply managers and stakeholders at various levels visit to learn from it. It is a model of sustainability, through empowerment of women to extend their role, and in so doing, their acknowledged contribution to their community. As MAR often comes with new technology development, provision of training is necessary to ensure women's participation in roles that support the viability of the schemes. In smaller communities, MAR schemes are typically used for multiple productive and non-productive uses, which are very important to support households in their varied water needs (van Koppen *et al*., 2014 [9]; Villholth and Ross, 2018 [10]).

Figure 8.
Regular user committee meeting at Khulna village MAR water supply project (from Ahmed *et al*, [Bangladesh]). The project has operated since 2010 and the user committee since 2015. © Kazi Matin Ahmed

2.8. Conclusions

These case studies demonstrate a wide range of circumstances where MAR has been implemented to support diverse water security, resilience, and environmental goals by adapting methods to account for local hydrogeology, local sources of water and concurrently meeting water quality and environmental requirements. This chapter has provided an overview of diverse case studies that provide stable, reliable and safe water supply or meet environmental needs, and, as will be seen in subsequent chapters, do it economically and with a view to environmental and social sustainability.

With increasing climate variability, growing populations, urbanization, intensified agriculture, and reduced land availability for surface water storage, MAR provides benefits beyond evaporation-protected storage. MAR supports the capture and retrieval of intermittent or seasonal water resources, recycled water, urban stormwater, and desalinated water and even perennial surface water sources. The subsurface natural biogeochemical processes provide low-cost in-situ treatment, which if managed properly can help enhance water quality. These exemplary cases illustrate the growing integration of MAR as a component of contemporary conjunctive water management.

Some highlights from the synthesis of metadata of the schemes:

- MAR schemes have developed over the last century and are now well developed across the globe.
- MAR schemes vary in size from local-scale to large-scale integrated basin-wide conjunctive management approaches.
- MAR is applied in very diverse climates and aquifer contexts, where land constraints, population growth, food demand, and drought risk drives MAR, increasingly also in more humid areas.
- MAR is applied successfully with rudimentary water resources management policies, but scaling up or use of unconventional source waters require effective policies and implementation for sustainable systems.
- Those case studies with drinking water supply as an end use or where treated reclaimed waters are recharged need good site selection, characterization, construction, operation and monitoring as well as effective land use planning to ensure health and environmental protection.
- Synergy is observed between urban and rural areas or between water supply and agriculture, in schemes recycling reclaimed domestic water through MAR schemes and applying recovered water for food production.
- Bank filtration and other surface water infiltration systems can provide highly efficient water treatment for improving water quality for use in drinking water supplies.
- MAR case studies have been shown to enhance acceptance of recycling water for potable use. This requires foresight, good planning, continuous monitoring, community engagement, transparency, accountability and trust.
- MAR schemes need monitoring and management commensurate with the public health and environmental risks. This can be a particular challenge for small-scale, household-level schemes.
- MAR is increasingly integrated into larger adaptive, conjunctive, and flexible, but more robust water supply and storage schemes, allowing the use and optimization of multiple and diverse water sources to enhance water security and resilience.
- Where the aquifer is suitable, well-designed and well-managed MAR case studies all show a net economic benefit, over their life span (Section I, Chapter 4).
- For the case studies recorded, MAR has not been used on its own for recovery of depleted aquifers, although an objective of many of the schemes is to avoid aquifer depletion. Recharge enhancement could be used to help the adoption of demand management in an integrated water management strategy to combat groundwater depletion.
- MAR can serve significant water security and equity goals in rural developing contexts, if vulnerable groups are empowered to provide self-management and maintenance of local schemes. Especially women can benefit from multi-purpose schemes that give access to water for both household needs and small-scale irrigation or other economic activities.
- Evolving water and wastewater treatment processes have presented more opportunities for MAR to buffer differences in supply and demand and to bank water for the future, and these opportunities will continue to grow if MAR is properly taken into account by water suppliers.

- While many MAR systems have low energy requirements, there is still potential for adoption of renewable energy for pumping and water treatment to enhance cost-efficiency and sustainability.
- While some maturation in MAR technology and experiences is seen, there is still room for learning, improving existing schemes, and lesson-sharing.
- As MAR technology and experience mature, documenting successes and failures and sharing knowledge, guidelines, while enhancing institutional and policy support, will continue to advance best practice and further widen the applicability of future sustainable MAR approaches.

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Chapter 3: Assessment of environmental and social sustainability of Managed Aquifer Recharge schemes

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ABSTRACT

Under the Eighth Phase of the Intergovernmental Hydrological Programme (IHP-VIII) of UNESCO, a publication "Managing aquifer recharge: A showcase for resilience and sustainability" is planned. In this process, it is realized that sustainability criteria and indicators need to be developed first because none exists specifically for water infrastructure projects. To do so, a framework for sustainability indicators of the U.S. Environmental Protection Agency (USEPA) is used as a guide, with an advantage that the framework is also rooted in risk assessment. Through a process of multiple expert consultations, 6 indicators for environmental sustainability and 3 indicators for social sustainability are established. To test the applicability of these 9 indicators, 28 schemes in this publication are analyzed qualitatively, resulting in a sustainability rating for each scheme that shed light on best practices likely to enhance environmental and social sustainability. An attempt to quantitatively assess sustainability is made for one scheme that supplies water for 300,000 inhabitants in Turku, Finland through a calculation of sustainability index. Thorough hydrogeological and water quality investigations and sound regulatory framework are found to assure sustainability. Objective assessment of progress towards goals of sustainability using indicators established here, if widely adopted to guide the design, construction and maintenance of managed aquifer recharge schemes, enhances sustainability.

3.1. Introduction

The desire to have sustainable water resources systems, shared by the 28 cases of managed aquifer recharge schemes in this publication, is not new. In 1999, a UNESCO International Hydrology Series publication defined sustainable water resources systems as those ***designed and managed to fully contribute to the objective of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity*** (Loucks and Gladwell, 1999) [1]. Relevant here is a sustainability guideline for water resource systems engineers and planners that covers 6 areas, each with its own set of points of consideration for a total of 59 points. Clearly, there remains a tremendous task to apply this broad, categorical guideline intended for use from design through construction and maintenance of water infrastructure projects, which can be difficult in practice.

Despite such guideline and good intentions, not much has been done to devise tools specific for evaluation of sustainability of water infrastructure projects. Part of the challenge is that sustainability can be approached both as a process and as a goal, thus an all-encompassing tool to evaluate both can quickly become complex and therefore risk being neglected by practitioners. Therefore, it is proposed here to focus first on sustainability as a goal and to develop tools to measure against indicators specifically designed to measure progress towards such goals, an approach distinct from those described by Loucks and Gladwell [1] and the ENVISION Scorecard developed for infrastructure projects (ASCE, 2019) [2] by the American Society of Civil Engineers (ASCE). Yet even if a simpler goal oriented approach is taken, how to ***measure*** sustainability of water resources systems remains challenging because future changes, especially the socio-economic forces that drive water demands and water quality changes can be highly uncertain, and that tools are not always available to make predictions. This is especially true for water infrastructure projects involving both surface water and groundwater systems including managed aquifer recharge schemes, with additional needs to manage water quality risks.

Fortunately, an operational framework of sustainability indicators (USEPA, 2015) [3] has recently been put forth by the U.S Environmental Protection Agency (USEPA). The U.S. National Environmental Policy Act of 1969 defined the goal of sustainability as "to create and maintain conditions, under which humans and natures can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations". It took more than 4 decades for the USEPA to request the National Research Council to form a "Committee on Incorporation Sustainability in the USEPA" to work on addressing sustainability. The NRC Committee's publication (NRC, 2011) [4] informed the current framework that includes the ***environmental, social and economic pillars*** of sustainability; under each pillar there are six broad topics forming a set of 18 sustainability criteria, sometimes referred to as indicators by USEPA (Figure 1). It is worth noting that one of the four tasks of the NRC Committee is to investigate how to integrate the USEPA decision-making process rooted in the risk assessment and management paradigm into the sustainability framework. Subsequently, the USEPA established a sustainability indicator project led by its National Risk Management Research Laboratory that published a guiding document titled "A Framework for Sustainability Indicators at EPA" (USEPA, 2012) [5] that also resulted in the release of a 1-page document "sustainability primer version 9.0" [3].

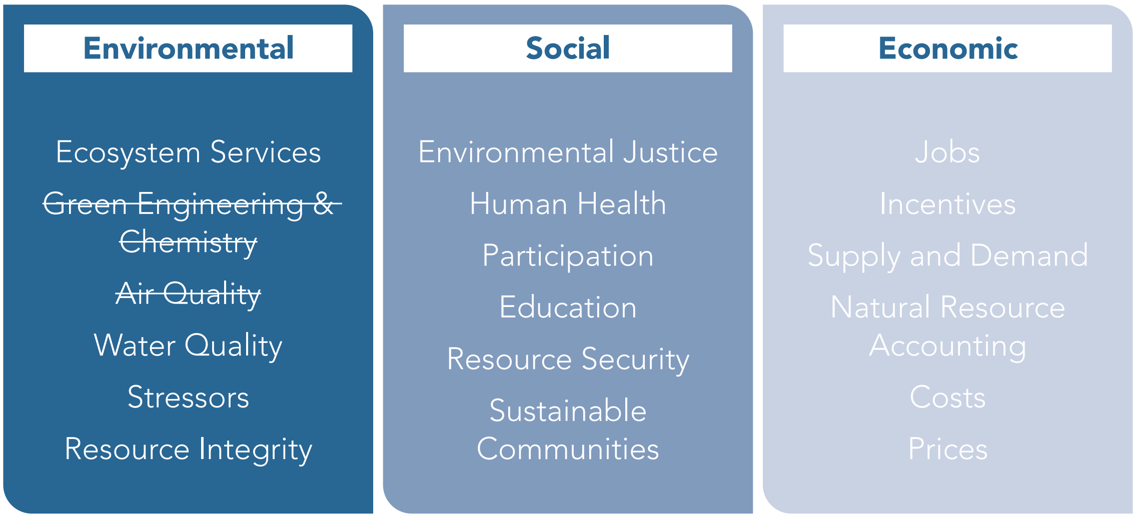

Figure 1.
The USEPA framework of sustainability indicators [3]. Under each of the environmental, social and economic pillars, six categories of indicators are included. This study focuses on environmental and social pillars, and excludes two categories (strike-through font) the least relevant to MAR. Source: Own elaboration

Here, an attempt is made to establish a set of sustainability indicators for managed aquifer recharge schemes. All indicators are devised to primarily measure progress towards goals of sustainability. First, a brief overview of existing methods used to measure sustainability of water resources system especially groundwater system is provided. Second, a set of environmental and social sustainability indicators are proposed for managed aquifer recharge schemes using USEPA's framework of sustainability indicators as a guide, with the 9 indicators eventually selected through an expert consultation process. Third, to test the applicability of these indicators, an analysis is provided to assess to what extent 28 managed aquifer recharge schemes from lower-middle (n=7), upper-middle (n=4) and high income (n=17) countries has met the sustainability criteria, with a sustainability rating assigned to each case. Lastly, a sustainability index is calculated based on time series data of selected sustainability indicators for one case to illustrate the utility of the objective assessment of sustainability.

3.2. Existing Methods to Measure Sustainability

The sustainability guideline for water resources systems from Loucks and Gladwell [1] is consisted of 59 points in 6 areas (Table 1). Further, to quantify sustainability of water resources systems, a method to quantify sustainability index values based on an assessment of reliability, resilience and vulnerability is proposed (see Chapter 4, Measuring Sustainability [1]), although it remains to be determined which criteria are suitable for different types of water infrastructure project. It is worth noting that under the Sixth Phase of the Intergovernmental Hydrological Programme of UNESCO (IHP-VI), a publication titled "Groundwater Resources Sustainability Indicators" describe 10 indicators (Table 1) that are suitable for assessment of groundwater resources usually at catchment or regional scales (Vrba and Lipponen, 2007)[6]. Nevertheless, these indicators are relevant parameters to consider to ensure integrity of the groundwater resource involved in managed aquifer schemes.

Table 1.
Existing Sustainability Guidelines and Indicators. Source: Own elaboration

Loucks & Gladwell (1999)[1]		**Vrba & Lipponen (2007)[6]**
Sustainability Guideline for Water Resources System		Groundwater Resources Sustainability Indicators
Covered Areas	Points	
1) design, management, operation of physical infrastructure	11	1) renewable groundwater resources per capita
2) environment and ecosystem	16	2) total groundwater abstraction/groundwater recharge
3) economic and finance	7	3) total groundwater abstraction/exploitable groundwater resources
4) institutions and society	8	4) groundwater as a percentage of total use of drinking water at national level
5) health and human welfare	5	5) groundwater depletion
6) planning and technology	12	6) total exploitable non-renewable groundwater resources/annual abstraction of non-renewable groundwater resources
		7) groundwater vulnerability
		8) groundwater quality
		9) groundwater usability with respect to treatment requirements
Total Points	**59**	10) dependence of agricultural population on groundwater

Recently, a GRACE groundwater drought index (GGDI), representing the normalized net deviation in groundwater storage to evaluate groundwater drought, has been adopted as a sustainability indicator for the world's largest aquifers (Thomas *et al.*, 2017) [7]. Following methodologies (Loucks, 1997; Mays, 2013) [8,9], similar to those described in Loucks and Gladwell [1], a ***sustainability index*** or a sustainability score is calculated based on assessments of the GGDI's reliability (historical likelihood that the aquifer storage falls below a normal condition), resilience (the likelihood of a return from unsatisfactory to satisfactory conditions) and vulnerability (a probabilistic measure that accounts for the extent and magnitude of failure) are undertaken using three equations as follows:

Reliability (REL) is defined by how often a system fails:

$$REL = \frac{\#\ \text{satisfactory conditions}}{\text{total}\ \#\ \text{conditions}} \qquad \text{eq. (1)}$$

Resiliency (RES) indicates how quickly a system returns to a satisfactory condition after an unsatisfactory condition:

$$RES = \frac{\#\ \text{times a satisfactory condition follows an unsatisfactory condition}}{\text{total}\ \#\ \text{unsatisfactory conditions}} \qquad \text{eq. (2)}$$

Vulnerability is defined as a probabilistic measure that accounts for the extent and magnitude of failure, where failure is synonymous with unsatisfactory [7]. Accounting for both the magnitude of the event (s_j = Indicator_j) and the probability of the severity of the magnitude (e_j), during the study period, F, where

$$VUL = \sum_{j \epsilon F} s_j \, e_j \qquad \textit{eq (3)}$$

Finally, sustainability index (SI) is calculated as follows:

$$S = REL \times RES \times (1 - VUL) \qquad \textit{eq (4)}$$

This approach is useful because when historical time series data of a managed aquifer recharge scheme is available for an indicator, a similar analysis can be made to calculate sustainability index based on such data on selected indicators as described in the Quantitative Analysis section later.

How should the sustainability of managed aquifer recharge schemes be evaluated given that it is a water infrastructure project with impact on groundwater resource although usually at a smaller spatial scale? For a broad range of infrastructure projects, the ASCE has devised an ENVISION approach (https://www.asce.org/Envision/). In addition to an ENVISION checklist or scorecard [2] which is an assessment tool structured as a series of Yes/No questions for comparing sustainability alternatives or to prepare for a more detailed sustainability assessment, there is also an ENVISION sustainable infrastructure rating system. These 60 sustainability criteria that encompass the full range of environmental, social, and economic impacts, called ‘credits’, are arranged in five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Risk. Each credit is ranked by the level of achievement, and the various ranks, from the lowest to the highest scoring, are: no added value, improved, enhanced, superior, conserving, and restorative (Table 2). Because the scoring is done by “experts” to give points to variable ranges of points possible to earn, so it is more subjective than the aforementioned approach based on time series data. Nevertheless, the ENVISION approach has been endorsed by the Institute for Sustainable Infrastructure (ISI).

The applicability of the ENVISION approach [2] was tested for the Twin Oaks aquifer storage recovery (ASR) project in San Antonio, Texas with a final sustainability score of 32 out of 100 points possible, which would earn a bronze award based on ISI guidelines (Saville *et al.*, 2016) [10]. Because the ENVISION approach is developed for any infrastructure project, the authors encountered five major problems: 1) conflation of project purpose and project design, 2) no weighting of points based upon local needs, 3) project-oriented focus omits systems scale, 4) uneven weighting of three sustainability pillars, and 5) positive scoring overlooks negative aspects of projects. Finally, the authors conclude that despite the flexibility and adaptability of the ENVISION approach, its broad focus may also be a liability that would make it unsuitable for evaluating water sustainability without additional consideration of water-specific topics, supported by prior research that finds no widely accepted l*et al*one useful groundwater sustainability indices (Chen *et al.*, 2015) [11]. Therefore, an attempt is made here to establish environmental and social sustainability indicators for managed aquifer schemes as described in the following section. Additionally, the level of achievement concept is adopted here to rate sustainability of cases as discussed in the Qualitative Analysis section, with a modification to include negative scores opposite to the positive scores of ENVISION to identify potentially harmful impacts (Table 2). To test the applicability of this expanded rating system, the rating is done by the authors themselves, to compare with rating provided by two editors of this book acting as “experts” who independently rated the cases.

Table 2.
Levels of Achievement in Envision with Modification for Sustainability Rating of Cases in this Study. Source: Own elaboration

ASCE Envision [2] 60 sustainability criteria in 5 categories			This Study 9 sustainability indicators in 5 categories of USEPA		
Level (+)	Performance Definition	Points for Rating*	Level (-)	Performance Definition	Points for Rating
No added value	comparable to conventional	0			
Improved	is at or above conventional	1	Degraded	is below conventional alternative	-1
Enhanced	Indications that superior performance is within reach	2	Diminished	Indications that there are risks for inferior performance	-2
Superior	noteworthy	3	Inferior	obvious poor performance	-3
Conserving	has achieved essentially zero impact	4	Harming	harmful impact in one aspect	-4
Restorative	restores natural or social system	5	Debilitating	harmful impact in all aspects	-5

*In Envision, the points possible is variable for each criterion, for example, «conserving» for «Protect fresh water availability» under category Resource Allocation (total points possible is 182) can earn up to 21 points. To simplify, this study assigns positive or negative points at a step value of 1.

3.3. Establishing Environmental and Social Sustainability Indicators for Managed Aquifer Recharge

According to the International Association of Hydrogeologists Managing Aquifer Recharge (IAH-MAR) Commission, managed aquifer recharge (MAR), also called groundwater replenishment, water banking and artificial recharge, is the purposeful recharge of water to aquifers for ***subsequent recovery or environmental benefit.*** There are several challenges in developing sustainability indicators for MAR. First, the purposes of recovered water for MAR include domestic (drinking), agricultural and industrial. Second, the target aquifers have a wide range of hydrogeological and hydrochemical settings. Third, the scale of MAR schemes can range from small with an annual recharge of 667 m^3 in Khulna of Bangladesh to massive with an annual recharge of 348 Mm^3 in Arizona of USA, considering only the cases included in this publication. Fourth, meeting water quality requirements for various end use purposes could also mean energy intensive pre- and/or post-treatment. Fifth, aside from complex institutional arrangements to enable permit granting processes and to engage community in decision making, maintenance and operation dealing with clogging and deteriorating water quality can be technically difficult. Finally, because the purpose of MAR is for recovery of recharged water, it would in theory do little to address large scale groundwater depletion. This is because any storage enhancement would only be temporary until it is recovered at a later time. Of course, if demand or groundwater extraction is also managed, the purpose of MAR may be legitimately for restoring a depleted aquifer for its environmental benefits.

Sustainability Criteria. What sustainability criteria are worthy of consideration for water resource systems infrastructure projects, and in this case, managed aquifer recharge schemes? Whereas sustainability needs to be seen in the wider context of basins and catchments to preserve integrity of groundwater aquifers and ecosystems, it is important to keep in mind that most MAR schemes are implemented to address issues at smaller local scale, and are not designed or intended to address large spatial scale water resources issues without replication and upscaling. Furthermore, there is a need for objective measurement, preferably based on time series monitoring data, to enable assessment against criteria. Because MAR always has a target aquifer for purposeful recharge, it is helpful to bear in mind the aforementioned ten groundwater resources sustainability indicators (Table 1) described in Vrba and Lipponen [6]. In principle, the MAR scheme's impact on the integrity of groundwater resource should already be investigated in the planning stage; first by determining whether the impact is positive or negative on groundwater quantity and quality, then by assessing the magnitude of such impact, preferably with pilot MAR projects to address risks. Due to the need to manage risks especially water quality risks in MAR schemes, and considering that the USEPA's framework of sustainability indicators (Figure 1) is rooted in a risk management paradigm, this framework is therefore adapted to establish environmental and social sustainability indicators for MAR schemes as follows.

Environmental and Social Sustainability Indicators. Because two (Air Quality, Green Engineering & Chemistry) of the six categories under environmental sustainability criteria according to the USEPA framework are not very relevant to water (Figure 1), indicators were therefore only proposed to fall under three categories: ***Resource Integrity*** (Water Quantity n=2; Water Quality n=2), plus ***Ecosystem Services*** (n=1) and ***Stressors*** (n=1, Table 3). The social sustainability indicators fall under re-combined two categories. Under ***Resource Security and Human Health*** there are 2 indicators, with all of the rest of the category having 1 indicator (Table 3).

For large MAR projects, additional indicators may also be considered for evaluation of catchment scale impacts (Table 3, grey). Several factors have been considered to establish these indicators. First, an effective water resource sustainability indicator should reflect systems principles and simultaneously assess both surface and subsurface water supplies, plus the less tangible environmental benefits. Second, the "damage" to groundwater aquifer especially threats to deteriorate water quality, must also be carefully considered as a vulnerability. Third, to what extent the indicators are practical to measure and to monitor is important. Finally, indicators are intended to capture the most salient features of sustainability. Their purpose is not to be confused with guidelines that assist engineers and planners to plan, design, construct, operate and maintain MAR infrastructure, with often complex risk management schemes to ensure end use water quality, for example, as described in NRMMC, NEPC and NHMRC (2009) [12]. Briefly, guidelines, including that of Loucks & Gladwell [1], and to some extent ENVISION, are devised to avoid future bad consequences whereas sustainability indicators established here are mostly about measuring what has already happened to inform progress towards sustainability goals, until the ability to predict changes in the future can be supported by sound science which remains extremely difficult at present.

A process of multiple expert consultations took place between February and May 2019 that resulted in six environmental and three social sustainability indicators (Table 3). In February, discussion with three co-editors of this publication solidified the support for the need to establish new indicators. A total of 20 indicators in five categories including Groundwater Quantity (n=5), Groundwater Quality (n=3), Governance (n=5), Costs (n=5), Benefits (n=4) and Externalities (n=3) were first proposed. Six experts with a broad range of technical background including water resources management, catchment hydrology and urban water supply, hydrological modeling, hydrogeology, climate modeling, water policy were consulted and asked to score the indicator using a scale from 0 to 10, with 0 equivalent to "Do not include", 4 equivalent to "OK to include", 7 equivalent to "Good to include" and 10 equivalent to "Must include". Besides scoring that reduced the number of indicators to 14, two important points were made by the experts. First, as long as the groundwater reservoir size stays constant or is increased to the desired level, maintaining adequate quality of water should be of paramount importance to ensure resource integrity. Second, lack of a sound regulatory framework is identified as a threat to sustainability. A regulatory framework for water allocations and for water quality management has been shown to be an effective way of assuring that MAR projects contribute to the sustainability of water resources. However, if regulations are absent or not enforced, proponents of MAR have a duty of care to use their investments and expertise to encourage a dialogue between the regulators and the community of concerned stakeholders and citizens. On May 19, 2019 during ISMAR10, a workshop participated by professionals interested in contributing a case study to this publication was held by the IAH-MAR Commission. The participants were consulted and were asked to score similarly as above to evaluate a set of 14 indicators now organized under the EPA framework of sustainability indicators (Figure. 1, economic indicators is beyond the scope of this study), with 11 responses (Table 3). Finally, 9 indicators are retained based on their mean scores being at least above 4 (OK to include), with minor revisions made to the energy requirement to quantify energy intensity after the ISMAR10 consultation. This concluded the step of establishing these indicators for application to case studies in this book.

Table 3.
Six Environmental and Three Social Indicators Established for MAR Schemes following USEPA Framework of Sustainability Indicators. Source: Own elaboration

	Score*
I. Environmental Sustainability Indicators	
A. Resource Integrity	
A.1 Water Quantity	
1. Monitoring of groundwater table demonstrates acceptable changes over 10 years, or > 3 years with high likelihood of maintaining resource integrity	7.6
2. The ratio of volume of recovered water vs infiltrated water on an annual basis	6.8
For large schemes, change in renewable groundwater resources in target aquifer per capita (m^3/year per capita)	1.6
A.2 Water Quality	
3. Exceedance rate based on time-series monitoring of recovered or ambient water quality parameters	7.8
4. Exceedance rate based on time-series monitoring of source water quality parameters	7.5
For large schemes, percentage use as drinking water sourced from target aquifer	3.1
B. Ecosystem Services	
5. Changes in ecological flow (m^3/yr) and improvement in water quality in ecosystem needing protection identified in a catchment water management plan	4.9
Change in peak flow (m^3/s) for MAR intended for flooding control	1.3
C. Stressors	
6. Energy requirements in KWh per cubic meter of recovered water, including monitoring and treating recovered water, solving clogging and low recovery efficiency issues	7.0
No unacceptable seepage, waterlogging, discharge occurs	3.4
II. Social Sustainability Indicators	
A. Resource Security/Human Health	
7. Clearly defined, transparent regulatory framework for MAR, preferably one that requires monitoring of resource integrity	8.6
8. Permit granting process is based on sound risk assessment aimed to protect human health	8.9
Assists resilience to adverse impacts of climate change	5.5
B. Sustainable Community/Participation/Education/Environmental Justice	
9. Systematic Institutional arrangements for public and stakeholder consultation, preferably with regular publicly available reports of scheme outcomes	7.4

*Average score by 11 participants. Score scale: Do not include 0, OK to include 4, Good to include 7, Must include 10.

Table 4.
Location, Purpose, Technique, Size, Energy Intensity, and the Ratio of Recovered vs Recharged Water Volumn of MAR Cases from High to Low Income Countries. Source: Own elaboration

Country	2018 GNI per capita (USD)	Location	Purpose	MAR Technique[a]
High Income: > 12,375				
Switzerland	83580	Geneva	Domestic/Drinking	Undergr. Perforated Pipes, Arve River
USA	62850	Orange County, CA	Domestic/Drinking	IBs for Santa Ana River
		Platte River, NE	Ecological Flow	Rehabilitated Irrigation Canals
		Hilton Head, SC	Domestic/Drinking	ASR of Drinking Water
		Arizona	Water Banking	IBs+ for Colorado River
Australia	53190	Perth, W Australia	Domestic/Drinking	ASTR of UF+RO+UV Treated Effluent
		Salisbury, S Australia	Non-Drinking/Industrial	ASR, ASTR of Wetland Treated Storm Water
Netherlands	51260	Dinterloord	Agricultural	ASR of UF+RO Treated Effluent
Finland	47750	Turku Region	Domestic/Drinking	IBs of Treated Kokemaenjoki River
Germany	47180	Dresden	Domestic/Drinking	RBF Siphoning Wells & IBs, Elbe River
Belgium	45340	Koksijde, Veurne Area	Domestic/Drinking	IB+Subterranean, UF+RO Treated Effluent
Japan	41340	Kumamoto	Domestic & Industrial	Rice Field Flooding of Shirakawa River
UK	41340	London	Domestic/Drinking & Industrial	ASTR of treated Thames and Lee Rivers
France	41080	Normandy	Coastal Ecosystem	SAT of Treated Effluent
Israel	40850	Shafdan	Agricultural	SAT of Secondary Effluent
Italy	33540	Luca, Pisa and Livorno	Domestic/Drinking	RBF (12 vertical wells) of Serchio River
Spain	29450	Serchio River	Agricultural	Aqueducts/Canals/IBs, Cega River Diver.
Upper Middle: 3,996 - 12,375				
China	9470	Shandong Province	Agricultural	Undergr. Dam, In-Channel Balisha River
Mexico	9180	Sonora[b]	Agricultural	Infiltration Basins of Treated Effluent
South Africa	5750	Atlantis	Domestic/Drinking	Infiltration Basins of Treated Effluent
Namibia	5250	Winhoek	Domestic/Drinking	Injection of Surface Water and Treated Effluent to Fractured Quartzite
Lower Middle: 1,026 - 3,995				
Jordan	4210	Madaba	Domestic/Drinking	Reservoir Infiltration (Wala Dam)
Egypt	2800	Sidfa	Domestic/Drinking	RBF of the Nile River
India	2020	Haridwar	Domestic/Drinking	RBF of the Ganga River
		Rajasthan	Agricultural/Drinking	4 Check Dams for Storm Water Detention
		Maharashtra	Agricultural/Drinking	Desilting of a Check Dam
		Uttar Pradesh	Agricultural/Drinking	Recharge Wells in Ponds
Bangladesh	1750	Khulna	Drinking	ASR of Pond Water to Brackish Aquifer
Min				
Max				
Mean				

Recharge		Recover/Discharge		Total	Ratio	Ratio
Volume (1000 m³/yr)	Energy Intensity (kWh/m³)	Volume (1000 m³/yr)	Energy Intensity (kWh/m³)	Energy Intensity (kWh/m³)	$V_{RECOVERED}/V_{RECHARGED}$	$V_{RECHARGED}/V_{RECOVERED}$
9000	0.61	13500	0.14	0.75	1.5	0.7
148000	0.06	148000	0.45	0.51	1.0	1.0
8380		1290			0.2	6.5
1000		1000	0.3	0.30	1.0	1.0
342000	1.23 - 2.16	76000	0.48 - 0.91	2.39	0.2	2.0
14000		14000		2.35	1.0	1.0
3500	0.06	2500	0.44	0.50	0.7	1.4
87.3	1.13	34.7	0.39	1.53	0.4	2.5
22800	0.32	22300	0.24	0.56	1.0	1.0
24638	0.1 - 0.14	26280	0.18 - 0.23	0.13	1.1	0.9
1960	0.75	1290	0.1	0.85	0.7	1.5
14000		2000 - 12000	0.3 - 1.2	0.75	0.5	2.0
15600		49200		0.25	3.2	0.3
730	0	0	0.15	0.94	0.0	
130000	0.14	145000	0.49	0.63	1.1	0.9
13600		16000	0.37 - 0.98	0.68	1.2	0.9
2248	0	8000	0.165	0.17	3.6	0.3
600	0	600	0.02	0.02	1.0	1.0
10500	0.08[b]	31500	0.175		3.0	0.3
5442		2057		1.80	0.4	2.6
500		200 - 5500		3.90	2.9	0.3
6700		11700		1.18	1.7	0.6
		2190	0.3	0.30		
15400		22000	0.16	0.16	1.4	
779	0	6492			8.3	0.12
78						
26 - 62	0					
0.667	0.27	0.226		0.27	0.3	3.0
0.667				0.02	0.0	0.1
342000				3.9	8.3	6.5
29496		**24671**		**0.9**	**1.5**	**1.4**

[a] IB = Infiltration basin, ASR = Aquifer Storage Recovery, ASTR = Aquifer Storage Transfer and Recovery, RBF = Riverbank Filtration, UF = Ultra-Filtration, RO = Reverse Osmosis UV = Ultra-violet

[b] Excluding waste water treatment energy, for water conveyance to infiltration basins only

MAR using treated effluent (n=7) is marked in red with a high mean energy intensity of 1.71 kWh/m³; RBF (n=4) is marked in blue with a mean energy intensity of 0.32 kWh/m³.

3.4. Qualitative Analysis: Sustainability Rating of Cases

3.4.1. Rating by Experts and Authors

There are 17, 4 and 7 cases from high, upper-middle and lower-middle income countries, respectively, with none from low income countries (Table 4). Following a scale from the lowest possible value of -5 (debilitating) to the highest possible value of +5 (restorative) as described in Table 2, each case is rated by two editors as "experts" (Table 5, columns E1 and E2), with 17 cases also self-rated by the authors (Table 5, column S) and 3 additional cases with authors indicating agreement with the rating by E1. Six out of 19 total author self-rated cases have ratings that are significantly above the average rating by the two experts, suggesting optimistic bias in about one third of the cases. There are also greater than 2 points differences for individual indicator rated by the two experts, with the mean score by E2 being 0.6 point higher than that of E1, suggesting that across the cases the results are comparable. Although this rating is subjective in nature, it is nevertheless based on careful consideration of data substantiating each indicator. Nevertheless, substantial knowledge and experience of MAR in general is necessary to be a qualified expert to conduct the rating. Scores by both experts are retained and reported below, with the mean value by two experts calculated to categorize the case as follows. For example, if the mean score of all 9 indicator is > +1, then the rating is "good". If the mean score is between 0 to +1, then the rating is "acceptable". Only when the mean score is <0, the rating is "needing improvement". Clearly, such rating is best understood in the context of the purpose and technique of a diverse range of cases from countries with significantly different income and institutional settings. A narrative of each MAR scheme (Appendix III) provides the background necessary and reveals caveats and nuances in the sustainability indicators and the rating of them. It also informs the discussion on the applicability of the indicators established here.

Table 5.
Sustainability Rating of MAR Cases. Source: Own elaboration

Country	Location	Rating by Two Experts	Indicator[1]: Expert Mean 2	1 GW level			2 Vrecharged/ Vrecovered			3 GWQ			4 SWQ			5 Ecol flow			6 Kwh/m^3			7 Regulation			8 Permit			9 Community		
High Income: > 12,375				S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2	S	E1	E2
Switzerland	Geneva	Good	2.4	4	5	5	4	3	3	2	2	2	0	0	0	4	0	3	0	0	3	5	3	4	4	3	1	2	3	4
USA	Orange County, CA	Good	2.3	4	2	5	4	3	3	0	0	4	0	0	1	0	0	0	1	0	3	5	5	3	0	5	3	4	1	3
	Platte River, NE	Good	2.4		2	2		5	2		0	1		0	0		5	5		1	2		4	4		3	0		3	4
	Hilton Head, SC[3]	Good	1.4	5	0	0	5	4	3	4	1	3	5	0	0	0	0	0	5	0	1	5	4	1	4	4	1	3	1	2
	Arizona[4]	Good	1.7		5	3		5	3		0	0		0	0		-3	1		0	-1		5	3		5	0		0	5
Australia	Perth	Good	1.7	0	0	1	0	3	1	1	0	3	1	0	2	0	0	2	3	0	2	2	3	3	2	3	4	2	0	4
	Salisbury[4]	Good	1.9		0	2		1	2		0	5		0	0		3	2		2	3		3	2		3	3		3	1
Netherlands	Dinterloord	Good	1.3		0	2		1	2		0	2		0	2		0	0		-3	0		3	3		3	3		2	3
Finland	Turku Region[4]	Good	2.8		3	4		4	4		2	3		0	3		0	4		1	3		5	3		3	3		3	3
Germany	Dresden	Good	2.5		3	4		3	3		1	3		0	2		0	2		3	4		3	3		3	3		3	2
Belgium	Koksijde, Veurne Area	Good	2.8	3	3	5	4	4	4	2	1	4	0	0	4	1	0	3	0	0	3	3	3	4	3	3	4	3	3	3
Japan	Kumamoto	Acceptable	0.9		0	0		0	2		-1	-1		0	0		0	0		1	1		3	3		3	0		3	3
UK	London	Good	1.8	5	5	4	2	2	1	0	0	1	1	0	4	0	0	0	0	0	0	3	3	3	3	3	3	1	0	3
France	Normandy	Good	1.2		1	1		0	0		0	1		0	1		5	2		-3	1		0	2		3	2		3	2
Israel	Shafdan[3]	Good	1.4	5	1	4	4	1	4	5	0	-1	5	0	-1	0	0	1	4	0	3	5	3	3	5	3	2	4	2	1
Italy	Luca, Pisa and Livorno	Good	1.4	3	3	0	3	3	0	2	1	5	0	0	0	0	-1	0	0	0	3	0	0	3	3	3	2	2	2	2
Spain	Segovia Province[3]	Good	1.6	5	5	5	4	1	2	3	-2	0	5	0	0	1	-1	3	1	0	2	5	3	3	4	3	0	4	2	3
Mean High Income (n=17)			1.9	2.5			2.4			1.2			0.5			1.1			1.0			3.0			2.6			2.4		
Upper Middle: 3,996 - 12,375																														
China	Shandong Province[3]	Good	1.3	5	2	3	4	3	3	0	-1	0	1	0	0	5	2	1	2	3	2	3	0	1	0	2	0	3	2	1
Mexico	Sonora	Acceptable	1.0		0	1		0	1		1	-1		-1	-1		1	1		1	3		3	3		3	3		0	0
South Africa	Atlantis	Good	1.2	3	1	2	3	3	2	3	0	-1	-1	0	-1	0	0	2	-1	-1	0	3	3	3	3	3	3	2	2	1
Namibia	Winhoek	Good	1.6		3	5		3	3		0	1		0	1		0	3		-1	1		1	3		0	3		0	2
Mean Upper Middle (n=4)			1.3	2.1			2.3			-0.1			-0.3			1.3			1.0			2.1			2.1			1.0		
Lower Middle: 1,026 - 3,995																														
Jordan	Madaba	Acceptable	0.2	5	1	2	-2	1	1	0	-3	0	-1	0	0	5	-1	1	-3	-1	1	2	0	0	0	1	0	2	0	0
Egypt	Sidfa	Acceptable	0.9	0	0	0	3	3	1	2	1	1	0	0	1	0	0	0	2	1	3	1	1	1	1	1	1	2	2	0
India	Haridwar	Good	1.5		0	2		3	2		1	2		0	3		0	0		3	3		1	2		1	1		2	1
	Rajasthan	Acceptable	0.7	4	1	1	2	3	1	3	-1	1	0	0	1	0	-1	-1	1	0	1	1	0	1	1	1	0	1	2	3
	Maharashtra	Acceptable	0.4	4		1	2		1	3		0			0	0		-1	0		2	1		0	1		0	1		1
	Uttar Pradesh[3]	Acceptable	0.1	2	0	2	2	0	1	1	-3	-1	1	0	-1	1	0	1	2	0	1		0	0		1	0	2	0	0
Bangladesh	Khulna[3]	Good	1.3	5	0	1	4	3	2	5	1	5	5	0	1	3	0	0	5	0	3	3	-1	0	3	1	0	3	3	5
Mean Lower Middle (n=7)			0.7	0.8			1.7			0.3			0.4			-0.2			1.3			0.4			0.6			1.5		
Min				0.0			0.0			-3.0			-1.0			-3.0			-3.0			-1.0			0.0			0.0		
Max				5.0			5.0			5.0			4.0			5.0			4.0			5.0			5.0			5.0		
Mean of all schemes				**2.1**			**2.3**			**0.9**			**0.5**			**0.8**			**1.0**			**2.4**			**2.2**			**2.2**		

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[1] Full description of Indicators 1 through 9 is available in Table 3

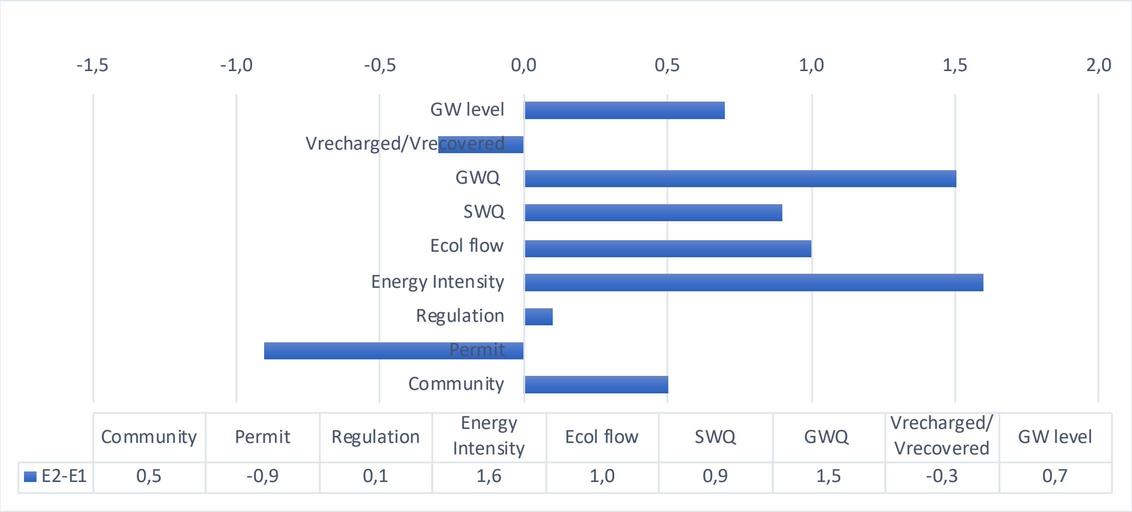
[2] Mean value of all 9 indicators scored following the scale from low to high: debilitating (-5), harming (-4), inferior (-3), diminished (-2), degraded (-1), no added value (0), improved (+1), enhanced (+2), superior (+3), conserving (+4), and restorative (+5) in Table 2.

[3] Red colour highlights the 6 cases with self-rating that are significantly (>1) above the average rating by two experts, and the indicators with self-rated scores significantly (>2) above the average rating by two experts. Blue corlor indicates the opposite, with self-rating significantly (<2) below.

[4] Authors agree with E1 rating

3.4.2. Variability in Rating Across Cases

How consistently can the experts and the authors rate the individual indicator and the case? If there were more experts to rate the cases, the variance on the score would likely be better defined. So the difference of the score between E1 and E2 for each indicator, and also for each case, is used to illustrate the reliability. Across the 27 cases that both experts provided rating, E2 generally rated the cases more favorably than E1, and gave on average a score 0.6±0.6 point higher (range: -0.3 to 1.9). Additionally, the rating by E2 is significantly (defined as the difference in mean rating score for each case) higher than that by E1 for 5 out of 27 cases: Perth, Dinterlord, Koksijde, Windhoek and Khulna. E2 rated groundwater quality and energy intensity with a mean score 1.5 point and 1.6 point higher than E1 did (Figure 2), suggesting that these are the two indicators more difficult to rate consistently. Again, rating by more experts are clearly desirable to calculate a variance for each individual indicator. For now, self-rating for 10 cases that do not differ significantly from the mean score of the experts is used to assess variance as a substitute (Figure 3). Again, ratings for groundwater quality and energy intensity are more variable, or less consistent, confirming that these are more difficult to rate.



	Community	Permit	Regulation	Energy Intensity	Ecol flow	SWQ	GWQ	Vrecharged/ Vrecovered	GW level
■ E2-E1	0,5	-0,9	0,1	1,6	1,0	0,9	1,5	-0,3	0,7

Figure 2.
The mean score difference for 27 cases rated by E2 and E1 for each indicator, with E2 generally scoring more positively than E1. Rating for energy intensity and groundwater quality is where the two experts disagree the most, with > 1 point difference.
Source: Own elaboration

Although the variability in rating appears to be small enough so that the rating is useful, it is clear that any quantitative comparison of the indicator rating (Table 5) is not recommended, with the rating itself interpreted with a giant grain of salt. A conscious effort should also be made to avoid creating a sustainability trap for lower income countries when applying the indicators. Furthermore, even with this seemingly large number of cases (Table 4), because the scheme ranged from a minimum recharge volume of 667 m^3/yr in Khulna, Bangladesh using ASR to supply drinking water to a village, to a maximum recharge volume of 342 million m^3/yr in Arizona, USA to bank water for a large portion of the state using mega infiltration basins and other means, it is best to view each scheme's rating against its own merits (see Appendix III for details). Besides the differences in recharge volume, the diversity of purpose, technique, and institutional setting across 28 schemes is astounding. Therefore, it helps to bear in mind that the sustainability rating for each case is subjective in nature, is a work in progress and have room for further improvement as discussed below.

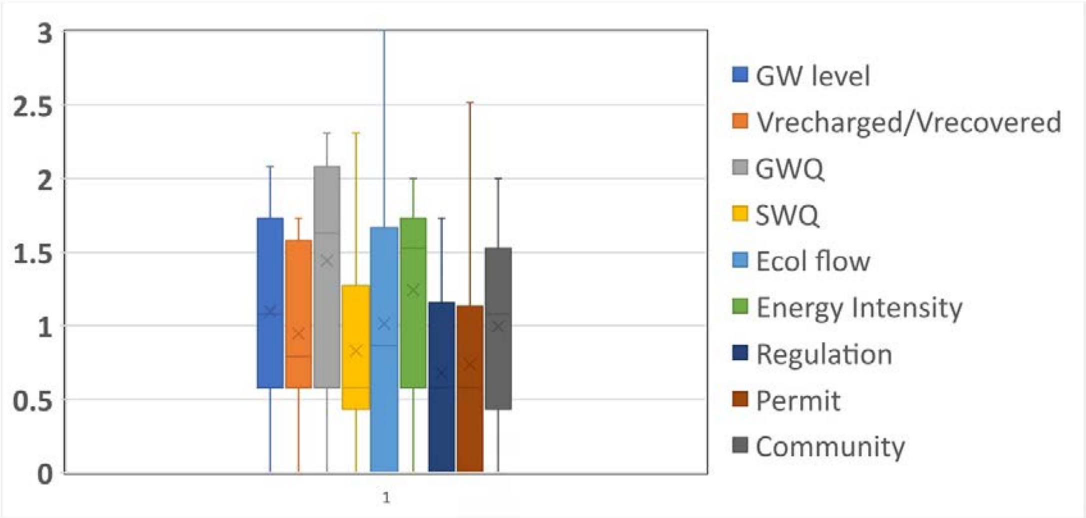


Figure 3.
The variance (standard deviation) of self-rating and rating by E1 and E2 for 9 indicators for 10 cases, excluding the 6 cases that differ significantly from the mean score of E1 and E2.
Source: Own elaboration

3.5. Discussion: Applicability of Sustainability Indicators

To what extent are the indicators useful? In the following, trends emerged from the rating of cases are described, followed by a discussion on further considerations on applicability of the indicators.

3.5.1. MAR schemes more sustainable in higher income countries

A clear trend is that the rating for 17 MAR schemes from the high income countries shows the highest mean rating of 1.9±0.9 (n=17), followed by 1.3±1.0 (n=4) achieved by upper-middle income countries and by 0.7±0.6 (n=7) achieved by lower-middle income countries. That all cases are "sustainable" is not surprising given that screening of contributing cases has sought only "successful" cases, i.e., those that had been in operation for > 10 years and if between 3 and 10 years, which had data to demonstrate likelihood of continued operation in the future (Appendix I). What is surprising is that there is not a single case from low income countries, suggesting that multiple barriers exist to implement MAR there. Further, It is worth noting that high income countries perform better in groundwater quality and two social sustainability indicators regulation and permit (average score 1.2, 3.0 and 2.6, Table 5) than the upper-middle income countries (average score -0.1, 2.1 and 2.1), and the lower-middle income countries (average score 0.3, 0.4 and 0.6). This suggests that proponents of MAR projects can benefit from strengthening water quality monitoring, governance and institutional capacities for MAR to succeed in developing countries. This means to look into whether existing groundwater allocation plans, groundwater quality protection policies, groundwater quality monitoring capabilities and public consultation procedures are adequate to allow for MAR to proceed, and if not, how they may be established or improved. The fact that effective MAR projects exist in countries with various limitations in these aspects suggests that although these may not be prerequisites for MAR, investments in MAR would be much better assured if such measures are in place.

3.5.2. Most MAR schemes are Medium-Sized

Although MAR schemes come in all sizes, it is interesting to note that the three mega (> 100 Mm^3/yr of recharge) MAR schemes are all from high income countries: Arizona and California of USA, and Shafdan, Israel (Table 4 and Figure 4). All are from water scarce regions where agriculture competes with other water demands suggesting perhaps a priori for development of large MAR is hydrological water scarcity. There are also two tiny MAR schemes with <0.1 Mm^3/yr of recharge: Khulna, Bangladesh and Dinterlord, the Netherland for drinking and agriculture, respectively (Table 4). Excluding these, the average volume of annual recharge is 10.3±9.3 Mm^3/yr across 20 MAR cases. Indeed, most cases appear to cluster around the 10 Mm^3/yr volume of recharged water (Figure 4) for reasons not yet apparent.

3.5.3. Applicability of Indicators by Category

Category 1: Environmental/Resource Integrity

Four indicators are in this category, with two each addressing water quantity and quality (Table 3). It is considered that these are sufficient to measure sustainability of MAR.

For Indicator 1 groundwater level, the expert rating range is from zero (no added value) to 5 (restorative) with a mean value of 2.1 (enhanced), suggesting that groundwater table demonstrate acceptable changes and are sometimes restorative (Table 4).

For Indicator 2 the ratio of volume of infiltrated water vs recovered water, it has now been revised to the ratio of volume of recovered water vs recharged water so that it is more intuitive and easier to understand. This revised ratio ranges from 0.0 to 8.3 (Table 4). When the amount of recovered water is less than that of the recharged water, as is the case for 10 schemes that fall below the 1:1 line (Figure 4), this means that there are basically zero chance of overexploiting the aquifer so the resource integrity of water quantity is assured. Indeed, some of these schemes such as Nebraska, USA and Normandy, France are meant for ecological flow and protection of ecosystem, respectively. This ratio is also <1 for Salisbury of Australia, Dinterloord of the Netherland and Khulna, Bangladesh because the target aquifer is brackish so mixing with ambient groundwater reduces recovery efficiency. For the 20 cases that cluster around the 10 Mm^3/yr volume of recharged water, several schemes clearly show much higher than 1 ratio, warranting a closer look because more water is recovered than recharged. It turns out that in these cases, MAR augments natural recharge so the recovered water contains a significant portion of ambient groundwater. For the three RBF schemes, this ratio is 1.1, 1.2 and 1.4 respectively, so this may be a useful figure to consider for other RBFs when estimating the proportion of infiltrated river water and ambient groundwater.

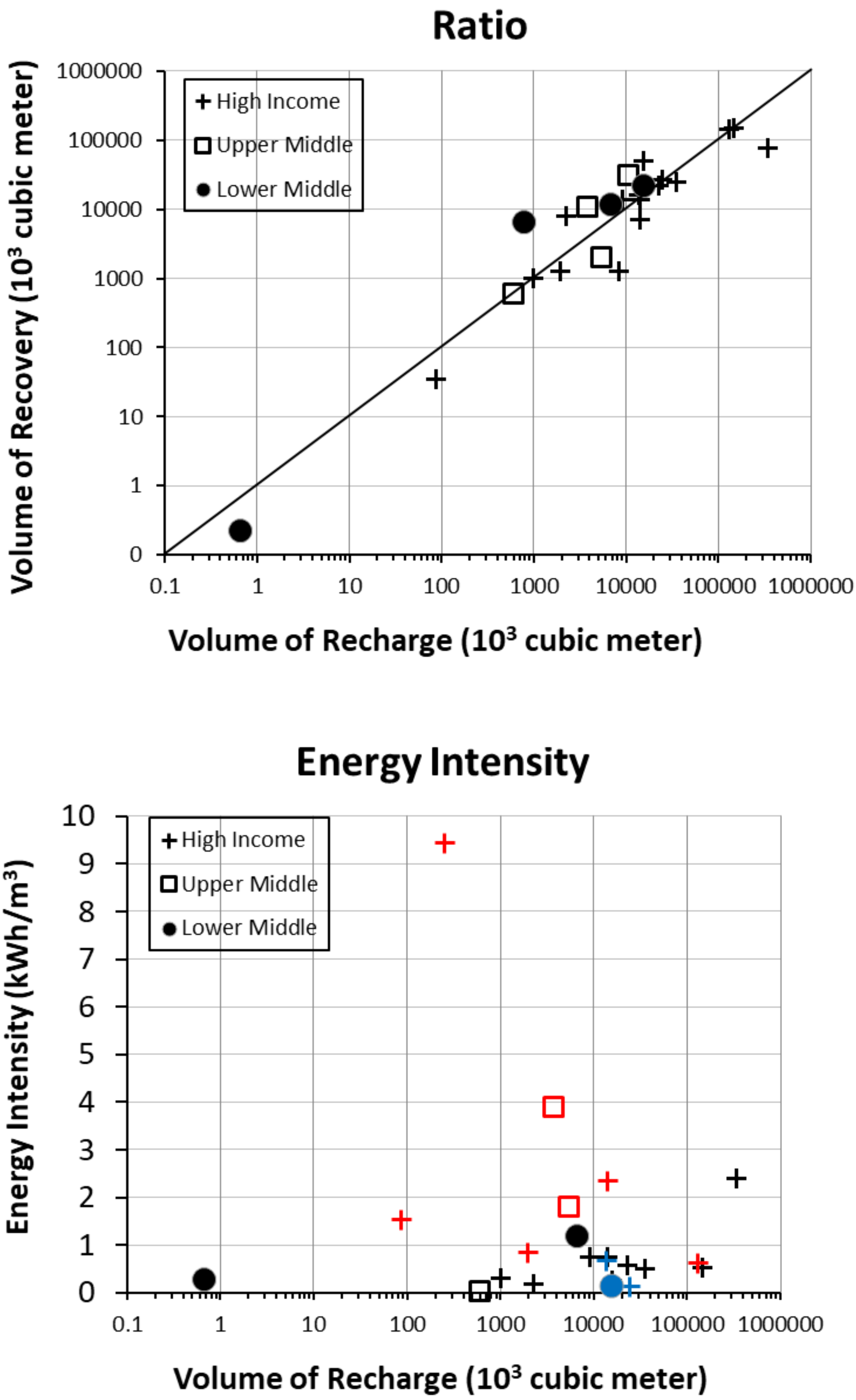


Figure 4.
The volume of recovered water (top panel) and energy intensity (bottom panel) vs the volume of recharged water. Red color indicates schemes using treated effluent as source water (see also Table 4). Blue color indicates schemes using RBF. Source: Own elaboration

If one must choose between indicators 1 and 2 to assess integrity of groundwater quantity, then clearly indicator 1 is the winner. This is because indicator 1 is more goal oriented whereas indicator 2 is more process oriented. Presumably estimation of the volume of recharge and recovery focuses the hydrogeological investigations essential for the success of the MAR schemes. Indeed, advanced understanding of groundwater flow and water balance by the Orange County Water District, California of USA and the Turku Region Water Supply, Finland has enabled these entities to manage and adjust recharge and recovery such that the MAR functions as an engineered natural system.

To ensure future use of the target aquifer, the experts consulted during the initial phase of establishing indicators have all emphasized the need to maintain integrity of groundwater quality. Indicator 3, exceedance rate based on time-series monitoring of recovered or ambient water quality parameters, is found to span the widest range of all indicators: a minimum of -3 (inferior) and a maximum of 2.0 (enhanced), with an average of 0.8 (no added value to improved). Although high income countries generally did better with a mean score of 1.2, significant water quality risks inherent to recycling waste water and from surface water pollution remain challenging for MAR scheme sustainability even in high income countries. Some of these risks are being dealt with by advanced treatment, however, this significantly increases energy intensity (Indicator 6, see below). This indicator is also most challenging to rate (Figures 2 and 3). A possible explanation is that perception of risks is well known to be variable, so even the experts are likely to view the same levels of risks as different threats. In addition, water quality data are not always clearly reported in the case themselves. Given that this indicator is of paramount importance to maintain resource integrity, it is therefore especially relevant to further improve the expert rating through additional consultation, and to explore quantitative methods as described later in the Quantitative Analysis section.

Indicator 4, exceedance rate based on time-series monitoring of source water quality parameters, is mainly a liability for MAR schemes, with some negative values. This rating exercise clarifies that Indicator 4 is more of a process oriented not a goal oriented indicator. Indeed, going through the sustainability index calculation using raw source water, treated source water and supplied water quality data confirms that the need to manage source water quality is a key to success of MAR. The likely reason for the different rating by E1 and E2 is that one of the experts is viewing source water quality from the perspective of the MAR success while the other is viewing source water quality purely from whether the MAR scheme would negatively impact the source water integrity. Because continued threat of source water pollution is mentioned in nearly half of the cases, indicator 4 is also retained but when rating this indicator, it is may be more useful to view whether the treated source water quality will help MAR to achieve its stated goal, so to rate the case more like E2.

Category 2: Environmental/Ecosystem Services

Only one, Indicator 5, change in ecological flow (m^3/yr) in ecosystems needing protection identified in a catchment water management plan, is in this category. It is recommended that this be retained as it becomes evident that in several cases, especially in water scarce India, food security has triumphed over ecological flow (Table 4). Ecological flow is not considered very important by some MAR practitioners because the mean score during ISMAR10 consultation was only 4.9 (Table 3). But it really should be something MAR community strive for, especially in Italy and Spain where river flow has been challenged possibly due to climate change. It is encouraging that in Nebraska, USA, this was what drove the rehabilitation of irrigation canals for restoring of base flow to Platte River. Further, although not intended to maintain flow but instead to maintain water quality, the goal of protecting sensitive coastal environment in Salisbury, Australia and Normandy, France has motivated MAR use to improve water quality before discharge. Finally, the underground dam in Shandong Peninsula, China, also helps to restore base flow for a stretch of the Balisha river. In summary, this indicator may be modified to reflect a broader ecosystem objectives. A revision to Indicator 5 may read "Changes in ecological flow (m^3/yr) and improvement in water quality in ecosystem needing protection identified in a catchment water management plan".

Category 3: Environmental/Stressors

Only one indicator 6, energy requirements in KWh per cubic meter of recovered water, including monitoring and treating recovered water, solving clogging and low recovery efficiency issues, belongs here. It is recommended that this indicator also be retained, but with clearer guidelines on data collection and reporting provided in the future to allow for meaningful comparison. Having this clarified is important for climate resilience and is a topic of interest for water-energy nexus. At present not all categories of energy involved in MAR, especially the construction of the infrastructure, has been included so this energy intensity likely represents an underestimation.

Despite this, it is clear 7 MAR schemes using treated effluent as source water display higher energy intensity (Figure 4 and Table 4, red color), averaging 1.7±1.1 kWh/m^3. The highest energy intensity documented is Winhoek, Namibia where energy intensity for treating waste water and lifting the water up for recharge was 3.9 kWh/m^3 (Table 4). Shafdan, Israel SAT of treated effluent has the lowest energy intensity of 0.63 kWh/m^3, but only because the energy intensity associated with waste water treatment is excluded. Four RBF cases in general display lower energy intensity, and from low to high being Dresden Germany, Haridwar India, Sidfa Egypt, and Luca, Pisa and Livorno of Italy. Because RBF's energy consumption is primarily from pumping, use of siphoning wells (Germany) clearly have advantages over submersible pumps only (Italy). However contaminants of emerging concern have triggered pilot testing of ultrafiltration at the RBF facility of Dresden, Germany and will likely increase the energy intensity further by 0.3 to 0.5 kWh/m^3. Despite limitations, the average total energy intensity of all 23 schemes with data is 1.3 KWh/m^3, which can still serve a useful benchmark.

It is recommended that proponents of MAR schemes consider energy intensity in design and implementation, and expand the use of renewable energy to reduce environmental stress. The proportion of energy from fossil fuel and renewable could also be tracked. Finally, infiltration of water also brings with it dissolved inorganic and organic carbon and may have had an added benefit of carbon sequestration as is suggested in the Hilton Head case. This warrants further research, accounting for aquifer and aquitard stability through carbonate dissolution. When it comes to rating, it would be helpful to define what is an acceptable energy intensity for water, should this be relative to available alternatives or should this be an absolute energy intensity requirement. The two experts appear to differ when rating this indicator, with E1 applying a more absolute acceptable level while E2 applying a relative to alternative option.

Category 4: Social/Resource Security and Human Health

Indicators 7 (regulatory framework) and 8 (permit granting process) are essential to ensure monitoring of resource integrity and protecting of human health. This falls under governance, and is where the lower-middle income countries lag behind the most, trailing also the upper-middle income countries (Table 5). There are several MAR schemes that were motivated or nudged by these regulatory requirements so these indicators should be retained.

Category 5: Social/Sustainable Community, Participation, Education and Environmental Justice

Only one Indicator 9, systematic Institutional arrangements for public and stakeholder consultation, preferably with regular publicly available reports of scheme outcomes, is included. However, the usefulness of this is difficult to assess because the diverse income, geographic and purpose of the MAR cases, with authors describing what they perceive to be community engagement and not necessary a measure against progress for this indicator. Therefore, this indicator should be retained, with further testing of its applicability. This is also an indicator with high variability (Figure 3).

3.6. Quantitative Analysis: Sustainability Index for Turku Regional Water Supply, Finland

The main purpose of conducting this quantitative analysis is to inspire more research, with a possible outcome of incorporating objective assessment of sustainability into a guideline for MAR in the future. An attempt is made here for the Turku regional water supply to illustrate the steps of calculating sustainability index (SI) for individual indicators with sufficient time series monitoring data following the methodologies proposed by Loucks and Gladwell [1] and later modified by Thomas *et al*. [7]. A lesson learned in this example below is that a key is to determine or know the satisfactory level or threshold value for each indicator. This means that calculating SI for Indicator 1, groundwater level or hydraulic head (Table 3), becomes more complex because very often such threshold value is not known and requires investigation and discussion due to spatially variable heads and management objectives. On the contrary, water quality parameters are regulated with satisfactory level usually known and defined by the maximum contaminant level (MCL). The challenge then becomes which water quality parameter out of the 7 categories (pathogens, inorganic chemicals, salinity, nutrients, organic chemicals, turbidity and radionuclides) to choose even though all of them are critical for human health protection. Inspired by how air quality index (AQI) is constructed, i.e., only the worst offender is used for calculation of AQI, it is suggested that either water quality parameters representing the main objective of MAR or the worst offender is used. In the specific case of Turku, because the main water quality challenges are two folds, turbidity and high total organic carbon (which leads to disinfection by-products upon treatment) in raw source water drawn from the river (Table 6), and the primary objective of pre-treatment and MAR are to deal with these, sustainability index are calculated for these two parameters (Table 7). It is worth noting that all the water quality parameters regulated for human health protection are monitored at Turku but never exceeded MCL, making its SI a wholesome value of 1 which is uninteresting as an example to illustrate methodology. How each indicator's contribution should be weighted and combined into one single sustainability index also requires further research that is beyond the scope of this study.

Table 6.
Median (Min, Max) Concentrations of Selected Water Quality Parameters for Turku MAR in 2018.
Source: Own elaboration

Parameter	Source River Water n=12	Treated River Water n=12	Recovered & Supplied Water[1] n=6	STM442/2014[2]
EC µS/cm	75 (66,87)	87 (77,96)	140 (140,140)	<2500 (b)
Turbidity FNU	4.4 (2, 9)	0.2 (<0.2, 1.1)	<0.1 (<0.1, 0.1)	No unusual changes (b)
TOC mg/L	9.1 (8.3,11)	4.3 (3.7,4.8)	1.9 (1.7, 2.0)	No unusual changes (b)
Enterococci cfu/100 ml	8 (2,36)	0 (0, 0)	0 (0,0)	0 (a)
Fecal coliform, cfu/100 ml	11.5 (4, 34)	0 (0,0)	0 (0,0)	0 (a)
As µg/L			1.7 (1.5, 1.8)	<10 (a)
Trihalomethanes µg/L			25 (24,30)	In total <100 (a)

[1] 29 basic and 4 microbial parmaters, 9 organic compounds were monitored mostly 4 to 8 times in 2018, with microbial parameters monitored 51 times for supplied water, 41 basic and 5 microbial parameters, 10 organic compounds were tested 1 to 6 times in 2018 in 12 production wells

[2] Finnish Ministry of Health Standards, (a) quality requirement, (b) quality recommendation

Although both groundwater quantity indicators are not used in this example for a calculation of SI, it is still useful to examine the time series variation of hydraulic heads in observation wells (Figure 5). Prior to the commencement of MAR in Dec 2011, groundwater has been extracted at a rate of 5000 m^3/day since Jan 1999, resulting in a decline of groundwater level as evidenced by 3 observation wells (Figure 5). Rise in groundwater level started in Aug 2010 and reached a new steady state level by 2013, despite a > 10 times increase in groundwater production rate to 64,000 m^3/day. The rise in groundwater level is also evident from the southwest (+0.5 m) to the northeast (+2.0 m) close to the center of the aquifer where most of the infiltration basins and production wells are located. In principle, it is possible to calculate SI. However, this would require a satisfactory threshold to be specified for the hydraulic head. This is not an easy task because although the groundwater level is not identical to pre-development stage, it may very well be sufficient to provide all the ecosystem's water needs so one cannot simply assume that the pre-development level should be the satisfactory level. In addition, climate change may have also altered hydrological cycle over decades. Nevertheless, the long term groundwater level monitoring as well as the carefully managed pumping relying on a three dimensional hydrogeological model based on aquifer geology constructed using numerous bore hole logs, gives the confidence of the high positive scores of sustainability rating of these two indicators (Table 5).

For the two water quality related indicators (Table 3), the satisfactory level needs to be determined first. Unfortunately, the two parameters, turbidity and TOC, chosen based on the fact that these are the two parameters that if not properly dealt with then the scheme fails, do not have specific MCL as the regulation only requires “No unusual changes” (Table 6).

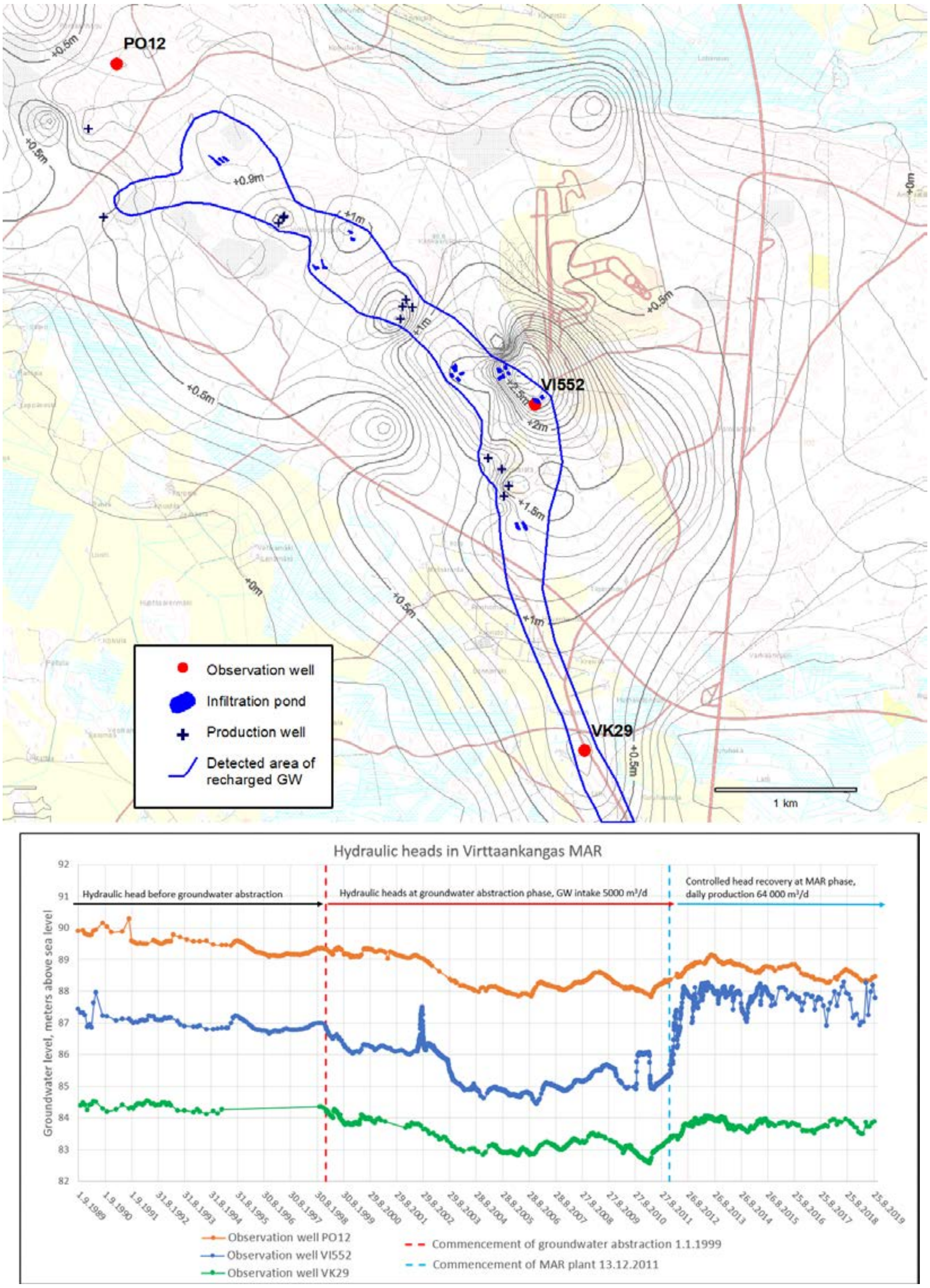


Figure 5.
Top panel depicts the rise of hydraulic heads from the groundwater abstraction phase (Aug. 2010) to recovered hydraulic heads of MAR production (Dec. 2013). The locations of infiltration basins, production wells and observation wells are marked, along with the zone of influence of recharged water (blue line) and recovery of groundwater levels extending the whole aquifer area. Bottom panel shows hydraulic heads of three observation wells that demonstrate a drawdown between 1999 and 2010, with subsequent recovery to a new steady state level since 2013. The graph shows that the natural trend of hydraulic heads is declining (PO12), but the hydraulic heads have recovered to and above the pre-1999 levels in the influence area of MAR production. Source: Own elaboration

It is worth noting that the pre-treatment has removed nearly all the turbidity (plus microbes), which reduces risks of clogging during infiltration later. TOC was halved in each step, first through pre-treatment, then through MAR system. This is significant because one of the distinct feature of Finish surface water is its high TOC level due to extensive northern peatland. Such organic compounds when subject to chlorination, react to form disinfection by-products, therefore removal of TOC is necessary for drinking water safety.

Time series data of turbidity and TOC (Figure 6) are analyzed to obtain descriptive statistics of the data set (Table 7). As an alternative, the satisfactory level for each parameter is based on identifying extremes, defined as events with above the 95th percentile value. Figure 6 illustrates only a few data points exceeding satisfactory level defined this way, allowing for assessment of the number of unsatisfactory events and therefore calculation of reliability and resilience using equation 1 and 2.

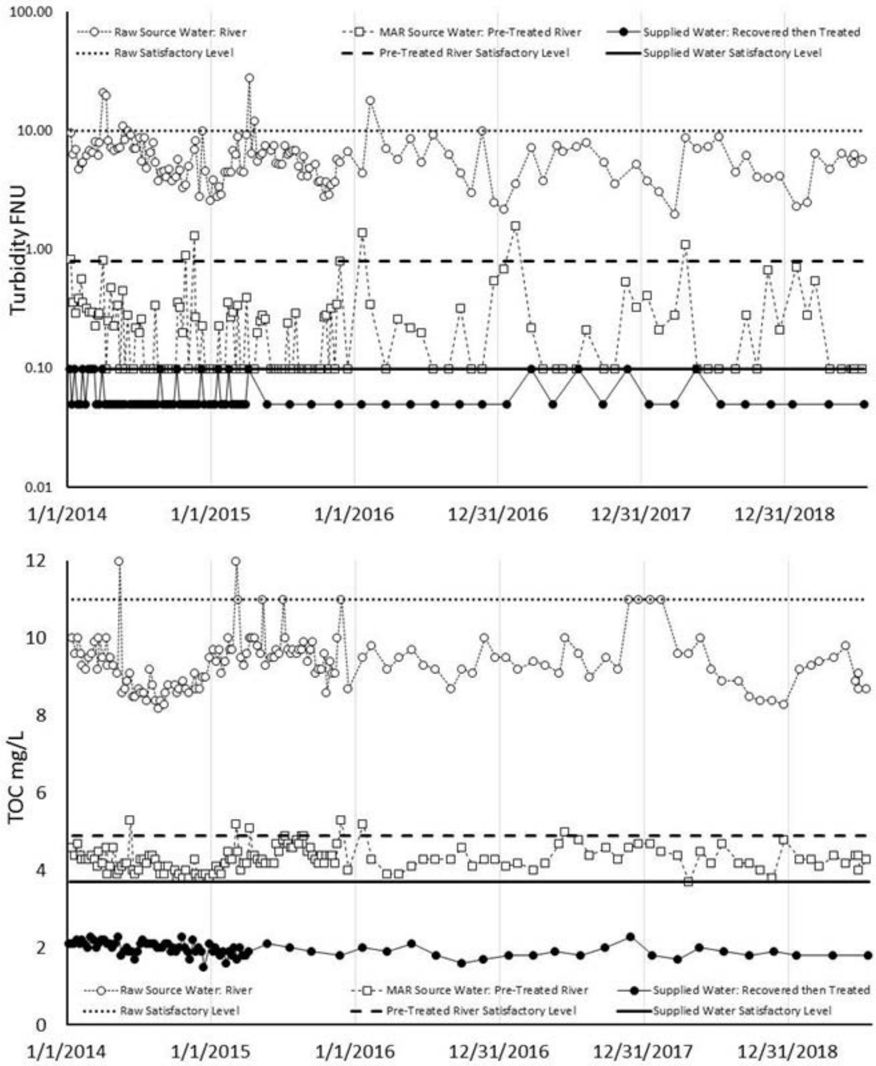


Figure 6.
Turbidity (top) and total organic carbon (TOC) levels in raw source water sampled at the river intake (open circle), the pre-treated river water (open square) for use at the infiltration basin, and the supplied water (solid circle) for consumers are monitored more frequently in 2014 and parts of 2015 and less frequently since 2016 to July 2019.
The satisfactory level is based on 95th percentile value of each time series data (Table 7).
Source: Own elaboration

For vulnerability, the severity is calculated by dividing the measured value by the 95th percentile value. This indicates to what extent the extreme event has exceeded the satisfactory level. The probability of each unsatisfactory event is equal to 1 divided by the total number of observations in the time series data set. Then equation 3 is used to calculate vulnerability. Finally, equation 4 is used to compute sustainability index (SI).

The sustainability index results (Table 7) reveal a couple of interesting features. First and foremost, frequency of time series monitoring is important. This is because any extreme events are unlikely to be frequent, thus infrequent monitoring will likely "miss" such events, resulting in an over estimation of SI. Most of the "unsatisfactory" events for both turbidity and TOC in raw river water took place in the first two years when the monitoring was more frequent. Increasing SI value as the water proceeds through pre-treatment to infiltration is not surprising, what is interesting is that both intake and pre-treatment still exhibit vulnerability, suggesting further optimization of operation may be warranted. Surprisingly, the SI for raw river water is already very high. This is attributed to the arbitrary designation of satisfactory level to 95th percentile value. It is better if a level of TOC allowable to ensure low levels of disinfection by-products can be determined from laboratory experiments, which may lead to lower threshold value for the satisfactory level. This means that there will be more exceedance for the raw river, and also pre-treated river water, making the SI more meaningful. Given the caveats, the SI is not combined in any weighted fashion for a single value and requires further research.

Table 7.
Sustainability Index from Turbidity and TOC Monitoring (2014.01 - 2019.07).
Source: Own elaboration

		Turbidity NFU			TOC mg/L		
		Raw River	Pre-Treated River	Supplied Water	Raw River	Pre-Treated River	Supplied Water
	n	140	141	89	140	140	90
	min	2	0.1	0.05	8.2	3.7	1.5
	max	28	1.6	0.1	12	5.3	2.3
	median	5.8	0.1	0.05	9.4	4.3	2
	mean	6.3	0.3	0.1	9.4	4.3	2.0
	STDEV	3.4	0.3	0.0	0.7	0.3	0.2
Satisfactory Level	95th percentile	10	0.8	0.1	11	4.9	2.2 (3.7)*
#Unsafisfied Events		6	7	0	2	6	0
#Satisfied-Following-Unsatisfied		5	7	0	2	6	0
Reliability		0.96	0.95	1.00	0.99	0.96	1.00
Resilience		0.83	1.00	1.00	1.00	1.00	1.00
Vulnerability		0.08	0.07	0.00	0.02	0.05	0.00
Sustainability Index		0.73	0.88	1.00	0.97	0.91	1.00

* The minimum value of pre-treated river water TOC is deemed satisfactory

A detailed breakdown of energy intensity for Turku is in Table 8, with a noteworthy feature that a turbine has been installed to generate energy that makes the bedrock reservoir operation carbon neutral. Further, water transfer accounts for most of the energy use as infiltration is gravity driven. The methodology presented above is not suitable for assessment of the energy intensity indicator, although collecting annual mean energy intensity data will be helpful to document environmental stress by MAR schemes.

Table 8.
Energy consumption breakdown, year 2018. Source: Own elaboration

Raw water intake	934,275	kWh	0.04	kWh/m³	Energy are used mostly for water transfer
Pretreatment	6,553,683	kWh	0.28	kWh/m³	Energy are used mostly for water transfer, water treatment is a minor part
Virttaankangas MAR	3,960,100	kWh	0.17	kWh/m³	Energy are used mostly for pumping water from production wells
Bedrock reservoirs	1,593,942	kWh	0.07	kWh/m³	Energy are used mostly for water transfer, water treatment e.g. with UV is a minor part
Energy production, year 2018					
Turbine	1,658,000	kWh	0.07	kWh/m³	Own green energy production with Saramäki reservoir generator

A critical lesson learned from the Turku MAR scheme is the value of thorough hydrogeological and hydrochemical investigations. This also explains in part the good rating of the groundwater quantity and quality indicators. Detailed sedimentological and hydrogeological investigations have resulted in a high resolution 3-dimensional (3D) hydrostratigraphic reconstruction and a 60-layer 3D groundwater flow model. This ability to model flow with confidence has enabled the scheme to produce drinking water in a reliable manner. Acquiring this knowledge has taken much work and many years, and has involved sediment coring, monitoring well installations, water quality analyses, geophysical studies, pumping tests, isotope analyses, tracer tests etc. Not only this knowledge has been critical to enhance the yield of the aquifer considerably without causing harm to the environment and natural flows of groundwater outside the production area, it has allowed for optimization of removal of TOC because it requires thorough understanding of the flow paths and residence times of the infiltrated water. The infiltration locations and infiltration rates as well as the pumping rates of the water intake wells are tuned so that the residence time of the infiltrated water is the same throughout the aquifer and is maintained at 4 months. This knowledge enabled the operator to negotiate "the terms of business" with nature to purify the infiltrated water within nature's acceptable limits to ensure sustainability. The ability to manage flow also means that the flow of ambient groundwater can now be diverted to feed springs to maintain a stable discharge, when in contrast, there have been significant drops in spring discharge rates in other esker areas in southwestern Finland in the last decade.

Another good practice is spectrometer and fluorometer monitoring of the intake river water that provides warning about rapid changes in water quality in real time. Water intake can be ceased when optically active substances, such as organic solvents, fuels, certain pesticides and unusual soluble organic substances are detected and are confirmed.

3.7. Conclusion

The newly established 6 environmental and 3 social sustainability indicators are found to allow for meaningful assessment of sustainability of 28 MAR schemes from 21 countries qualitatively through a sustainability rating system. A quantitative assessment, calculation of sustainability index based on time series water quality monitoring data, is also demonstrated for a MAR scheme in Finland. In this set of cases water quality challenges are typically greater than water quantity challenges for maintaining resource integrity across all schemes. Ecological flow and ecosystem impacts are often secondary to other objectives and these need more attention by MAR proponents to be ready with information and data to better inform their community that may have increasing expectations of high standards. Energy intensity is a parameter that is poorly tracked for most cases and needs to be considered, including tracking the proportion of fossil fuel and renewable energy to document environmental stress. Strengthening institutional capacity for sound regulatory framework for water allocation and permit granting process for water quality protection is especially relevant for developing countries. Community engagement is still a work in progress for most MAR schemes. Applying the same vigorous assessment in the planning and design of new schemes can shed light on best practices that are likely to enhance sustainability.

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Chapter 4: Economic costs and benefits of Managed Aquifer Recharge Case Studies

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4.1. Introduction

Water has a number of special biophysical, socio-economic and institutional characteristics including spatial and temporal variability and uncertainty of flows and difficulties in establishing ownership and regulating use. The development of water resources offers economies of scale, and often involves widespread impacts on both quantity and quality. This has resulted in a high degree of public intervention in water management, and limited development of private markets for trading and pricing water. As a result, water allocation and management decisions are often guided by synthetic estimates and shadow prices (Young 2005)[1], and cost recovery objectives.

Groundwater resources have additional special characteristics. Groundwater supplies most of global freshwater, and quantities are relatively stable, but many groundwater resources recover slowly from depletion or are non-renewable. Groundwater resources are developed by individual landowners, who pump groundwater within their property boundaries. It is often difficult to agree on the sustainable yield of aquifers or limits to groundwater use, resulting in weak regulation of groundwater. Weak regulation and shortcomings in enforcement often result in areas of unsustainable groundwater use, with continuously falling groundwater levels and increased pumping costs (FAO 2015)[2]. While managed aquifer recharge can serve multiple purposes, a strong driver for MAR is often needed to provide reliable access to water while counteracting intensive and unsustainable use of groundwater resources.

There are usually a number of alternative ways of meeting demands for water resources and supplying water for domestic consumption, agricultural and industrial uses and the environment. It is important to establish a consistent methodology for comparing and evaluating the impacts of alternative water resource management options, including MAR.

Cost-benefit analysis provides a systematic approach for evaluating the impacts of alternative water management options on society as a whole. Although costs and benefits are key determinants of the global uptake of MAR, there are few studies of the costs and benefits of different kinds of MAR or of the performance of MAR compared to other water resource management options. Existing studies focus on small regions or individual cases and do not provide cross scheme synthesis at cross-continental scales. The International Association of Hydrogeologists (IAH) has established an Economics of MAR Working Group under its MAR Commission to document the financial cost and economics of MAR.

This chapter includes assessment of the costs and benefits of 24 MAR schemes from 18 countries. It was not possible to get suitable data on the costs or benefits of three schemes included in this publication[3]. A benefit cost ratio was estimated for the Orange County scheme[4]. The analysis in this chapter draws on methodology developed by the IAH Working Group (Ross and Hasnain 2018)[3] as explained below.

MAR schemes show a great diversity of type and scale. This diversity, is reflected in the wide range of costs and benefits of different schemes, which are influenced by a wide variety of hydrogeological, environmental, socio-economic and institutional factors at various scales. For example, hydrogeology, soil and vegetation characteristics affect water recharge and recovery rates, socio-economic conditions affect the demand, availability and cost of labour and capital, and regulatory arrangements influence project set up costs (ASR Systems 2006, Dillon *et al* 2009)[4,5].

This chapter contains two components:

Analysis of cost data from 24 MAR schemes from 18 countries, including capital and operating costs combined with data on volumes of water recharged and recovered, to estimate levelised costs per cubic metre of water recharged and/or recovered. A separate method for costing of three schemes that bank water for drought and emergency supplies was based on capital costs of daily emergency supply capacity;

Estimates of benefits and benefit cost ratios (BCRs). Benefits have been estimated using a range of approaches notably the costs of the next best alternative source of water or water treatment and the value of production using recharged water.

The chapter proceeds as follows. Materials and methods for assessing the costs and benefits of MAR schemes are presented. The capital and operating costs of MAR schemes are analysed and key factors influencing cost differentials between schemes are identified. Benefits of MAR schemes are analysed and benefit cost ratios (BCRs) are presented. The chapter ends with a summary of the main conclusions.

4.2. Materials and methods for assessing the costs and benefits of MAR schemes

Cost-benefit analysis provides a systematic approach for valuing and evaluating alternative water supply and management options by quantifying their impacts on society as a whole (Boardman *et al* 2017)[6]. A distinction should be made between financial and economic values. Whereas a private investor is interested in actual money costs and returns of a water project, governments need to consider the overall effects of the project on the economy in terms of the “opportunity costs” or the next best alternative use for the resources.

A further distinction can be made between extractive and non-extractive values (Qureshi *et al* 2012)[7]. The extractive value of groundwater includes municipal use and agricultural, industrial and mining production. Non-extractive values of groundwater can be divided into in situ benefits, natural discharge benefits and option values. In situ benefits include protection of groundwater quality, avoidance of land subsidence and prevention of seawater intrusion. Natural discharge benefits include maintenance of springs and wetlands, and recreational and cultural values. Option values include maintaining aquifers and connected ecosystems for use by future generations.

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[3] These are the schemes from Shafdan, Israel; Hosterwitz, Germany; and Atlantis, South Africa.

[4] A levelised cost estimate could not be supplied for the Orange County scheme because the scheme was built in a number of stages and it was difficult to arrive at a single capital cost.

The direct costs and benefits of aquifer recharge such as water storage and recovery and additional water supplies (extractive values) are easier to account for and measure in monetary terms than indirect costs and benefits to third parties and the environment (non-extractive and option values). This study focuses on extractive values because of lack of data available to measure non-extractive values. The range of valuation techniques used in the analysis of benefits of MAR schemes is also limited by data availability and the need to make consistent analysis across a wide and diverse set of MAR schemes, but includes several widely used methods.

Time is an important dimension when comparing projects. Some projects may have a large flow of benefits early in their life whereas others might have long delayed benefits. Discounting costs and benefits provides a framework to compare different flows of costs and benefits over periods of time.

4.2.1.Costs of MAR schemes

Levelised cost is the preferred method to estimate and present the costs of MAR schemes following the methodology established by Ross and Hasnain (2018)[3]. Levelised cost is a widely accepted method of costing infrastructure projects. Levelised cost of a water supply project is defined as the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply. Levelised costs of water recharged and/or recovered per cubic meter provide an effective means to compare the costs of water from MAR and alternative solutions (Dillon *et al* 2009)[5].

Levelised costs per cubic meter of recharged water were estimated for schemes with the primary objective of aquifer recharge[5]. Levelised costs per cubic meter of recovered water were estimated for schemes that were established primarily to provide additional water for domestic water supply or agriculture, or water security during droughts or at times of exceptional demand. Annual average levelised costs were estimated for 20 out of the 24 schemes as explained below. Market prices for sales of stored water were used to estimate costs of supply from the Arizona water bank. The cost of recovery capacity in cubic metres per day was used in the case of three schemes that were established to provide short-term or emergency supplies during periods of exceptionally high demand or drought.

Levelised costs were processed and standardized in three steps:

Financial cost data (capital and operating costs) were collected for each scheme in local currency units (LCUs). Data was collected for each scheme on capital and annual operating costs. Some schemes were built in several stages and where the levelised cost for the entire scheme could not be estimated, levelised cost was estimated for selected stages of the scheme. In a few cases, capital costs were estimated by scaling up the costs of components of infrastructure such as wells. External costs including water quantity and quality impacts on downstream water users and the environment were not generally included because of lack of data and/or inconsistent coverage and methods of estimation. These impacts are expected to be small for schemes less than 20 Mm^3 annual recharge, i.e. the majority of schemes included in this study. External costs were included in the estimation of benefit cost ratios for a few schemes.

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[5] Schemes established with the primary objective of aquifer recharge and recovery often have a secondary objective of enabling continuing use of aquifers for domestic water supply and agriculture.

The capital costs of MAR schemes apply to different years and periods of time, depending on when the scheme is assumed to start. The capital cost of each scheme was standardized to year 2016 values in local currency units (LCUs) by multiplying costs by a GDP deflator, which measures changes in prices of all domestically produced goods and services[6].

Local Currency Costs were then standardized by converting them to 2016 US dollars[7].

A standardised estimate of the levelised cost of each scheme was estimated assuming an operating life of 30 years, a discount rate of 5.0% and hence a capital recovery factor of 0.0650. Further details of this calculation are shown in Attachment 1 at the end of this chapter. This standardised approach has the crucial advantage of enabling comparison between heterogeneous MAR schemes across different regions and scales. The standardised assumptions of 5% discount rate and 30 year project life are a good approximation in most cases although discount rates range from 3% in a few European countries to 10% in some developing countries, and operating life can range from 10 to 50 years or more.

A different method is used to assess the cost of three water security supply schemes; North London, Hilton Head and Windhoek. Supply capacity for these schemes in cubic metres per day is estimated by dividing the capital cost by the daily amount recoverable from storage measured in cubic metres. Operational costs are not assessed in these cases because facilities only operate occasionally, during emergencies or periods of exceptional demand, for durations that are unknown in advance.

4.2.2. Benefits of MAR schemes

The valuation of benefits of MAR is complicated because of the general absence of a market price for stored or treated water. Drinking water and irrigation water prices often reflect what people can afford to pay and what is politically acceptable rather than water scarcity, reflected in a market price. Some scheme costs may be met by government grants or subsidies, and the system owner and water users may receive most or all of the benefits of the system while not having to pay the full costs.

In the absence of market prices, a range of techniques have been established to value the benefits of MAR schemes. These include the avoided cost of the cheapest alternative supply or treatment, or net value of production using recharged water (e.g. farm production). In situ groundwater values are estimated by the costs avoided because groundwater resources are protected by MAR - avoided costs include costs of pumping, saltwater intrusion and subsidence (Marsden Jacobs and Associates 2013, National Academies of Sciences, Engineering, and Medicine 2016)[8,9]. Brief details of the approach used to value the benefits of individual MAR schemes in this publication are included in Table 3. There are also various methods to value unpriced social and environmental benefits and to estimate the price people are willing to pay for services from MAR (Qureshi *et al* 2012, Maliva 2014)[7,10]. An example of the application of the

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[6] The GDP deflator is a measure of price inflation/deflation with respect to a specific base year. The GDP deflator of the base year is equal to 100. The GDP deflator measures the change in price of all domestically produced goods and services by dividing an index of GDP measured in current prices by a constant price index of GDP. A GDP deflator is used instead of a consumer price index because it is assumed that the inflation of MAR construction costs is related more closely to changes in GDP than to consumer price changes. GDP deflator values were taken from World Bank website https://data.worldbank.org/.

[7] https://data.worldbank.org/

analysis of willingness to pay for benefits from a MAR scheme can be found in Ruperez Moreno *et al* (2015)[11].

The choice of valuation techniques depends on the context and objectives and scope of MAR and the availability of information. If the main benefit of a MAR scheme is additional water supply, the monetary value of additional supply (either annual supply or reserve supply for drought years) may be estimated by one of the following methods:

Volume of water recovered or supplied multiplied by the price of water. Theoretically this is the best way to estimate the value of additional water, but it is often impossible because water is supplied at rates that do not reflect its full economic value;

The cost of recovering or supplying an equivalent amount of water of similar quality by the next cheapest supply option. This may be described as the alternative cost of production or the avoided cost of production. This method is used for estimating benefits of most of the schemes included in this study;

In the case of water for agricultural or industrial use additional supply can be valued by the net benefit (revenue minus cost) of additional production made possible by the additional water supply owing to MAR.

If the main benefit is an improvement in water quality, to meet a specified standard, as might be the case in a MAR scheme using recycled stormwater or wastewater, the benefit can be valued by the costs of the next cheapest water treatment facility.

In the case of water banking to provide groundwater reserves that maintain supplies in drought conditions or buffer against climate change, there may be no viable alternative supply, or the costs of such a supply would greatly exceed the average marginal cost of additional supplies from conventional sources. At the time of MAR construction, it is unknown how much, how frequently and when such water will have to be be supplied. Ross and Hasnain (2018)[3] describe the relevant cost as capital cost divided by supply capacity ($/m^3/day) rather than levelised cost of supply. The benefit of such schemes can be estimated by the avoided cost of an alternative that will provide the equivalent supply capacity.

4.3. Results and discussion

4.3.1. Costs of MAR schemes

An overview of the costs of 24 MAR schemes is presented in Table 1. This includes the average annual volumes of water recharged and recovered under each scheme and the levelised cost per cubic meter recharged and/or recovered, standardised to US$ 2016 values[8].

An assessment of the costs of 21 MAR schemes (Ross and Hasnain 2018)[3] included a breakdown of capital costs and operating costs. Their analysis indicated that some of the schemes with the highest costs involve recharge or injection and recovery of recycled storm water or wastewater. These schemes may require relatively costly treatment to meet standards for drinking and agricultural water use (NRMMC, EPHC, NHMRC (2009)[12] but MAR using recycled water approaches can still be substantially cheaper than alternative water supplies. Recycled wastewater schemes have the advantage that they can generally be used continuously at full capacity whereas stormwater schemes lie idle during dry periods.

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[8] Recharge volumes for cases 5, 11, 13, 23 in Table 1 differ significantly from recharge volumes in Table 1, Chapter 2 and Table 4, Chapter 3 because they refer to specific project components and/or time periods for which cost and/or benefit data was available.

Table 1.
MAR case studies: recharge volumes and levelised costs of water (costs are in US\$ at year 2016 values). Source: Own elaboration

	Case Study Location	MAR type +	Source Water ++	Annual volume recharged (10^3 m^3)	Annual volume recovered (10^3 m^3)	Levelised cost per m^3 recharged (US\$)	Levelised cost per m^3 recovered (US\$)
1	Khulna Bangladesh	W	N	0.677	0.225	1.752	5.252
2	Turku, Finland	IB	N	22,800	22,300	0.892	0.912
3	San Luis Rio Colorado, Mexico	IB	R	11,000	11,000	0.020	Ne
4	Dharta basin, Rajasthan, India	ICM	N	779	779	0.007	0.007
5	Genevois France-Switzerland	IB	N	6,320	6,320	0.754	Ne
7	El Caracillo, Spain	IB	N	2,400	2,400	0.209	Ne
9	Perth Australia	W	R	14,000	14,000	Ne	1.292
11	Baramati India	ICM	N	78	78	0.160	0.160
12	North London UK	W	N	60 per day[9]	66,000 [10]	Ne	US\$730/m^3 /day
13	Windhoek Namibia	W	N	12,000	19,000	Ne	US\$860/m^3 /day
14	Salisbury, S. Australia	W	R	3,500	2,500	Ne	0.98
15	Uttar Pradesh India	IB	N	45	45	0.048	Ne
16	Agon-Coutainville France	IB	R	730	0	1.10	Ne
17	Central Platte Nebraska USA	IC	N	11,110	2,340	0.044	0.212[11]
18	Hilton Head USA	W	N	950	950	Ne	US\$490/m^3/day
19	Serchio R Lucca Italy	RBF	N	16,000	16,000	Ne	0.138
20	Haridwar India	RBF	N	22,000	22,000	Ne	0.076
21	Arizona water bank USA	IB	N	342,000[12]	ne	0.092	ne
22	Sidfa Egypt	RBF	N	2,190	2,190	Ne	0.038
23	Kumamoto Japan	IB	N	11,600	11,600	0.026	Ne
25	Koksjide Belgium	IB	R	1,959	1,392	0.500	Ne
26	Balisha R Longkou China	IB	N	600	600	0.042	Ne
27	Wala Wala Jordan	IB	N	6,739	11,734	Ne	0.388
28	Dinteloord Netherlands	W	R	125	125	Ne	0.760

\+ W= wells, IB= infiltration basins, ICM= in channel modifications, RBF= riverbank filtration
++ N= natural water and R = recycled water including wastewater and urban stormwater
ne = not evaluated

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[9] Maximum daily recharge rate
[10] Annual licensed recovery capacity
[11] Cost per m^3 of increased flow to the river from groundwater
[12] Average annual recharge 2000-2009

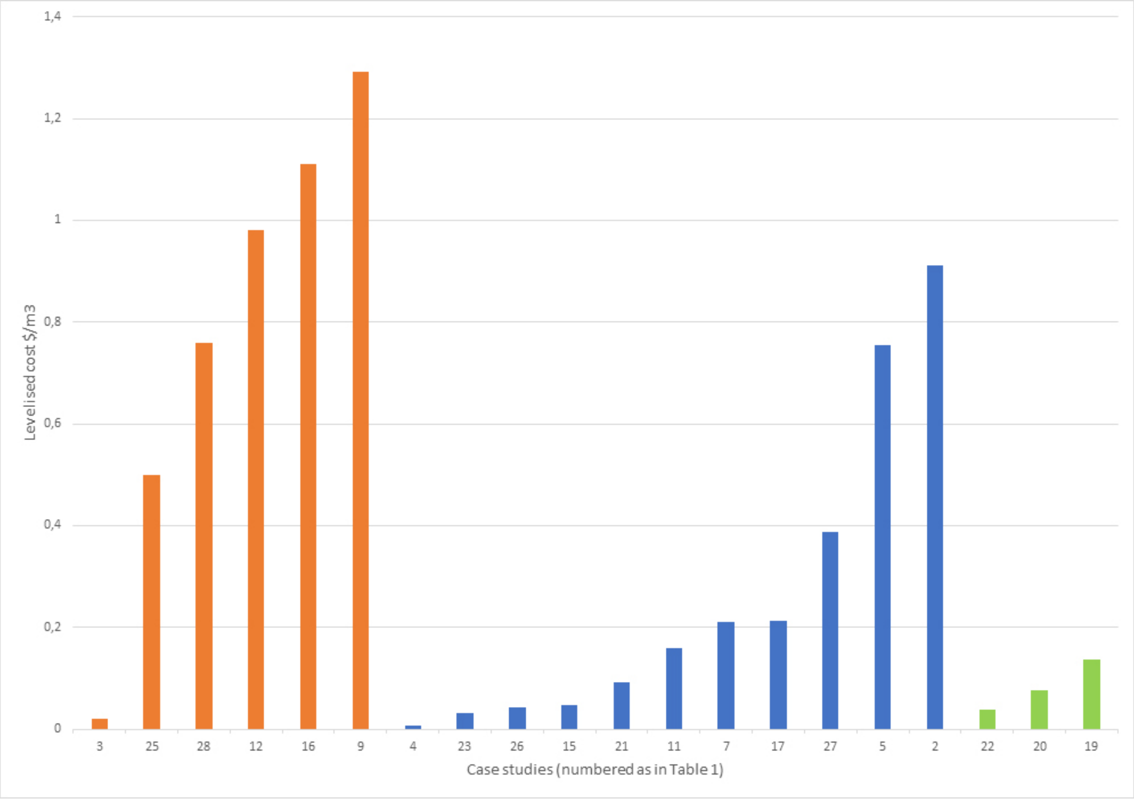
Data collected for this publication did not generally include breakdowns of capital and operating costs but the results are broadly consistent with findings by Ross and Hasnain. Schemes using recycled water, such as Perth and Salisbury in Australia, Koksjide in Belgium and Dinteloord in the Netherlands are more expensive than schemes using natural water. There are insufficient schemes in the wells and riverbank filtration categories to draw reliable conclusions about the relative costs of different MAR types. However riverbank filtration schemes are generally the least costly, as they maximize the use of natural resources and involve less new infrastructure, although there are exceptions where treatment, e.g. for iron removal, is required. Streambed structures and infiltration basins such as the Dharta and Baramati schemes in India have relatively low costs because they are located in a lower middle income country and their sites are selected to have high infiltration rates.

Table 2 shows average levelised costs of 20 of the 24 schemes in Table 1 divided into three categories, recycled water wells and infiltration, natural water wells and infiltration and riverbank filtration. The average levelised cost of schemes using recycled water - US$0.75 per m^3 - is much higher than the average levelised cost of schemes using natural water - US$0.16 per m^3 for wells and infiltration, and US$0.10 for riverbank filtration. The Khulna scheme in Bangladesh is not included because it has an exceptionally high levelized recovery cost of US$5.292 per m^3 which cannot be displayed at a comparable scale to the other schemes included in Figure 1. Finally, Table 2 does not include the North London, Hilton Head, and Windhoek schemes which were established to provide reserve supply capacity. The costs of these schemes are estimated in terms of the average cost of supply capacity rather than levelised cost, and are not comparable with the other schemes in Table 2. The average cost of daily supply for these projects is US$752 per m^3/day.

Table 2.
Average (AV) levelised costs of MAR schemes in US$ per m^3 and standard deviations (STDEV)(in year 2016 values), by water source (number of schemes in brackets).
Source: Own elaboration

Recycled water wells and infiltration	Natural water wells and infiltration	Riverbank filtration (RBF)
0.75 (AV) (6) 0.47 (STDEV)	0.16 (AV) (11) 0.06 (STDEV)	0.10 (AV) (3) 0.03 (STDEV)

The levelised cost of each of the 20 MAR schemes in Table 2 is shown in Figure 1. There are significant variations among the schemes in each of the three categories but most of the schemes using natural water shown in blue (wells and infiltration) and green (RBF) are much cheaper than schemes using recycled water shown in orange. There are 6 schemes from lower middle income countries that use natural water (Khulna (scheme 1, Table 1), Dharta (4), Baramati (11), Uttar Pradesh (15), Haridwar (20) and Sidfa (22)). Other than Haridwar these schemes have relatively small volumes of water recharged and recovered. The average levelised cost for these schemes is US$0.07 per m^3 compared to US$0.15 per m^3 in high income and middle income countries.



Legend: recycled water schemes 🟧 natural water schemes 🟦 riverbank filtration scheme 🟩

Figure 1.
Average levelised costs of MAR schemes in US$ per m³. Source: Own elaboration

4.3.2. Benefits and benefit cost ratios (BCRs) of MAR schemes

The following section presents a brief overview of the levelised costs and BCRs for 22 MAR schemes excluding the three schemes established to provide reserve supply capacity. BCRs for 14 out of these 22 schemes were estimated based on information supplied by the authors of the case studies. Quantitative estimates could not be provided for the remaining 8 schemes but in 6 cases, including the 3 riverbank filtration schemes, there was no feasible alternative to MAR or the costs of the alternative were very large. Further information about the levelised costs and BCRs is presented in Table 3.

Volume weighted average BCRs for 10 schemes using natural water averaged 2.16 and BCR's for 4 schemes using recycled water averaged 2.19. The 10 schemes using natural water include the Orange County and Arizona water bank schemes which are unusually large and expensive, with BCRs of 1.8 and 2.17 respectively. When they are included they dominate the natural water category and push the average BCR down to 2.16. When they are excluded the average BCR rises to 3.5.

Table 3.
MAR case studies: levelised costs of water and benefit cost ratios. Source: Own elaboration

	Case Study Location	Levelised cost per m^3 recharged ($US)	Levelised cost per m^3 recovered ($US)[13]	Benefit Cost or (BCR)	Explanatory comments about benefits and BCR
1	Khulna Bangladesh	1.752	5.272	1.5	Cost of MAR compared with next best alternative, reverse osmosis
2	Turku Finland	0.892	0.912	1.4	Cost of MAR compared with renovation and use of two local surface water plants
3	San Luis Mexico	0.020	ne	3.0	Cost of MAR compared with water treatment in a surface-based facility
4	Dharta basin India	0.007	ne	5.3	Benefit measured by increase in net profit owing to extra crops grown with additional irrigation enabled by MAR
5	Genevois France-Swiss	0.754	ne	5.8	Cost of MAR compared with a new water treatment plant
7	El Caracillo Spain	0.280	ne	ne	Gross value of additional agricultural production is estimated at €12 million, no estimate of net value or BCR
9	Perth Australia	ne	1.292	1.5	Cost of MAR about 2/3 of cost of new seawater desalination plant providing equivalent volume of water
10	Orange Co California USA	ne	ne	1.8	BCR based on ratio of price paid by OCWD for MWD treated water (US$0.82) to the required pumping fee or Replenishment Assessment to support the Groundwater Replenishment System (US$0.45)
11	Baramati India	0.16	ne	>1	BCR inferred from comparable schemes in India in the absence of reliable estimates for the project
12	North London UK	ne	US$730/m^3 /day	ne	Cost per unit water supply capacity is substantially less than alternatives
13	Windhoek Namibia	ne	US$860 / m^3 /day	ne	Cost per unit of water supply security is substantially less than alternative infrastructure expenditure
14	Salisbury S. Australia	ne	0.98	2.5	Cost of MAR treatment of stormwater used for public open space irrigation compared with lowest cost alternative - mains water supply
15	Uttar Pradesh India	0.048	ne	1.3	Net returns from additional agricultural production
16	Agon-Coutainville France	1.10	ne	ne	Avoided cost of wastewater discharge to marine environment
17	Central Platte Nebraska USA	0.044	0.212[14]	6.7	Ratio of unit value of agricultural production to levelised cost

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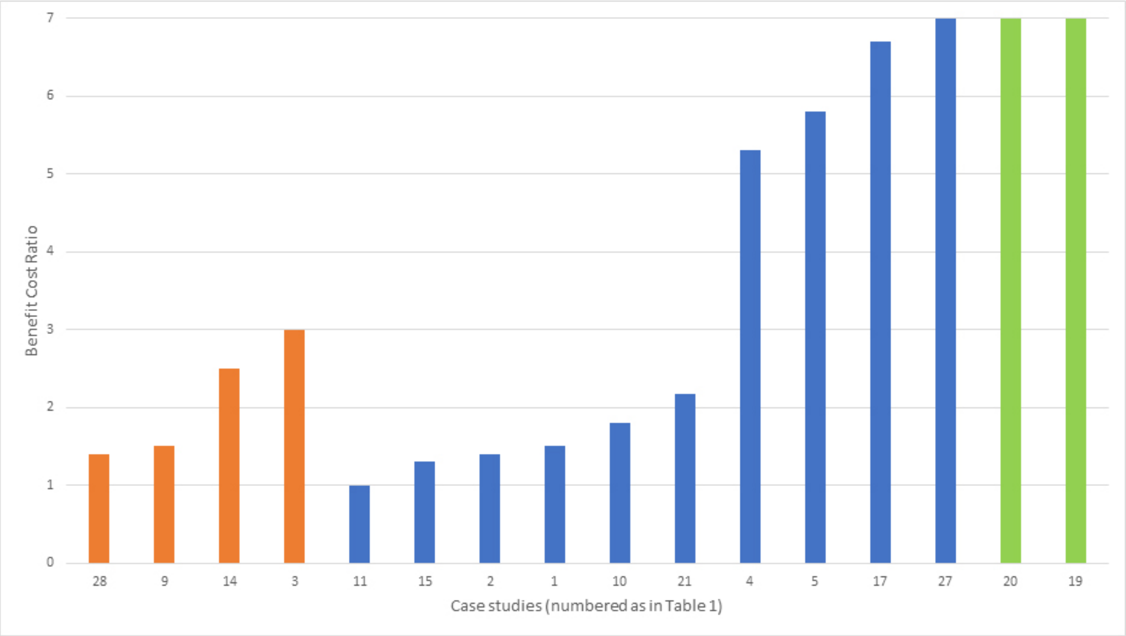
[13] Cost of water supply capacity per cubic meter per day is reported for three schemes (North London, Hilton Head and Windhoek), which were established to provide water supply security during extreme water shortages or periods of exceptionally high demand.

[14] Cost per m^3 of increased flow to the river from groundwater.

Table 3.
MAR case studies: levelised costs of water and benefit cost ratios. Source: Own elaboration

	Case Study Location	Levelised cost per m^3 recharged ($US)	Levelised cost per m^3 recovered ($US)[13]	Benefit Cost or (BCR)	Explanatory comments about benefits and BCR
18	Hilton Head USA	ne	US$980/ m^3 /day	2	Cost of MAR compared to alternative treatment and transmission facilities sized to meet peak day demands
19	Serchio R Lucca Italy	ne	0.138	ne	No viable alternative
20	Haridwar India	ne	0.102	Very large	No economically feasible alternative to supply drinking water. Conventional surface water treatment plant very expensive
21	Arizona water bank USA	0.092	ne	2.17	BCR estimated by ratio between average purchase price of AWBA stored water and AWBA's average cost of purchasing water
22	Sidfa Egypt	ne	0.038	Very large	RBF costs tens of times less than SW treatment plant or treatment of GW in municipal wells
23	Kumamoto Japan	0.026	ne	ne	No feasible alternative source of additional water supply for Kumamoto
25	Koksjide Belgium	0.500	1.12	2.23	Cost of MAR compared to cost of purchasing drinking water from neighbouring area
26	Balisha R China	0.042	ne	ne	Benefits not quantified but include annual water supply and output of irrigated agriculture
27	Wala Wala Jordan	ne	0.388	~7	Ratio of current average water tariff to estimated unit cost of recovered water
28	Dinteloord Netherlands	ne	0.760	I.4	Cost of MAR compared with cost of buying agricultural land for water storage

The quantified BCRs for 14 MAR schemes in Table 2 are shown in Figure 2. The four schemes with the highest BCRs; Dharta, Genevois, Central Platte and Wala Wala, are all based on natural water. Their BCR's range between 5.3 and 7.0. BCRs for the remaining schemes are within the range of 1.0 to 3.0. BCRs for the Serchio and Haridwar riverbank filtration schemes are included in the figure for comparative purposes. The BCR's of these schemes are in fact are likely to be higher than 7.



Legend: recycled water schemes 🟧 natural water schemes 🟦 riverbank filtration scheme 🟩

Figure 2.
BCRs of MAR schemes in US$ per m³. Source: Own elaboration

Figure 3 plots the relationship between BCR and levelised cost and shows that BCRs are inversely related to costs although the relationship is not very strong. Figure 3a includes the Khulna case study which has an exceptionally high levelised cost. Figure 3b excludes the Khulna case and may give a more accurate indication of the relationship.

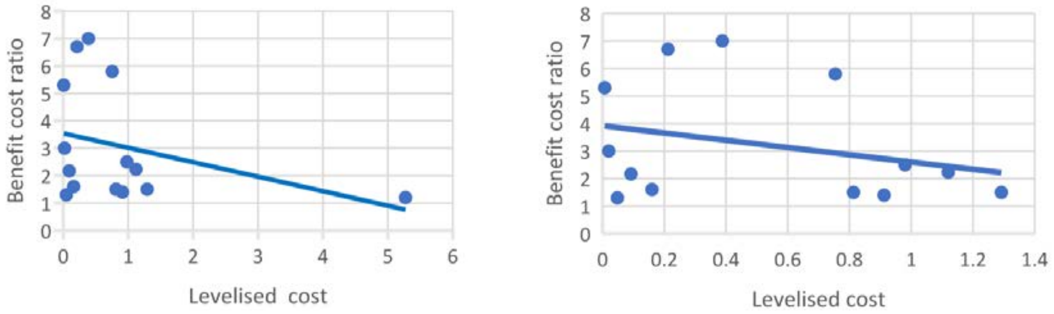


Figure 3 a

Figure 3 b

Figure 3.
BCRs of MAR Schemes in US$ per m³. Source: Own elaboration

This summary of BCRs provides an indication of the returns to investment in the reported MAR schemes. These are examples of well designed and executed MAR projects that are the preferred and most economically viable alternative for water resources development, enhancing resilience and/or water quality. Case studies for which economic data was expected to be available did influence selection for this book. However, economic evaluations were not used to select case studies. Hence this selection is not expected to be biased towards more economically viable cases. The case studies for which evaluations are not reported had numerous expansions of MAR over many decades making cost assessments uncertain.

Recent work has given a broader inventory of several thousand MAR projects around the world and discusses factors favoring MAR projects (Stefan and Ansems (2018)[13]. Another paper describing historical development of MAR and its current global status (Dillon *et al* 2019)[14] shows that in 2015, the global volume of MAR was 1% of groundwater extraction, and both were growing at 5% pa. Hence, MAR can make a useful contribution to sustaining groundwater resources where extraction is also managed.

4.4. Conclusions

MAR schemes are highly heterogeneous with a wide range of types, objectives and sizes which can be matched with local hydrology, hydrogeology and geomorphology and demand for water storage and supply. Although scheme diversity complicates comparisons between schemes, evidence from this study confirm results of previous studies.

Schemes recharging unconfined aquifers using infiltration basins with untreated water and riverbank filtration are relatively cheap. These schemes either have high measured BCRs, or there is considered to be no feasible alternative. Schemes requiring wells with substantial drilling infrastructure and or water treatment are more expensive, but even when water requires substantial and relatively costly treatment before recharge and recovery, MAR schemes using storm water and wastewater recycling can offer substantial benefits that exceed costs.

Although the MAR schemes included in this publication are broadly representative of global schemes, collection of data on a larger number of projects is needed to improve coverage of some regions and MAR types.

Water banking to increase security and resilience of water supplies has very significant social and environmental benefits that are not accounted for in the cost-benefit analysis above. Further analysis of these benefits would provide additional evidence to guide investment in MAR and water resources management policies that seek to buffer against shortfalls by giving incentives for MAR and water banking, and protections for banked water.

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Attachment 1: Illustration of method of estimating levelised cost. Source: Own elaboration

1	METADATA	
2	Country	Finland
3	Name/location	Virttaankangas
4	Coordinates	60°58′54»N 22°37′54»E
5	Year commenced operation	2013
6	MAR type	Infiltration Basins
7	Source Water	Treated River water
8	Correspondent	Aki Artimo
9	Notes, exceptional features	None
10	COSTS	
11	Capital costs (LCU in year scheme commenced operation)	190000000
12	Index in year scheme commenced operation	108.309
13	Index in 2016	112.139
14	Row 15/14	1.035361789
15	Indexed capital cost (LCU 13x16)	196718739.9
16	Exchange rate LC/USD 2016	0.904
17	Indexed capital cost USD (17/18)	217609225.6
18	Annual operating cost in LCU	5600000
19	Annual operating cost in USD (20/18)	6194690.265
20	Water recharged per year (m^3)	22,800,000
21	Water recovered per year (m^3)	22,300,000
22	Operating life	30
23	Capital recovery factor at 5% discount rate = 0.0650	0.065
24	Levelised cost = (19x25)+21	20339289.93
25	Levelised cost per m^3 recharged (26/22)	0.89207412
26	Levelised cost per m^3 recovered (26/23)	0.912075781

LCU = Local currency Units

Section II.
Case Studies

Shutterstock/Eric Valenne geostory

Case Study 1: A resilient drinking water supply using aquifer storage recovery for coastal communities in Batiaghata, Khulna, Bangladesh

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1.1. Introduction

Since 2010, a communal aquifer storage recovery (ASR) facility has been in operation in Gangarampur Village of Batiaghata Upazila of Khulna district, south-western coastal Bangladesh for drinking water supply to 45 families with 160 beneficiaries.In a shallow aquifer the original brackish water with electrical conductivity (EC) of 3000 µS/cm (~2010 mg/L total dissolved solids (TDS)) has been "replaced" by fresher water (EC 1000 µS/cm, TDS ~670 mg/L) sourced from ponds after 6 months of infiltration at a rate of ~7 m3/d. However, pond EC increases to about 2000 µS/cm during dry months when infiltration is stopped until the monsoon rain dilutes the pond water to lower EC. The recovered water displayed improved quality, with EC consistently below 2000 µS/cm and As <0.01 mg/L, with reduced frequency of E. coli detection. Although the turbidity of pond water has decreased significantly after filtration by a sand chamber, clogging requires management and is dealt with through manual washing of the filter sand. After community members completed training on operation and maintenance by the project team in 2015, a five-member user committee consisting of all women took charge of operations, with users paying Bangladesh Taka 20 (~US$ 0.24) per month towards the electricity bill to run the pump for lifting water from pond to filtration tank and for some small maintenance too.

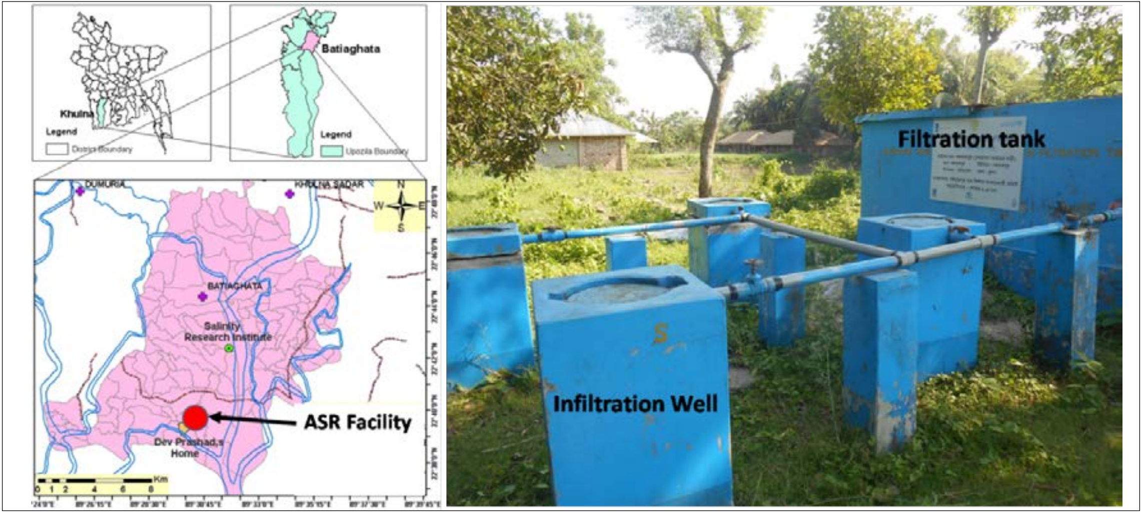

Figure 1.
Location of ASR facility in Batiaghata Upazila of south-western coastal Bangladesh (left) with a photograph of the facility (right) showing 4 large diameter infiltration wells and the sand filtration tank. Source: Own elaboration; Photo © Kazi Matin Ahmed

Box 1: Salient features of the BAG ASR facility

Location: N22.6673667, E89.51281111Gangarampur Village, Batiaghata Upazila, Khulna, Bangladesh

Operator: A 5-member user committee consisted of all women since 2015

Constructed by: Dhaka University (DU) and Department of Public Health Engineering (DPHE) with technical support from Acacia Water

Funding Source: UNICEF Bangladesh

Design: 4 infiltration wells (300 mm dia, gravel filled) with an over ground sand filtration tank and 1 abstraction well (50 mm dia) fitted with hand pump

Installation year: 2009

Infiltration started: November 2010

Abstraction started: April 2011

Quantity of water infiltrated: 5757 m^3 by February 2019 (ave 640 m^3/y)

Quantity of water abstracted:1804 m^3 by February 2019 (ave 200 m^3/y)

End use: drinking water

Source of water: pond

Aquifer: shallow-brackish, semi-confined, unconsolidated fine to medium grained sand.

Type of recharge: aquifer storage (ASR) recovery wells, gravity driven

Main advantage: year-round source of drinking water and safe storage for disaster

1.2. Motivation, conceptualisation and implementation

Millions of inhabitants of the southwestern coastal Bangladesh face severe seasonal water shortage despite monsoonal rain during the wet season. Wide spread salinity in groundwater and saline intrusion of rivers in the dry season limit the quantity of available fresh water. Bacteriological contamination of fresh water ponds used for water supply and frequent occurrence of arsenic in shallow groundwater exacerbate water scarcity (BGS and DPHE 2001 [1]; BBS and UNICEF 2011 [2]; Ahmed *et al*. 2004 [3]; Sultana *et al*. 2015 [4]). In addition, fresh water ponds are increasingly being salinized due to inundation during storm surges and brackish-water shrimp aquaculture (Khanom and Salehin 2012 [5]). Much of coastal Bangladesh is vulnerable to a range of hazards, included extreme weather events, and exacerbated by climate change, which can disrupt water supplies to coastal rural communities (DoE 2007 [6]; Kabir *et al*. 2016 [7]).

Cyclones Sidr and Aila in 2007 and 2009 highlighted the need for safe, year-round and disaster resilient potable water sources. Managed aquifer recharge (MAR) such as aquifer storage recovery (ASR) schemes offers a potential solution utilizing abundant wet season rainfall (Pyne 2005 [8]; Maliva and Missimer 2008 [9]).With funding from UNICEF Bangladesh, an action research project to explore the feasibility of ASR through constructing 5 and 15 pilot facilities in Phase I and II respectively was implemented by the Department of Geology, University of Dhaka and the Department of Public Health Engineering, Government of Bangladesh with technical support by Acacia Water of the Netherlands. One of the 5 Phase I pilots was the BAG ASR facility (Box 1). Following the success of the pilot project, similar facilities have been constructed at 99 locations to provide much needed safe drinking water (Sutana *et al*. 2015 [4]; Hasan *et al*. 2018 [10]).

Source water used at the BAG facility is a freshwater pond, although many of the other facilities use rooftop rainwater together with pond water. At the BAG facility, source water is pumped into a tank fitted with a graded sand filter to remove turbidity and pathogens. Water after filtration is diverted to a set of 4 large diameter gravel-filled infiltration wells (Figure 1). Recharge occurs under gravity to create an underground freshwater storage in a locally confined brackish aquifer. Abstraction of fresh water is through a small diameter well fitted with a conventional Number 6 hand pump, in the centre of the infiltration wells.

Rigorous site selection criteria consisting of social and technical elements have been developed. In locating the MAR construction site, social criteria such as willingness of the households to share a piece of land, and pond or roof for source water collection, willingness to pay and participate in the user committee are considered. Surveys of existing water supply options, measurements of water quality parameters such as groundwater EC and As, and subsurface exploration including drilling to ascertain hydrostratigraphy were conducted. Construction needs to meet specific design requirements. Facilities are put to extensive performance monitoring through water quality testing, water table monitoring, assessment of infiltration and abstraction rates, etc. Clogging is managed through periodic removal of fine materials deposited on top of the sand filtration tank and infiltration wells, plus manual washing of sand (Sultana and Ahmed 2016 [11]). Effective O&M mechanisms including low cost clogging management have been developed by involving local communities through NGO Partners. NGOs also trained users for community mobilization and awareness building.

1.3. Environmental sustainability

In terms of water quantity, the target aquifer being brackish and locally confined, it is not subject to extensive pumping thus no decline of water table has been observed since the ASR facility began operation in 2010. The average infiltration rate is 677 m^3/year while the average abstraction rate is 226 m^3/year. The abstraction has never exceeded the infiltration due to the need to withdraw only fresh water. Therefore, the ratio of the volume of infiltrated water to the volume of recovered water has always been > 1. However, it is still desirable to improve the recovery efficiency (RE) because the RE achieved from is only 31%, even though 100% can never be expected as there is dispersive mixing of fresh source water and ambient brackish groundwater. A numerical groundwater model suggests RE can reach ~50% if the abstraction well is placed in the center of the infiltration wells configured in a square pattern (Barker *et al*. 2016 [12]) as in this BAG case.

In terms of water quality, there are only limited data available due to insufficient water quality monitoring capacity in rural Bangladesh. Because provision of fresh water is the aim of the ASR facility, it is important to note that the facility has mostly succeeded in this regard. The ambient groundwater was brackish (EC~3,000 µS/cm or TDS ~2010 mg/L). The EC of recovered water follows that of the source pond, averaging 1,150 µS/cm (TDS ~ 770 mg/L) with a maximum value of 1,930 µS/cm (TDS ~ 1293 mg/L). Although ~19% of recovered water exceeded the Bangladesh drinking water quality standard for TDS of 1,000 mg/L (DPHE 2019 [13]), this standard is not health based but is based on human taste preference. Tolerance of raised salinity is conditioned by previous experience. In coastal Bangladesh where fresh water is scarce, villagers routinely tolerate such levels of TDS (Sultana *et al*. 2015 [4]). Pond water is generally fresh during the rainy season. The average EC of the source pond is 1,000 µS/cm (TDS ~ 670 mg/L) with a maximum value of 3,980 µS/cm (TDS ~ 2660 mg/L) during dry period (Figure. 2), with nearly ~9.5% of source water exceeding the Bangladesh drinking water quality standard. It is important to point out that the demand for fresh water by the community is often what determines when villagers stop recovering water, i.e. until it's too salty for their taste, not the water quality standard. This trade-off means that more facilities are needed so that the community can be better served.

The Bangladesh drinking water quality standards for turbidity, E. coli and arsenic are 10 NTU, 0 cfu/100 mL, and 0.05 mg/L, respectively (DPHE 2019 [13]). The turbidity of source pond water ranges from 50 to 150 NTU. It is lowered to below 5 NTU after passing through the sand filtration chamber. The recovered water is effectively free from any suspended material. E. coli is not monitored regularly, but it appears that the system efficiently reduces E. coli from pond water (80-100 cfu/100 ml) to 0 cfu/100 ml in recovered water based on testing in May 2013, September, 2013, March 2014 and November, 2014. Weekly arsenic monitoring based on ITS Econo Quick As test kits between July 2012 and May 2014 also confirm that As is less than 0.01 mg/L, the WHO guideline value for drinking water, although iron and manganese exceed the national standards (1 mg/L and 0.1 mg/L; Sultana *et al*. 2015 [4]). It is worth noting that WHO's guideline value for iron is not health based (WHO 2003 [14]), unlike that for manganese (0.4 mg/L;WHO 2011 [15]). Nitrate and sulfate are within acceptable limits based on monitoring between 2011 and 2015 (Hasan *et al*. 2018 [10]). Although it is desirable to monitor all 61 parameters in the drinking water quality standard of Bangladesh (DPHE 2019 [13]), samples taken in 2014 for ICP-MS measurements of 20 parameters did not identify any major issues. Given resource constraints, it is recommended that recovered water should be regularly monitored for arsenic and E. coli at the ASR site.

The energy requirement of the ASR operation/infiltration is low at 0.27 KWh/m^3 to lift water from the pond to the filtration chamber, estimated from electricity consumption of 360 kW/yr for 226 m^3/yr water production. The recharge is gravity driven, with lifting water from the pond to the filtration chamber consuming electricity. No energy is required for recovering water as the abstraction is by a hand pump. Most of the materials used for construction are locally sourced and of low cost (Sultana *et al*. 2015 [4]). Neither the construction nor the completed facility pose any significant threat to the local ecosystem.

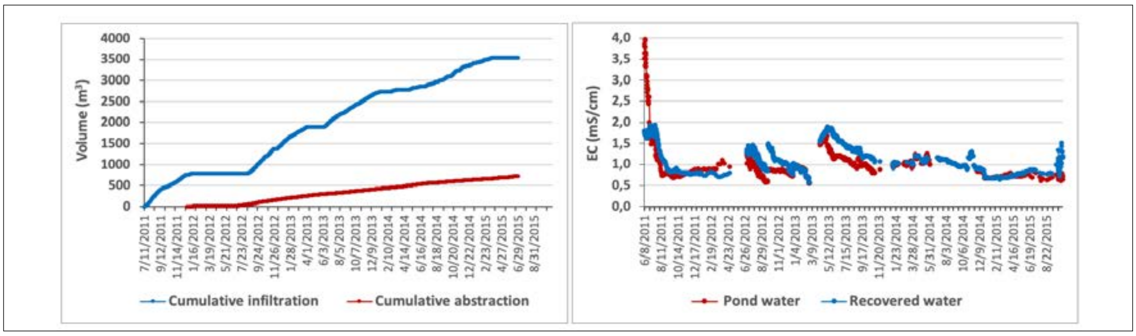

Figure 2.
Between July 1, 2011 and Aug 31, 2015, the volume of infiltrated water and abstracted water (left) and the EC of pond water and recovered water (right) at daily monitoring interval. EC of 1 mS/cm is equivalent to TDS of 670mg/L. Source: Own elaboration

1.4. Financial costs and benefits

The installation cost of the scheme was about Bangladeshi Taka (Tk) 650,000 ($7,650 @85Tk/US$) and land involved no cost due to the generosity of the land owner. Annual maintenance cost is around Tk 30,000 (Table 1) which includes fuel cost to pump pond water to the filtration tank (Tk 6,000), filtration tank maintenance (Tk 2,000), recharge well washing (Tk 16,000), replacement of jute canvas (Tk 1,000), small repair and maintenance etc (Tk 5,000). The levelised cost of recharged water is estimated to be US$1.75 per m^3 (150 Tk/m^3) while the levelised cost of recovered water is US$5.25 per m^3 (450 Tk/m^3) (based on current recovery efficiency).

Table 1.
Construction, maintenance and production cost of recovered water.
Source: Own elaboration

Year	Amount of abstraction		Installation cost (Tk)	Maintenance cost (Tk)	Total cost (Tk)	Cost of recovered water (Tk/L)
	m^3	L				
1	225	225,000	650,000	30,000	680,000	3.0
5	1125	1125,000	650,000	150,000	800,000	0.7
10	2250	2250,000	650,000	300,000	950,000	0.4

The cost of water production as shown in the Table 1 confirms that the longer the life of the scheme the lower the cost of the produced water. However, the cost incurred for site selection and technical monitoring until freshening of the ambient groundwater has not been taken into account in the unit cost of water. Table 2 compares the ASR scheme with other available, and nominally safe, water options like Reverse Osmosis (RO), Rainwater Harvesting (RWH) and Pond Sand Filter (PSF).

Table 2.
Comparison of ASR and other water supply options in coastal areas of Bangladesh modified after Nawrin *et al* (2016) [16].
Source: Own elaboration

Water supply option	Installation cost (TK)	O&M cost	Supply capacity (L/d)	Average cost of produced water (Tk/L)	Year Round availability	Safe for drinking	Disaster resilient
BAG-MAR	650,000	Low	~5,000	~0.5	Yes	Yes	Yes
RO	1,200,000-27,500,000	High	1,000-35,000	0.5-2.5	Yes	Yes	No
RWH	6,000-30,000	Low	5,000-1,0000	NA (mostly private)	No	Subject to cleaning	No
PSF	100,000	Low	5,000	~0.0	Subject to salinity	Subject to cleaning	No

The beneficiaries of this small-scale MAR scheme are part of a poor rural community (50 to 100 families) who actively participate in O&M and make nominal contributions towards operation cost.

Reverse osmosis is the only alternative to MAR that will deliver an equivalent quantity and quality of supply. Rainwater harvesting does not guarantee continuing supply, and pond sand filters do not remove salinity. The levelised cost of reverse osmosis is estimated at about US$6.34 per m^3. This implies that the benefit cost ratio of MAR compared to the next best alternative, reverse osmosis is 1.2:1.

1.5. Social sustainability

Currently there is no national strategy and/or guideline for construction and operation of MAR systems. UNICEF and the project partners are now working on policy advocacy for inclusion of MAR in relevant national policies as a viable water supply technology although the challenges remain in the site selection due to subsurface uncertainty and most importantly in social sustainability. Overall, this coordinated project is the first successful implementation of ASR at pilot scale in Bangladesh and has gained appreciation from diverse stakeholders, and is informing the national committee for formulating MAR Strategy and a Guideline.

Local people are very happy to obtain clean water through a hand-pumped tubewell (Figure 3), the most popular option across the country. BAG-MAR site was one of the initial 5 sites and has been successfully operated since 2010.Through the scheme, poorer households get water at a cost of Tk 20/month while other households pay Tk 50-100/month. Water is abstracted mainly during dry season and recharged largely during wet season. The abstraction has not exceeded the recharge as abstraction is principally confined to drinking purposes. Awareness building activities like courtyard meetings, tea-stall meetings, mass meetings etc. were conducted among user groups on the benefits of safe water, water safety plans and building ownership. Beside these, regular stakeholder meetings at the Union and Upazila levels and a coordination meeting among project partners were arranged to ensure active participation of all the stakeholders in operation and maintenances of the system. The User Committee arranges regular monthly meetings (Figure 3) to ensure proper O&M. This BAG-MAR site has become now a demonstration site in Bangladesh where water supply managers and stakeholders at various levels visit to learn from it.

Figure 3.
Left: Water abstraction from the BAG-MAR site (the abstraction well is in the middle of the infiltration well in the backyard of the house and the well head has been extended horizontally via PVC pipes with check valve to the front yard for better accessibility (DPHE and UNICEF 2011 [17])); Right: User group meeting. © Source: Kazi Matin Ahmed

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Case Study 2: Managed Aquifer Recharge for drinking water supply, Turku Region, Southwestern Finland

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2.1. Introduction

Turku Region Water Ltd., a wholesale company owned by 9 municipalities, produces drinking water for 300,000 inhabitants in the Turku area using managed aquifer recharge - MAR (Figure 1). The company is the only provider of drinking water for all the shareholder municipalities. Full scale water production started in 2013. The current water production rate is about 64,000 m^3/d.

Water is sourced from the River Kokemäenjoki, which has the 4th largest catchment area of all Finnish rivers. In the Virttaankangas MAR plant, river water is pre-treated first to remove solid particles before its infiltration through 19 basins into the Virttaankangas sand and gravel esker aquifer.

Pumping rates of the 13 screened wells are precisely controlled to ensure constant flow paths and residence times to achieve the natural purification of the infiltrated water, which is a vital part of the water production process. Therefore, the operation and use of the MAR plant require a thorough understanding of the geological and hydrogeological features of the aquifer. The unique part of the Virttaankangas MAR system is that it utilizes an extensive geodatabase with integrated 3D hydrogeological modelling and 3D groundwater flow modelling tools, which are used together with a modern automation system to control the groundwater flow in the aquifer.

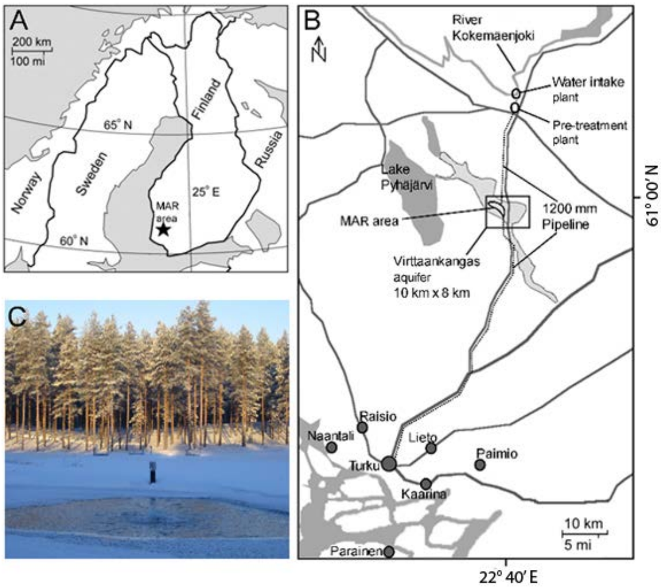

Figure 1.
A: Location of the Virttaankangas MAR site.
B: Operation area of Turku Region Water Ltd. Map shows locations of water intake point from the river, pre-treatment plant, MAR area, pipelines and locations of shareholder municipalities.
C: Infiltration in winter. Infiltration basins are sized between 700 m² to 1 900 m².
Source: Own elaboration; Photo © Aki Artimo

Main features of Virttaankangas MAR water supply

Owner and operator: Turku Region Water Ltd.

Company type: Wholesale company, 23 employees

Raw water source: River Kokemäenjoki, pre-treatment by flotation and sand filtration

Aquifer: Quaternary sand/gravel esker formation

MAR site: 19 infiltrations basins, 13 production wells

Production rate: 64 000 m^3/d, drinking water for area of 300 000 inhabitants

First year of MAR production: 2011, full scale 2013

MAR site location: 60° 58′ 54″ N 22° 37′ 55″ E

Unique for Virttaankangas MAR: Natural and sustainable way to purify infiltrated water with the use of sophisticated data management and modelling tools

2.2. Historical background of the Virttaankangas MAR project and the stages of implementation

Prior to MAR project, the drinking water produced from nearby rivers and aquifers did not meet the needs of the Turku area, both in quality and quantity. The new MAR plant replaced all the older water production plants except for the old Turku City Waterworks that remained as a backup system. The backup plant derives its water from different water sources than the MAR plant, which improves resilience for the water supply as a whole.

Turku Region Water Ltd. is owned and funded by the city of Turku and its neighboring municipalities. Project planning was done in cooperation with local EPA. Geological studies were planned and managed by Turku Region Water in cooperation with Geological Survey of Finland along with several Finnish Universities and research institutes. Geosciences were widely applied during the planning phase by Finnish as well as international study groups (Artimo *et al.* 2003a [1], Artimo *et al.* 2003a [2]).

Environmental impact assessment was a prerequisite for the implementation of environmental permit process for the MAR system. The final environmental permissions defined a strict framework for the operations and the environmental monitoring of the MAR plant. Extensive geological understanding of the MAR site along with the proven ability to manage the aquifer in a sustainable manner played an important role through the legislative permitting process.

The initial MAR layout plans were significantly different from the final completed plant layout because consideration of the geological architecture of the system led to improvements. The new MAR plant design benefited from a 3D hydrogeological and groundwater flow modelling of the area [2]. These models made use of all the geological data that had been collected from the area, and they were used to quantitatively predict the residence times and the flow paths of the infiltrated water prior to the construction of the wells and infiltration basins.

2.3. Environmentally sustainable water production system

Geodatabase and modelling tools

Virttaankangas MAR project's aim was to produce sustainable and safe drinking water with high efficiency and low environmental impact. To achieve this goal, quantitative understanding of the hydrogeological system was essential throughout different stages of the project.

A vast amount of data has been collected from the geological studies conducted in Virttaankangas esker area since 1970's. The availability of all the data played a key role in a successful implementation of the Virttaankangas MAR project. The geodatabase maintained by Turku Region Water Ltd. enables the use of the data in a commensurate form (Figure 2 A). These data can be obtained from the database for many purposes; e.g. 3D hydrogeological modelling (Figure 2 B), groundwater flow modelling, data management, water quality analyses or environmental reporting. In addition, commonly used calculation routines have been integrated with the database to enable the automated re-creation of model input datasets, which allows the users to update any of the models with ease. The same geodatabase tools are used on a daily basis to manage the production of the MAR plant.

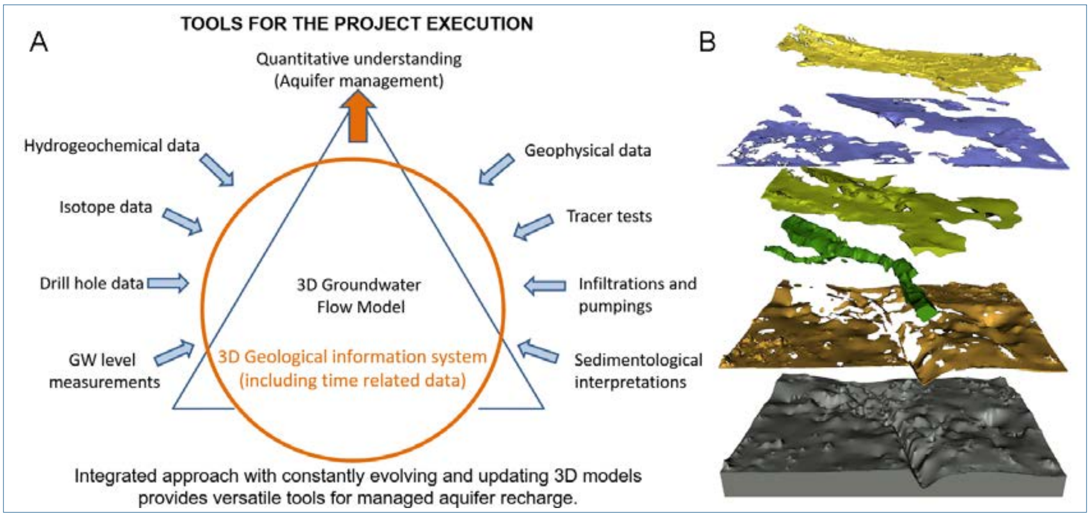

Figure 2.
A: Examples of data in the geodatabase maintained by Turku Region Water Ltd. Figure adapted from [3].
B: 3D hydrogeological model units.

Optimization of the MAR process

According to the permit of the MAR plant, the amount of infiltrated water needs to be at least the same as the amount of produced water. Indeed, production well pumping rates have been 99 % of the infiltration rate on a yearly basis. Further, MAR has increased the aquifer's water producing yield 10-15 times higher than the natural capacity. Flow routes and average residence times of the infiltrated water have been optimized with the modelling tools to ensure the water quality improvement throughout the year. The average residence time of the infiltrated water is more than 3 months.

The water quality at each production well resembles the quality of naturally formed groundwater, therefore the well clogging is negligible and the water is ready for consumption without any post-treatment, e.g. iron removal or pH adjustment. The oxygen content of the produced water has been close to the saturation point which has kept the iron and manganese concentrations below the detection limits 10 µg/l and 1 µg/l, respectively. Measured average TOC levels have been 2 mg/l and EC 140 µS/cm. The nutrient content of water has been low. The hygienic quality of water has been impeccable. Tables presenting the water quality analyses are available at: www.turunseudunvesi.fi/en.

The monitoring of groundwater table has been conducted for more than 30 years. During the years of operation, no unwanted changes have been detected outside the MAR operation area (Figure 3). In an area of approx. 20 km^2 with more than 200 monitoring wells, water levels remain at the natural state in the aquifer with the maximum increase in water level of 4 meters observed next to the infiltration areas. With the geodatabase tools the future groundwater table changes and water storage can be easily optimized.

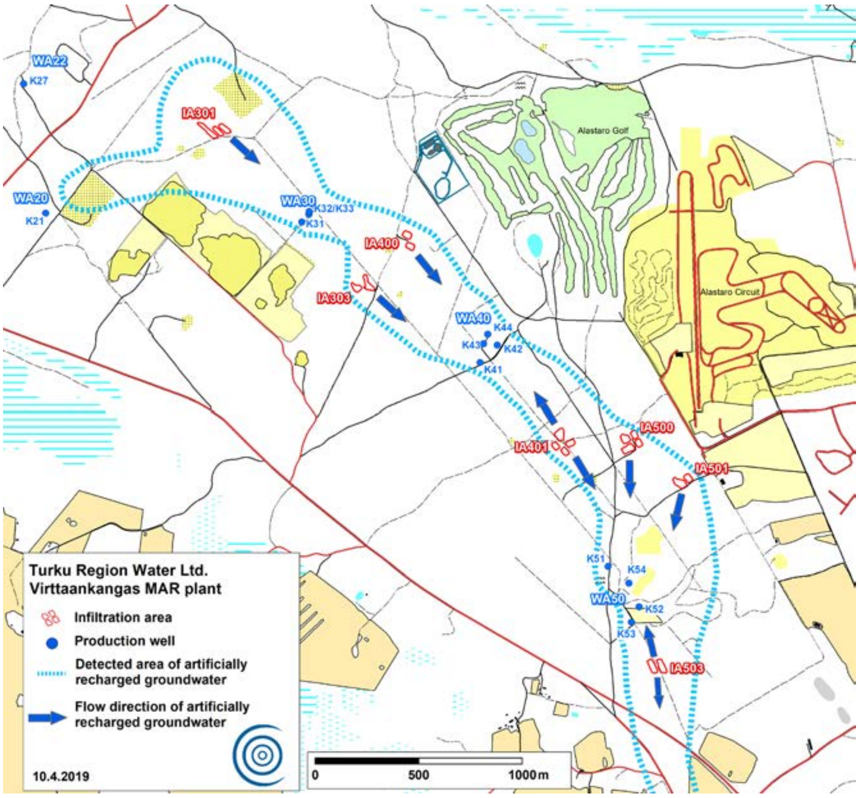

Figure 3.
Layout of the MAR plant area. Source: Own elaboration

Multi-barrier approach for safe drinking water

Water quality and safety are the key factors throughout the production process. All the phases of water treatment create a multi-barrier system that ensures the water quality. In addition, extensive work has been conducted to develop a Water Safety Plan (WSP) to ensure the continuous operation of the water production system.

The water quality of the ***River Kokemäenjoki*** is affected by seasonal changes especially in turbidity (Jokela *et al*. 2017 [4]). River water quality is monitored using online devices (YSI, S::CAN, TriOS). These measurements are connected to the automation system, and they are remotely monitored continuously. In case any potentially harmful substances are detected, automation triggers the alarm, and the river water intake can be ceased by the operator. River water quality meets all the requirements of the Finnish legislation. In addition, technical issues caused by water quality are non-existent.

Phases of ***pre-treatment*** process include sieving, flocculation, flotation and sand filtration. Water pre-treatment process uses only a minor dosage of one flocculation chemical (polyaluminiumchloride, PAC) in comparison with traditional chemical water treatment plants. Solid particles are removed from the raw water during the pre-treatment process. In addition, the same process reduces the amount of soluble substances in the river water (e.g. TOC and P) and removes more than 99% of the microbes. Pre-treatment of water also protects the esker aquifer from many harmful substances, should they be present in the river water (Ahkola *et al*. 2017 [5]).

Aquifer infiltration is the most important purification process of the drinking water production. Also the size and volume of the aquifer used for MAR add security to the water production system - the depth of the saturated zone of the aquifer exceeds to over 90 meters in the deepest parts and forms an extensive water reservoir. In case of ceased infiltration, the water intake from the wells can continue for at least 19 days according to the environmental permits.

The only ***post-treatment*** for the produced water is disinfection with UV and chloramine to prevent quality changes in the water supply network. The post-treatment takes place in three bedrock reservoirs that are located near the water distribution network and customers. No exceedances in water quality have been observed in the produced groundwater since the initiation of the MAR plant in year 2011. Water quality meets all the requirements of Finnish (drinking water quality, Ministry of Health) and European authorities (On the protection of groundwater against pollution and deterioration, 2006/118/EC)

Additional environmental benefits are as follows. The operation of the MAR plant enables controlled diversion of groundwater flow to the surrounding areas. Measured spring flows have remained at a natural state during the operation years. Energy consumption in 2018 for raw water intake, pre-treatment, pumping, water transfer and MAR-process (23 Mm^3/a) totaled 14.7 GWh. Resulting energy use was 0.64 kWh/m^3, which is close to the average drinking water supply energy use in Finland (Personal communication, June 5th 2019, Finnish Water Utilities Association), even though the raw water is extracted and transferred from almost 100 kilometers away from the consumers.

2.4. Economic costs and benefits

Table 1.
Opex and Capex, 2018

OPEX, 2018	
Personnel	1.4 M€
Electricity	1.4 M€
Chemicals	0.3 M€
Monitoring	0.2 M€
Subcontracting	0.3 M€
Maintenance	0.2 M€
Other materials and services	0.3 M€
Other costs	1.5 M€
Total	**5.6 M€**
CAPEX, 2018	
Interests	4.6 M€
Leasing financing	1.5 M€
Amortization	5.6 M€
Total	**11.7 M€**

During 2018, a total amount of 22.8 Mm^3 of water was recharged into the aquifer. Recovered volume of water was 22.3 Mm^3, the difference of the recharged and recovered volumes is based on the permits and the intended over-infiltration to adjust hydraulic heads. The water supply (MAR) for the customers during 2018 was 23.2 Mm^3. The company pumped an additional 1.0 Mm^3 of natural groundwater from the Oripäänkangas aquifer.

Based on costs presented in Table 1, annual operative costs (opex) in year 2018 were 0.24 €/m^3, and the annual capital costs (capex) were 0.50 €/m^3, respectively. Since 2013, the water sales have been relatively constant and the opex have been declining slightly. The time of amortization of debt is 30 - 40 years for major pipeline investments.

The levelised cost of water recharged by the scheme was US$ 0.89 per m^3 recharged and US$ 0.91 per m^3 recovered.[1]

At the time when the MAR scheme was constructed it was estimated to be to be about 30% cheaper than the next best alternative source of supply - renovation and use of 2 local surface water plants. This implies a benefit cost ratio of 1.4:1. In addition raw water quality was superior in the MAR scheme.

The organization of the Turku Region Water Ltd. wholesale company consist of only 23 employees, which helps to maintain the personnel expenses at low level. In addition, the old waterworks can be used as a backup facility for the MAR plant. Prior the MAR there were no backup facilities for water production in any of the municipalities of the area.

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[1] These estimates are based on an assumption of a thirty-year project life and 5% discount rate, converted to US$2016 consistent with levelised cost estimates for other schemes in this publication. The estimates in the previous paragraph are lower mainly because they assume a 3% discount rate.

2.5. Social sustainability

The final environmental permissions of the Finnish Supreme Administrative Court (KHO 1883, 13.8.2008) defined a strict framework for the operations and the environmental monitoring of the MAR plant. Environmental impact assessment (EIA) and permit granting process based on the EIA were performed during the years 1999 - 2008. The main considerations included harmful substances in raw water, land use and suitability of the aquifer for the MAR production. During the planning phase of the project, unwanted environmental effects and land use restrictions were suspected in some instances. However, the ongoing water production has proven the suspicions wrong, which has also affected and changed the public opinion. Land areas of the MAR plant can also be freely used for recreational purposes.

The MAR project has also promoted cooperation with the scientific community resulting in numerous Ph.D. and M.Sc studies conducted in the MAR plant operation area (e.g. Ahokangas 2019 [6])

Sustainably produced and safe tap water promotes health and well-being of the 300,000 people of the Turku region. Qualitatively uniform and naturally produced drinking water has improved the competitiveness for economic development of the region because it has benefited the food and medical industries.

The United Nations has set 17 targets for sustainable development. Of these goals, Virttaankangas MAR water supply system meets the six that are most relevant (Figure 4).

Figure 4.
Turku region MAR meets 6 of the sustainable development goals set by the UN.
The clean energy comes from the electric turbine (1.7 MWh/a, 2018) located at the end of a large pipeline producing energy while slowing down and controlling the flow of water. In addition, plans to build a solar power park next to the pre-treatment plant have been examined.

2.6. Conclusions

The main reason for replacing the old water supply systems was the inadequate amount and variable quality of water during dry years. The water supply of Virttaankangas MAR can produce adequate amounts of good quality water consistently. The water supply system takes advantage of modern technology along with well proven natural processes. This results in a sustainable water production system, in which the terms and conditions have been “negotiated with nature” using the best knowledge about the aquifer’s ability and limitations to naturally purify the infiltrated water. Indeed, the water quality of all the

MAR production wells has been faultless even without any post-treatment. Total number of well samples since the beginning of the MAR operation is more than 900, resulting in more than 25,000 individual water quality analyses.

Good design with the sophisticated data management and modelling tools makes the drinking water production of MAR plant well balanced. Therefore, there are no unintended changes in groundwater levels, spring flows or water chemistry. As a result, the company can provide the 300,000 inhabitants of Turku area with naturally produced and safe drinking water resilient to climate change.

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Case Study 3: Managed Aquifer Recharge to recycle water for agricultural use in San Luis Río Colorado, Sonora, Mexico.

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3.1. Introduction

San Luis Río Colorado (SLRC) city is located in the Sonoran desert bordering the Colorado River (CR) delta with a very low annual mean precipitation of 55 mm. The water scarcity in this region is further exacerbated by economic growth of the Mexican border cities and intensive farming. There are two main sources of water for supply: groundwater of the SLRC aquifer and surface water delivered from the USA according to an International agreement between Mexico and USA to share water from transboundary basins. Currently 77% of water use is for agriculture. The water demand by the SLRC city is 31.5 Mm^3/year (1 Mm^3 = 1X10^6 m^3), yet both of its sources are at risk. The SLRC aquifer is overexploited and is depeted at a rate of 7.58 Mm^3 anually (DOF, 2015 [1]). A prolonged drought of the CR basin has diminished surface water supply. Recently, Mexico has accorded

Box 1: CHARACTERISTICS OF THE MANAGED AQUIFER RECHARGE PROJECT.

Location: 32°23.502’N, 114° 49.521’W. MEXICO-USA border.

Project manager: OOMAPAS.

Source water: treated waste water.

Technique: 12 infiltration basins (1.21 Ha of area each).

Year of commencement: 2007.

Recharge: ~10.5 Mm3/year.

Final use: Agriculture, aquifer recovery.

Aquifer: Quaternary alluvial deposits.

Monitoring network: Observation wells.

Main advantage: Sustainable water reuse in arid region.

with USA a reduction of the water allotment for the agriculture year 2019-2020 (CILA, 2017 [2]) settled in the International Treaty "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande" signed in 1944.

To address the water scarcity facing the SLRC city, managed aquifer recharge (MAR) in SLRC aquifer through infiltration basins was initiated. Prior to MAR, waste water collected by the SLRC city drainage network was discharged to the dry bed of the CR, located 10 km west of the city, resulting in pollution. In 2005, the wastewater treatment plant WWTP of SLRC was built, with an average inflow of 280 l/s or 8.75 Mm^3/year over 12 years of operation and continually growing to reach 341 l/s in 2019. The treated waste water is infiltrated through an Infiltration Basin Artificial Recharge (IBAR) system, followed by reuse primarily for agriculture. This IBAR consists of 12 infiltration lagoons of approximately 1.21 Ha for each lagoon, recharging to the aquifer more than a third of the water that is used for municipal supply of SLRC.

3.2. Conceptualizations and Implementation

Both the WWTP and IBAR were funded by the North American Development Bank under the Border Environmental Infrastructure Fund (BEIF) which administrated grants provided by the US Environmental Protection Agency (EPA). Once the construction of the WWTP was completed, the Municipal Operator of Drinking Water, Sewerage and Sanitation of San Luis Río Colorado Agency (OOMAPAS) took charge of the operation, maintenance and monitoring of the WWTP and IBAR. The infiltration project commenced with site assessment for soil and hydrogeological properties that led to a pilot recharge experiment with a 28 m^2 infiltration pond and 4 observation wells with monitoring of infiltration rates and water quality. This provided 'proof of concept' and enabled the design of the large scale system that was subsequently constructed (Hérandez Aguilar *et al.*, 2018 [3]).

There are two key aspects of this MAR scheme. The first is the increase in regional water availability because the additional recharge has resulted in the reduction of pumping from the overexploited aquifer, partially relieving the stress on the underground water resource. The second is that the IBAR, the first of its kind in Mexico, has served as a benchmark to carry out other MAR projects and to develop regulations based on learned practices (SEMARNAT, 2008 [4]).

Figure 1.
Location of San Luis Río Colorado Infiltration Basin Artificial Recharge (IBAR) system in Mexico (top) and an aerial photo of the IBAR (bottom). Basins are operated alternately (ie Soil Aquifer Treatment) with drying times between to assist treatment and to help manage clogging. Source: Own elaboration; Photo © Jorge Ramirez Hernandez

3.3. Environmental sustainability

Groundwater quantity

Evaluation of the hydrological properties of the aquifer (soil mechanics and geophysical tests) for IBAR design allowed for maintaining the required recharge volumes. Water volume recharged is variable from 100 l/s during the winter to 60 l/s during the summer seasons, because of the high evaporation rates during the summer when temperature can reach 50 °C. During the infiltration process, an increase of only a few centimeters in the groundwater level has been measured in observation wells located on both sides of the lagoons. This negligible response in water level is due to the relatively small infiltrated volume compared to the high permeability of the aquifer. The projected volume of 10.75 Mm^3/yr recharged by the IBAR in 2019 (up from 10.02 Mm^3/yr in 2018) is 4.5% of the estimated total annual recharge to the aquifer of 237 Mm^3 (CONAGUA, 2013 [5]). However this recharge constitutes an important component to achieve the water balance between inputs and outputs of the aquifer system. The recharge volume by the IBAR is 34% of the projected 2019 total water extraction from the aquifer for urban use by OOMAPAS (31.5 Mm^3) (Figure 2).

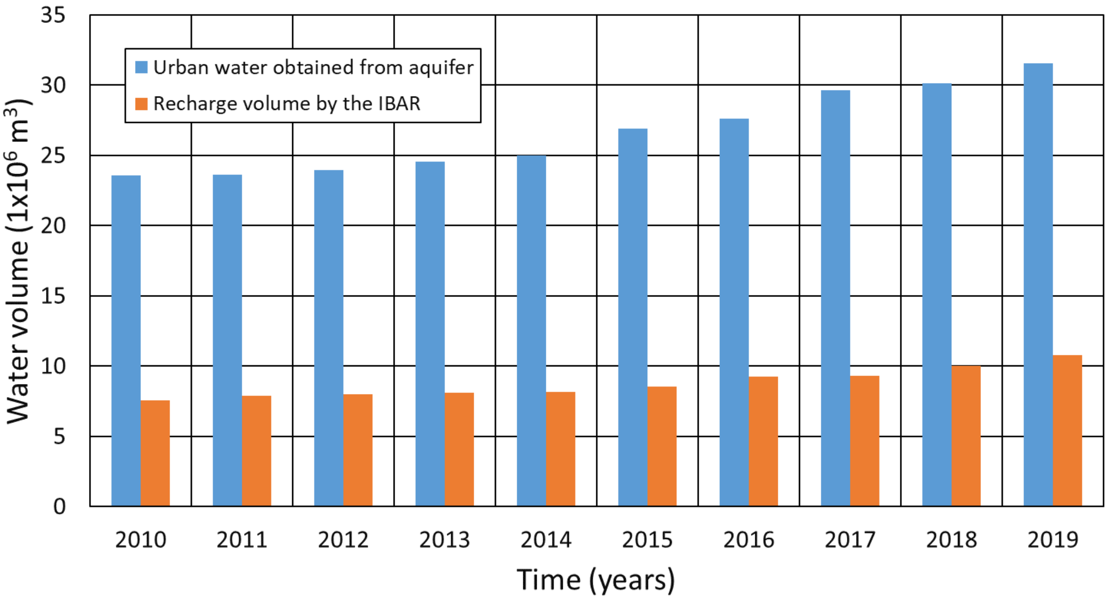

Figure 2.
Water volume obtained from the aquifer for urban use in San Luis Río Colorado City and volume infiltrated to the aquifer by IBAR between 2010 and 2019 with an average annual recharge volume of 8.75 Mm³. Data from OOMAPAS. Source: Own elaboration

Groundwater quality

Since the commencement of the MAR project and through the 12 years of operation, testing of the main physicochemical parameters in the inflow and outflow waters of the WWTP and the observation wells located in the vicinity of the lagoon to monitor the aquifer has been done every 15 days to ensure that the limits established in the official standards are not exceeded. The water must meet two different standards; for WWPT outflow the NOM-001-SEMARNAT-1996 (NOM-001) (1997) [6] and for aquifer recharge NOM-014-CONAGUA-2003 (NOM-014) [4]. NOM-001 is the official standard for water discharged to another body of water and NOM-014 considers water quality for safe human use and consumption (NOM-127-SSA1-1994) [7]. Table 1 shows selected parameters for which concentration levels are below the maximum levels allowed by the standards NOM-001 and NOM-014 from 2010 to 2019, suggesting that the system is functioning. Manganese and chloride exceed the permissible concentrations for recharging according to the NOM-014.

The increase in chloride concentration from WWTP outflow to observation well (Table 1) is because of the evaporation process in the WWTP and by the natural contribution of the lower strata through which the water travels to the aquifer (Sol, *et al.*, 2008 [7]) these strata also contain manganese and iron showing an increasing in their concentrations too. At 7 observation wells drilled to 15, 20 and 25 m depth on 2007, hydrochemical studies have found that the removal of the most common contaminants from the treated waste water, with 99.99% for removal of fecal coliforms, 98.36% for total suspended solids (TSS) and up to 98.74% for biochemical oxygen demand (BOD) (DOF, 1996 [8]). The effluent obtained from the WWTP has met the levels of contaminants required by Mexican official regulations NOM-001. Given further water quality improvements observed, the recovered water is suitable only for reuse in agriculture not for drinking.

Table 1.
Annual mean water quality of WWTP inflow, outflow, and an observation well from 2010-2019.
Source: Own elaboration

Parameter*	WWTP inflow		WWTP outflow		NOM-001	observation well (25 m)		NOM-014
	conc	s.d.	conc	s.d.	conc**	conc	s.d.	conc**
Turbidity (NTU)	274.5	25.1	136.5	16.6	n/s	7.24	1.1	5
TSS (mg/l)	99.1	15.3	70.6	8.9	75	1.69	0.4	n/s
Fecal Coliforms (NMP/100 ml)	2,400,000	n/s	260.6	30.86	1,000	0	n/s	0
BOD (mg/l)	154.7	19.26	25.80	4.59	75	12.0	1.04	n/s
Iron (mg/l)	0.147	0.016	0.16	0.013	0.2	0.19	0.005	0.3
Manganese (mg/l)	0.27	0.022	0.28	0.012	n/s	0.28	0.033	0.15
Chloride (mg/l)	477.3	24.5	510.6	10.3	n/s	541.3	20.59	250

* conc= concentrations were obtained from annual mean based on samples taken every 15 days from 2010 to 2019 (~240 samples, 24 each year for 10 years). s.d.= standard deviation. n/s = not specified

** NOM-001 values are the maximum concentration level permitted for agriculture irrigation disposed in artificial reservoirs. NOM-014 values are the maximum concentration level permitted for aquifer recharge.

Energy requirements

The most important energy consumption of the combined WWTP and IBAR system, is to recover municipal wastewater from the city and convey the water to the WWTP. Pumping and conveying of wastewater 5 km away from the city has a total energy demand of 893 MW (1 MW = 10^6 watts) annually, equivalent to 0.08 KWh/m^3 recharged. Once the wastewater is in the WWTP, water treatment is carried out using the incoming water pressure using only anaerobic, facultative and maturation ponds. There is no aeration pond. The IBAR water feeding system has no additional energy consumption because the transfer of treated wastewater and movement along the ponds is by gravity.

3.4. Cost-benefit considerations

The pilot infiltration test, design of the system and construction of the IBAR system had a total cost of one million dollars. The operation and maintenance costs of the IBAR are very low, reaching $ 140,000 per year in 2017. This is due to the fact that the transfer of water from the WWTP to IBAR is by gravity. The costs include the operation personnel, the mechanical removal of clogging layer on the surface of the lagoons to maintain the desired infiltration rates, the monitoring of the water levels and chemical analysis of samples from observation wells and the expenses of external certified laboratory. The levelised cost of recharged water is estimated to be US$0.02 per m^3. The IBAR is cheaper compared to next best alternative, secondary treatment in a surface-based facility at a cost of US$0.06 per m^3 to bring the water to a quality fit for the same amount of additional agricultural production. The implied benefit cost ratio for MAR is 3:1. OOMAPAS is seeking exemption from the payment of US$445,000 dollars per year by not discharging the effluent from the WWTP to the river and also avoids US$153,113

(Hérnandez, 2013 [9]) cost of pumping to the river the volume of water that it recharges. The exemption sought would recognize the environmental benefits of aquifer recharge and provide an incentive for OOMAPAS to conduct MAR operations.

3.5. Social sustainability

IBAR at SLRC was the first in Mexico, and no health and aquifer recharge regulations existed at the time. Incidental aquifer recharge induced by discharge of treated and untreated wastewater to the Colorado River or the irrigated land was common in Mexico. Once this project was proposed, a regulatory document entitled NOM-014 was elaborated, although it was not until 2008 when the norm was approved. This official standard for aquifer recharge requires achieving levels of water quality that meet the limits specified by CONAGUA including parameters regulated by the potable water standards (NOM-127-SSA1-1994 1994)». OOMAPAS must carry out groundwater quality analysis every 15 days for keeping operation permits of IBAR from CONAGUA. The CONAGUA is the Federal Regulatory and Financial Organism has the authority of regulating all water management activities and help local governments to design, construct and in some cases maintain the MAR facilities. CONAGUA encourages local governments exempting them from paying water rights based on the volume of water infiltrated (CONAGUA, 2013 [10]). This exemption of payment is only obtained if the quality levels of different chemical components meet norm's maximum allowed levels. These periodic water quality reports are contracted by OOMAPAS to a certified independent laboratory who deliver these directly to CONAGUA in order to reduce the possibility of any results alteration.

However, although these official documents are available to the public through a specific request, they are often not consulted because the possible effect on the aquifer is not easily understood. Unfortunately, there has been no public and stakeholder consultation about operation, recharge volumes, and water quality of IBAR to raise awareness. Recently, NGOs and OOMAPAS have promoted via social networks. Elementary school students also visit an artificial wetland with a botanical park connected to the lagoons that will generate habitat for local and migratory birds. Such visits hopefully will raise the awareness of the importance of the IBAR among the inhabitants of SLRC.

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Case Study 4: Recharge structures in ephemeral streams in Dharta watershed, Rajasthan, India

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4.1. Introduction

A study of the hydrology and economics of four streambed recharge structures, locally called check dams, was conducted over 3 years, 2014-2016, in hard-rock granitic terrain typical of the Aravalli Hills, in Rajasthan, India, to evaluate their contribution to agricultural production (Dashora et al. 2018, 2019 [1],[2]). The check dams are in a semi-arid monsoonal area with a mean annual rainfall of approximately 700-800 mm. Most of this rain falls in heavy monsoon storms in less than 20 rain days each year, and runs off in ephemeral streams that are dry between storms. Groundwater is relied on exclusively for winter (rabi) crops and is also used to sustain summer (kharif) crops if there are extended dry periods during the monsoon. With the expansion of groundwater irrigation since electricity became available for pumping in the 1980s, groundwater levels have fallen, and any streams that were previously perennial became ephemeral. Consequently in the 1990s and 2000s check dams were constructed in this area, largely under government programs for drought relief and economic development, although some check dams were also constructed by non-government organisations. These were small weirs, generally of concrete, to detain stream water so it could soak into the ground and enhance groundwater recharge, and help secure groundwater supplies in this area with an unreliable monsoon. The results of the study showed that these check dams were economically attractive at the local level for securing irrigation water supplies at an average benefit-cost ratio > 4 due to increased agricultural production of between 8% and 16%.

4.2. History of the check dams

Prior to 1950s, irrigation water was accessed from large diameter dug wells with water lifted in buckets powered by oxen walking down ramps. When electricity supply commenced in the 1960s, pumps were installed, the cropped area rapidly expanded, and groundwater levels fell. Wells were deepened from about 10 m to around 30 m. The introduction of tube well construction in the 1980s helped sustain production but continued to lower the dry season water table, rendering dug wells unreliable (Shah, 2009 [3]; Shankar *et al*. 2011 [4]). To help enhance groundwater recharge, check dam construction in ephemeral wadis that flow intermittently during the monsoon season has continued over the last four decades by government agencies and non-government organizations in Western and Southern parts of India (Agoramoorthy and Hsu, 2008 [5]; Kulkarni *et al*. 2015 [6]).

4.3. Monitoring of check dam performance

The four check dams selected for this study were constructed between 1995 and 2005 and have a combined storage capacity of 469,000 m^3 and catchment areas of 3,003 ha, hence a capacity to detain 16 mm of rainfall (Dashora *et al*. 2018 [1]). The check dams had been in operation for between 9 and 19 years without any monitoring before this study commenced in 2014. Like many cases in India, farmers attested to improvements in access to groundwater and increased crop production, but there was no documented evidence of the role that recharge structures played. Hence, as part of a broader applied research project on groundwater management at village level (MARVI- Managed Aquifer Recharge through Village-level Interventions), monitoring commenced for rainfall, water levels in check dams and dug wells, and farm water use and yields. This allowed assessment of the hydrological and economic impacts of groundwater recharge and to differentiate between recharge from check dams and natural recharge. Field measurements were taken by farmers on a daily basis, with training and support and data quality assurance from experts in natural resources management. A simple excel-based water balance was used to estimate recharge from the check dam. A cost benefit analysis was conducted using present value analysis on investments and maintenance (if any) to estimate the levelised cost of measured recharge from check dams and compared with the unit levelised net profit from crop sold with respect to groundwater used to produce it.

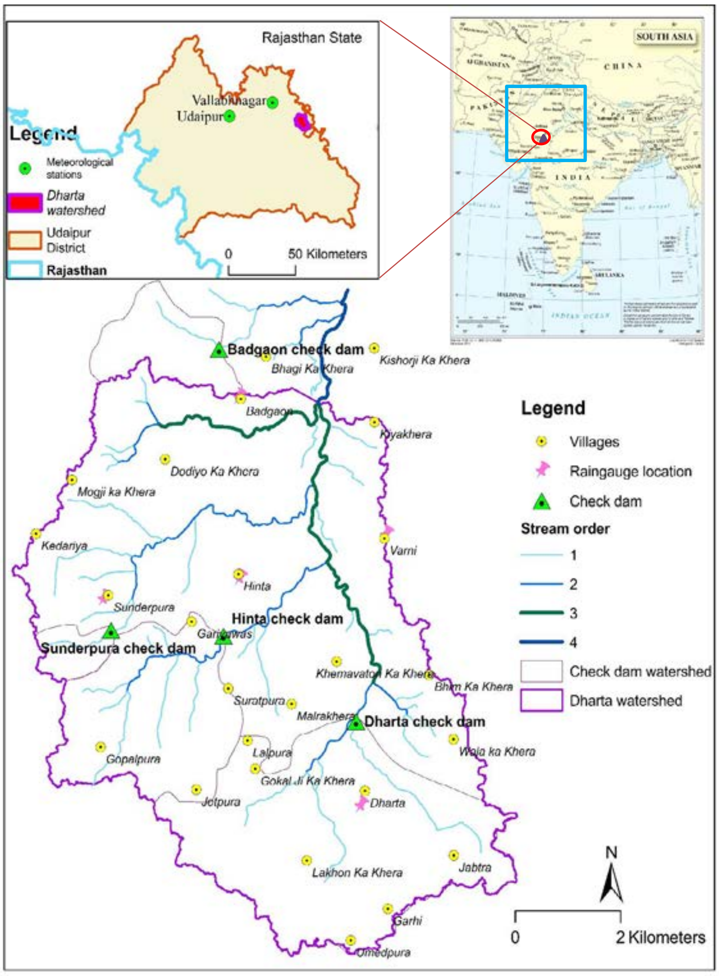

Figure 1.
Site location and overview information.
Source: Own elaboration; Map © UN Maps

Description

Type of recharge: 4 check dams on ephemeral streams

Current scale recharged: 779,000 m^3/year (Dashora *et al.*, 2019 [2])

Location: The watershed is situated 65 km east of the city of Udaipur within the Bhinder Block, Udaipur District of Rajasthan, India.

Latitude 24°37' to 24°39' N
Longitude 74° 09' to 74°15' E
Altitude ~ 470 m above sea level

Mean annual rainfall: est ~700-800mm, monsoon, June to October

Source of water: Storm water runoff from rural catchment

Aquifer: Unconfined granitic hard rock. Bhinder Block groundwater is in overdraft (CGWB, 2013 [7]).

End use: Irrigation (mainly winter wheat and mustard) and drinking

Dates constructed: 1995-2005

Uniqueness of this case study: While there are estimated to be millions of streambed recharge structures in India, these are the only ones known to be monitored by farmers to accurately assess their performance, using simple methods that are easily replicated. A mobile phone app (MyWell) (Daly et al. 2018 [8]) was developed and, along with gaugeboard stencils for painting wing walls, now supports replication elsewhere in India, and can easily be used by farmers, Gram Panchayats and government to assess infiltration rates and prioritise recharge structures for maintenance. At several check dams the impact on recharge rates of manual and mechanised desilting were also assessed (Dashora et al. 2019 [2]) and were found to be quite different for different desilting methods.

The four representative sites for monitoring were selected to cover a geographic spread within the Dharta catchment, on both first and second order streams, and give a range of sizes of MAR structures. The Sunderpura check dam was constructed by a Non-Government Organisation in 1995. Hinta check dam was built by the Public Health Department in 2000. Badgaon and Dharta check dams were constructed by Gram Panchayats (local government at village level) in 2001 and 2005 respectively. Check dam dimensions are given in Table 1. Before the MARVI project in 2014 the watershed was un-gauged and no basic information of size and design capacity was available with concerned departments. Hence initially dumpy level surveys were conducted to prepare area-volume – elevation curves for each check dam.

Table 1.
Check dam dimensions in relation to catchment area (from Dashora *et al.* 2018 [1])

	Recharge structure	Total depth#, m	Water spread area##, m^2	Capacity##, m^3	Catch-ment Area, ha	Check dam area## as % of catchment	Check dam capacity## as mm over catchment
1	Badgaon	1.57	39,000	*42,000	338	1.15	12.4
2	Dharta	1.82	136,600	*140,000	1,705	0.80	8.2
3	Hinta	2.62	127,200	223,000	851	1.49	26.2
4	Sunderpura	2.05	62,800	64,400	109	5.77	59.1

depth from weir crest to contrete apron at stream bed level which is the base of gaugeboard
calculated from area- and volume- elevation curves when water elevation is at weir crest
* mean of pre- and post-scraping volumes

Figure 2.
Badgaon check dam during a storm event. The gaugeboard is visible on the wing wall opposite. © Yogita Dashora

It was reported by locals that there was no regular maintenance schedule for check dams. After a year of data collection, maintenance of 2 structures was done before the 2015 monsoon by manual labour for Badgaon, and using earth moving machinery for Dharta. In 2016 mechanical scraping was done at Hinta and repeated at Dhata (see Figure 3). A dumpy level survey was repeated to confirm the excavated volume. Ongoing maintenance is anticipated to occur as needed under NREGA (National Rural Employment Guarantee Act). Monitoring has occurred since 2014 by local champions (farmers -Bhujal Jankars) with support of research scientists (local & International).

Figure 3.
Desilting methods used for check dams before the 2015 and 2016 monsoons: (a) manual desilting of Badgaon check dam before 2015 monsoon, (b) mechanical desilting of Hinta check dam 2016. © Yogita Dashora

4.4. Hydrological performance of check dams

Hydrological data (Table 2) were reported by Dashora *et al.* (2019) [2]. The years 2014, 2015 and 2016 were considered 'average', 'dry' and 'wet' years respectively by farmers, based on flows, and the mean figures are considered a good representation of mean annual figures. With high spatial variability in convective monsoonal storms, and no long term rainfall stations within 30 km, it was not possible to verify this but monitoring is continuing. Mean annual recharge from the 4 impoundments was 779,000 m^3 or 26 mm for their total catchment areas. This volume is 1.66 times the total detention capacity. 87% of recharge occurred during dry weather and recharge during wet weather when check dams were spilling was assumed to be at the average dry weather rate. Recharge volumes are considered reliable. However runoff calculations are considered to be crude estimates, as level measurements were only taken daily, so the recharge to runoff ratio, 19%, is also considered a crude estimate.

Table 2.
Components of the annual water balance for four check dams (2014-2016).
Means (bottom row) are given in italic.

Recharge structure	Year	Rain fall (mm)	Inflow (m^3)	Recharge (m^3)	Spill (m^3)	Evaporation (m^3)	Recharge/ Inflow (%)	Recharge/ Capacity (-)
Badgaon	2014	505	349,000	113,000	218,000	19,000	32%	2.86
	2015	614	189,000	56,000	129,000	4,700	27%	1.34
	2016	1161	1,145,000	143,000	980,000	26,000	12%	3.40
Dharta	2014	535	1,312,000	299,000	954,000	64,000	23%	2.19
	2015	596	192,000	157,000	0	44,000	81%	1.12
	2016	1151	6,502,000	180,000	6,228,000	94,000	3%	1.27
Hinta	2014	771	949,000	518,000	358,000	91,000	55%	2.32
	2015	673	331,000	286,000	0	63,000	86%	1.28
	2016	1387	750,000	388,000	246,000	115,000	52%	1.48
Sunderpura	2014	485	54,000	46,000	0	8,000	85%	0.71
	2015	406	13,000	11,000	0	1,600	88%	0.17
	2016	1069	360,000	139,000	177,000	44,000	39%	2.16
Mean or Total		779	12,146,000	2,336,000	9,290,000	574,300	19%	1.66

4.5. Economic performance of check dams

An evaluation of the costs and benefits of these check dams is provided in Dashora *et al* (2019) [2]. The analysis was based on calculation of present values of costs and benefits. Capital costs of each check dam were converted to 2014 prices and expressed as an annuity, based on an assumed life of 30 years and a discount rate of 8% (based on CPI). To this was added the average annual maintenance costs of all check dams in 2014 prices. The unit cost per m^3 recharged was found by dividing the annualised capital and maintenance cost by the mean annual recharge volume for each check dam, as measured in 2014-2016. This unit cost was expressed in Indian Rupees (INR) in the year 2014 per cubic metre of recharge (Table 3).

The benefits of recharge in this case study is calculated from the profit returned to farmers after deducting costs of production, for each rabi season crop using statistical data for area planted, yield, price, production cost and irrigation water use. Water use rates were confirmed by field experiments for the two major crops, wheat and mustard. Unit benefits per cubic meter of water use, in INR adjusted to 2014 prices , were the crop area fraction weighted net profits for the existing mix of crops divided by their area-weighted irrigation water use. As the groundwater level data from the 250 weekly-monitored wells revealed that the storage was depleted each rabi season due to irrigation, the full volume of recharge from recharge structures was assumed to contribute to irrigation use and crop production. Hence the benefit cost ratio for recharge structures is simply the present value of the unit benefit divided by the PV of the unit cost.

In this case study, those figures are recalculated to be expressed as US$ in the year 2016, as follows. The annuity equivalent of capital costs were recalculated at 5% pa over a 30 year project as used in other case studies in this compendium. This consequently reduced the annuity cost of capital and slightly increased the benefit cost ratio. All costs and benefits that had been determined in 2014 INR were inflated to 2016 at 5%pa and the 2016 exchange rate of 68 INR / US$ applied. This gave an average cost of water recharged of 0.7 US cent per m^3 and the benefit of US 3.8 cents per m^3. The average benefit cost ratio increased from about 4 to 5 as a result of the differences in assumed discount rate.

Table 3.
Levelised unit costs and benefits of recharge from check dams (adapted from Dashora *et al* 2019)

Recharge structure	Avg. annual recharge 2014-2016 (m^3 /yr)	CR # (INR/m^3) (2014)	BR ## (INR/m^3) (2014)	BCR * (-) (8%, 30 yrs)	CR ** (US$/m^3) (2016)	BR *** (US$/m^3) (2016)	BCR * (-) (5%, 30 yrs)
Badgaon	104,000	0.61	2.36	3.9	0.008	0.038	4.6
Dharta	212,000	0.55	2.36	4.3	0.007	0.038	5.4
Hinta	397,333	0.36	2.36	6.6	0.005	0.038	8.3
Sunderpura	65,333	1.73	2.36	1.4	0.022	0.038	1.7
Total	778,667						
Mean		0.56	2.36	4.1	0.007	0.038	5.3

CR, average unit cost of annual recharge from check dams in INR 2014;
BR, average unit benefit of annual recharge from check dams in INR 2014;
* BCR, benefit cost ratio
** CR, average unit cost of annual recharge from check dams in US$ 2016;
*** BR, average unit benefit of annual recharge from check dams in US$ 2016;

4.6. Indicators of sustainability of recharge from check dams

Resource integrity –water quantity

1. Monitoring of groundwater table is now undertaken by farmers who have had training and been provided equipment and follow up on quality assurance. This enables decisions to be made on what fraction of the crop area to plant for the rabi season based on post-monsoon storage levels.
2. The ratio of volume of infiltrated water from the 4 check dams to volume of recovered water on an annual basis varies between 8% and 16% as determined from check dam studies (Dashora *et al*. 2018, 2019 [1],[2]) and groundwater monitoring across the catchment (Chinnasamy *et al*. 2018 [9]). Maintaining a balance depends on cooperative groundwater management by farmers, informed by the groundwater level data that they collect and share (Maheshwari *et al*. 2014 [10]; Jadeja *et al*. 2018 [11]).

Resource integrity – water quality.

3. Exceedance rates on water quality parameters based on a sampling program of 150 dug wells (used for irrigation and some also for drinking) in this catchment in 2017 revealed (in unpublished data of MARVI project) that only 31% met the Bureau of Indian Standards permissible limit (for drinking in the absence of an alternative water source, BIS 10500, 2004 [12]) for total dissolved solids (TDS) (2000mg/L), 44% met the pH range (6.5-8.5) and 93% met the value for fluoride (1.5mg/L). Only 10% samples met the value for turbidity (10 NTU), and this has triggered testing the impacts of well covers to improve dug well water quality. BIS Standards for irrigation water (BIS 11624, 1986 [13]) cover trace elements and boron (not analysed here), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), exchangeable sodium percentage (ESP) and electrical conductivity of irrigation water (EC iw). The permissible values depend on crop and soil types, rainfall range, and interactions between parameters. Most crops were salt tolerant and soils friable, so groundwater samples, with a few exceptions, were compatible with use for irrigation.
4. In the case of 13 surface water samples taken from check dams in August to November 2017, for each parameter a higher proportion met the guideline – for TDS 100%, for pH 62%, for fluoride 100%, and for turbidity 31%. As stream water recharged to the unconfined aquifer from check dams is the same source as is being recharged naturally through the same alluvium to the same aquifer, there is no obvious increase in inherent risk for drinking water or irrigation supplies. Under these circumstances, the only guide so far on water quality in MAR in India (Dillon *et al*. 2014 [14]) does not impose additional treatment requirements.

Ecosystem Services

5. Currently there is no water sharing policy nor a catchment water management plan in place to protect water supplies for the riparian ecosystem nor downstream water users. These ephemeral streams have lacked baseflow at least since groundwater extraction increased after electricity distribution in the 1960s. Restoration of ecological flows is considered of secondary importance to sustaining agricultural crops and farm livelihoods. It is possible to achieve ecological objectives through designing bypasses or low flow leakages in check dams, but objectives would need to be clearly defined and supported.

Stressors

6. Check dams recharge water under gravity so there is no ongoing energy cost. By replenishing unconfined aquifers the pumping energy requirements for recovery of groundwater would be diminished. In this case by 8% to 16% of the difference in energy requirements between pumping from low water table at the start of the monsoon and high water table at the end of the monsoon. This range was from 5 to 18 m and averaged about 11 m. Actual savings in KWh/m^3 will vary across the area depending on aquifer hydraulic parameters, average water table depth and pumping rate.

Social Sustainability Indicators

7. There is no clearly defined, transparent regulatory framework for MAR, nor requirement to monitor resource integrity. However in this project informed farmers monitor the groundwater and share the data to make informed cooperative decisions about the area to plant for rabi season crops. They are also now able to make informed decisions on which check dams have the greatest need for scraping or other maintenance. Varua *et al* (2015) [15] have assessed farmer attitudes as a way of tailoring design of groundwater management collectives in this catchment. There is some evidence for higher school absenteeism among girls, attributed in part to the need to carry water when household wells run dry in this catchment (Kookana *et al*. 2016) [16], and MAR could reduce the period over which water needs to be carried.
8. A permit granting process for MAR based on sound risk assessment aimed to protect human health is unnecessary for this class of MAR as covered in item 4. However greater attention is warranted on improving the quality of water extracted from dug wells for drinking, through a well head protection program, informed by monitoring. Precluding runoff water from being recharged directly or adjacent to wells used for drinking water supplies, should be included as a preventive measure in such a well head protection program.
9. There is a voluntary arrangement for farmers to monitor groundwater and self-manage their aquifer through village groundwater cooperatives. Several of these have formed legal entities so they can be recognised and work more expeditiously with government to sustain groundwater and livelihoods.

4.7. Conclusions

Four studied check dams illustrate an average benefit to farmer net income in levelised terms of 4 to 5 times the levelised cost of construction and maintenance of the checkdams. There is a spread of values with benefits exceeding costs even for the first check dam built, at Sunderpura, that had an excessive detention capacity with respect to its catchment size. This suggests information gained can improve performance. Monitoring of check dams by farmers was highly effective in determining their annual recharge, and along with groundwater monitoring allowed estimation of the contribution of check dam recharge to the overall resource, in this case 8-16%. Importantly, in this area, local groundwater cooperatives are forming, making use of check dam and groundwater level data for collective groundwater management. Water quality data suggest a higher quality of water in the check dams than in the dug wells of the aquifer, in part due to current failures in well head protection. Check dams can potentially lower the salinity of recovered water, but check dams should not be allowed to admit water directly to drinking water supply wells because of the health risks. Effectiveness of check dams to improve local livelihoods is not disputed for the check dams studied. However, governments should be alert to the possibility that ongoing construction of check dams within a catchment may lead to oversaturation, with consequent decline in local effectiveness of any downstream check dam or water supply. This case study suggests that water sharing policies in catchments be developed, along with hydrological models to encourage and support efficient use of resources at whole of catchment scale. This also calls for a governance process based on Ostrom's principles for managing common resource pools (Jadeja *et al*. 2018 [11]).

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Case Study 5: The MAR of the Geneva Aquifer: A 40-year success story for the management of transboundary aquifers at local level

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5.1. Introduction

The Lake Geneva and the Genevois Aquifer provide drinking water for nearly 700,000 inhabitants of the Franco-Genevan region. In 2019, the aquifer, shared by the Canton of Geneva (Switzerland) and the Department of Haute-Savoie (France), is jointly exploited through ten wells in Switzerland and four in France. In the 1960s and 1970s, the level of the aquifer dropped considerably, because of the large and uncoordinated pumping of the various distributing and beneficiary entities, both from Geneva and Haute Savoie side. Dry wells had to be closed. This was the starting point of the technical discussions undertaken at transboundary level to seek solutions to limit the overexploitation of the Genevois aquifer groundwater resources. Motivated by the protection of this shared resource, decision makers have therefore expressed their support for the artificial replenishment of the aquifer. The main idea was to return to initial groundwater levels, to replenishment the aquifer during winter with water from the Arve River, and then use it as a large seasonal reservoir during summer periods, when demand is higher. While the managed aquifer recharge system of the transboundary aquifer of Geneva has proved useful since 1980, negotiations on the organizational, administrative, financial, legal, and political aspects have been developed in parallel with technical research and developments aimed to achieve an efficient and pragmatic organization for the joint management and protection of the aquifer through consensus [1,2,3,[4].

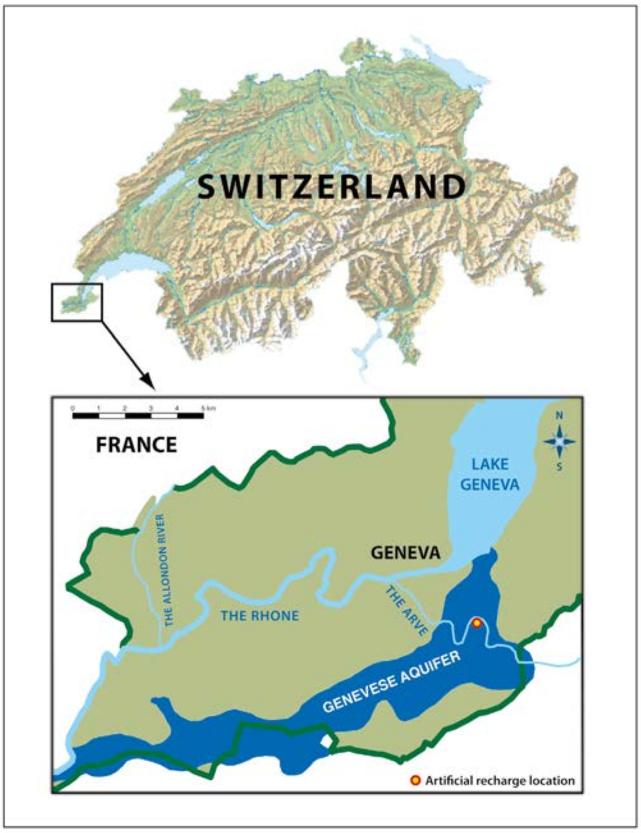


Figure 1.
Location of the Genevese aquifer.
Source: Own elaboration

Box 1 Salient Features of the Geneva MAR

Location : Geneva – Switzerland
46°18.65'N – 06°16.56'E

Operator : SIG (Geneva Public Utilities)
Public company

Design : underground reverse drainage (total length of 5,000 m) in an infiltration area (total surface 3 ha.)

Commencement of operation : 1980

Quantity of water artificially recharged : 8-10 Mm^3/year

End use : drinking water supply for the Canton of Geneva and French communities

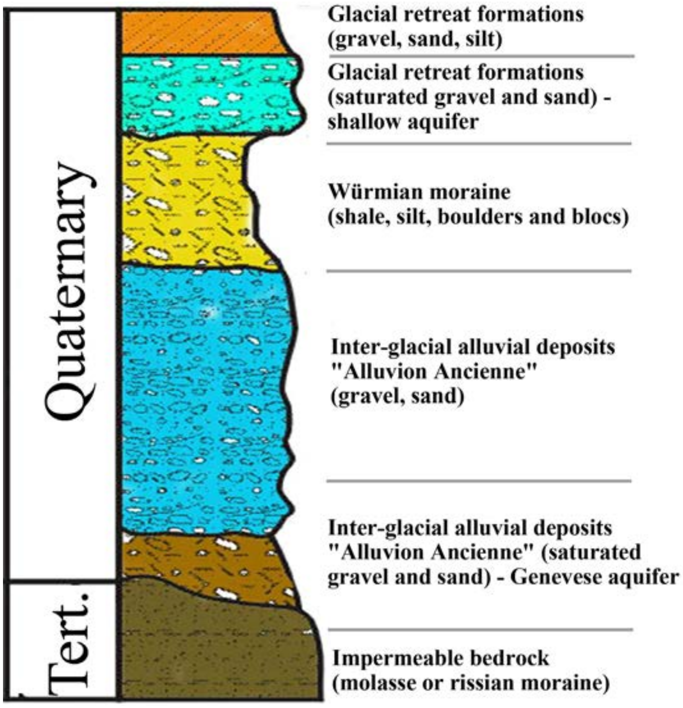
Source of water : Arve river and groundwater

Aquifer : Silty-sandy gravel of glacial and fluvioglacial deposits (Wurm)

Type of recharge : natural and artificial (by water pumping, treatment and reverse drainage infiltration)

Main advantage : sustainable abstraction of high quality and quantity of water by aquifer recharged

As a transboundary aquifer, the Genevese aquifer, also known as Arve aquifer, as it is recharged naturally by the waters of the Arve river, extends over 19 km, between the lake and the Rhône River on the western side of the canton of Geneva (Figure 1). Its width varies between 1 and 3.5 km. The aquifer lies partly on the French border. The thickness of saturated gravel may reach up to 50 m. Depending on topographic conditions the average water level may range between 15 m and 80 m below ground level. The aquifer is made up of silty-sandy gravel of glacial and fluvioglacial origin (Wurm), lying directly on the molasse formation, which is considered to be the impermeable substratum (Figure 2). The aquifer is overlain by a clayish Wurmian moraine which reduces meteoric water infiltration, but which has the advantage of providing natural protection against pollution. The hydraulic conductivity of the aquifer is around 1-2 $x10^3$ m/s (80-170 m/d), but it could range from 5 $x 10^7$ to 3 $x 10^2$ m/s.



General characteristics of the Genevese aquifer

Area extension: ~ 30 km

Length ~19 km

Width: 1 to 3,5 km

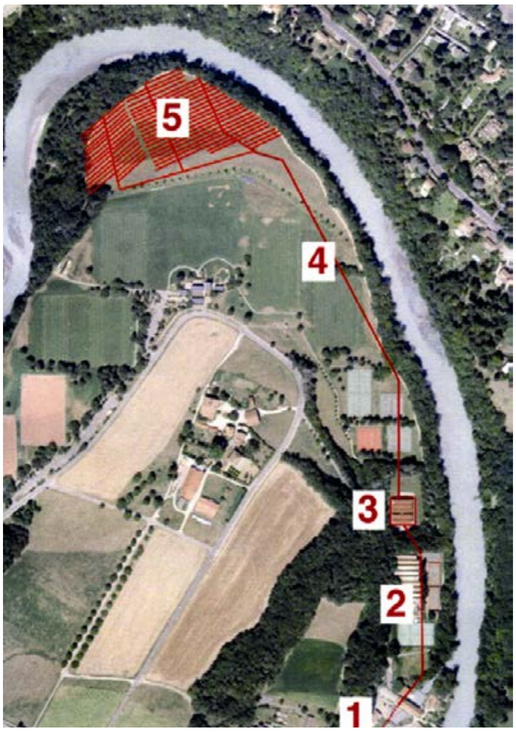
Thickness of saturated gravel: up to 50 m

Darcy's permeability : 1-2. 10^{-3} m/s

Storage coefficient: ~ 7 %

Figure 2.
Geology of the aquifer context and general characteristics. Source: Own elaboration

The managed aquifer recharge (MAR) system has been carried out in the Swiss part of the aquifer where the hydrogeological condition and recharge capacity are showing the best efficiency. The recharge scheme includes the following:



1. A water-intake structure in the Arve river, 300 m upstream of the plant, with a self-cleaning screen in order to eliminate any floating or suspended coarse elements
2. Piping to channel the raw water to the treatment plant (700 mm in diameter, 340 m in length)
3. The water treatment plant with sedimentation, filtration and chlorination units. The treatment of raw water from the Arve river in the aquifer recharge plant allows for the elimination of suspended particles as well as most of the pollution which could accidentally spread to the Arve river. The total capacity is 630 l/s.
4. Piping to channel the treated water to the infiltration area (800 mm in diameter, 700 m in length)
5. The underground infiltration area includes perforated pipes of a total length of 5,000 m. These pipes (of a diameter of 200 mm) are placed at a depth of 2 m in the glacial gravels, 7 m above the groundwater level of the aquifer, in the unsaturated zone. The total surface area is about 3 ha.

Figure 3.
The MAR system. The plant is operated from Geneva Public Utilities's headquarters, located 6 km away. Only two part-time employees are needed to monitor, maintain and operate the facilities, in order to ensure optimal performances.
Source: Own elaboration; Photo © Canton of Geneva

5.2. Historical background

Between 1940 and 1960, groundwater abstraction from the Genevese Aquifer was very close to the average exploitable flow (7.5 Mm^3/year). There was a slow trend of water level lowering, without any indication of a serious threat. Between 1960 and 1980, the aquifer was overexploited with up to 14 Mm^3/year withdrawal in 1971, almost twice the exploitable quantity. The average water level of the aquifer dropped by 6 to 8 meters in twenty years, equivalent to about one third of the total storage. By this time, hydraulic management had become urgent. One option envisioned then was a withdrawal reduction, by exploiting another resource and implying the construction of a new filtration and water treatment plant on the lake. A second option was to replenish groundwater storage of the aquifer through artificial recharge (later renamed as managed aquifer recharge).

The choice between the two possibilities was not easy. It contrasted a well-known technique with artificial recharge, which remained an adventure when we think of the number of unknowns in the balance-sheet equation. Two criteria led to the latter choice: security of supply criterion and economic criterion (cf. § 5.4.). Security requires the diversification of resources (water from Lake Geneva and water from the aquifer in this case), to ensure the continuity of distribution, in the event of a mechanical failure or serious pollution of a resource.

5.3. Environmental sustainability

The recharge scheme plays a very important role in the drinking water supply due to:

- its capacity to stock the water;
- its ability to purify groundwater between the recharge site to the wells used for groundwater supply to the community.

5.3.1. Groundwater quantity

Monitoring of groundwater table since 1966 demonstrates that the scheme has succeeded in restoring the groundwater level, with a rapid rise of about 5 m in 1980-1981 (Figure 4). The total capacity of the MAR plant is about 17 Mm^3/year. The typical capacity of the plant is about 11 Mm^3/year (Figure 4) due to high turbidity of the Arve River which causes the plant to be shut down when turbidity exceeds 120 NTU (around 65 days/year). Automatic stops are in place when pollution of the Arve River is detected by an automatic laboratory with online monitoring of the quality of the river water located about 1 km upstream of the intake.

In more than 38 years of use, the MAR system of Geneva has brought over 295 Mm^3 of treated water into the Genevese aquifer. This supply has contributed to approximately 595 Mm^3 of withdrawal. Based on the experience of the last 20 years, to maintain a stable water table level, a recharge of 8 to 10 Mm^3/year (infiltrated water) is required to allow for a pumping rate of 12 to 15 Mm^3/year (recovered water).

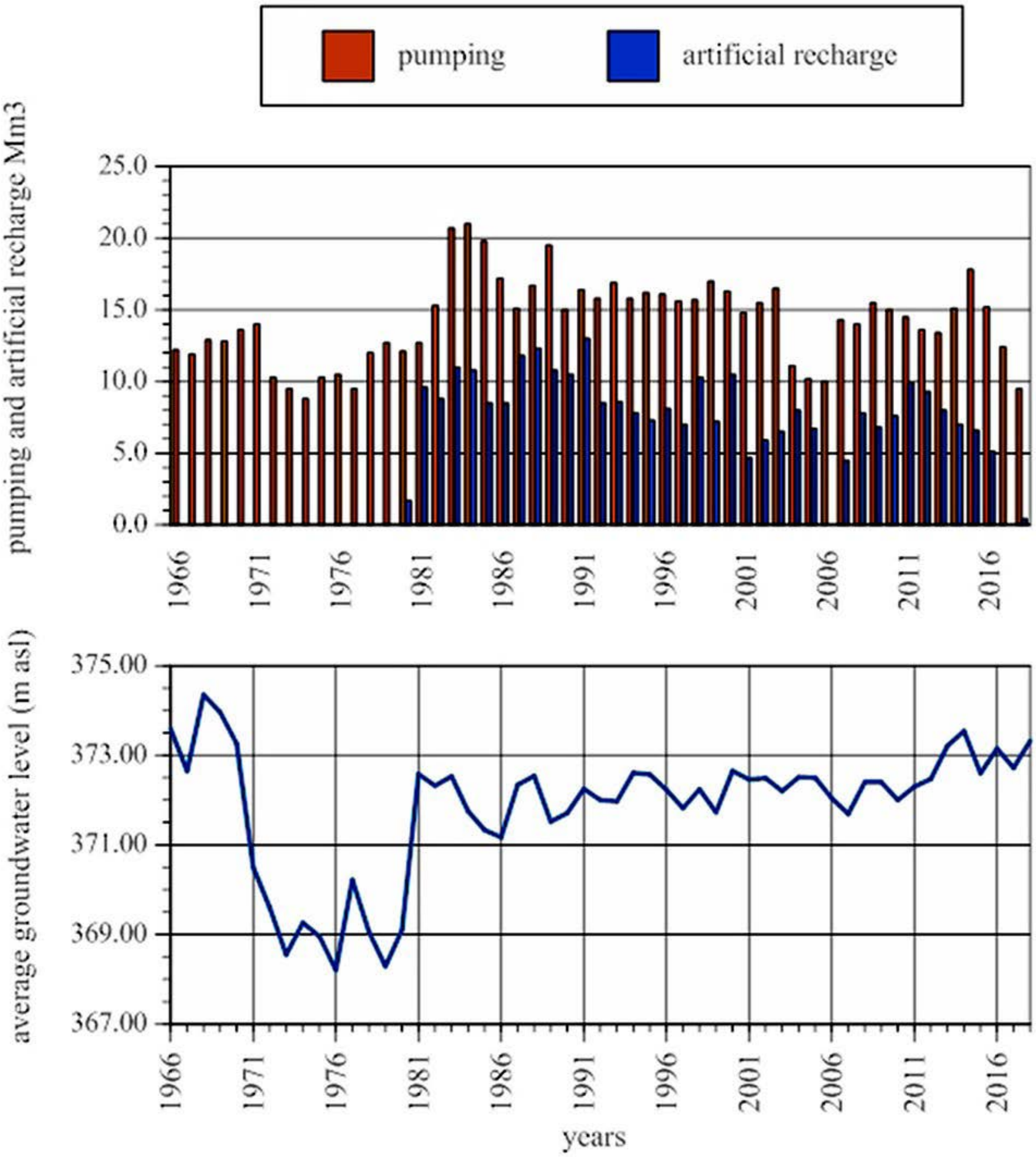


Figure 4.
The impact of withdrawals and managed aquifer recharge on the water table from 1966 to 2018. Source: Own elaboration

5.3.2. Groundwater quality

The MAR system also brought positive results to overall water quality, especially with regard to its hardness and nitrate content. Systematic monitoring of water quality in accordance to cantonal and federal water regulations has found no particular problems, except a recent discovery of perchlorate pollution (from 2 to 10 microgram per liter) coming from an old explosives factory on the Arve River watershed. The Cantonal Department Public Health has an acceptance process to provide oversight for water quality monitoring.

5.3.3. Impact on river flow and energy requirements

Until 1980, the year in which the artificial recharge station was put into service, the Genevese aquifer was naturally recharged by the Arve River only at a rate of roughly 7.5 million m^3/year. The Arve is a torrent river with a catchment basin of 2060 km^2 at an average altitude of 1400 m and includes about 120 km^2 of glaciers, or over 6% of its total surface.

The flow rate of the Arve at Geneva is 80 m^3/s on average but can decrease to below 20 m^3/s in winter and to exceed 600 m^3/s or even 800 m^3/s during flooding, with a peak value of 905 m^3/s recorded on 2nd May 2015. Therefore, the MAR system is taking less than 5% of the river flow when it is at its lowest rate.

In 2015, the energy requirement to infiltrate water at the aquifer recharge plant and to recover water by pumping the wells was 0.61 kWh/m^3 of recharged water and 0.14 kWh/m^3 of recovered water, respectively.

5.4. Economic costs and benefits

As said before, the choice between the two possibilities to stop the overexploitation was difficult; it was governed by two criteria: water supply security and economics. Considering the last one, the cost of a new water treatment plant in the lake, with the necessary modification of the supply network, was budgeted at approximately 150 million Swiss francs (as of 1975). The cost of setting an artificial recharge mechanism of the aquifer, including an advanced automatic laboratory for detection of pollution of the Arve River, amounted to 26 million Swiss francs. A transboundary committee was created to oversee all the administrative and technical issues.

Numerous meetings and discussions were held in the framework of technical studies and the preparation of a draft agreement. In the course of 1975, the French side declared its intention to abandon the exploitation of the groundwater resources and use other other French resources, but expressing its wish to keep the possibility of a subsequent participation in the recharge and the related benefits. It was foreseen that the cost of the recharge (depreciation, interests, renewal and operating costs of the equipment) would be shared and applicable to all water withdrawals, irrespective of the source of water (natural or artificial recharge). Finally, the costs of the recharge plant (land, construction, operation and maintenance were borne by the Canton of Geneva and SIG. The French part got a maximum pumping of 5 Mm^3/year, however with an annual concession of 2 Mm^3. Above this quota, the price per m^3 would be calculated as per an equation established according to various parameters: the station's operating costs (the SIG invoice), depreciations, the total pumping (CH + F), the share of the estimated natural recharge (7.5 Mm^3/year), and the out-of-quota volume pumped by the French side.

The costs (in Swiss francs / 1 CHF ~ 1 US $) for the Genevese scheme can be presented as follows (example year 2015 which is considered as an average year):

Table 1.
Capital and operating costs for the Genevese recharge scheme

Total capital Cost	Annual financial and operating costs	Capital cost	Recharge m^3/year	Capital cost/m^3 recharged	Operational cost/m^3 recharged
25,926,188	1,688,188	1,661,194	6,319,617	0.26	0.27

The operating costs include fixed costs (maintenance fees, manpower activities, management costs, land lease, vehicles use), proportional charges (electrical power, water consumption for the process, wastewater tax, treatment products) and financial expenses, including the depreciation and capitalized interest of the assets.

The levelised cost of recharge is estimated to be US$ 0.75 per cubic metre. The benefit cost ratio is estimated to be about 5.8:1 on the basis of comparison with the alternative option of a new water treatment plant.

5.5. Social sustainability

The political will to develop a cross border project emerged naturally in parallel with the studies and tests that were carried out on the experimental plant. Indeed, although roughly 90% of Genevese groundwater is located in the canton of Geneva, the remaining 10% is to be found across the border in France. From the time the first Franco-Swiss meetings were held in 1972, it was noted that groundwater resources had shrunk dramatically and continued to do so. The problem not only affected Geneva but the entire adjoining French region as well.

A Franco-Swiss commission in charge of groundwater exploitation was set up to regularly review the state of the resource according to pumping and artificial recharge. The volumes of water reserved (quantities of pumped water planned by each user for the coming year) were discussed and accepted according to the quantitative and qualitative conditions of the resource and the functioning of the artificial recharge station. The Commission should be composed of representatives designated by the Council of State in Switzerland and by the sub-prefect on the French side. In addition to the aspects related to the annual artificial recharge program, budget, repair and maintenance projects, the commission should give advance notice on all matters submitted to it in connection with the management and protection of the Genevese aquifer.

An agreement relating to the use, recharge and monitoring of Franco-Swiss Genevese groundwater was signed between, on the one hand, the communes of the greater Annemasse region, the Genevese communes and the commune of Viry and, on the other hand, the State Council of the Republic and the canton of Geneva, on December 18, 2007. This new agreement succeeded the 1978 arrangement and entered into force on

January 1, 2008 for 30 years. The agreement is a rare example of a transboundary aquifer management agreement between a Swiss canton and European Union communities. This is the result of what could be considered as the legal validation of a pragmatic approach. Swiss Federal Law and Ordinance on water protection on MAR was followed: https://www.admin.ch/opc/en/classified-compilation/19983281/index.html#app7

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Case Study 6: Soil aquifer treatment of secondary effluent for irrigation in the Negev desert area, Israel

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6.1. Introduction

The Shafdan Soil Aquifer Treatment (SAT) system, owned and managed by Mekorot, the Israeli National Water Company, is located between the cities of Rishon LeZion and Ashdod in central Israel. The SAT system treats 135 million cubic meters (MCM) [1] of secondary effluent from the Shafdan Wastewater Treatment Plant (WWTP) every year. The SAT treated water is reclaimed for unrestricted irrigation of fruits and vegetables eaten raw. First established in 1977, the system has been in operation over 4 decades [1]–[4]. The conventional mechanical-biological treatment is followed by managed groundwater recharge. The effluent undergoes soil aquifer treatment (Figure1, Box 1). The main advantage of the Shafdan SAT system is that it is resilient to drought. It has turned one man's trash (Shafdan WWTP effluent) to another man's treasure (unrestricted irrigation for a region located about 100 kilometres to the south).

6.2. History

Located in a semi-arid climate zone, Israel continuously struggles to improve its water security. Nowadays, it is reusing over 75% of the sewage for agricultural irrigation, which is about 50% of its total water supply for agriculture [6,7]). As early as 1965, TAHAL (Water Planning for Israel Ltd) submitted a primary plan to collect and exploit the sewage of the Dan region (the central and most populated area in Israel) for reuse in agriculture [8]. Despite the opposition raised by many stakeholders to this plan, especially from neighborhoods adjacent to the proposed site, the Israeli water authority decided to execute the plan. On April 20th, 1967 an agreement was signed between the executive branch of the Water Authority (Mekorot National water company) and the Dan region association of towns [8].

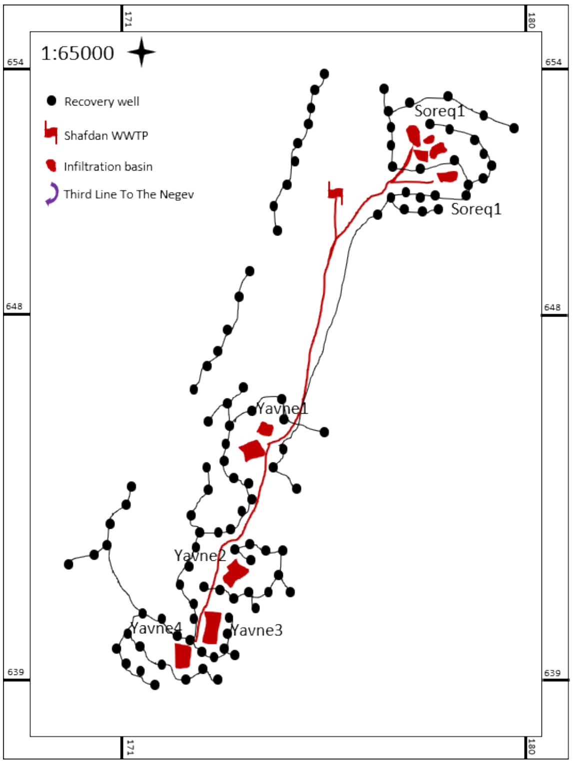

Figure 1.
Layout and Location of the Shafdan WWTP and the Shafdan SAT systems sites in Israel. Adapted from Icekson-Tal, 2014 [4].

Box 1: Shafdan SAT system scheme

Location: 31°57.651′N, 34°45.869′E to 31°50.606′N, 34°42.467′E

Operator: Mekorot; the Israeli National Water Company

Design: 6 recharge sites, 60 recharge basins, total recharge area 110 hectares. 150 recovery wells and about 75 observation wells located in a ring formation around the recharge sites

Commencement of operation: 1977

Quantity of water abstracted: 145 Mm^3/year

End use: Unrestricted irrigation of crops

Source of water: Secondary effluent

Aquifer: The Shafdan aquifer consists of Pleistocene-age coastal sedimentary rocks, dominated by calcareous sandstone with interbedded layers of conglomerates, silt, and clay [5]. It overlays a thick, impermeable clayish unit which slopes westward [5]. Consequently, the overlying aquifer reaches its maximum thickness (180–200 m) along the coastline and gradually wedges out eastward until it vanishes some 10–15 km inland. The vadose zone below the infiltration basins is approximately 20–40 m thick.

Type of recharge: Surface spreading basins.

Main advantage: Complete and sustainable solution for effluent treatment and recycling; High quality of reclaimed water; Seasonal and multi-annual operative storage

The agreement defined the purpose of the so-called «Third line to the Negev» (Figure 2) based on mutual interests. Firstly, the Dan region association of towns benefited from the plan to build the WWTP by transferring wastewater out of its jurisdiction and preventing the pollution of the sea and rivers in the area. Secondly, Mekorot was interested in reclaiming the wastewater from the Dan region for agricultural reuse. The agreement stipulated that Mekorot had the responsibility to build and operate the reclamation plant with funding from the State of Israel. The first SAT infiltration site, Soreq 1, was established in 1977 (Figure 1). Over the years, as the amount of effluent increased, more infiltration sites were established: Yavne 1 in 1987, Yavne 2 in 1988, Yavne 3 in 1996, Yavne 4 in 2003 and the last one, Soreq 2, in 2006; Ever since, the reclaimed water has helped to increase the supply of water and to flourish agriculture in the Negev desert area of Israel, providing sustainable water source even in the frequently occurring drought years and dry summers, thus contributing to the sustainable development of the Israeli water sector.

Figure 2.
On the left; pipeline construction of the «third line to the Negev» (Daniel Rosenbloom,1985).
On the right; a recent aerial view of the Yavne 4 recharge site («Albatros», 2004).
© Mekorot Water Company

The recharge-reclamation process is based on intermittent flooding and drying of the spreading basins, with cycle time (i.e. flooding – drainage - drying) ranging between 3 to 5 days [9].

6.3. Environmental Sustainability

6.3.1 Groundwater quantity

The Shafdan's SAT exploits a specific section of the Israeli coastal aquifer to create a «controlled closed system», with hydraulic separation of the SAT system from the pristine aquifer [10, 11]. Between the years 1977 to 2017, the total volume of secondary effluent infiltrated was 3,209 Mm^3 while the total abstraction after SAT was 3,661 Mm^3 [1], with annual figures shown in Figure 3. In 2018, a total infiltration of about 130 Mm^3/year and a recovery of 145 Mm^3 was achieved [1]. The ratio of the volume of infiltrated water vs recovered water on an annual basis averaged at 0.86 +/-0.10 between 1990 and 2017. Groundwater level monitoring since 1970s indicates that hydraulic head varies between +8 m above sea levels (msl) under the recharge ponds, to about -2 msl in the buffer areas that separate the Shafdan basins from the regional aquifer. Care is taken to maintain positive hydraulic heads of 0.5 to +2 msl near the coast line to prevent sea water intrusion.

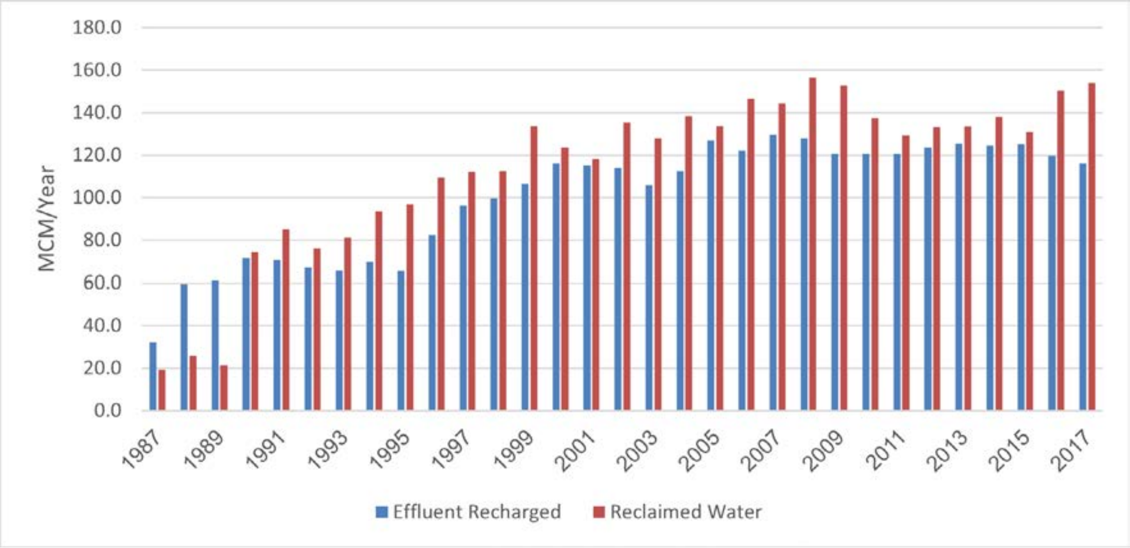

Figure 3.
Volume of water infiltrated and recovered between 1987 to 2017(data from [1]).

6.3.2 Groundwater quality

Results of weekly water quality monitoring of recovered water since 1977 confirms high removal of coliforms, faecal coliform, viruses, turbidity, organic carbon and inorganic parameters (e.g. nutrients, metals) [2, 3], ([12]–[19]). They are within the limits of the Israeli drinking water standards [19]. This is attributed to efficient removal of contaminants in the unsaturated zone, before the effluent reaches the saturated zone. The observed removal efficiency exceeds 4 logs and 5 logs for viruses and for faecal coliform, respectively [2, 3]. The mean dissolved organic carbon (DOC) concentration in the effluent before SAT is in the range of 10-12 mg/L and about 1 mg/L [1] after SAT. In addition, it has been recently demonstrated that the Shafdan SAT system is not a vector for spreading Antibiotic Resistance Genes (ARGs) [3].

The energy intensity of the SAT is estimated to be 0.63 KWh per cubic meter of recovered water. This includes energy for pumping effluent to the recharge basin at 0.14 KWh/m^3 and energy for recovering the water from the aquifer (the reservoir is located 30 km south) at 0.49 KWh/m^3.

6.4. Social Sustainability

Each year, Mekorot produces an annual report that contains all the operational data and the monitoring program results. The Shafdan SAT reclamation project is controlled and managed by the regulator through several committees: (i) The Water Authority Committee for Effluent Recharge; This committee approves the annual operating plan i.e. the monitoring program and the quantities of the effluent recharge and production; it also issues annual recharge licenses. (ii) An Interministerial Steering Committee, subordinate to the Ministry of Health but also includes the Ministry of Agriculture and consumer representatives (farmers); This committee evaluates the annual report and guides the Water Authority toward changes or operational actions. (iii) Water Allocations Committee; Allocates the reclaimed water to the farmers according to the planned annual production quantities.

These committees include representatives from the Water Authority, the Ministry of Health, the Ministry of Agriculture, the Ministry of the Environment, the Dan region association of towns, the Shafdan operators and local farmers.

6.5. Cost and Benefit Analysis

The Shafdan SAT system comprises of six recharge sites, 60 recharge basins, a total recharge area of 110 Ha including 150 recovery wells and about 75 observation wells. It reclaims 135 Mm^3/yr. The treatment costs less than US\$0.40/m^3 including maintenance, energy and operation expenditures. The energy footprint is particularly low and amounts to 0.63 KWh/m^3, which correspond to less than 15% of the treatment cost.

Since in the near future the Shafdan WWTP is predicted to produce more effluent than the current facilities can handle, two alternative treatments have been examined for the excess secondary effluent: i) [Ultrafiltration (UF) ➔ Reverse Osmosis (RO)], and ii) [UF ➔ ozonation (O_3) ➔ Biological Activated Carbon (BAC) ➔ Granular Activated Carbon (GAC) ➔ UV]. The estimated costs (taking in consideration only the core processes without infrastructure costs) for [UF-RO] alternative is US\$0.60/m^3 and for the [UF - O_3 - BAC – GAC – UV] alternative it is US\$0.40/m^3. All three alternatives (SAT and the two upper ground treatments) deliver high quality reclaimed water that provide a sufficient bacteriological barrier for using the treated water for irrigation of crops eaten raw. However, the effluent quality, which can be presented by the Dissolved Organic Carbon (DOC) concentration differs widely between the three treatments. The average DOC in the Shafdan SAT system is 0.86 mg/L. The [UF-RO] alternative is expected to reduce the DOC down to 0.5 mg/L, and the [UF - O_3 - BAC – GAC – UV] alternative is expected to attain only 5 mg/L of DOC. It should be noted that any above-ground treatment involves a higher energy footprint (and CO2 emissions) and involves the construction of additional water reservoirs.

Acknowledgment

We thank the people of Mekorot National Water Company for providing the information in this case study. Especially we are grateful to the employees of Mekorot in the Shafdan Unit who have successfully operated the project for over four decades.

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Case Study 7: El Carracillo Managed Aquifer Recharge System for rural development in Castilla y León, Spain

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7.1. Introduction

Los Arenales aquifer is a large groundwater body that occupies 2,400 km² of Castilla y León, Spain, with 46,000 inhabitants in 96 villages. Due to excessive groundwater extractions that resulted in a groundwater exploitation index (I.e.=extraction rate/recharge rate) of 1.3, the Spanish Ministry of Agriculture and the Regional Government (Junta de Castilla y León) responded through initiating demonstration projects of Managed Aquifer Recharge (MAR): Santiuste basin area in 2002, El Carracillo in 2003 and Alcazarén-Pedrajas in 2011.

El Carracillo MAR site is located in the Northernmost part of Segovia province, in a low slope countryside around 150 km² wide surrounded by pine woodlands between the Cega and Pirón rivers (Figure 1). It has become one of the most successful MAR systems in Spain.

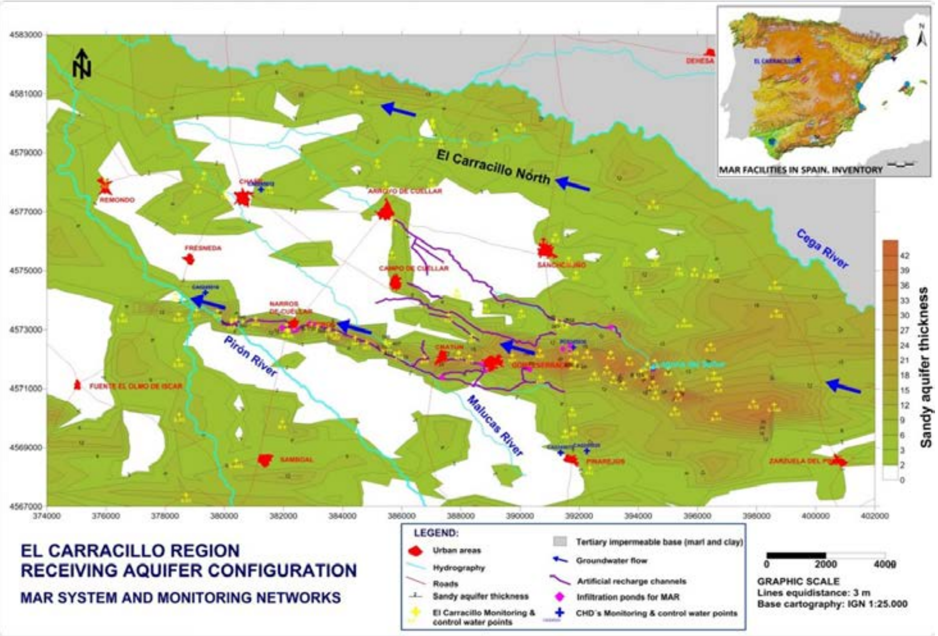

Figure 1.
MAR systems in El Carracillo region, Spain. Receiving aquifer is the Quaternary aquifer, with the thickness shown as contours. MAR canals (purple lines) and infiltration ponds (pink diamonds), monitoring networks (yellow and blue crosses) and regional ground water flow directions (blue arrows) are shown. Source: Own elaboration

7.2. MAR systems for Los Arenales aquifer

7.2.1. History

In 1994, farmers from 9 municipalities of the region joined in an irrigation association and proposed a plan to the political (MAPA & JCyL) and river basin authorities (CHD). The plan was approved in 1999 with a maximum 1,370 L/s or 14.2 Mm^3/yr water concession diverted from the Cega river yearly between January and April. The diverted water has supplied a source of water for an opportunistic MAR project for the Los Arenales aquifer. By 2000, Phase I of the MAR project construction was completed, so as to transport water by gravity inside a pipeline over 19.6 km from the Cega river to Lastras de Cuéllar and Gomezserracín Villages for MAR. Activity began in 2003. By 2005, Phase 2 of the project was accomplished with the construction of 14 extra km of ditches for MAR including four additional villages involved in the Irrigation Community, Chatún, Campo de Cuéllar, Narros de Cuéllar and Fresneda de Cuéllar (Figure 1).

7.2.2 Motivation

According to the Spanish Water Law (Ley 29/1985), Art. 40, each aquifer with an exploitation index exceeding 0.80 requires an urgent intervention from Water Authorities. The evolution of the groundwater level at Los Arenales aquifer since 1972 to 2002 registered an accumulated decline of 24 m in a sector of the aquifer (La Moraña). This situation had a rapid response from the central government, establishing a set of limitation for the use of water, the compulsory constitution of farmers associations as units of cooperation with the central administration, and the development of artificial recharge facilities to reduce the observed impact.

El Carracillo MAR system was originally allowed for as a response from the central government to the overexploitation of the aquifer by means of de Decreto-Ley 9/1998, of August 28th, to approve and regulate hydraulic constructions for the "General Interest of the Nation", which was published on 29/01/1999 [1]. It was regulated again in September 2015 and included in CHD, 2016, establishing the environmental minimum flow rate for the Cega river [2].

7.2.3. Implementation

Los Arenales aquifer consists of two aquifers one above another. The MAR system targets the Quaternary shallow aquifer consisting of a fine dune sand layer, alluvial deposits and clay with a 20-m-average depth and a maximum depth of 45 m (Macías *et al.*, 2014 [3]). Underneath lies a deeper Tertiary detrital layer of lower hydraulic conductivity. El Carracillo MAR system is passive and intermittent being operated opportunistically. When a water surplus is available generally during the rainy season (winter-spring), the largest possible volume within the allowance is introduced into the MAR system at the highest possible rate. The system integrates a fish-bone pipeline working as an aqueduct from the Cega river to 14 points of distribution, either in infiltration ponds or to the heads of MAR canals. Several MAR techniques are used including 16 infiltration ponds, 17 km of MAR canals, 2 spreading basins, 3 artificial wetlands, reuse of abandoned wells and reuse of sand-pits (Figure 2).

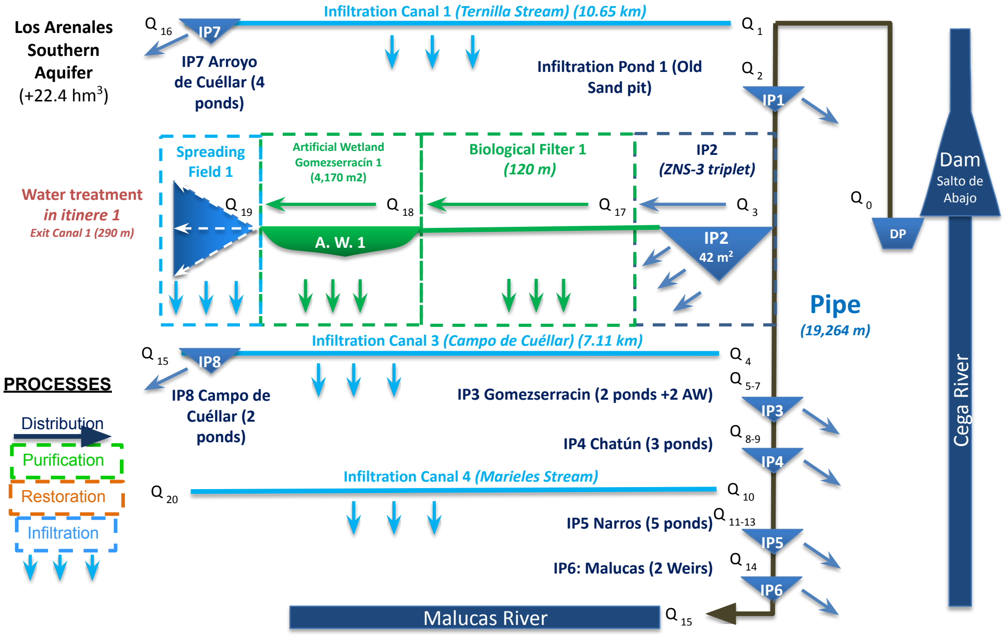

Figure 2.
Components of El Carracillo MAR system. Source: Own elaboration

Total recharged volume for the period 2002-2015 amounted to 31.47 MCM. The water processed by MAR facilities (unitary) rises to 24.18 m³/ ha as an average for the period 2003-2015 (Figure 3).

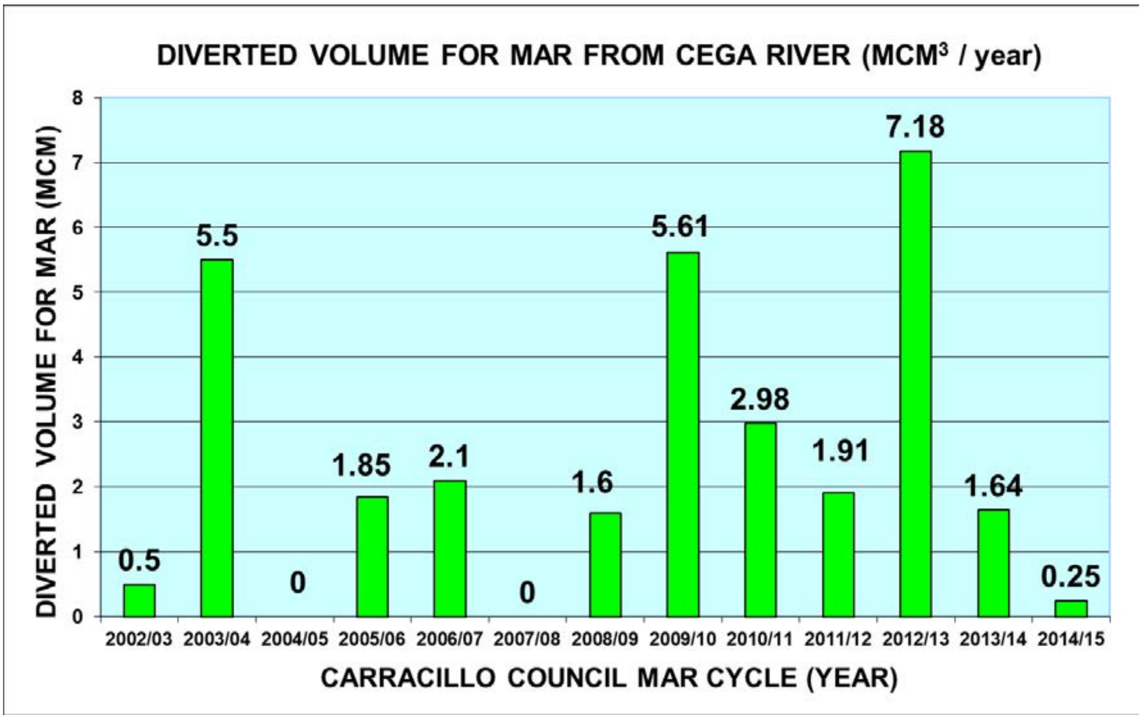

Figure 3.
Volume of water diverted from the Cega River to El Carracillo MAR system between Jan and Apr, 2003-2015. Source: Own elaboration

Box 1: El Carracillo MAR system features

Location: Intervention area between UTM coordinates. Huse 30, X: 376.000-402.000 and Y: 4.569.000-4.579.000.

Operator: El Carracillo Irrigators Community under Confederación Hidrográfica del Duero (CHD) supervision.

Design: 19.2 km aqueduct from Cega river diversion, 17 km of MAR channels, 14 distribution points, 16 infiltration ponds, 1 RBF, 3 artificial wetlands.

Commencement of operation: 2003.

Quantity of water diverted from Cega River: Licensed to divert until 1,370 L/s in the heading if Cega River flow-rate exceeds 6,898 L/ s.

End use: Agriculture, incipient environmental uses.

Total cost of the studies and constructions: 5,273,999 €, unit cost (€/ha): 684.93 €/ ha; unit cost (€/m^3): 0.167 (€/m^3) for first 13 years.

Aquifer: Quaternary dunes (Arévalo geological formation).

Type of recharge: superficial (channels, infiltration ponds and wells) recharged with fluvial water.

Average rate: 4,908 m^3/ day. Average water level rise: 2.3 m after 13 years.

Main advantage: 23.8% irrigation water comes from MAR (314 m^3/ha out of 1,318 m^3/ha as pumping average).

Some stretches of the canal network have been designed to perform three functions: decantation, biofiltration and restoration. Such structures implemented during R&D projects with the support of the farmer association have been called “triplets”. An El Carracillo triplet typically consists of a 42 m^2 stagnation strainer-infiltration pond, a 125 m-long-green-filter canal and a 4,170 m^2 artificial wetland (Figure 4). Usually, a nearby sandy meadow receiving occasional spillway flow from the last marsh acts as a spreading field for recharge so as to increase the infiltration in the heading (Eastern side) of the system.

Studies in the Laguna del Señor (Figure 1), in a restored wetland in Gomezserracín, an experiment has found that where plants are taken out in one side but not in the other side, an extra 12 % to 15% of infiltration volume has been gained in the area beneath plants compared to the area without plants (Fernández Escalante *et al* 2016 [4]).

Figure 4.
Components of El Carracillo MAR system: construction sign (a); Gomezserracín infiltration pond in the dry season (b); gate in a MAR canal (c); pipe for a spreading field (d); former sand pit reused as a MAR infiltration pond (e); valve and gate (Narros) (f); flow-meter to monitor the volume poured into the infiltration pond (g); Gomezserracín infiltration pond in winter season (h and i). © Jon San Sebastian

7.3. Environmental Sustainability of El Carracillo MAR

7.3.1. Groundwater quantity

The River´s flow rate was measured in a gauge station installed in Lastras de Cuéllar by CHD with data available from 2004 to 2007 and in the diversion point: Station ROEA 714. Since 2007, the River Basin Authorities´ civil servants have supervised the diversion of water from the Cega River, managed by the irrigation community. There is a specific allowance period revisable yearly that fall between January 1st and April 30th. All of diverted water is used for MAR by means of a fish-bone pipeline aqueduct (evaporation losses are negligible), with volumes diverted shown in Figure 3. Water availability varies dramatically over time, with two dry periods with no diversion at all and one wet period (2012-2013) allowing for 7.18 MCM of water for MAR (hydraulic year 2012-13). The distribution of MAR water in the aquifer was assessed by applying the Water Table Fluctuation Volume-Algebraic (WTF-VA) method (Fernández-Escalante 2005 [5]), and amounted to practically 100% of the diverted volume. Evaporation losses are negligible as infiltration takes place primarily during the rainy season. It is evident that there is an increase in groundwater level after MAR (Figure 5).

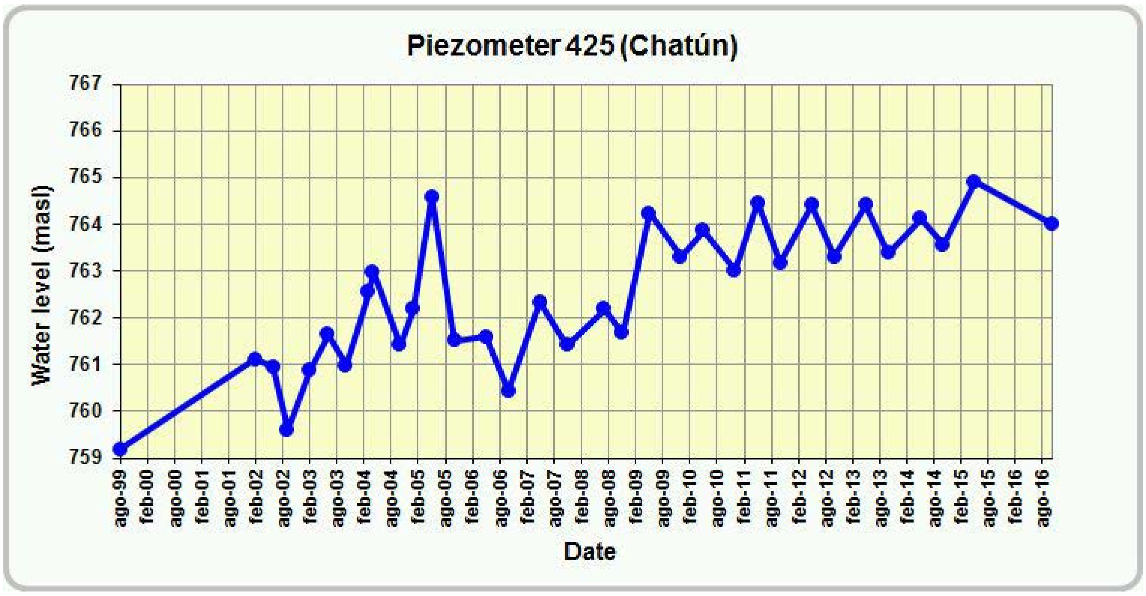

Figure 5.
Evolution of groundwater level of El Carracillo network piezometer 425 (Chatún) from 1999 (before MAR) to 2016. Source: Own elaboration

The groundwater extraction averaged about 8 Mm^3/yr based on 314 inventoried wells data collection, with an average pumping rate about 9,957 m^3 per well per year. Considering the area of irrigation is 3,500 hectares, there is then on average 1,318 m^3 of irrigation water supplied from groundwater in each hectare (132 mm), of which 314 m^3 (31 m) is from MAR. Between 2003 and 2015, groundwater level monitored at El Carracillo network (yellow dots in figure 1) rose from 6.30 m below ground level to 4.00 m below ground level in 13 years based on the annual mean values from all the wells monitored.

7.3.2. Groundwater quality

Water quality analysis and groundwater level monitoring have been carried out in a series of sampling points in the whole area, with the regional piezometers network (CHD's monitoring network, Figure 1, blue crosses) complemented by a local water level and water quality networks. Fourteen water quality parameters were tracked at four piezometers, although the economic crisis from 2007-2008 interrupted the data collection. The measured and reported parameters have found exceedance for nitrate, with two out of four observation points containing over 50 mg/L NO$_3$ (point 036 up to 87 mg/L , and point 014 with 70 mg/L , by 2006 June). Both areas have been declared as "vulnerable" for nitrates contamination by river basin authorities (CHD), with the general command for the farmers to fertilize with less than 3 kg/m^2 of manure (what was a normal dose) and less than 20-10-15 gr/m^2 for N-P-K. These recommendations are subject to external inspections only eventually, as farmers have participated in training workshops where the negative effect of over-fertilization on groundwater is duly explained. Moreover, engineers of the irrigation community provide assessment to their associates when they require it.

There is no SAIH network (i.e. real time monitoring network of the Spanish government) stations at El Carracillo, due to the fact that water has a very good quality. In the headwaters of the Cega River that drains the granitic rocks, conductivities are about 200 µS/cm. The quality fulfils standards required by RD 1620/2007, where the required quality limits for water used for SAT-MAR in Spain are published (https://www.boe.es/buscar/pdf/2007/BOE-A-2007-21092-consolidado.pdf).

Nitrate concentrations in groundwater mainly derive from irrigation return flow. The evolution in groundwater, according to the available data from four piezometers (Chañe, Fresneda, Gomezserracín and Pinarejos) from 2003 to 2016 is a steep increase in nitrate after MAR began, rising more slowly until the year 2012, with peak concentrations reaching 21.5 ppm to 43.0 ppm (as NO_3) compared with initial concentrations below 5 ppm. From 2012 nitrate concentrations have generally declined. This trend has been interpreted as the flushing of nitrate from the unsaturated zone to the saturated zone by MAR and by irrigation. Fertilization rates have also been adjusted so as to avoid over-fertilization.

Pesticides have not been revealed as a concern in Cega river nor in this sector of Los Arenales aquifer. Where groundwater was considered to have potential water quality concerns drinking water is supplied from a purification-specific treatment plant located at Villaverde de Íscar. This was constructed by the Junta de Castilla y León by 2005 to remove any potential contamination by arsenic and currently supplies water to about 20 villages.

7.3.3. Energy intensity and environmental benefits

All the MAR facilities rely on gravity for water infiltration, without any energy consumption. Regarding water extraction and on average for 314 inventoried wells, total energy consumption for pumping is estimated to be 49,737 KWh for the irrigation period pumping about 8 h/day. For total annual extractions about 8 MCM, the mean is calculated to be 0.165 KWh/m^3. This is reasonable because groundwater table is very shallow after MAR (4 mbgl on average). The rise of water table by about 2.3 m has benefited the farmers, with between 12% and 36% saving. The monetary saving depends on the specific site, with a total saving of about 3,000 €/year (Fernández Escalante 2005 [5]). However, these are only rough estimates, pending an energy audit.

El Carracillo system has built 16 infiltration ponds that have also become a recreational attraction for the villages' population. Additionally, three artificial wetlands and two weirs have been reinstated for ecological reasons. In many cases, all these devices have been installed restoring old dry or degraded wetlands, or even degraded areas as sandpits for construction or illegal landfills around some villages. Infiltration canals (17 km) provide natural corridors for flora and fauna among the cultivated areas as vegetation grows in their beds and banks. It is also worth mentioning that the presence of artificial wetlands in MAR facilities plays a very complementary role into local biodiversity (Fernández Escalante *et al* 2015 [6]).

At Los Arenales aquifer about 5% of total water diverted from Cega River for MAR is used for environmental purposes (wetlands restoration), e.g. Lagunas del Señor complex. Most of the wetlands count on specific flow-meters embedded in the MAR network.

7.4. Economic costs and rural development benefits for El Carracillo MAR system

The capital cost of the project was €5,274,000 with an operating and maintenance cost of €40,000 per year. The estimated levelized cost of recharge is US$0.21 per m^3.

The core water usage is irrigation. The unique water source for MAR is Cega River. 3,500 hectares are irrigated in 11 municipalities (out of 7,586 ha of total cultivated area). It is worth mentioning that El Carracillo district ranks highly in the Spanish agriculture for its production of horticultural products (80% of vegetable production of Segovia province and 30% of Castilla y León Autonomous Region). There are 0.46 agroindustries/km^2 in the region, with 0.67 workers/km^2; El Carracillo District has 1.28 agroindustries/km^2 with 2.38 workers/km^2.The related industry figures are 0.81 workers/km^2 in Industry sector for Castilla y León vs 2.74 workers/km^2 in El Carracillo (ITACyL, 2015 a & b [7,8]).

As the first producer in Spain of strawberry mother plants, 60 M units are produced per year on only 600 hectares. Horticultural industries stand out with a turnover of about 45 M€/year. Important industries apart from horticultural are milling, spirit beverages and meat (Figure 6).

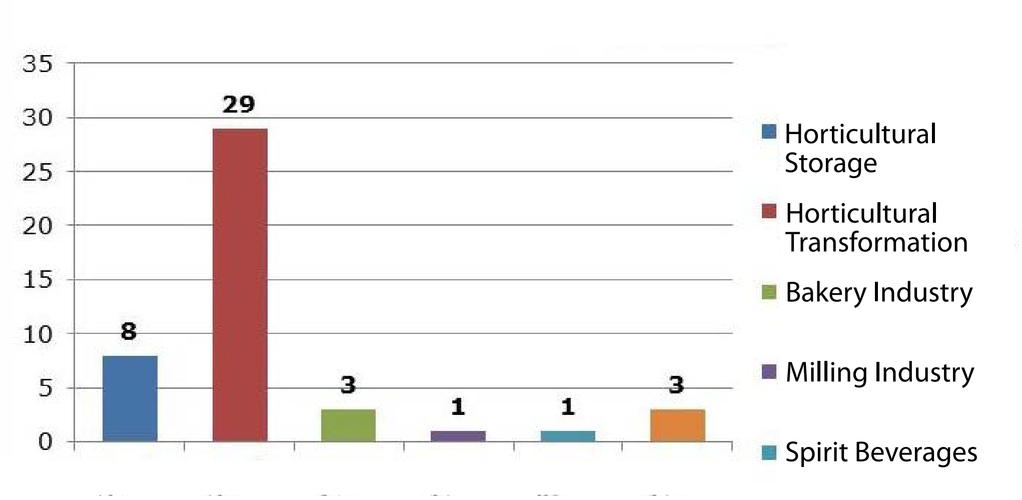

Figure 6.
Agroindustry distribution in El Carracillo District. Source: Own elaboration

713 farmers make up the association supplied by the MAR system with a mean annual aquifer extraction about 8 Mm^3/ year. The effect of MAR can be measured as 314.3 m^3/ ha out of 1,318 m^3/ ha extractions on average, so the MAR contribution to total irrigation is about 23.8%. This is an important contribution, valued at about €12 million, out of the overall value of agriculture production from El Carracillo system of about 50 M€/year.

Irrigated agriculture plays a "vital" role in rural employment. The figures of agroindustry, agricultural and industrial workers triple the regional rural area they belong to (ITACyL, 2015 a,b [7,8]).). Strawberry and vegetables industries generate about 700 direct jobs and 3,000 indirect jobs.

High employment rates contribute to the retention of population in rural areas. Since 2000 the population in the region has decreased by an average of 6% while the population of e.g. Chañe Village, since the MAR began, has grown by 28% (INE, 2002-2014 [9]).

MAR increases water availability allowing the transformation of rain-fed lands into irrigated lands, leading to greater production. Yields per hectare are doubled in most cases (e.g. garlic, rye), and even tripled e.g. for sweet melon (Junta de Castilla y León 2014; in JCyL, 2015 [10]). Greater production has balanced the decrease in prices for agricultural products during the economic crisis.

7.5. Social sustainability

As it has already been mentioned, this MAR system was originally deployed as a response from the central and regional governments to the overexploitation of the aquifer by means of the Decreto-Ley 9/1998, of August 28th, to approve and regulate hydraulic constructions for the "General Interest of the Nation", and it was published on 29/01/1999. It was regulated again in September 2015 and included in CHD, 2016, establishing the environmental minimum flow rate for the Cega river.

According to the Environmental Statement published in September 2015 and included in CHD, 2016, an environmental minimum flow rate of 6,898 l/s must be met, while a maximum rate of diversion of 1,370 l/s from January to April is allowed. These water rights are revised every 6 years with the next revision due for 2022-2027. Public consultation is conducted and ruled by Chapter IX of Annex IV of the Water Basin Plan (PHD, 2016 [11]).

Despite its success, the proposed phase 3 (MAR and extra irrigation at El Carracillo north) has faced opposition by groups against further diversion of water from the river Cega. This proposal has required the mediation of river water authorities and started a conflict awaiting resolution in the near future, with the possibility of a final decision being made by courts.

In summary, El Carracillo constitutes an exemplary system of MAR for rural development and it plays a vital role in avoiding rural depopulation.

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Case Study 8: Managed Aquifer Recharge by riverbank filtration and infiltration basins for drinking water supply at Dresden-Hosterwitz, Germany

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8.1. Introduction

Dresden-Hosterwitz is the second largest waterworks in the city of Dresden, which is located at the Elbe River. This waterworks has a total capacity of 72,000 m^3/day, and 111 vertical siphon wells and 36 wells with submersible pumps that extract water from a depth of 10–14 m at a distance of 60–120 m to the river. For average abstraction, water is mainly abstracted from riverbank filtration wells along the Elbe River and a small portion of river water is directly abstracted, pre-treated, recharged via infiltration basins and recovered from wells in 15–60 m distance to the infiltration basins. The maximum abstraction of bank filtrate is about 30,000 m^3/day, depending on river water level. During periods of low or average demand, the pre-treatment train for directly abstracted river water and selected infiltration basins are operated at low flow rates to ensure quick changes to higher rates. During periods of higher demand, the portion of MAR is increased from about 5,000 to 42,000 m^3/day.

Figure 1.
Aerial photograph of Hosterwitz water works for Dresden, Germany (©DREWAG NETZ GmbH)

Box 1: Salient features of MAR scheme

Location: (GMM) 51.029814, 13.840836 to 51.014634, 13.854330

Operator: DREWAG NETZ GmbH

Design: 5 infiltration basins, 111 siphon wells, 36 vertical wells with submersible pumps (Tab. 1)

Commencement of operation: 1907/1983

Quantity of water abstracted: 72,000 m^3/day

End use: domestic (drinking) water

Source of water: Elbe River and groundwater

Aquifer: medium–coarse Pleistocene alluvium

Type of recharge: induced riverbank filtration (RBF) and infiltration basins

Main advantage: sustainable abstraction of high quality and quantity of water by RBF and MAR

8.2. Motivation, conceptualisation and implementation

The MAR site is located on an alluvial aquifer on the Elbe River in Dresden, Germany. The surficial geology is comprised of two stratigraphic units: (1) the Quaternary sand and gravel aquifer with a thickness of 9–14 m, and (2) 1–3 m thick overlying Holocene clay. The hydraulic conductivity and porosity of the aquifer range from 156–216 m/day and 0.26–0.4, respectively.

Water is taken from the Elbe River as riverbank filtrate and infiltrate from five open recharge basins supplied with pre-treated (coagulation with aluminium sulphate, sedimentation, and open multimedia sand filtration) Elbe River water. Post-treatment (after recovery from the aquifer) is performed by cascade aeration, activated carbon filtration, pH adjustment, and disinfection with chlorine (Figure 2).

During periods of high water demand, pre-treated river water is artificially recharged into the aquifer via infiltration basins (Figures 1 & 3) to take advantage of natural treatment processes and buffering quantity and quality. Currently, the waterworks operates four high-capacity basins with an area of 2650 to 2975 m² each and an average infiltration rate of about 6.7 m/day and one so-called Doppstadt-basin with an area of 10,540 m² and an infiltration rate of about 2 m/day. In 2018, a 25 m long and 1 m wide infiltration trench was constructed to investigate advantages and disadvantages compared to the basins. The artificial recharge significantly increases the capacity of the waterworks. The infiltrated water is pumped together with the bank filtrate to the treatment stages aeration, activated carbon filtration, and disinfection.

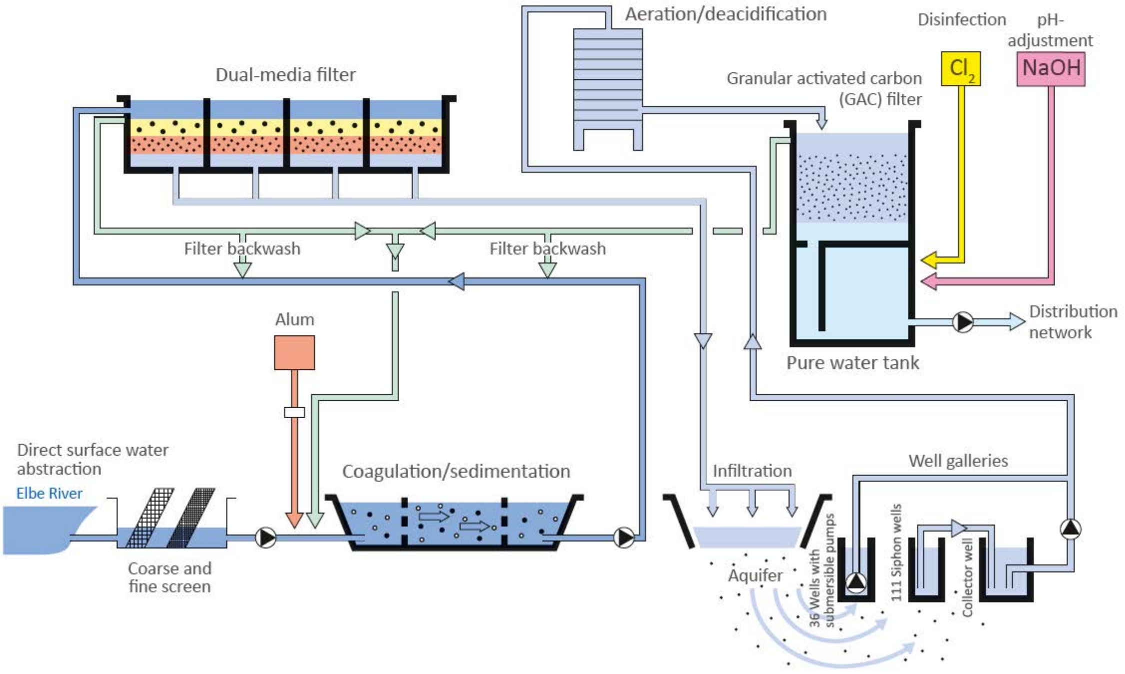

Figure 2.
Treatment schemes of Dresden-Hosterwitz Waterworks. © DREWAG Netz GmbH

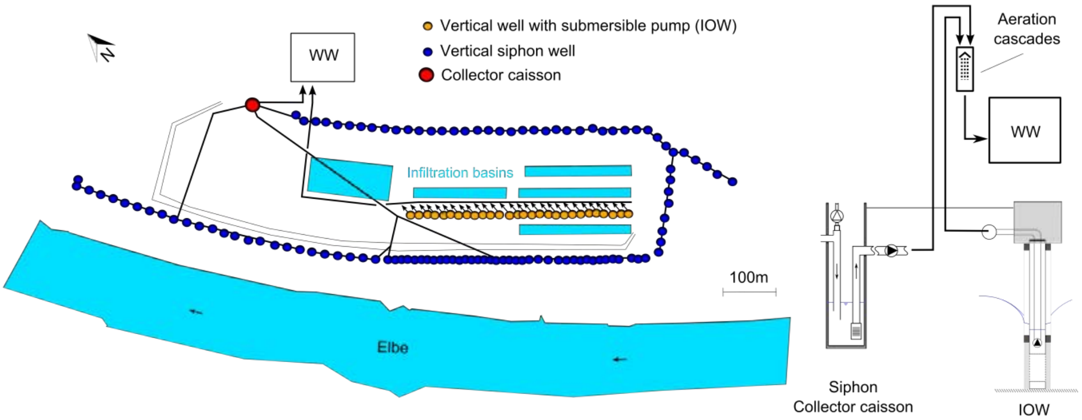

Figure 3.
Map of Dresden-Hosterwitz Waterworks with approximate well locations. Source: [1]

Table 1.
Well design parameters Dresden-Hosterwitz Waterworks, Germany. Source: [1]

Parameter	Siphon Wells	Individually Operated Wells
No. of wells	111	36
Year of construction	1908, 1928/29	1980s
Well design	Vertical well	Vertical well
Filter screen material	Copper and stoneware, slotted and some stainless steel wire	Steel, bridge slotted
Filter screen length	3 – 5 m	3 m
Screen diameter	250 – 300 mm	350 mm
No. of pumps	3 (in collector caisson)	46
Type of pump	Dry mounted pump	Submersible pump
Variable frequency drive	Yes	No

8.3. Environmental Sustainability

8.3.1. Ecological flow, resource integrity and water quality

Due to the local geological boundary conditions the catchment area of the waterworks and the portion of groundwater abstraction (about 4,500 m^3/day during full operation) are small compared to other RBF waterworks. The share of groundwater is on average less than 10% and at maximum MAR operation about 6%. The major source is the Elbe River, either as bank filtrate or for direct abstraction and subsequent pre-treatment and artificial recharge. The maximum water production of 72,000 m^3/day minus 4,500 m^3/day groundwater abstraction results in river water abstraction of 67,500 m^3/day (0.78 m^3/s). Compared to a mean average and mean low discharge of the Elbe River of 329 m^3/s and 110 m^3/s respectively, the abstraction accounts to less than 1% of the river discharge. Also, most of the produced water is given back to the river as treated sewage downstream of the city.

The groundwater table changes are dominated by the dynamic river water level. No long-term changes in groundwater levels have been observed due to MAR operations. Due to the combination with riverbank filtration and the location of wells, the ratio of volume of infiltrated water versus recovered water on an annual basis is near to one, depending on model-based operation of infiltration basins and abstraction wells.

Riverbank filtration and aquifer passage after infiltration of pre-treated river water via basins were found to provide very reliable treatment, removal of turbidity, pathogens and organic compounds as well as high safety against shock loads in the river. The site has been operated for more than 100 years, proving high sustainability of MAR. Of course, not all organic micropollutants are removed by natural treatment, thus GAC filtration was added as post-treatment. Risks include flooding of the wells and – during extreme floods – of the infiltration basins resulting in very short residence times of the bank filtrate and infiltrate in the aquifer (see 3.3). For prevention, flood protection measures were improved and well mounds and heads brought to higher levels and better sealed. River water pollution with trace organic compounds cannot be stopped by the waterworks. Post-treatment will be further adapted to the water quality monitored after MAR but may be costly or not capable to fully remove health affecting compounds – thus the waterworks are politically active to protect the source (see 8.6).

8.3.2. Energy-saving operation of siphon wells

Nowadays groundwater wells are commonly equipped with submersible pumps. Multiple wells from one well group discharge into a main pressure pipe. Before the development of submersible pumps, common groundwater wells were connected via suction pipes to a main gravitational pipe (siphon pipe). The groundwater is hereby abstracted and piped to a central collector caisson without a permanent energy input using gravitational flow (Figure 4).

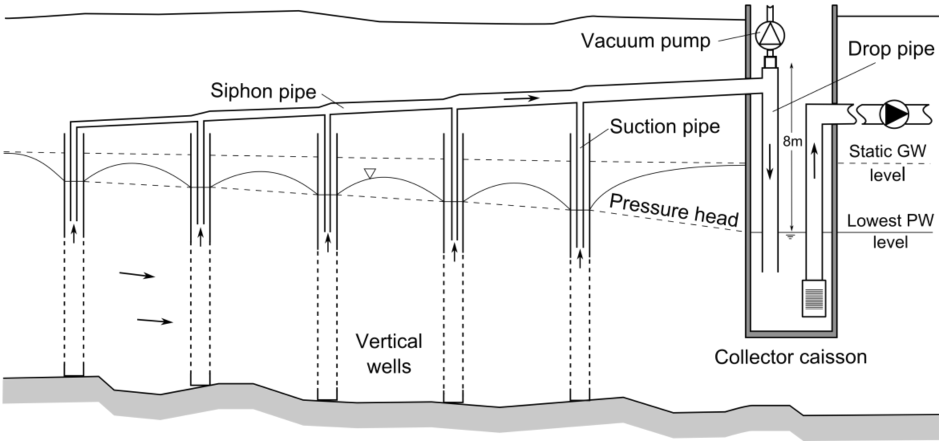

Figure 4.
Schematic of five siphon wells and one collector caisson. Source: [1]

Opposite to the free-flow gravity pipes, the pressure inside the siphon pipe is below atmospheric pressure (vacuum) as the water must be first lifted to the top of the siphon crest. Traditionally multiple well groups were connected via individual siphon pipes to a single collector caisson, which acted as sand collector and open air vessel. Gravitational flow is induced from the abstraction wells to the collector caisson after the siphon pipe has been air-evacuated (primed) using a vacuum pump and the water level inside the collector caisson has been lowered below the static groundwater level. The siphon system only works if (1) the outlet of the drop pipe and the inlets of the suction pipes are permanently submerged, (2) the siphon pipe is continuously air evacuated (degassing of dissolved gases or air entry through small leakages) and (3) the piping is permanently vacuum-tight. At the transition from the siphon to the drop pipe a so called "siphon head" is installed. It collects escaping gas, so that it can be automatically extracted by a vacuum system. The maximum suction head is found at the "siphon head". It is equal to the suction lift from the lowest pumping level to the inside "siphon head" and should not exceed the vapor pressure of water, which would cause a failure of the gravitational flow. In practice this suction head is limited to 8 m, including a safety margin. The groundwater is pumped from the collector caisson to the waterworks using high-flow pumps [1].

The first siphon wells were built in Europe in the mid- to late-19th century preferably in Pleistocene deposits along major rivers. Numerous large scale siphon systems were constructed in Germany, Poland, Czech Republic, and Hungary with capacities ranging from 35,000 m^3/d (Dresden-Tolkewitz, Germany) to more than 100,000 m^3/d (Poznan-Debina, Poland). In recent decades the well-known siphon technology has been replaced by the use of submersible pumps to allow more flexible operation of individually operated wells (IOW) or because of lost experience or missing knowledge in planning of siphon systems.

The specific energy consumption (SEC, kWh/m^3) was calculated as energy consumption (kWh) at the pump divided by the volume of water abstracted (m^3). The SEC of siphon wells at WW Dresden-Hosterwitz ranged between 0.081 and 0.108 kWh/m^3, 36% to 52% less than measured for the IOW gallery (Figure 5). The offset in the siphon well curve between 750 and 1000 m^3/h was caused by the activation of another variable frequency drive (VFD) pump. The real data already include losses for cables and VFDs but also pump aging. It should be noted that these values reflect the current state of the art in pump technology. Future advances in pump technology or different site-specific conditions may increase or decrease the energy savings potential for every individual case. However, the authors are confident that an energy savings potential of 30–50% can be achieved by rehabilitating old siphon wells instead of an alternative equipment with submersible pumps, which justifies the higher investment costs [1].

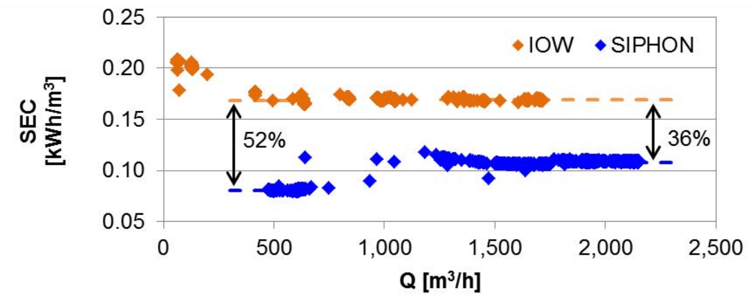

Figure 5.
Measured specific energy consumption as a function of discharge for siphon wells and IOW at Dresden-Hosterwitz . Source: [1]

8.3.3. Resilience against flooding

Experience from the Elbe flood in August 2002 and June 2013 showed that existing protection measures are not adequate for a flood with a 100-year return period. When flooded, groundwater levels below the pump house rise as the local aquifer is recharged with untreated Elbe water through the basins. Basin clogging and coliform removal were investigated onsite during a summer flood in June 2013 [2]. Monitoring was started 6 days after flooding when the basin was still completely filled. During the flood event and throughout the investigation, 11 siphon wells with filter screens from 9–14 m below surface at a 70-m distance from the basin (330 m from the riverbank) were operated at a total discharge of 1,200–1,600 m^3/h. The general flow direction was towards the wells. The proportion of infiltrate (4,400 m^3/day) in the total well discharge was calculated to be 14% from day 6–8 after flooding. The water quality interpretation during the flood must be divided into two sequential phases, as follows: (1) flooding and direct contamination of the non-flood-proof well heads, and (2) operation after water level decreased below well heads. In the first period, flooding and water intrusion into the wells caused an increase of pathogen numbers in the well discharge. Turbidity increased due to intrusion but also due over-pumping (and the mobilization of fine aquifer sediments and particles near the well). When the river stage decreased below the elevation of the well heads, turbidity and pathogen numbers continued to decline although the infiltration basin was still fully filled. No breakthrough in turbidity or pathogens was observed after 4–5 days travel time (Figure 6). In conclusion, a flood event of the infiltration basin and the subsequent infiltration of untreated river water into the aquifer and its impact on water quality were evaluated to be manageable in terms of E. coli, total coliform, and turbidity. Experimental results indicate effective removal by slow sand filtration even for untreated river water at infiltration rates from 1–3.6 m/day for some of the investigated parameters. In column tests *E. coli* and total coliform counts (TCC) were mainly removed through the filter sand and removal increased after further development of the clogging layer [2].

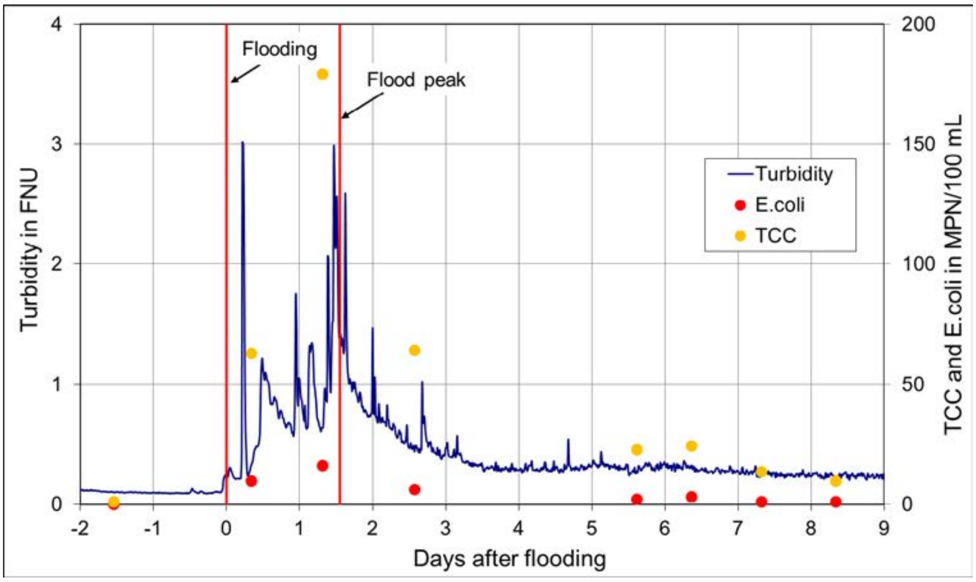

Figure 6.
Turbidity, E. coli, and TCC measured in the summed well discharge. Source: Own elaboration

8.4. Cost and benefit considerations

There is no cost estimate available as the site has been developed over many years and adapted to changing river water quality and regulations.

In the AquaNES project, both bank filtrate and untreated river water has been used as feed water for an ultrafiltration pilot plant. From May 2018 to September 2018, river water was directly treated via ultrafiltration [3]. A robust feed pump with a capacity of 30 m^3/h delivered river water directly into the storage tank of the membrane plant through a 435-m long supply pipe. Bank filtrate was extracted from a well group of eight vertical filter wells with submersible pumps. The wells are located at a distance of 80–110 m to the river with a depth of 6–8 m. Depending on raw water quality and associated operation settings for cleaning, membrane pressure, and flux, the energy consumption was 0.23–0.18 kWh/m^3 for bank filtrate and 0.34–0.2 kWh/m^3 for river water (Figure 7). The results show that the energy consumption per cubic meter of produced filtrate was 28% higher for the filtration of river water than for bank filtrate. The total energy consumption includes filtration, backwashing, and chemical backwashing [3].

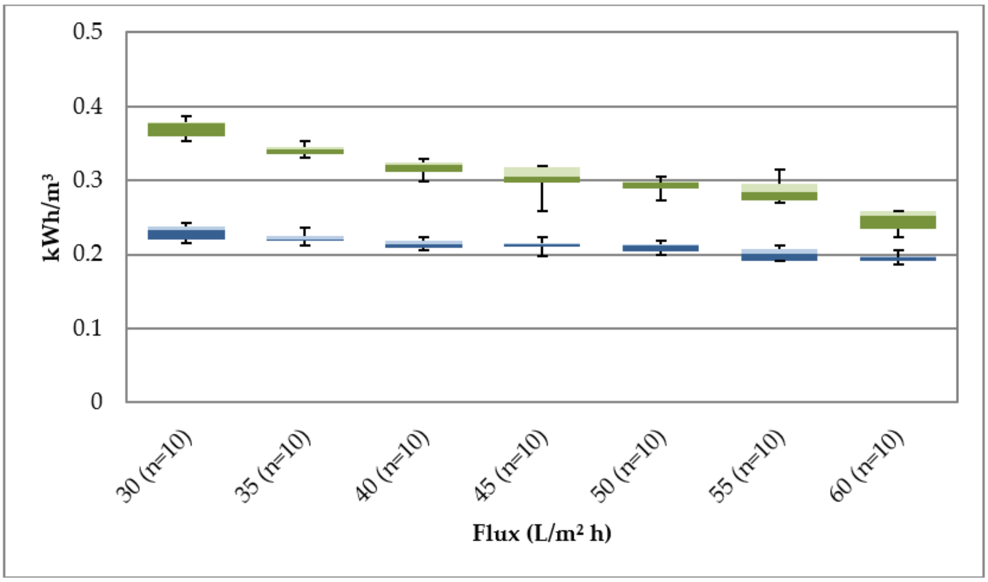

Figure 7.
The energy consumption per m^3 filtrate produced from Elbe River water (green) and bank filtrate (blue) with identical operation settings of the membrane plant . Source: [3]

Bank filtration significantly reduces the number of micro-organisms but does not assure complete removal. Therefore, an efficient barrier against bacteria and viruses is essential, especially with regard to reduced residence times of bank filtrate during to floods or increased water abstraction. The advantages of the combination of both treatment processes are the production of safe drinking water independent from the raw water quality and the residence time of the bank filtrate in the aquifer as well as a more efficient operation of the ultrafiltration. Higher content of particles in the river water leads to a significantly higher fouling potential than during ultrafiltration of bank filtrate. This means that bank filtration acts as an efficient pre-treatment step for membrane filtration. The reduction of fouling indicators, such as bacteria, DOC, and UVA, as well as particulate matter minimizes the accumulation on the membrane. Bank filtration is comparable to slow sand filtration. The result is an economically efficient operation compared to direct treatment of surface water. The low fouling potential of the membrane leads to longer filtration times and minimizes wastewater/backwashing. This reduces operating costs. A longer filtration time also leads to a more efficient use of energy in relation to energy consumption and filtrate production. This was demonstrated by the reduction in energy consumption for filtration of river water from 0.25 kWh/m^3 to 0.18 kWh/m^3 for filtration of bank filtrate at a flux of 60 L/(m^2 h) [3].

8.5. Unique, temporarily used tailor-made high-frequency filter sand cleaner

Due to the predicted rise in water demand, the capacity of the recharge basins had to be increased. However, additional land was not available and a solution had to be found for the existing basins. The clogging layer was the limiting factor and was traditionally removed by hand. In the late 80s, a new technique for cleaning the upper filter layer for the designed long and narrow infiltration basin with an area of 2800 m^2 was developed, called "FIREG" (filter regeneration) and later "KUROF" (Kurztaktoberflächenfiltration – short cycle surface filtration) [4]. The frequent cleaning of the upper filter sand layer ensured a high infiltration rate. Whereas the aim was to achieve an infiltration rate of up to 15 m/day, the capacity in the 90s ranged from 7 to 10 m/day [4].

A tailor-made cleaning trolley was developed to run on rails (spaced at 8.4 m) mounted on the concrete walls of the basin (Figure 8). An 8-m long washing drum was used to lift and wash the upper sand layer (Figures 9 & 10). The washing depth could be set between 0 and 40 cm but was typically 5 to 10 cm. Two pumps transported turbid wash water into open channels running alongside the basins. The forward trolley velocity was between 0.1 and 1 m/min, the backward velocity (without washing process) was about 1.5 m/min. The cleaning process for the 150 m long basins typically took 6 to 7 hours. Energy supply of max. 16 KW was needed for pumps, motor, automation.

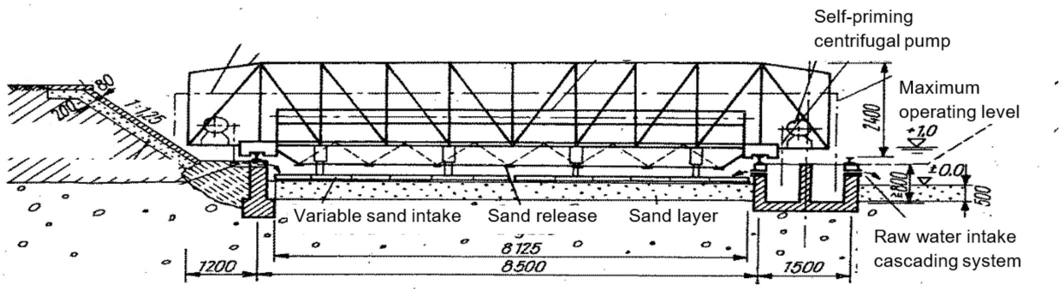

Figure 8.
Schematic of mobile filter sand cleaning unit [5, 6]. © T. Grischek

Figure 9.
KUROF unit in operation in winter
© T. Grischek

Figure 10.
Washing drum and rake
© T. Grischek

Advantages: A large volume of water could be recharged over a limited area; proven high infiltration velocity of up to 10 m/day; KUROF units could be easily transferred between basins; parallel operation and cleaning process; adjustable washing depth; operation in winter possible at river water temperatures > 3°C; one person could operate the unit.

Disadvantages: Flushing water pumps needed frequent replacement as the high sand content affected the performance (4 of the 12 pumps were replaced annually); weed growth (> 5 cm) affected the operation and required removal prior to cleaning the sand layer; relatively high maintenance costs due to the frequent changing of the pumps, corrosion protection, the maintenance of the measuring and control system and the lubrication of the moveable bearings.

After damage during high floods, the unique cleaning system was put out of operation. In 2018, a pilot test started to investigate the advantages of covered infiltration trenches compared to wide basins.

8.6. Social Sustainability

Abstraction rates, regular monitoring and reporting are regulated via contracts with the Department for Environment of the city of Dresden. There is a strong interaction also concerning water protection zones which are difficult to maintain inside a city. The guidelines of the German Technical and Scientific Association for Gas and Water (DVGW) are followed in all technical and operational issues as well as procedures for water quality monitoring and risk assessment. A description of treatment processes and actual water quality data are provided to the public via the DREWAG web-site. Furthermore, the water company is a member of the AWE – a consortium of waterworks in the Elbe River catchment. The consortium was founded in 2008 and represents the interests of its members in politics, e.g. affecting political decisions to improve Elbe River water quality and to define emerging pollutants to allow natural water treatment (RBF) in the future. Special activities include additional water quality monitoring programmes focusing on relevant organic micropollutants, preparation of leaflets and reports for stakeholders and the public about monitoring results and required actions to protect the water source and organisation of information events for the public. The waterworks has special guides (actual and retired staff members) for excursions offered to the public and especially universities and schools, organises events at the Water Day and during public cultural events. As a result, the public is fully accepting MAR as source of water supply and respecting required measures in protection zones.

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Case Study 9: Perth Groundwater Replenishment Scheme using recycled water, Australia

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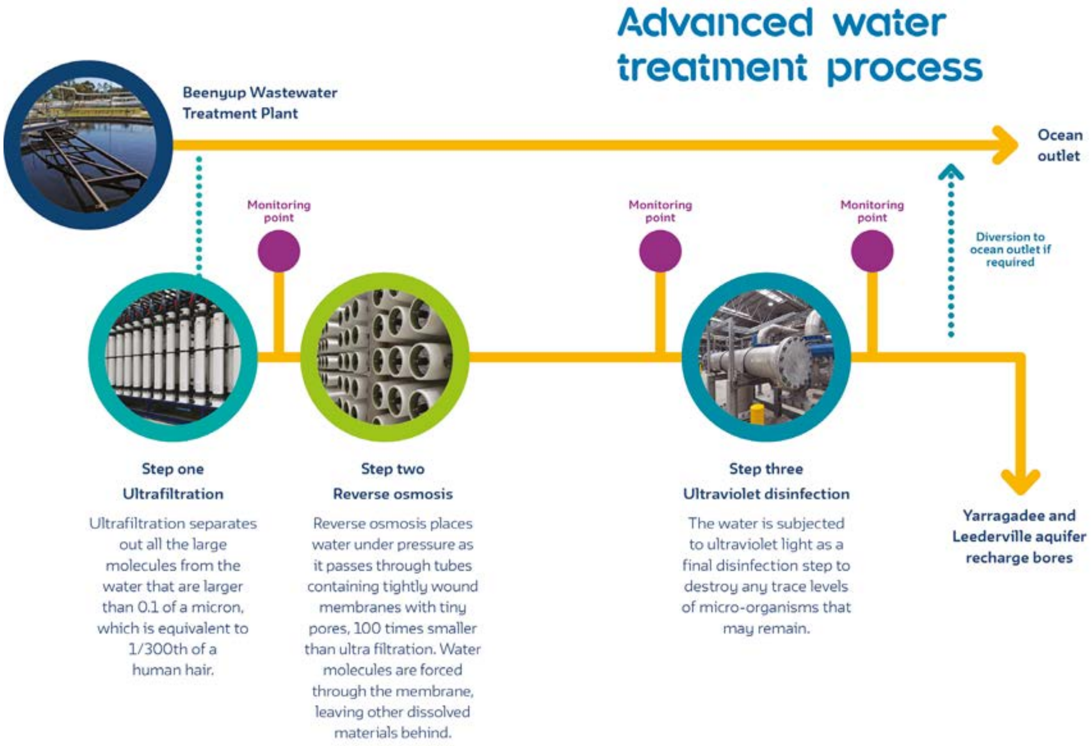
9.1. Introduction

As the first water project of its kind in Australia, Water Corporation's Groundwater Replenishment Trial (GWRT) demonstrated groundwater replenishment (GWR) has made a significant contribution to Western Australia's long-term security of water supplies, making this a ground-breaking scheme for the nation (Water Corporation, 2013 [1]). The three year trial (2010-2012) has provided a technical pathway, community engagement strategy and regulatory framework for other water providers to follow as well as demonstrating a viable new water source option not reliant on climatic conditions. The GWRT validated an advanced water treatment process can consistently and reliably produce recycled water fit for groundwater recharge in Western Australia, which adequately protects human health and environmental values.

Groundwater Replenishment is the process by which secondary treated wastewater undergoes advanced treatment (ultra-filtration, reverse osmosis, UV disinfection) to produce water that meets, or exceeds, the Australian guidelines for drinking water, prior to being recharged to an aquifer for later use as a drinking water source. It is banked in the aquifer and abstracted at a later date followed by treatment in a groundwater treatment plant before supply through the Perth Integrated Water Supply Scheme.

Based on the success of GWRT, Water Corporation has commenced operation of Stage 1 of the Perth GWR Scheme, which has the capacity to recharge up to 14 gigalitres per year (GL/y) into two confined aquifers, and is currently constructing the second stage. This second stage includes duplication of the Advanced Water Recycling Plant, four new recharge and four new monitoring bores up to 1400m below ground across two offsite locations, and a 13km recharge pipeline connecting the plant with the recharge sites.



Ultrafiltration separates out all the large molecules from the water that are larger than 0.1 of a micron, which is equivalent to 1/300th of a human hair.

Reverse osmosis places water under pressure as it passes through tubes containing tightly wound membranes with tiny pores, 100 times smaller than ultra filtration. Water molecules are forced through the membrane, leaving other dissolved materials behind.

The water is subjected to ultraviolet light as a final disinfection step to destroy any trace levels of micro-organisms that may remain.

Figure 1.
Schematic of the GWR Scheme. Source: Own elaboration

Box 1: Features of the GWR Scheme

Location: Latitude -31.784265, Longitude 115.776971

Operator: Water Corporation of Western Australia - principal supplier of water, wastewater and drainage services for Western Australia

Design: Commencement of operation: Trial: 2009, Stage 1: 2017, Stage 2: 2020

Quantity of water abstracted: Stage 1 design capacity 14Mm^3/yr, Stage 2 design capacity 28Mm^3/yr

End use: Domestic Drinking Water

Source of water: Reclaimed/treated wastewater

Aquifers: *Leederville*: early Cretaceous, confined interbedded sandstones, siltstone and shale. Sandstone interbeds are weakly consolidated, pale grey, predominately course grained, poorly sorted, angular to sub-angular.

***Yarragadee*:** Jurassic, confined interbedded sandstones, siltstone and shale. Sandstone interbeds are weakly cemented, pale grey, predominately medium to course grained, poorly sorted.

Type of recharge: Well Recharge

Main advantage: Safe climate independent drinking water source for Perth

9.2. Concept to implementation

The South West of Western Australia is experiencing climate change, which has driven review of the long term feasibility of traditional water sources, such as dams and groundwater. Water Corporation's 50 year water supply strategy Water Forever: Towards Climate Resilience (Water Corppration, 2009 [2]) identified increasing water efficiency, water recycling, and development of new water source options to achieve water security for Perth. This approach included the development of the Perth Groundwater Replenishment Scheme.

During a three year trial, Water Corporation worked collaboratively with regulators (Department of Health and Department and Water and Environmental Regulation), and technical specialists and researchers with expertise in hydrogeology, geochemistry, geophysics, groundwater quality, groundwater modelling, managed aquifer recharge, wastewater treatment and advanced water treatment.

The GWRT was preceded by two research projects to characterise the target aquifer and wastewater/recycled water characterisation including;

1. Four years of aquifer characterisation (2007 – 2010) including:
   - diamond cored investigation bores
   - 22 monitoring bores at five sites
   - aquifer testing of the recharge bore and monitoring bores,
   - geophysical logging
   - surface and in-bore seismic surveying
   - petrophysical and mineralogical analysis of core samples
   - groundwater sampling and analysis
   - Laboratory based column studies to assess water quality evolution.

2. Three years of wastewater/recycled water characterisation (2005 – 2008):
   - characterisation of the microbial and chemical constituents of the three large metropolitan wastewater treatment plants
   - analysis of recycled water to assess the performance of micro-filtration and reverse osmosis (MF/RO) at the specially constructed pilot plant, to inform final design of an Advanced Water Recycling Plant (AWRP) for GWRT
   - Use of the research results to develop and refine health and environmental guidelines for GWRT

Engagement with community, stakeholders and regulators was to has been and continues to be a critical component in developing and maintaining the GWR Scheme, to build trust that the scheme can be consistently operated to always produce safe water. This ongoing engagement is supported by robust scientific investigations and trials (hydrogeological investigations, water quality characterisation, appropriate online monitoring with process control) which demonstrate to all parties the right process, systems and people are in place.

Figure 2.
Groundwater Replenishment Scheme Stage 1 Advanced Water Recycling Plant.
© Water Corporation of Western Australia

9.3. Environmental sustainability

The key benefits of groundwater replenishment include;

- Climate independent water source, not reliant on rainfall
- Sustainable water source
- Potential to recycle large volumes of water naturally
- Enables equivalent groundwater to be taken out while reducing impacts to the environment or other water users
- Lower energy usage over other new sources i.e. desalination

Water Corporation currently abstracts approximately 120ML/yr of water from the three main aquifers; shallow superficial aquifer and two confined aquifers; the Leederville and Yarragadee. This provides approximately 40% of Perth's water supply each year. GWR has the ability to store and bank recycled water, for later abstraction and treatment, and with further expansion, could potentially provide up to 20% (115GL/yr) of Perth's water supply by 2060.

The ability to continuously meet treatment performance criteria and mitigate chemical and microbiological hazards at the Advanced Water Recycling Plant (AWRP) is achieved by maintaining process control. Process control has been implemented for the GWR Scheme by operation of the wastewater treatment plant and AWRP according to Process Control Tables (PCTs). PCTs provide a day-to-day operating guide and describe the operating criteria (Target criteria, Alert limit and Critical limit) for each Critical Control Point (CCP) and Process Control Point (PCP) for the GWR Scheme. The PCTs also provide a brief description of the corrective actions required to be undertaken in the event that Alert Limits or Violation Limits are breached and references work instructions where more detailed information is required. The AWRP is always expected to operate in accordance with the PCT to ensure it is operating within the management systems and processes described in the Water Corporation's Recycled Water Quality Management Plan (RWQMP), and to ensure safe water that meets all required guidelines is recharged.

The purpose of the RWQMP is to formally identify the requirements for management of the GWRS to provide recycled water which meets all water quality requirements for recharge to the confined aquifers. Water Corporation has developed a Wastewater Quality Framework in accordance with the Australian Guidelines for Water Recycling to manage the GWRS under a 12 element framework. The RWQMP provides an overview of how all 12 elements of the Wastewater Quality Framework have been addressed for the GWRS and provides a central reference for all documentation related to management of the GWRS. Since Scheme approval, the GWRS has been 100% compliant with the RWQMP.

Replenishing an aquifer with high quality water may result in a number of geochemical or physical changes. Knowledge of the local groundwater system and information about other managed aquifer recharge schemes was used to develop the research objectives and monitoring program for the GWRT. While geochemical changes are occurring as a result of recharge (buffered pyrite oxidation, sedimentary organic matter mineralisation, trace carbonate (siderite) and crandallite dissolution, feldspar weathering and aerobic degradation of trace organics) no metals or chemicals are being mobilised above required health guidelines.

To verify the water quality of the aquifer after breakthrough of recycled water a recharge management zone set at 250m around each recharge bore has been set, with a monitoring bore located approximately 50m from each recharge bore. Ongoing verification monitoring occurs to provide regulators with confidence risks are managed and the groundwater quality meets the water quality guidelines at the boundary of the recharge management zone.

9.4. Economic costs and benefits

The investment for constructing the Stage 1 GWR was approximately $128M AUD ($85M USD), for construction and commissioning of the the Stage 1 AWRP, four recharge and monitoring bores, all on Water Corporation property. Expansion of the GWR scheme is approximately $294M AUD ($194M USD), for an additional AWRP, four recharge bores located approximately 12km north, pipeline to transfer the recycled water, plus additional abstraction bores and upgrade to an existing Groundwater Treatment Plant. This is expected to be completed in 2020. Annual operating costs of the Stage 1 AWRP is approximately $4.2M AUD ($2.9M USD), including power and chemical consumption, maintenance, sampling and staff costs.

9.5. Regulation

The GWRT defined the approvals pathway required to develop, approve recharge and provide ongoing regulation for a GWR Scheme. This was developed in collaboration between the Department of Health, Department of Environment and Conservation and Department of Water (Now the Department of Water and Environmental Regulation) and Water Corporation. It defines the roles and responsibilities of each agency to ensure human and environmental health are protected, as well as management objectives, water quality guidelines, recharge management zone (minimum distance between recharge of recycled water and abstraction of groundwater for public drinking water supplies) and where environmental values are protected, and a risk assessment process guided by the Australian Guidelines for Water Recycling; Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge (NRMMC, EPHC, NHRMC, 2009) [3]. The risk assessment considers preventative measures and operational procedures and verifies the scheme can be managed without compromising the environmental values of the aquifers. Regulators have set 166 water quality guideline values that must be met at the point of recharge and the boundary of the recharge management zone. Regular compliance reports are produced, such as Water Corporation (2019) [4.]

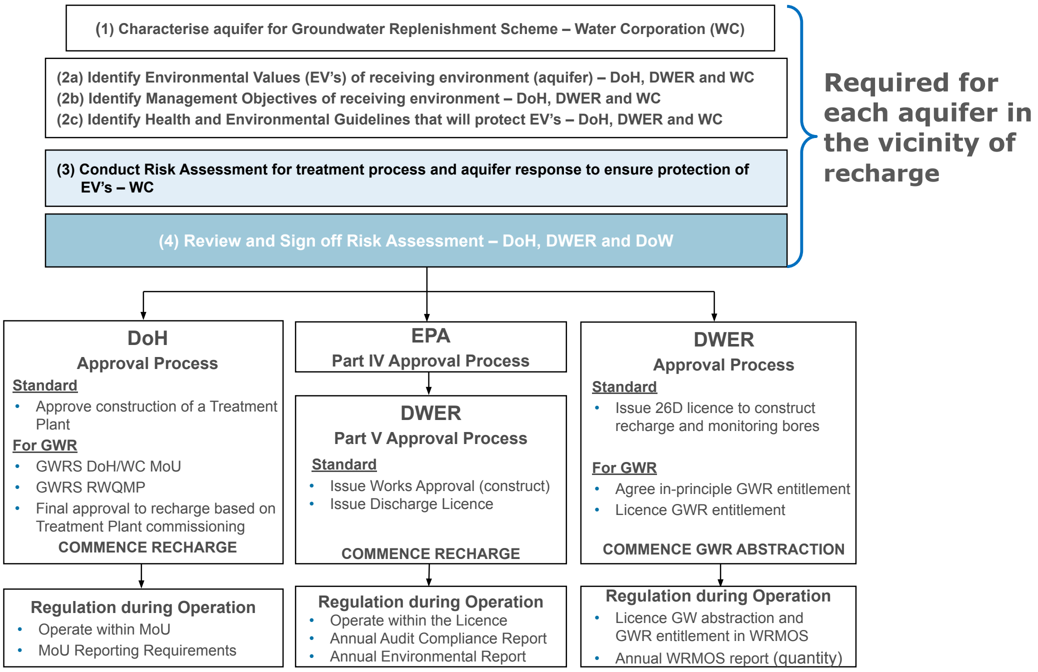


Figure 3.
GWR Regulatory Framework. Source: [5]

9.6. Key Dates

2004	Water Corporation began engagement with regulator and community regarding GWR
2005	Wastewater and recycled water characterisation commenced (2006-08) (DoH, 2009 [6])
2007	Aquifer characterisation commenced Interagency Group Formed (Department of Health, Department of Environment and Conservation, Department of Water and Water Corporation)
2008	Baseline groundwater sampling commenced
2009	Commissioned Advanced Water Recycling Plant (AWRP) for GWRT
2010	Commenced recharge Launched visitors centre
2012	Trial completed
2013	Recharge continued Final GWRT report and Government decision
2014	GWRT decommissioned Construction Stage 1 commenced
2016	Commissioning of Stage 1 AWRP Announcement of Stage 2 GWR
2017	Commenced Stage 1 GWR Recharge Construction of Stage 2 GWR commences
2018	Construction of Stage 2 GWR recharge and monitoring bores
2019	Commissioning of Stage 2 GWR AWRP
2020	Commence Stage 2 GWR Recharge

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Case Study 10: Orange County Groundwater Basin Managed Aquifer Recharge Program using Santa Ana River flow

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Source water: Santa Ana River (SAR) base flow and storm flow

Aquifer: Unconsolidated terrestrial and marine sediments

End Use: Groundwater used for municipal, domestic, industrial and irrigation

MAR System: In-channel and recharge ponds. Covers 4.5 km^2 (1,100 acres)

Annual Average Recharge of SAR Water: 148 Mm^3/yr (120,000 acre-ft/yr)

Annual Average Recovery of SAR Water: 148 Mm^3/yr (120,000 acre-ft/yr) (100%)

Owned and Operated: Orange County Water District

Operations Started: 1936

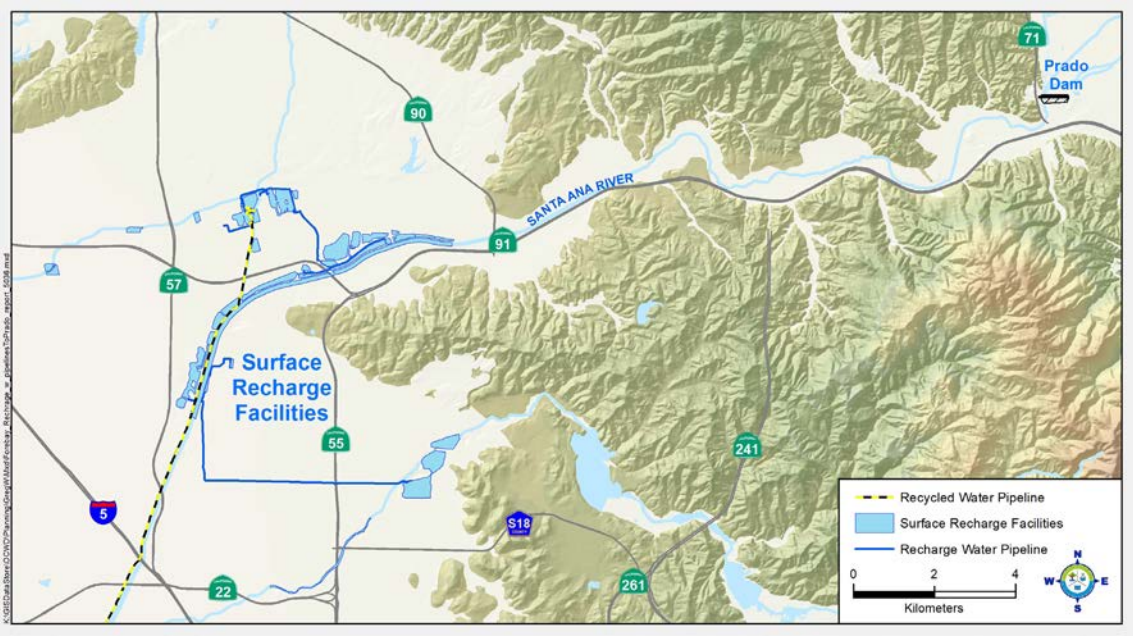

Figure 1.
OCWD's Surface Water Managed Aquifer Recharge System. Source: Own elaboration

10.1. History of the MAR system

In the early 1900s, it was recognized that the Orange County Groundwater Basin (Basin) was being overdrafted. By the early 1920s, sea water intrusion was occurring and flows of the Santa Ana River (SAR) were declining. To address these issues and others, the California State Legislature passed the Orange County Water District Act in 1933, which created the Orange County Water District (OCWD) with the mission to protect the quantity and quality of groundwater in the Basin (OCWD 2014; 2018a [1],[2]).

Starting in 1936, OCWD began constructing its surface water recharge system by purchasing land within the SAR channel. Over time, OCWD has purchased over 4.5 km^2 (1,100 acres) of land for recharge of surface water. These lands include desilting basins, in-channel recharge facilities and a number of recharge ponds. The first phase of land purchases occurred from 1936 to 1945 when 10 km (6 miles) of the SAR channel was purchased. OCWD managed this reach of the SAR to maximize recharge of base flow and storm flow. Starting in the 1980s, as the flows of the SAR began to increase due to treated wastewater flows from upstream development, OCWD began purchasing land to expand its MAR system and further develop its capabilities. This included investing in infrastructure such as inflatable dams to divert water from the SAR, transfer pumps to move water to various facilities and to dewater recharge ponds for cleaning, and heavy equipment to maintain and clean facilities.

OCWD has also invested in working with the United States Army Corps of Engineers (USACE), the owner and operator of Prado Dam on the SAR upstream of OCWD's MAR system (Figure 1), to utilize Prado Dam to temporarily store up to 24 Mm^3 (20,000 acre-feet) of storm water behind Prado Dam in the winter months. Prado Dam was constructed in 1941, but water conservation activities began in earnest in the early 1990s. Storm water captured at Prado Dam is released at a rate that can be diverted and recharged by OCWD. This cooperative arrangement results in a significant capture of storm water that would otherwise be lost to the ocean.

OCWD's MAR system has increased the sustainable yield of the Basin, which has a total storage volume of 82,000 Mm^3 (66 million acre-feet). Sources of recharge to the Basin include natural recharge 74 Mm^3/yr (60,000 acre-feet/yr), SAR recharge 148 Mm^3/yr (120,000 acre-feet/yr), imported water 80 Mm^3/yr (65,000 acre-feet/yr) and recycled water produced by the Groundwater Replenishment System (GWRS) 123 Mm^3/yr (100,000 acre-feet/yr). The recharge of SAR water and these other sources allows for average sustained groundwater pumping of 425 Mm^3/yr (345,000 acre-feet/yr), or more than three times the natural yield. The Basin's natural yield is 123 Mm^3/yr (100,000 acre-feet/year), which consists of 74 Mm^3/yr (60,000 acre-feet/yr) of natural recharge and 49 Mm^3/yr (40,000 acre-feet/yr) of SAR recharge that would occur without MAR.

The entire population within OCWD's service area benefits from the increased supply of water in the Basin.

10.2. Environmental sustainability

OCWD's MAR system benefits the environment by maximizing the capture of local supplies, primarily SAR water (baseflow and stormflow). Uncaptured flows are lost to the ocean and are considered to serve no environmental benefit. Captured and recharged SAR water directly off-sets the need to purchase more expensive imported water. Imported water not only has its own environmental impacts but also a larger carbon footprint with an energy intensity of 2 KWh/m^3 (DWR, 2017 [3]) compared to a value of 0.05-0.07 KWh/m^3 for OCWD's MAR system.

A primary goal of OCWD is to balance abstraction and recharge over time. OCWD plans for an equal amount of abstraction and recharge based on an average over time. Over the past 50 years, Basin storage has been maintained within a target operating range of 123-617 Mm^3 (100,000 to 500,000 acre-feet) below full condition. As a result, Basin storage generally rises and falls due to local rainfall conditions. On average, OCWD plans for 148 Mm^3/yr (120,000 acre-feet/yr) of SAR recharge. For calculation of the water budget, it is assumed that all recharged SAR water is extracted annually (OCWD 2015; 2018b [4],[5]). OCWD is able to sustain this level of abstraction because it is able to recharge other sources of water, including imported water and recycled water, although recharge of these waters are not considered in this case study's cost and benefit analysis below. The energy cost to extract groundwater from the basin varies from 0.3 - 0.6 KWh/m^3 (390-730 KWh/acre-feet).

Actions are taken to ensure that the Basin remains within the target operating range and does not become too full or too empty. Such actions can include managing pumping rates with financial incentives and recharging additional water. Basin storage conditions are determined annually by measuring the groundwater water level in hundreds of monitoring and production wells throughout the Basin. These data are used to create groundwater contour maps of the three main aquifers in the Basin. Groundwater contours from the prior year are compared to the current year to develop water level change maps, which are then used to calculate the change in storage in all three aquifers (OCWD, 2015; 2018b [4],[5]).

All of the water recharged by OCWD is eventually recovered except for some minor losses to Los Angeles County, which is adjacent to Orange County.

Almost all groundwater produced from the basin is used for municipal and industrial purposes. Less than 2% is used for agricultural purposes. The recharge water and recovered groundwater meets all drinking water standards of US EPA based on required monitoring of the over 200 groundwater production wells in the Basin. In a number of isolated areas, naturally occurring contaminants in groundwater, not related to MAR activities, require treatment before being served for use.

10.3. Economic costs and benefits

To evaluate the costs and benefits, it is assumed that the source of water recharged is SAR water and only the costs and benefits of recharging SAR water is considered.

The OCWD scheme has been built in a number of stages and it is difficult to arrive at a single capital cost. The 2019 total equivalent cost current asset value of US$238,600,000 is the most appropriate estimate of capital costs over the lifetime of the scheme, including land and infrastructure. To arrive at the total costs associated with recharging SAR water, the total operating budget of the District was pro-rated by 55% to reflect the quantity of SAR water to the total volume recharged by the District. All costs associated with operating the Groundwater Replenishment System and purchasing imported water were excluded. This approach results in an annual operating cost of US$66M to fund the MAR program with SAR water. Other sources of revenue, such as property tax, have been excluded. Assuming pumping equals SAR recharge (148 Mm^3/yr), the required pumping fee, or Replenishment Assessment (RA), to support District activities is $0.45 per m^3 (US$550/acre-feet).

The benefits of OCWD's MAR scheme is the water recharged and cost savings by avoided purchases of more expensive imported water. Future projections estimate that recharge of SAR water will average 148 Mm^3/yr (120,000 acre-feet/yr). Over a 30-year period, the total volume recharged would be 4,440 Mm^3 (3.6M acre-feet).

Imported water is purchased from the Metropolitan Water District of Southern California (MWD). Typically, 25% of total water demands in the OCWD service area is met with imported MWD water. Every cubic metre of SAR water recharged offsets the need to purchase imported water. The price of treated MWD water in 2018 was US$0.82 per m^3 ($1,015/acre-feet) and is projected to increase to US$1.05 per m^3 ($1,297/acre-feet (by 2028). The ratio between the price of imported MWD water (US$0.82 per m^3) and the RA attributable to SAR recharge (US$0.45 per m^3) indicates that the OCWD scheme has a benefit cost ratio of approximately 2:1.

In addition, reduced reliance on imported water improves reliability and reduces carbon footprint due to high energy costs to transport imported water. It also reduces the impact to the environment associated with imported water. Increased local reliability has benefits to the local economy in ensuring future investments will have a secure and reliable source of water.

10.4. Social sustainability

The OCWD Act provides the governance framework for groundwater basin management. OCWD's MAR system is a key feature that allows for sustainable basin management. An annual engineers report is prepared that documents basin conditions and MAR activities (OCWD, 2018b [5]). OCWD has a 10-member board of directors. Seven of them are elected and three are appointed. Regular board meetings are held and open to the public. OCWD staff holds monthly meetings the 19 groundwater producers in the basin, which are the primary stakeholders.

Since OCWD's MAR operations have been in operation so long, permits are not required for the recharge of water; however, permits are required for ongoing maintenance of the recharge facilities. OCWD has aggressively studied the quality of the water recharged in collaboration with the regulatory community. These studies have shown that recharge of the multiple sources used by OCWD is safe (NWRI 2004 [6]). OCWD continues on-going monitoring of SAR water and other water supplies recharged into the Basin. Water quality data from the SAR is reviewed approximately every two years by an expert panel convened by the National Water Resources Institute (NWRI). The panel has found that SAR water remains safe for recharge (OCWD 2018c [7]). This proactive approach to water quality monitoring and working with the research and regulatory community has fostered goodwill, increased knowledge, and minimized regulatory bureaucracy.

Anyone that drills a well in OCWD's service area is required to register the well and report groundwater production two times per year and pay an appropriate fee for the water extracted. The fees collected from groundwater extractions, called the Replenishment Assessment (RA), fund OCWD's activities. Other agencies oversee well construction permitting, extracted groundwater quality, and discharges to surface water. There are several agencies involved in groundwater quality, ensuring that groundwater used for drinking meets all regulatory standards and that any contamination is addressed.

OCWD also maintains surface water rights issued by the State of California for the SAR and Santiago Creek, which is a tributary to the SAR.

In 2014, the California State Legislature passed the Sustainable Groundwater Management Act (SGMA). This act identifies OCWD as the exclusive agency to manage the Basin within its boundaries. OCWD collaborated with several other adjacent agencies that overlie fringe areas of the Basin to develop a plan that shows the Basin has been sustainably managed for more than a decade (OCWD, 2017 [8]). Annual reports are submitted to the California Department of Water Resources (DWR) to document continued compliance with SGMA.

Because OCWD overlies a heavily urbanized area and there have been extensive modifications for flood control purposes, there are no ecosystems affected by MAR or other Basin management activities. MAR activities do not cause any seepage, waterlogging, or artesian conditions.

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Case Study 11: Streambed recharge structures with periodic desilting to improve recharge of aquifers at Baramati, Maharashtra, India

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11.1. Introduction

In the Baramati Taluka of Pune District of the semi-arid Western Ghats of Maharashtra recharge enhancement structures have been constructed in ephemeral streams since 1968. By 1978 a total of 149 recharge structures in this district had increased detention capacity by 14.7 Mm^3 and annual recharge by a larger volume, benefiting about 5400 ha agricultural land and increasing the value of crops by an estimated 8 million Rupees per year (Dillon 1983 [1]) equivalent to US$2-4 M p.a. at 2016 prices. However that study also reported that there was no hydrological monitoring of the performance of these structures and no assessment of the need for removal of accumulated silt. Although without hydrological monitoring since, the claimed benefit by farmers has led to further investment under national programs and by 2019 the number of recharge structures had reached 289 (pers com Dr. Ratan S. Jadhav).

In recent years there has also been considerable coordinated investment in silt removal to maintain elevated recharge from these structures. Investment in desilting of check dams had occurred spasmodically at about every 10 years or so. In 2011 national funding (NICRA) enabled the capacity of 7 targeted check dams in the Karha River Basin (Shakir *et al* 2014 [2]) to be increased by 40%. Again, without hydrological monitoring, the perceived benefits were such that between 2014 and 2019 the Baramati Agricultural Development Trust has desilted an additional 52 check dams from 52 villages. This case study explores the desilting of check dams to sustain recharge rates over the long term and uses available information to crudely estimate benefits of desilting. Various sustainability indices for environmental, social and economic aspects have been estimated where data permit.

11.2. History of Project and Motivation

Rain fed agriculture in the semiarid Western Ghats is undertaken by farmers on small land-holdings that are vulnerable to climate variability. Such farmers are less endowed with financial, physical, human and social capital that limit their capacity to adapt. Years of low rainfall markedly affect the livelihood of farmers due to reduced production threatening viability of farming enterprises. One direct adaptation measure to buffer small land holders against low rainfall is recharge enhancement using check dams or percolation tanks on ephemeral streams. Mr Sharad Pawar, the founding member of the Agricultural Development Trust, Baramati, later to become Maharashtra's Minister of Agriculture and Food Supplies, observed the frequent shortage of water for drinking and agricultural supplies. Farmers were often unable to grow crops as this is a rain shadow area that comes under the Western Maharashtra Scarcity Zone (MH-6), receiving an annual rain fall of only 400-530 mm, the majority of which falls between June and October. Drought commonly led to crop failure, famine and shortage of drinking water. The government used to make arrangements for water tankers for drinking supplies and animal camps. Then came the concept of detaining the runoff from monsoon storms to allow infiltration into the river bed to augment the natural recharge of groundwater and enhance supplies from dug wells.

Mr Sharad Pawar, together with Misses Hazel Skuce and Edna Vawser (Australian Churches of Christ missionaries), USAID (Food for Peace Program, PL480), Church Agency for Social Action (CASA), Action for Agricultural Renewal in Maharashtra (AFARM) and the State Government of Maharashtra, embarked on a program to enhance groundwater recharge during the monsoons using streambed recharge structures (Pawar *et al* 1990 [3]). Local villagers, predominantly women, provided labour for building earthen embankments. They were paid in the form of oil and wheat (provided by USAID), administered by the missionaries, and the government's role was to assess and prioritize investments based on the ratio of detention capacity to embankment volume, on potentially benefiting area capable of irrigation from dug wells and on the willingness of villagers to participate. Government also took responsibility for design and oversight of construction of each embankment and concrete spill weir.

In 1968 the first percolation tank was built at Tadulwadi village near Baramati. It completely filled with water in its first year, and the impounded water infiltrated within several months. This CASA scheme percolation tank was considered a success and the same scheme was replicated with eventually 289 percolation tanks constructed in the Baramati area. Generally these tanks accumulate silt due to intense storms on initially bare soils reducing water storage capacity and infiltration rate. Recognising that desilting was required to sustain recharge capacity, a pilot project under the National Initiative on Climate Resilient Agriculture (NICRA) scheme was commenced in 2011 to desilt a series of seven recharge structures on one reach of one ephemeral stream. This project was awarded to Krishi Vigyan Kendra Baramati, which had been established in 1992 as a district level Farm Science Center by the Indian Council of Agricultural Research (ICAR) in affiliation with the Agricultural Development Trust Baramati. The site chosen was at Jalgaon Kade Pathar. This was one of 100 NICRA projects in which the Government of India gave high priority to research and development to help agriculture cope with climate change investing ~US$50M (Rs. 350 crore) in Indian Water Management Plans XI and XII (2007-17).

Jalgaon Kade Pathar, a village in Baramati in the Western Maharashtra Scarcity Zone, was selected for an intervention (Table 1). The source of water is only rain water and groundwater from 86 open wells. Nearby is the small ephemeral Karha River and its tributary, Bedicha Odha. Most of the monsoon runoff flows in Karha River and Bendicha Odha that together have 7 old check dams and 5 newly constructed ones capable of harvesting the entire rainfall runoff of the catchment. These check dams were silted reducing water storage capacity by ~40%, enabling runoff from Karha River to reach Nira River and coincided with shortage of water for drinking and agriculture. In some local wells water quality is poor and unfit for drinking supplies and even agriculture.

Table 1.
Characteristic of Jalgaon Kade Pathar village

Name of the village	Jalgaon K.P.
Name of the gram panchayat	Gram Panchayat Jalgaon K.P.
Name of the taluka	Baramati
Name of the district	Pune
GPS Location & Elevation	Latitude - 18.2282° Longitude- 74.4561° Elevation- 574 m
Agro climatic zone	Western Maharashtra Scarcity Zone (MH-6)
No. Of house holds	319
Population	1268
Average annual rainfall (mm)	504 mm
MAR intervention	De-silting of 7 check dams in an ephemeral stream
Implementer and operator	Krishi Vigyan Kendra, Baramati
Funder	Govt of India, ICAR
Estimated ave. annual recharge increase	78,000 m^3/year
Estimated ave. annual extraction increase	78,000 m^3/year
Source of water	Monsoon runoff in ephemeral stream
Gender aspects	Expected that women need to cart water less often
Soil detail	Medium black & calcareous
Major crops (Rabi)	Pearl millet, Rabi Sorghum, Maize, Onion, Wheat
Total cultivated area (ha)	1094
Rain fed area (ha)	980
Irrigated area(ha)	114
Major climate variability challenge	Drought and dry spells

11.3. Enhanced Storage through Desiltation of Check Dams during the NICRA Project 2011-2013

Over 3 years, 2011-2013, 55,800m^3 of silt was removed from seven check dams increasing water storage by 40% to 195,200m^3 (Shakir *et al* 2014 [2]). This is expected to increase recharge by at least 40% due to the additional storage capacity and possibly more through likely increase in the permeability of the floor of the check dams. Dashora *et al* (2018) [4] found the median annual recharge was 1.4 times the check dam detention capacity for 7 Indian studies. Shakir *et al* (2014) [2] reported 2 to 3 fills per year in 2011-2013 (not necessarily draining completely between fills). Conservatively estimating annual recharge to increase by 1.4 times the volume of silt removed, recharge would be 78,000 m^3/yr. The good quality silt removed from the 7 check dams was applied on 35 ha barren land which came under cultivation and 35 farmers benefited. The additional recharge would be sufficient to irrigate 19 ha of wheat, one of the lower water use rabi crops (410mm, Dashora *et al* 2019 [5]). Poor quality light silt mixed with sand was applied on farm and village roads and 5 km road was built up by the villagers at their own expense. Photos in Figure 1 show the mechanized removal of silt and the desilted streambed upstream of a check dam together with the silt applied to barren land. In addition the project constructed a number of contour banks on fields with flat beds 10m x 10m for soil water conservation. The rainfall received during the monsoon was entirely conserved in these beds thus avoiding runoff. The crop yield of these beds was three times that of control plots of farmers, suggesting that a combination of contour banking and streambed recharge structures may be optimum for crop production. The primary aim of contour banking is to increase soil moisture, as opposed to increasing recharge which may also be a byproduct. Figure 2 shows a check dam during the monsoon, seasonal changes in well water levels, and the field water conservation measures.

After the first three years of the project it was scaled up for a five year period to a further 52 villages (pers. com. Dr. Ratan S. Jadhav). By 2018 more than 500,000 farmers had attended training courses, exhibitions or field days at KVK Baramati, and through this the fundamental message of water conservation has been widely spread. More than 500 farmers from the surrounding villages and from elsewhere in Maharashtra have visited the specific project at Jalgaon Kade Pathar to see the success of de-silting of check dams, and of other innovations in silage making, housing systems for livestock, biogas production, back yard poultry production and to purchase fodder crops seeds and to avail the silage making services.

Women farmers from the village have particularly benefitted as the drudgery of carrying drinking water from a long distance was reduced as daily drinking water became available in their houses, due to higher groundwater levels replenishing depleted wells. If there had been a groundwater monitoring program, or records of wells running dry, these benefits could be expressed quantitatively.

Removal of tank silt from check dam in Jalgaon K.P. NICRA village.

De-silted check dam in the year 2012

After removal of silt from check dam in Jalgaon K.P. NICRA village.

Silt was applied on barren land and then spread to make 35 Ha arable

Figure 1.
Before, during and after silt removal from a check dam in Jalgaon K.P. (NICRA project) and demonstration of seasonal range in water level in a nearby dug well.
Photo © Chapter co-authors

Bendicha odha water stream after rains in Jalgaon K.P. village

Full and spilling new check dam constructed by KVK . Baramati 2014

Low water level of well near check dam in summer season

High water level in well near check dam after the monsoon

Rabi sorghum demonstration of in-situ soil moisture conservation technology

Rabi sorghum demonstration of in-situ soil moisture conservation technology showing vigorous crop

Figure 2.
Monsoon season following check dam desilting showing spread of water in a check dam, the discharge over the check dam, and the water level in a dug well belore and after the monsoon. A demonstration of contour banks and flat depressions for soil water conservation is shown as a supporting measure for securing resilient farm incomes and boosting farm productivity.
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11.4. Economics of Constructing Recharge Structures and of Desilting

The original recharge structures were constructed in the 1960s and 70s with substantial labour by villagers, reimbursed in the form of 15 kg wheat and 400 mL cooking oil per person per week, with the constraint that only one person per household was paid, in order to disperse the benefits evenly. Percolation tanks have an earthen embankment and a separate concrete spillway, whereas check dams are just a weir on a stream. The earthen embankments constructed were between 3 m and 8 m in height and several hundred metres long and wide enough for a bullock cart track. More than 90% of the labour for constructing compacted earth embankments with a clay core, was provided by women. The Maharashtra Irrigation Department provided supervision for this and for construction of all concrete weirs to convey spill. Hence the design of recharge structures took account of village labour and costs of construction were considerably lower than commercial rates. At 1980 the feasibility criterion for construction of percolation tanks was for cost to be less than 1.9 INR/m^3 detention capacity and the average value was 0.92 INR/m^3 (Dillon 1983 [1]).

Based on Maharashtra Irrigation Department (MID) records, the mean capacity of these first 149 percolation tanks was 98,700 m^3, and the average area benefitted by each tank was estimated to be 36.2 Ha. The crop mix in this area was jowar (millet) (45%), wheat (30%), sugar cane (10%), and vegetables, onions and gram (each 5%). MID's estimated average annual increase in income per tank was 56,000 Rs and net costs of production were not reported. The capacity of a tank divided by the MID estimated benefitted area is 272 mm. This is not inconsistent with water use results reported by Dashora *et al* (2019) [5] in southern Rajasthan considering crop types and the likelihood of annual recharge to exceed detention capacity as it does in the current study. The resulting benefit:cost ratio (BCR) derived by Dillon (1983) based on a discount rate of 10% was >6. Using a 30-year life and 5% discount rate it would have been 7.0 using the same assumptions. However, for comparison with current data from Rajasthan (Dashora *et al* 2019 [5]) where profit is 28% of the increase in income and allowing 3% capital costs for annual maintenance, and a 30-year life and 8% discount rate gives a BCR of 1.5. Making use of INR to US$ exchange rates in 1978 (8.23) and 2016 (67.92), and inflators from 1978 to 1916 (for INR (18.539) and US$ (3.681)), the actual cost of detention in 1978 (0.92 INR/m^3) and the average rate of recharge to detention (for 7 Indian studies, 1.4) and assuming a 30 year life and 5% discount rate to be consistent with other case studies reported, gives a levelised unit cost of recharge of 0.012 to 0.019 US$ /m^3.

In this area MID also estimated a silt loading to percolation tanks of 1.7 m^3/year per hectare of catchment area (Dillon 1983 [1]). Hence the removal of 55,800 m^3 silt from the 7 check dams with a total catchment area of 1098 Ha at Jalgaon Kade Pathar approximates 5.1 m^3/ha/year of sediment accumulation over the estimated 10 years since last desilted, suggesting that the early figure for siltation rate is somewhat low by a factor of about 3.

The cost of desilting these 7 check dams was approximately 3,750,000 INR and the cost borne by farmers for transporting and spreading the silt on barren fields and farm roads was 2,150,000 INR, a total of 5,900,000 INR. (This is taken to be in 2014 prices.) This amounts to (106 INR/ m^3 silt removed) at an average cost of 10.6 INR m^3 silt/yr if desilting is required each 10 years as expected. Assuming annual recharge is 1.4 times the volume increase, the levelised cost of recharge per m^3/yr is 9.8 INR/m^3 (in 2014) or 0.16 US$/m^3

(at 2016 prices). These figures are high because the effective life of desilting is taken to be 10 years, the expected period between desilting events. This is expected to be considerably extended through use of soil and water conservation measures described earlier. The net benefit of 2.36 INR/m^3 for recharged water that is used in agricultural production in 2014 prices derived by Dashora *et al* (2019)[5] in the Dharta catchment of southern Rajasthan, in the absence of other information, is assumed to be relevant to Baramati, even though monsoon rainfall is a little higher at Dharta (~700-800 mm). Rabi crops in Baramati- wheat, sorghum and onions- are also grown in Dharta catchment.

Note that this does not take account of additional benefits of 35 Ha of barren land becoming arable as a result of silt application about 15cm thick. This would increase the kharif season agricultural production by an estimated 274,000 INR/yr assuming net profit per ha of kharif crops is similar to profit per ha of rabi crop. Expressing this extra production in terms of annual increment in recharge gives 4.3 INR/m^3. There is some value in having silt available for remaking roads but this has not been estimated. The benefit cost ratio for the desilting component of the NICRA demonstration project was found to be 0.60, but if benefits were sustained for 30 years (as other projects are commonly evaluated, and plausible with soil and water conservation measures) the BCR would exceed 1.0 not accounting for enhanced infiltration rates that were not measured (and could be significant) nor cost savings in road making, nor labour savings through reduced carting of household water. It must be remembered that the original construction of recharge structures generally involved volumes of fill that were only a small fraction of the detention storage created, whereas in desiltation the increase in the detention capacity is the same as the volume of silt removed. Finally, Dashora *et al* (2019) [5] warn that heavy earthmoving machinery has the potential to reduce infiltration rates due to subsoil compaction as they observed in Rajasthan, and this should be taken into account in designing any desilting program, by substituting hand labour or light-weight equipment with “balloon tyres” on compactable soils.

11.5. Indicators of Sustainability

Food production is of such paramount importance in this area that this takes precedence over all other ecological indicators of sustainability that might normally be expected of recharge structures. Since the spread of electricity supplies to this rural area, groundwater extraction has greatly increased and few if any streams have baseflow in the dry season. MAR unless accompanied by a reduction in groundwater extraction would be unable to re-establish pre-development riparian ecosystems.

Resource integrity –water quantity

1. Monitoring of groundwater table in dug wells has shown higher rises in groundwater levels during the monsoon near the scraped check dams (2.1m) than in more remote dug wells (0.9m), however it is recognised that there are other factors involved such as aquifer hydraulic properties, topographic position of wells, occurrence of pumping from the same or nearby wells, in addition to recharge quantity. Monitoring of check dam water levels (such as described in Dashora et al 2018)[4], and more groundwater level and water quality observations would be required to establish a quantitative measure of volumetric impact. With the advent of MyWell mobile

phone app (Daly et al 2018)[6] this could be undertaken by farmers who have had training and been provided equipment and follow up on quality assurance. This would also enable changes in infiltration rate to be measured over the longer term and feed into decisions on the desilting schedule for check dams. This work on desilting, along with that reported by Dashora et al (2019)[4] helps ensure that the quantity recharged by recharge structures can be sustained into the foreseeable future.

2. The ratio of volume of infiltrated water from the 7 check dams to volume of recovered water on an annual basis is unknown. Sustaining a groundwater balance will depends on cooperative groundwater management by farmers, informed by the groundwater level data that they collect and share.

Resource integrity – water quality.

3. No water quality data were recorded even though some wells, including dug wells that are likely not to meet microbial drinking water standards, are used as drinking water sources. Higher recharge rates are likely to dilute the salinity of ambient groundwater. Because the recharge mechanism is similar to the natural recharge from the streambed it is presumed that no new water quality hazards will be introduced. However in the absence of data it is not possible to confirm these hypotheses.
4. There appears to be no point-of-use treatment given to water extracted for drinking water supplies. The only guide so far on water quality in MAR in India (Dillon et al. 2014)[7] does not impose additional treatment for natural waters recharged to unconfined aquifers through the unsaturated zone as per natural recharge processes.

Ecosystem Services

5. Currently there is no water sharing policy nor a catchment water management plan in place to protect water supplies for the riparian ecosystem nor downstream water users. In fact, it is seen as a loss if surface water discharges downstream. It is presumed that baseflow ceased in these ephemeral streams once groundwater extraction increased by more than an order of magnitude after electricity distribution in the 1960s. Restoration of ecological flows is considered of secondary importance to sustaining agricultural crops and farm livelihoods. It is possible to achieve ecological objectives through designing bypasses or low flow leakages in check dams, but objectives would need to be clearly defined and supported.

Stressors

6. Check dams recharge water under gravity so there is no ongoing energy cost. By replenishing unconfined aquifers the pumping energy requirements for recovery of groundwater would be diminished. Actual savings in KWh/m^3 will vary across the area depending on aquifer hydraulic parameters, average water table depth and pumping rate.

Social Sustainability Indicators

The interventions in each village panchayat (local government) were finalized following a participatory approach through the Village Climate Risk Management Committee (VCRMC) after an assessment of the climate related problems in the village and a baseline survey. In each village, the interventions were made to demonstrate effective natural resources management, to show an integrated package of proven technology in one village, and to enhance the resilience of agriculture to climate variability and to develop and apply risk management technologies.

7. The primary motivation for expansion of the number of the recharge structures and in investment in de-siltation was the perception by farmers that these increased groundwater storage and groundwater supplies to support agricultural irrigation and drinking water. There is no evidence to dispute that perception, however there are no quantitative measurements that explicitly link recharge structures to increased farm income and reduced time in carrying water for household use. This suggests a monitoring program to do this would be a useful next development.
8. So far there has been inadequate water quality monitoring to demonstrate that groundwater quality is protected, improved or impaired by streambed recharge structures. Nor is there evidence of groundwater sampling and analysis to suggest whether ambient groundwater quality is fit for its uses. A well head protection program would warrant including prevention of runoff water from being recharged directly or adjacent to wells that are used for drinking water supplies. Installing covers for open dug wells used for drinking, would be another valuable preventive measure.
9. The KVK / Agricultural Development Trust provides technical information and assistance aiming to make farming operations sustainable and profitable for farmers. From the outset enhancing groundwater recharge has been a foundation for this. The training programs also enable villages to have informed and consistent views about how to achieve sustainable development and also develop adaptive capacity as will be required to sustain the groundwater resource and the benefits it provides. It also provides a pathway to secure national and state funding to implement sustainable initiatives.

11.6.Conclusions and Recommendations

The Government of Maharashtra declared the Baramati area to be a Precarious Scarcity Area in 1963 due to near total failure of crops on average once every three years, resulting in famine, poverty and continuing vulnerability to drought. Large scale government irrigation projects conducted in favorable areas brought some relief, but outlying villages received little or no benefit. Conservation of monsoon runoff by ponding it in streambed structures to enhance recharge to alluvial aquifers was conceived as a solution and implementation began in 1968. This was reported by villagers to be immediately beneficial in increasing and securing crop production, and the practice proliferated to now 289 recharge structures today. A recent NICRA project enabled desilting of structures and this was found to be effective in sustaining the enhanced recharge and in converting barren land to productive crop land.

In the absence of measurement of infiltration rates, and very conservatively assuming that these remain unchanged as a result of desilting, the economic benefits of desilting of existing check dams appear less cost effective than the construction of the original check dams. However care needs to be taken to avoid compaction of subsoils under heavy earth moving machinery, which Dashora *et al* (2019)[5] showed in Rajasthan can reduce infiltration rates and thereby allow more of the detained water to evaporate and less to be recharged. There are additional benefits of turning barren lands into productive crop lands through the spreading of a 15 cm of silt, and the poorer quality silt to be used by villagers to rebuild farm roads.

Social benefits include claims that less time is spent by women in carrying water to their home because nearby wells contain water for longer. There is still a lack of data on water levels in check dams to enable infiltration rate to be estimated, and the density, frequency and duration of groundwater monitoring needs to be increased to enable an assessment of impacts of recharge structures alongside seasonal and spatial effects including changes in natural recharge and in groundwater extraction. Water quality in this area is mentioned as a localized problem for some wells, but the absence of monitoring does not permit water quality changes as a result of recharge structures to be assessed. As an interim measure it is suggested that wells used for direct recharge not be used for drinking supplies, and wells very close to recharge structures be monitored for water quality changes, notably for bacterial pathogens.

As part of the NICRA project contour banks to enhance soil water conservation, and as a by-product, groundwater recharge were implemented. While contour banks reduce runoff and may potentially reduce the volume of water recharged through check dams, they increase localized recharge as a by-product and reduce sediment loads to check dams, extending the benefits of de-silting. An integrated approach with both contour banks, other soil and water conservation measures and streambed recharge structures are likely to be most effective. Monitoring of rainfall, check dams and groundwater levels in control studies before and after intervention via contour banks or scraping of check dams in matched catchments would yield more information of value to inform investment in large-scale replication of such interventions. Another part of the NICRA project addressed fodder production and silage management that was found to increase milk production by 22% in parallel with increase in crop production by 30% as observed over a short term from limited measurements without accounting for confounding factors. Hence, based on empirical evidence from Baramati, managed aquifer recharge is an important early part of a package of mutually supporting measures to increase resilience of agricultural systems in semi-arid drought-prone areas.

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Case Study 12: North London Artificial Recharge Scheme, UK: a water supply for drought

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12.1. Introduction

The North London Artificial Recharge Scheme (NLARS) is a strategic component of London's public water supply. It is a managed aquifer recharge (MAR) scheme used primarily during drought, and to support water supply emergencies, by abstracting stored groundwater from the confined Chalk and Basal Sands. Following use, groundwater levels are assessed and recharge with potable water under mains network pressure supplements natural recovery of storage. NLARS has a long history, but now comprises two wellfields with 48 boreholes and wells located along the New River aqueduct and Lee Valley raw water reservoirs [1; Figure 1, Box 1]. To supplement water abstracted mainly from the rivers Thames and Lee, NLARS pumps groundwater into the 400 year old New River or the reservoirs that are more than 100 years old. The water is treated at three water treatment works (WTW). NLARS has the potential to provide up to 66 Mm^3 of groundwater over a year to supplement reservoir storage, ultimately providing around 6% of London's 840 Mm^3/year drought water supply capability.

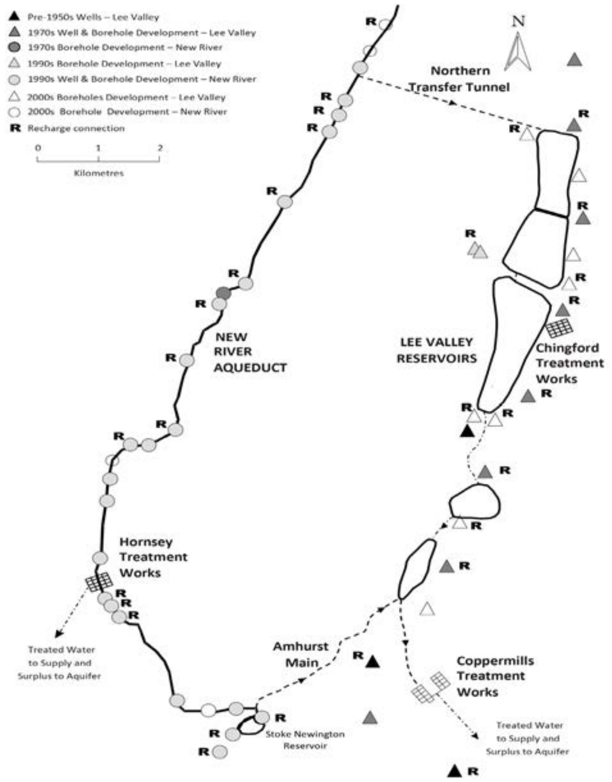

Figure 1.
Layout of NLARS [after 1].
Source: © Chapter co-authors

Box 1: Salient features of NLARS

Location: 51°33.980'N, 0°7.057'W to 51°42.868'N, 0°0.688'W

Operator: Thames Water

Design: 48 boreholes & wells up to 130 m deep along an aqueduct & raw water reservoir chain

Commencement of operation: 1995

Quantity of water abstracted: Licensed to abstract up to 66 Mm^3/year

End use: public supply of drinking water quality

Source of water: Thames and Lee rivers

Aquifer: confined Cretaceous Chalk and Palaeogene Sands

Type of recharge: boreholes and wells recharged with potable water under mains network pressure, at a rate of up to 60,000 m^3/day

Main advantage: strategic scheme for drought and emergency use to support raw water reservoir storage and water supply to London

12.2. History of the development of NLARS

The history of MAR in the Lee Valley can be traced back to the 1890s following decades of over-abstraction from the confined Chalk aquifer. This over-abstraction resulted in the decline in yield from existing wells and the formation of a dewatered zone in the overlying Basal Sands aquifer, the Thanet Sands and the lower part of the Lambeth Group, as well as the Chalk [Figure 2].

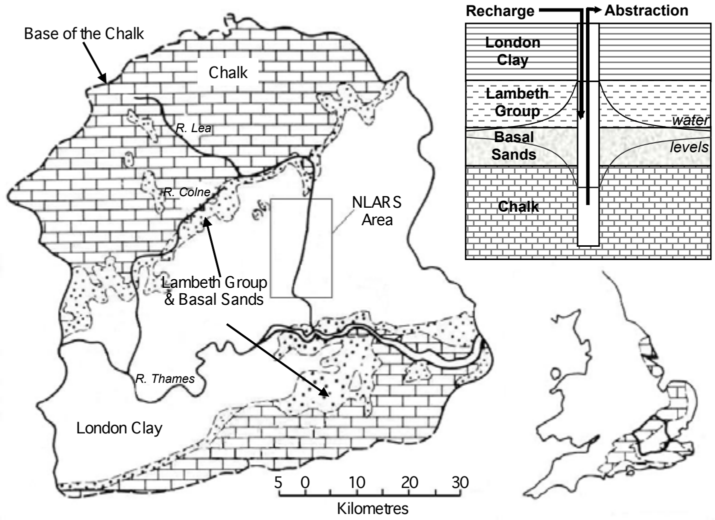

Figure 2. Hydrogeological setting & MAR conceptualisation. Source: [1] © UNESCO-IHP

This decline in yield and dewatering led to investigation of the viability of aquifer recharge, via existing wells, to refill aquifer storage, and so restore abstraction yields. Subsequently, the evolution of NLARS into its current form as a strategic water supply scheme occurred in phases in the 1950s and into the 2000s [1]. Throughout this evolution, NLARS was envisaged as a strategic drought water source to help provide a secure water supply for Thames Water's customers, now numbering 10 million, while meeting the challenges of population growth, climate change and delivering further reductions in network leakage.

1950s: Aquifer recharge of two existing wells with filtered and chlorinated river water demonstrated recovery of previously declining groundwater levels with no adverse impacts on water quality (Boniface, 1959 [2]). The Metropolitan Water Board (MWB) considered this a successful demonstration of MAR.

1970s: Aquifer recharge investigations by the MWB at existing wells and newly drilled boreholes were developed by its successor, Thames Water Authority, into a pilot Lee Valley Scheme of six existing wells and seven new boreholes (Hawnt *et al* 1981 [3], Flavin and Joseph 1983 [4]). From 1977 the scheme was licensed to abstract 80,000 m^3/d, with potable water recharge demonstrated at an average of around 40,000 m^3/d over five months.

1990s: The water industry was privatised in 1989 resulting in a significant increase in investment. Thames Water continued investment in the Lee Valley, constructing 14 new boreholes along the New River (O'Shea *et al* 1995 [5]). Pairs of observation boreholes were drilled to understand the hydraulic connectivity between the fractured, higher permeability Chalk and the higher porosity Basal Sands, where most groundwater is stored. Investigations with the British Geological Survey assessed risks of poor quality groundwater caused by pyrite oxidation in the Basal Sands (Kinniburgh *et al* 1994 [6]). Dilution with Chalk groundwater and maintaining high groundwater levels were considered to reduce this risk and, in practice, this has not constrained the operation of NLARS. Capable of contributing 150,000 m^3/d to secure London's water supply, the expanded scheme was commissioned as NLARS in 1995 with its first significant use in 1997 (O'Shea and Sage 1999 [7]).

Figure 3.
Test pumping an old, large diameter well in 2000 at 20,000 m^3/d, and a modern NLARS borehole building with discharge into the New River. © Thames Water Utilities Ltd

2000s: Following implementation of NLARS, further opportunities were identified to augment its yield, and so improve security of water supply. Existing sites were refurbished to maximise their abstraction capability and new boreholes commissioned, bringing the total to 48 with 30 equipped for aquifer recharge. This increased the peak abstraction potential to >200,000 m^3/d, with an annual licensed capability of 66 Mm^3 (180,000 m^3/d), and the aquifer recharge capability up to 60,000 m^3/d.

12.3. Environmental Sustainability of NLARS

Since being commissioned in 1995, NLARS has been used for London's water supply during drought and dry weather challenges in 1997, 2003, 2005/06, 2011/12 and 2018/19 [Figure 4]. This shows how both abstraction and subsequent recharge vary significantly, with a mean value for the ratio of volume of infiltrated water to recovered water of 0.36 from 1995 to 2019. During times of need, the volume abstracted (maximum of 4.1 Mm^3/month) is greater than the volume of recharge (maximum of 1.3 Mm^3/month. Following significant abstraction, rarely has recharge exceeded 100% of that abstracted, with remaining storage replenished by natural recovery. In practice, the approach to managing NLARS is to assess aquifer storage following abstraction, using observation borehole groundwater level data to establish where recharge is required, then implement recharge and reassess whether optimum storage recovery has been achieved. Over the last 20 years, groundwater storage has increased progressively, reaching 98% of its maximum practical capacity prior to use in 2018. Between 2009 and 2018, the average storage has been 95.8%. MAR supplements natural recovery of storage following abstraction, with evidence of a decadal increase in groundwater banked in the confined Chalk and Basal Sands, reversing the impacts of historical over-abstraction, with NLARS operation having no impact on surface water resources or dependent ecosystems.

An NLARS Operating Agreement documents groundwater level and quality monitoring required to ensure environmental sustainability. The recharge water is of potable quality, taken from the same network used for public supply. Monitoring of groundwater quality, and its response to recharge, has demonstrated no significant impact on the stored water or its treatability. This is important as there was concern that disinfection by-products in the potable water could accumulate within the aquifer.

The energy requirements for operation of NLARS abstraction and recharge are estimated as 37MWh for 200,000 m^3 of water, i.e. 140,000 m^3 abstraction and 60,000 m^3 recharge, the latter being based on energy requirements for potable water output. This energy requirement equates to a total of around 0.25 KWh for abstracting 1 m^3 and recharging 1 m^3, which is considered to translate to an overall energy intensity of around 0.25 KWh/m^3. This is within the range of 0.1 to 0.3 KWh/m^3 for other groundwater supply sources operated by Thames Water.

12.4. Economic costs and benefits of NLARS

Since the main objective of NLARS is to support London's water supply during drought and other emergencies, the most appropriate metric to measure performance is the cost of supply capability rather than the levelised cost of putting water into public supply. Fundamental to the development of NLARS were the Lee Valley reservoirs and New River aqueduct, providing inexpensive transfer of groundwater to existing WTW, plus existing abstraction wells repurposed to become part of NLARS. As a result, the cost of developing NLARS has largely been restricted to drilling, testing and equipping of boreholes. No WTW expansion was required, nor was there any significant land purchase, as existing Thames Water land was used. The expansion of NLARS in the 2000s cost £15.8M, of which about 10% was for telemetry plus observation borehole enhancements, with a further 10% for design and management. With this increasing the scheme yield by 30,000 m^3/d, it equated to a unit cost at that time of about £0.53M per 1000 m^3/d of water supply capability. Other MAR schemes conceptualised or trialled at operational scale by Thames Water have unit costs of around £2-3M per 1000 m^3/d. This is significantly greater than the unit cost of the 2000s NLARS expansion, partly reflecting the need for water treatment enhancements. Alternatives for increasing water supply to London in the water-stressed south east of England now include effluent reuse, desalination and inter-catchment water transfers, with capital costs around £3M to £9M per 1000 m^3/d for options with yields up to 100,000 m^3/d, which may require significant investment in water transfer pipelines. Accounting for inflation and changes in project procurement, the capital cost to develop the full NLARS scheme now is estimated to be about £98M, with a capability of 180,000 m^3/d this equates to around £0.54M per 1000 m^3/d or US$730 per m^3/d, helping to confirm NLARS economic cost effectiveness relative to other future water supply options.

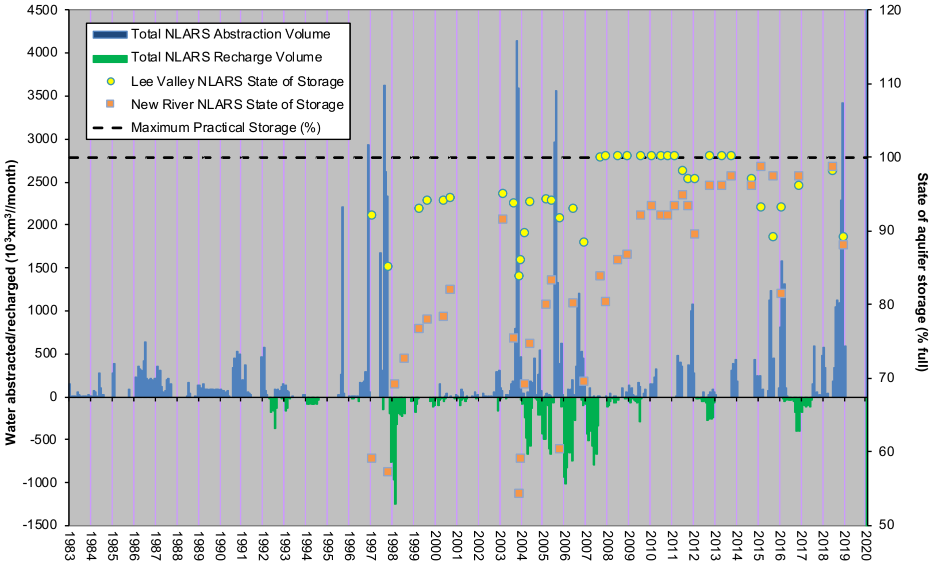

Figure 4.
NLARS operational abstraction, recharge and state of storage.
Source: Own elaboration

The highest annual volume abstracted from NLARS was around 10 Mm^3 in 1997 and 2018, with the maximum recharge after abstraction being about 5 Mm^3 in 2005/06. To illustrate NLARS operating costs, operation in a more severe drought could abstract 25 Mm^3 over 6 months, with recharge of 7.2 Mm^3 over 4 months to assist storage recovery. This would equate to an operating cost of around £0.8M, covering abstraction, production of treated water for recharge, as well as staff and management costs. As neither the recharge nor abstraction capability of individual boreholes and wells has shown significant evidence of deterioration via clogging, rehabilitation costs are negligible.

12.5. Social sustainability of NLARS

There is a well-established regulatory environmental framework administered by the Environment Agency (EA). For NLARS, an abstraction licence and an over-arching operating agreement, plus a series of discharge consents that enable recharge, have been authorised via the Water Resources Act 1991 and Environment Act 1995 by the EA. The operating agreement sets out the management rules for NLARS use as well as the water quantity (groundwater levels) and water quality monitoring requirements. These authorisations required the demonstration of need, the absence of significant hydro-environmental impact, including risk to ambient groundwater quality and flood risk from recharge, and no derogation of existing abstractors, all within a public consultation process. The EA also reports annually on the management of the London Basin Chalk Aquifer, including NLARS abstraction and recharge and the consequences for groundwater levels (Environment Agency, 2018 [8]). This helps raise awareness of NLARS, but Thames Water enhances this by making information available to customers on its web site ([9]), providing more technical information on its contribution to London's water supply in Water Resource Management Plan (WRMP19) documents available during public consultation on future plans ([10]).

The NLARS Operating Agreement does not define specific recharge requirements; there is no regulatory requirement for recharge to match or exceed the volume abstracted. In practice, NLARS storage is maintained to ensure its potential supply capability is maximised within operational and financial constraints, ensuring that security of water supply is not put at significant risk. In its confined aquifer setting, recharge of NLARS creates a low risk of seepage, artesian discharge and waterlogging. Furthermore, with managed recharge to a confined aquifer, NLARS is largely resilient to the potential adverse impacts of climate change on rainfall recharge to the unconfined Chalk in south east England.

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Case Study 13: A Managed Aquifer Recharge Scheme in a complex fractured quartzite aquifer for securing water supply to Windhoek, Namibia

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13.1. Introduction

The City of Windhoek lies on the central plateau of Namibia, the most arid country south of the Sahara Desert. The average annual rainfall in Windhoek is 360 mm, while the average annual evaporation is 2,170 mm (Mendelsohn *et al* 2009 [1]). There are no perennial rivers within the country's borders and the nearest perennial river to the capital city is the Okavango River 700 km north of Windhoek which partly constitutes the northern border of the country. In terms of water supply the city relies primarily on three surface water dams (the Von Bach, Omatako and Swakoppoort Dams), direct potable reuse of treated waste water from the Goreangab Water Reclamation Plant, supplemented by the Windhoek Aquifer during periods of limited availability of surface water to provide for its population of around 400,000. By 2050 the population is expected to reach 790,000 and the water demand to increase from the current unrestricted demand of 28 Mm^3/yr (2019) to ~50 Mm^3/yr. Water Demand Management plays an important role due to expected future water supply shortages. In the coming 2019/20 supply period, the projected demand is actively managed at a reduced target of 24 Mm^3/yr.

Since 2002 numerous water supply augmentation options were investigated. The Windhoek Managed Aquifer Recharge Scheme (WMARS) in combination with additional direct potable reuse were identified as the most viable alternatives (LCE 2019 [2]). With ever increasing demand and the acute threat to water supply security posed by periodic droughts and climate change, (Turpie *et al* 2010 [3]), WMARS was targeted as the swiftest counter response. Over the past 10 years the record highest as well as the lowest annual rainfall was experienced and as a result WMARS was keenly taken up by the municipality and the first major MAR scheme in the world in a complex, fractured, hard-rock aquifer was constructed. The aim is to be able to utilize as much of the aquifer's available storage as practically possible to enhance the city's water supply security. More than 400,000 direct beneficiaries will gain from improved water provision during periods of drought. WMARS, once fully developed, aims to provide a 99% security of supply through an abstraction capacity of 19 Mm^3/yr and installed recharge capacity of 12 Mm^3/yr.

Salient features of WMARS scheme:

Location: 22° 38′ S; 17° 08′ E

Operator: Windhoek City Council

Extent: 3.75 Mm^3/a installed injection capacity and 11 Mm^3/a installed abstraction capacity

Commencement of operation: 2004

End use: Potable supply (drinking water)

Source water: Surface water and reclaimed wastewater

Aquifer: Mostly confined aquifer characterised by fractured pure and micaceous quartzites

Type of recharge: Injection wells with separate abstraction installations

Main features: Offers drought and climate change resilience by curbing extensive evaporation, maximising aquifer storage and providing a short term alternative supply source

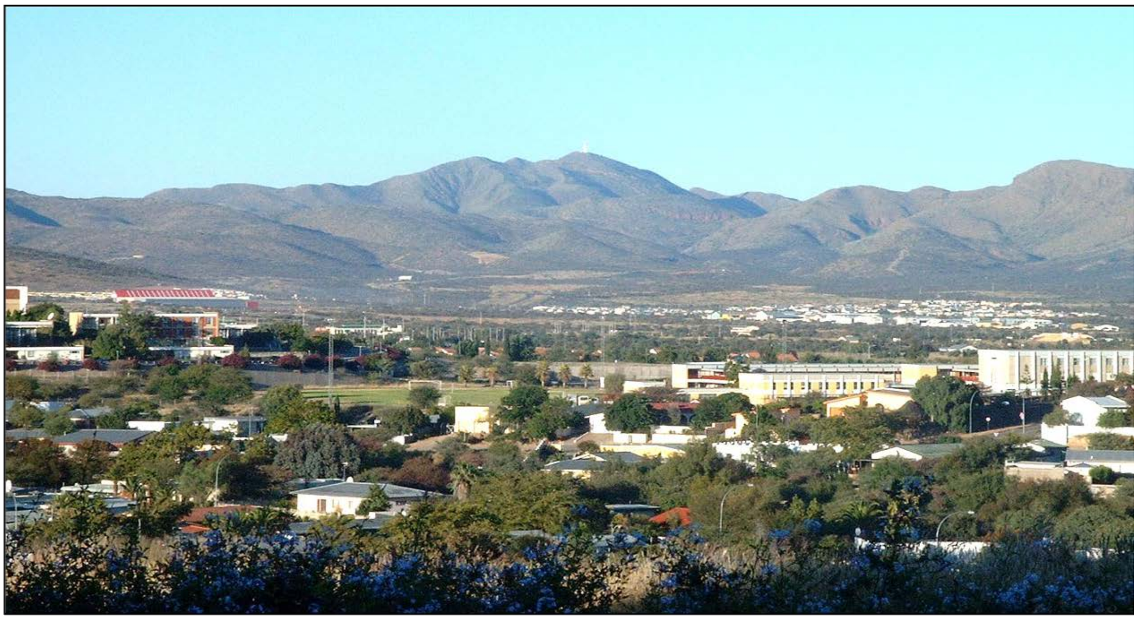

Figure 1.
"Windhoek with the Auas Mountains in the background".
The map © Wiki Commons **and the Photo** © Ricky Murray

13.2. Hydrogeology of the complex, fractured, hard-rock Windhoek Aquifer

The hydrogeology of the Windhoek Aquifer is dominated by faulted and fractured quartzite and schist formations within a colluvium infilled graben structure (Figure 2). These quartzites, being brittle and highly fractured as a result of folding and faulting, have developed secondary porosity and permeability. The schists on the other hand are ductile and have poorly developed secondary permeability. Both the schists and the quartzites are considered to have no primary porosity. The dominant groundwater flow direction is northwards from the quartzite mountains south of the city towards the city which is underlain by schists. The flow follows preferential pathways along the numerous faults and fracture zones that transect the area. The quartzites can be divided into pure quartzites that form the Auas Mountains south of Windhoek (primarily the Auas Formation), and impure or micaceous quartzites that lie between the city and the Auas Mountains (primarily the Kleine Kuppe Formation). Interbedded and north of the micaceous quartzites are impermeable schists.

The transmissivity values obtained from the highest-yielding boreholes range between 100 – 1000 m^2/d for the early-time fracture flow component of the constant discharge pumping tests, and the late-time transmissivities which reflect the permeability of the micro-fracture network range between 50 – 350 m^2/d (Murray, 2002 [4]). The storage coefficients reflect the predominantly confined nature of the aquifer: The pure quartzites (0.009 – 0.010), the micaceous quartzites (0.005 – 0.008) and the schists (0.001) (Murray 2002 [4]).

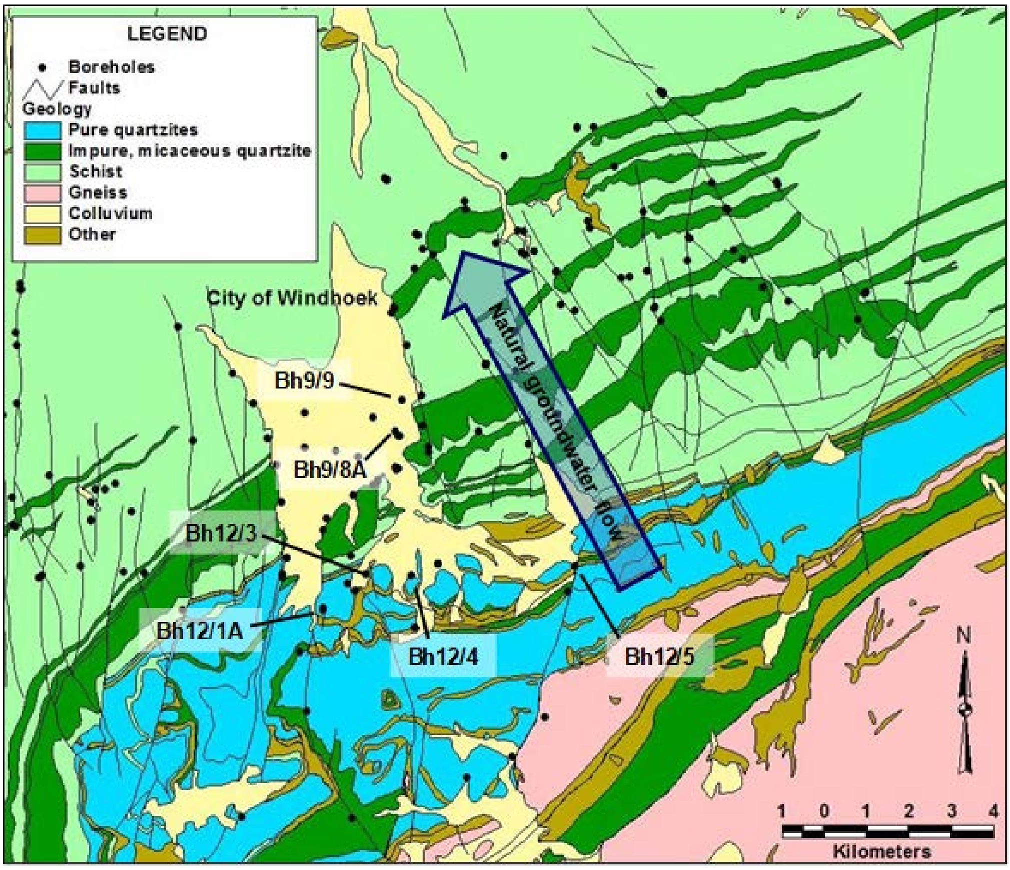

Figure 2.
Simplified geology of the Windhoek Aquifer. Source: [4]

Natural recharge is estimated to be on average 1.73 Mm^3/yr. This value was obtained after calibrating a MODFLOW numerical flow model with 51 years of groundwater level and abstraction data (Zhang, *et al* 2002 [5]). Over a period of 10 years, estimated losses in the Windhoek Aquifer are less than 3% based on this model, mostly as a result of favourable geological conditions within the Windhoek Graben structure. In comparison, approximately 50% of the water in the surface water reservoirs is lost to evaporation.

13.3. Motivation for MAR and its feasibility

From the onset of large-scale abstraction from the Windhoek Aquifer in the 1950s, to the time MAR was investigated in the late 1990s, water levels had dropped by about 40 m in the micaceous quartzites, that constitute the main wellfield areas, and were steadily declining in the pure quartzite areas. In order to establish the feasibility of recharging this complex aquifer system, four borehole injection tests were carried out in both the pure- and micaceous quartzites between 1997 and 1999. The injectant was treated, potable water mainly from the Von Bach Water Treatment Plant which derives its water from three dams. Despite the very different hydraulic characteristics between the two quartzite formations influenced by preferential flow paths and barriers to flow, in total 450,300 m^3 was recharged successfully. Figure 3 presents an example of a borehole injection test at Bh 12/3 which was recharged at 118 m^3/h (32.7 L/s) for 35 days (99,000 m^3). Water levels were monitored in the surrounding boreholes.

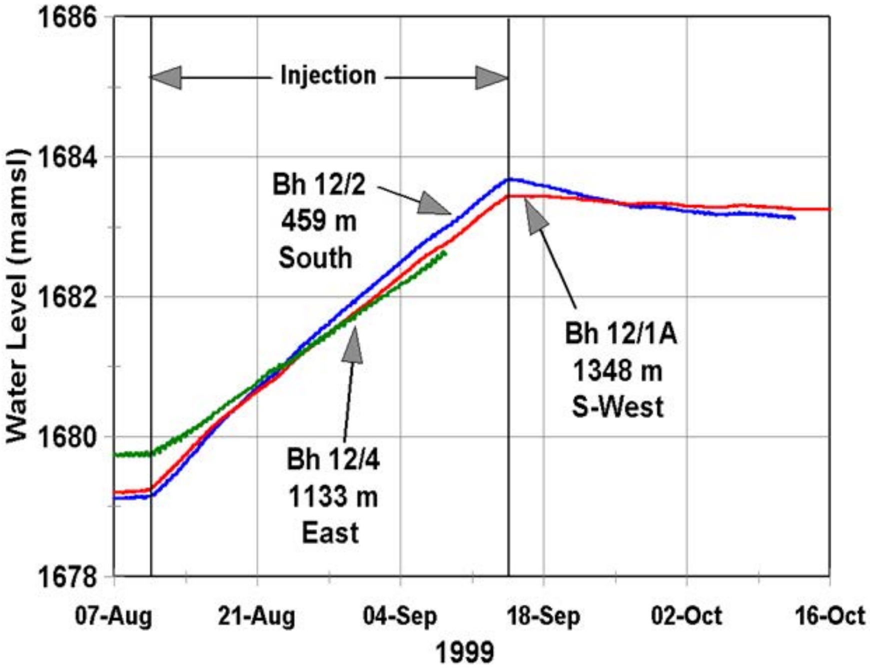

Figure 3.
Water level response (shown in metres above mean sea level) in monitoring boreholes to injection test at 118 m^3/h into Bh 12/3 located in the pure quartzites.
Source: Own Elaboration

Following the success of the injection tests it was evident that managed aquifer recharge was possible and recharge was planned for the existing wellfield areas (the micaceous quartzites) and the main natural recharge and storage area (the pure quartzites) (Murray 2002 [4]; Murray and Tredoux 2002 [6]).

13.4. Environmental Sustainability

Groundwater quantity

The over-pumped or "mined" micaceous quartzite portion of the Windhoek aquifer where water levels dropped by about 40 m took up to a decade for water levels to recover to their pre-abstraction levels (Figure 4). The volume of water that had been abstracted from storage since 1950 was estimated in 2002 using the numerical model to be 28 Mm^3. The water level data showed the need to artificially recharge the aquifer in: i) the wellfield/micaceous quartzite areas to replenish the localized water level depressions, and ii) in the pure quartzites to replenish the main "water bank" where most of the aquifer's storage is held, and which had actually been dewatered the most as a result of the large-scale abstraction since the 1950s. The different water level response are due to differing aquifer characteristics between pure and micaceous quartzites.

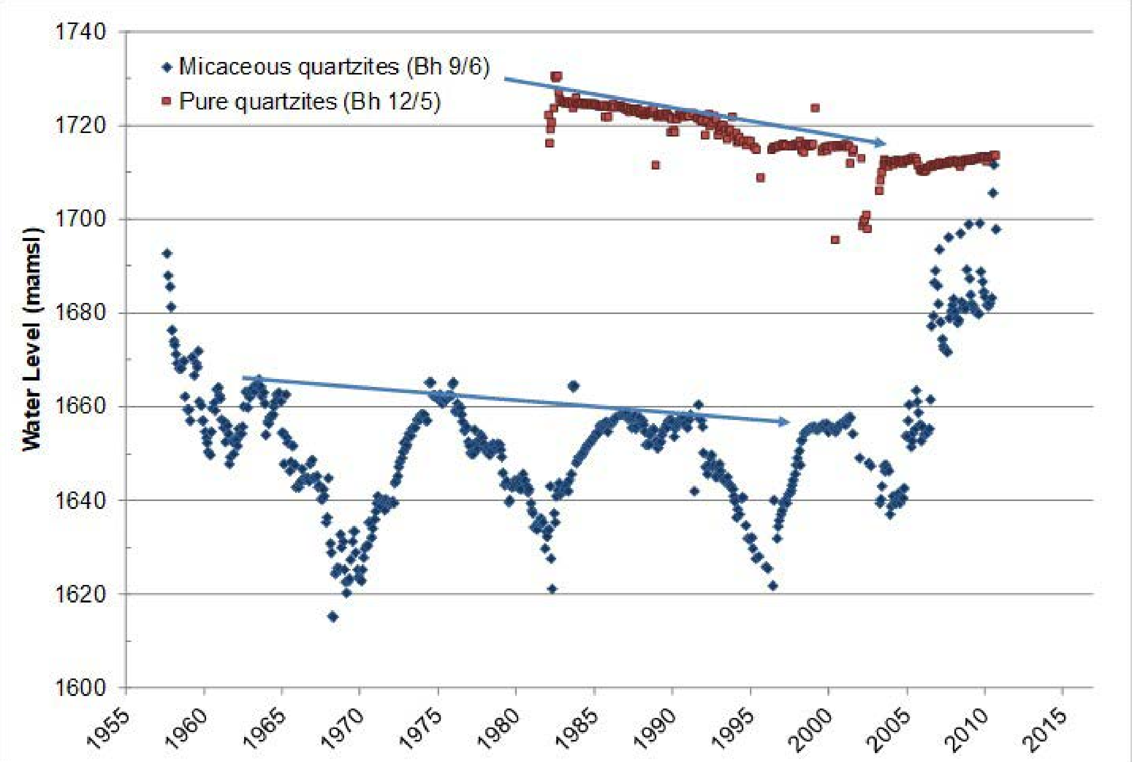

Figure 4.
Borehole water level decline due to large-scale abstraction and subsequent response to artificial recharge that began in 2005. Even after 5 year rest periods (e.g. 1970 – 1975), the water levels never recovered to their original levels. Source: Own Elaboration

By 2005 four boreholes were equipped for recharge and by 2011, an additional two boreholes were equipped bringing the combined recharge capacity to 10,000 m^3/day. Five of the six injection boreholes were placed in the micaceous quartzite/wellfield areas, and one in the main storage area of the pure quartzites. In all cases, the injection water was fed under gravity from municipal water supplies and passed through activated carbon columns to reduce DOC followed by pre-chlorination.

Since the onset of artificial recharge the water levels in Bh 9/6 in the micaceous quartzites rose by ~50 m and the aquifer in this area is considered to have been replenished to the pre-abstraction water levels (Figure 4). The average annual rainfall in Windhoek for the period 2002-2011 was 536 mm which far exceeded the long-term average rainfall of 360 mm recorded since 1890. Coincidentally, this higher rainfall experienced in the area occurred during the same time as the first operational period of artificial recharge. While the rise in water levels observed in the aquifer is mainly attributed to injection, the exceptionally high rainfall and associated natural recharge over this period certainly contributed to this.

Following the 2006-2011 period of artificial recharge and high rainfall a dry period ensued where there was little inflow into the city's supply dams and groundwater abstraction intensified, particularly from 2014 until the end of 2015 (Figure 5). While the water levels in the aquifer dropped accordingly, this level of abstraction may not have been possible without the preceding period of artificial recharge and above average rainfall.

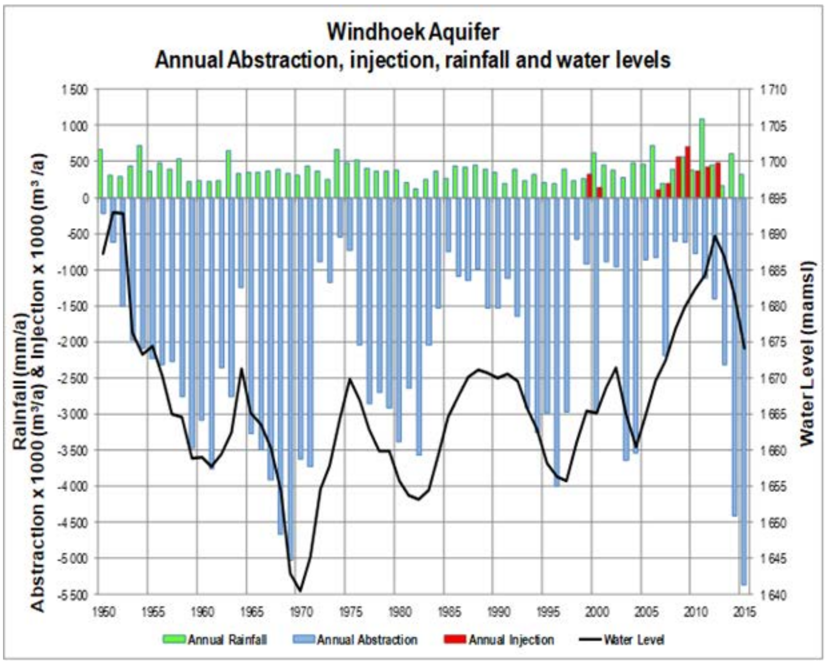

Figure 5.
Total aquifer abstraction, injection, rainfall and average water level from all boreholes.
Source: Own Elaboration

Groundwater Quality

The arsenic concentrations in the ambient groundwater are generally very low and close to the detection limit of 0.5 µg/L. However, the highest concentration of 13 µg/L occurs in groundwater associated with mineralized faults in the schists in the northernmost part of the aquifer, which is slightly above the World Health Organization guideline value as well as the maximum allowable level of 10 µg/L. The electrical conductivity (EC) values in the pure and micaceous quartzites which comprise the main aquifer and wellfield areas are ~500 and ~700 µS/cm respectively (Murray, 2002) and below the WHO guideline values. In the mica schists, borehole temperatures as high as 84°C are found due to deep-circulating groundwater, and here EC values range between ~1000 – 2000 µS/cm (Murray, 2002). With the blending of borehole water with water from alternative sources, in particular surface water from the three dam system, the water quality complies with WHO guideline values.

The injectant is treated potable water with very strict water quality requirements that are aimed at preventing the deterioration of the groundwater quality and minimizing clogging of the boreholes and aquifer. The water is injected directly into the hard-rock fractured aquifer via boreholes at depths below the piezometric level where it blends with the natural groundwater. To date the recovered water quality has had a salinity of 910 µS/cm or 610 mg/L TDS (95% percentile) and a DOC of 1.1 mg/L (based on a 95% percentile) (Tredoux *et al* 2007 [7]; Murray *et al* 2018 [8]).

Since the onset of artificial recharge a concern was expressed around the potential for clogging of the aquifer due to water temperature differentials between the injected and the aquifer water. This is however unlikely to be a significant problem as the injection boreholes are all located in the pure and micaceous quartzites where temperatures range between 25 – 30°C which are similar to the temperature of the injectant. In some areas iron and manganese levels are high and it is contemplated to install water treatment systems to oxidise and precipitate the iron and manganese.

Energy Intensity

In terms of energy requirements, the weighted average for a combination of injection and abstraction is 3.9 kWh/m^3 compared to the power requirement of alternative supply sources such as the transfer water from the Okavango River (~700 km north of Windhoek), which is 4.9 KWh/m^3 and desalination (from the coast ~400 km west of Windhoek), which is 11.3 KWh/m^3.

13.5. Costs and Benefits

Capital investment to date by the local authority, the City of Windhoek, amounts to U$ 11 Million with the central government availing U$15 million towards implementing the project (exchange rate of US$ 1 = N$ 14). It is foreseen that the national bulk supplier, NamWater, will contribute U$ 4 million to implement water treatment at Swakoppoort Dam, bringing this into the scheme as a crucial source of water to recharge the aquifer in years of higher rainfall.

The WMARS provides water security during droughts when surface water supply is limited. The cost per m^3/d of water supply capacity is deemed an appropriate measure of water supply efficiency in this case. The total capital cost of the existing facilities (US$26 million) divided by the daily supply capacity of 30,100 m^3/d equates to US$0.86 per litre per day.

The bulk water tariff for 2019/20 is US$ 1.68/m^3 while the dynamic prime cost amounts to US$ 2.48/m^3 based on average injection/abstraction volumes over 15 year.

An often overlooked and major benefit of the WMARS is the downsizing or deferment of future water supply infrastructure. This would either entail transferring water from the Okavango River over 700 km north of Windhoek or transferring desalinated water from the coast over 370 km west of the city and to an elevation of 1650 m above sea level. Volume based savings are calculated at 33% based on the 99% security of water supply to Central Area of Namibia by 2030. (Van der Merwe 2016 [9]). Besides significant energy savings, the expected capital savings on the cost of future augmentation supply infrastructure will be at least two times the total investment of the capital required for full implementation of the WMARS.

In considering water augmentation options, the economic implications of the "do nothing" scenario is also relevant. The economic loss of a "run-dry situation" where water is only supplied to "wet" industries (breweries, abattoirs, bottling plants, etc.) and mining downstream of the Von Bach Dam amounts to US$ 1.5 million per day or US$ 388.5 million/year. (Van der Merwe 2016 [9]).

To complete the project a further amount of US$ 54 million is needed to eventually be able to abstract 19 Mm^3/yr from an enlarged water bank of 61 to 71 Mm^3, dependent on the thickness of the aquifer that can be utilised, which in turn is dependent on the final drilling depths of intersection of target fault zones (LCE, 2019 [2]). In addition to capital funding requirements it is expected that beneficiaries shall co-finance the operation of WMARS over the economic lifespan of the project with US$ 115 million for operational costs and capital replacement over 30 years. Yet, it yields a positive net present value despite a set of conservative assumptions and irrespective of the future choice of water supply augmentation scheme i.e. desalination and transfer or transfer from the Okavango River. When WMARS is integrated with the desalination scheme option, the economic internal rate of return (IRR) is 94%. In the case of integration with the Okavango River Transfer scheme, the IRR is 68%. In both scenarios, the IRR by far exceeds 10%, the economic opportunity cost of capital (UNDP 2017 [10]).

13.6. Social Sustainability

Institutional Arrangements

Significant challenges were overcome prior to the operation of the scheme. These included assessing whether the aquifer could receive and store water, constructing the conveyance infrastructure and ensuring the quality of the injectant met the agreed requirements. However, probably the biggest challenge lies in the institutional arrangement. The source water, obtained primarily from the 3-dam supply system, is bought from the bulk supply authority (NamWater) and sold to the municipality for storage in the municipal-run aquifer. Although not finalised yet the agreement between the two organisations aims to improve the security of supply during extended periods of drought and may generate income for NamWater during these periods when normally they would sell less water. It can be argued that low-value water which would have evaporated from the surface water sources is now stored in the aquifer or water bank for use during times of water scarcity; thereby transforming it from low-value water to high-value water at the time of supply to consumers. The main benefit however remains the security of supply to the Central Area of Namibia and its consumers.

Environmental Risk Management

Due to the high pollution potential especially in the Auas Mountain quartzites and the vulnerability of the Windhoek Aquifer, it is crucial that development on it be considered according to possible pollution sources and risk to the aquifer. The City of Windhoek has delineated a development limit line to protect the most vulnerable parts of the aquifer to the south of the city. All development to the south of the Kleine Kuppe and Auasblick neighbourhoods (10,000 potential residential properties) has been halted for this reason. The value of these properties based on average plot size and current land values in Windhoek is estimated at more than US$ 350 million. In addition specific limits and restrictions have been set in the pre-existing Prosperita area to prevent any future pollution and an outright ban on fuel stations in the southern areas of Windhoek has been instituted. A groundwater vulnerability map was completed to protect the aquifer against future pollution threads.

An Environmental Management Plan (EMP) for the project was initiated in 2014 which includes the provision for ecological monitoring. Issues include impacts possibly due to system changes and alterations, including requirements for maintaining an ecological reserve in downstream ecosystems of the ephemeral rivers, water quality issues and biodiversity hotspots in the Auas Mountains.

13.7. Conclusions

Between the late 1990s and the early 2000s the viability of artificially recharging the complex Windhoek Aquifer was demonstrated. By 2005 six injection boreholes were equipped and after seven years of recharge parts of the aquifer were filled back to the levels recorded in the 1950s before large scale abstraction began. The success of the scheme led to the drilling of additional deeper abstraction boreholes (up to 450 m deep) from 2005 until 2017. The aim is to maximize the use of the aquifer's available storage, and with this in mind, another expansion phase is planned for the near future. When fully developed and correctly operated, it is expected that the city's water bank (the Windhoek Aquifer), in combination with direct potable reuse will be able to provide security for more than three-years as the sole water sources during extended drought periods.In 2014 an Environmental Impact Assessment was conducted and it acknowledged the positive socio-economic impacts of the project in relation to its significance in creating a sustainable water source for the central area of Namibia. This project is therefore considered an essential component for securing the future of the population in the City of Windhoek and will play a key role in sustaining development and socio-economic health.

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Case Study 14: Multi-site urban stormwater aquifer storage and recovery to supply a suburban non-potable water distribution system in Salisbury, South Australia

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14.1. Introduction

The City of Salisbury is a local government region with over 130,000 residents in the Northern suburbs of Adelaide, South Australia. The City has developed a unique integrated approach to managing urban water (Box 1, Figure 1) [1]. Wetland treated urban stormwater is stored via aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) in confined limestone aquifers to provide a sustainable water supply that is distributed to customers via a dedicated non-potable 'purple pipe' network.

The distributed water is delivered at a standard fit for 'dual reticulation for indoor and outdoor use' [2]. However, several customers choose to treat the water to higher standards for their specific purposes.

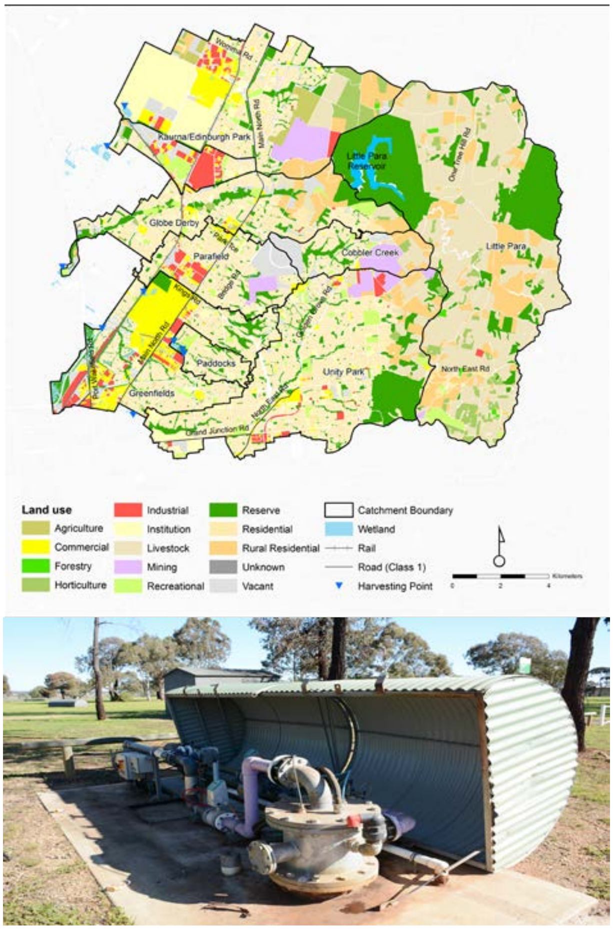

Figure 1.
Salisbury stormwater harvesting network and MAR well. Source: [3]; Photo © CSIRO

Box 1: Salient features of the Salisbury Water MAR scheme

Location: Adelaide, South Australia, Australia

Operator: Salisbury Water, a local government owned utility

Design: 9 urban stormwater harvest hubs, 31 ASR wells, 4 injection only wells, 28 extraction only wells, 150 km 'purple pipe' reticulation network

Commencement of operation: sale of water commenced in 2004

Quantity of stormwater harvested: 3.0×10^6 m^3/year (mean), 20% of average annual run-off

Quantity of water abstracted: 2.5×10^6 m^3/year (mean)

End use: domestic non-drinking and industrial supply

Source of water: primarily constructed wetland treated urban stormwater

Aquifer: Tertiary aquifers (T1 and T2) of the Port Willunga Formation, consisting of upper (T1) and lower (T2) sandy limestone aquifers separated by 5 -10 m thick confining layer of Munno Para Clay

Type of recharge: ASR, ASTR

Main advantage: reliable fit for purpose water supply using large scale cost-effective MAR storage to make effective use of seasonally-available urban stormwater

14.2. Motivation, conceptualisation and implementation

The initial and ongoing focus of Salisbury's urban water management is to manage the drainage and flood mitigation infrastructure that provides protection of property. From the 1960s, housing developments grew, and urban drainage became a serious issue. An extensive network of flood control dams, detention basins, drainage pipes and open swales direct the urban storm water run-off into three heavily modified 'natural' water courses, Dry Creek, the Little Para River and Adams Creek, which in turn discharge into the Barker Inlet, a tidal inlet of the Gulf St Vincent. This approach enabled the Council to develop land at a much lower cost than the traditional approach of a fully piped stormwater drainage network. While flood mitigation for new developments was the main objective, many of the basins and swales were planted with native vegetation and further developed with paths and boardwalks to provide recreational opportunities for residents.

In the early 1990s, community concern was rising about polluted urban stormwater and wastewater discharge into the Barker Inlet and Gulf St Vincent, a sensitive marine environment and important fish breeding area. Important legislative changes were made that resulted in waste water discharges being licenced by the SA EPA and resulted in significant capital expenditure to treat and reuse waste water from Adelaide's main waste water treatment plants. The regulatory reforms were not applied to stormwater discharge. One consequence is that management of urban stormwater in Adelaide remains disjointed, and largely falls to the coastal Councils who are most visibly impacted, to wear the burden of treatment. Salisbury's response at the time was to voluntarily set an ambitious goal of treating all stormwater through constructed wetlands, prior to discharge to the marine environment.

Over 70 wetlands and bio-filters have been constructed to intercept and reduce this pollutant load. Due to the low average annual rainfall (460 mm), the cost to irrigate Public Open Space (POS) was becoming an increased burden on the City's finances. While some native groundwater was suitable for irrigation, the majority of accessible groundwater is brackish and cannot be used without significant dilution or treatment. Prior to using stormwater, the City was typically using 0.8×10^6 m^3 per year of mains (drinking) water to supplement groundwater, in addition to a minor volume of recycled water from the Bolivar waste water treatment plant. Hence, development of the Salisbury MAR scheme was primarily driven by the community's desire to sustain the amenity of the City at an affordable price.

Cleansed stormwater from the City's constructed wetlands was an obvious solution but required large-scale cost-effective storage to facilitate the effective use of this highly variable water source. In order to manage the operation of the numerous schemes to harvest, store, treat and distribute their water, Council created their own dedicated water utility, the Salisbury Water Business Unit (SWBU). While predominantly of storm water origin, Salisbury Water supplies a combination of 'alternative' water including native ground water, rainwater, recycled industrial water, and recycled water from Bolivar waste water treatment plant.

The MAR network has progressed over several decades. Key partners in the initial stage of MAR scheme feasibility and implementation were from government and private sectors and demonstrate collaboration between private industry, resource managers, regulators and research (Table 1).

Table 1.
Key partners in MAR scheme feasibility and implementation in Salisbury, South Australia

Partner	Role
South Australian (SA) Department of Mines and Energy	Initial proponent of MAR in SA
SA Department for Environment and Water (DEW)	Resource regulator
SA EPA	Environmental regulator
Heyne Nursery – Commercial plant nursery	First external customer
Michell Wool – large industrial water user	First external funding partner and large-scale alternative water user
Parafield Airport Limited (PAL)	Provided land for the first large scale wetland/ MAR project in Salisbury
University of South Australia	Early advocate for alternative stormwater management
CSIRO	Research and validation of MAR
Australian Government	Funding partner over several projects

Several significant phases in urban water network development are described below:

Initial research on the feasibility of stormwater MAR: The Paddocks and Parafield ASR projects

In the early 1990s, monitoring at one of the early constructed wetlands, The Paddocks, demonstrated that water quality flowing through these wetlands was being significantly improved. An adjacent cluster of sports fields was also becoming an expensive burden on Council to irrigate with mains water. Thus, Council commenced an investigation of options for use of the wetland water on the playing fields. The key issue was storage, as the majority of rainfall falls in winter and the irrigation demand stretches across a long hot dry summer. Council worked with the State Government (SA Department of Mines and Energy) to undertake Salisbury's first ASR trial commencing in 1994, targeting the T1 aquifer (Paddocks ASR, capacity $0.05\text{x}10^6$ m^3). Recovered water was used by Council to fill an ornamental lake and subsequently irrigate adjacent sports fields.

This trial triggered the next significant step in the evolution of Salisbury MAR schemes; significant expansion of the customer base. Water recovered from the Paddocks ASR well was transported by tanker trucks to the Michell Wool scouring and carbonising factory at Salisbury South for scouring trials. The low salinity recovered water required less detergent, compared to mains water, in the wool scouring process. The trial resulted in a unique partnership between Salisbury Council, Michell Wool and Parafield Airport Limited, with funding support from the Australian Government (Parafield Partners Urban Stormwater Initiative). A purpose built stormwater recycling facility was built on buffer land adjacent to the runways of Parafield Airport, commonly referred to as the 'Water Factory'. This initiative has supplied 1-3 $\text{x}10^3$ m^3 per day to the Michell Wool processing operations, for the past 15 years (i.e. $5\text{-}16\text{x}10^6$ m^3). The Paddocks and Parafield schemes (capacity $1.1\text{x}10^6$ m^3) are now key supply hubs for the scheme that directly supplies recycled water to over 1,000 customers, and indirectly (i.e. via 3rd party retailers) to over 5,000 homes. The customer base includes 32 schools and over 100 sporting facilities across Salisbury and neighbouring council areas.

Capacity expansion: Water Proofing Northern Adelaide (WNA) project

The WNA project was a collaborative project to improve urban water management in Adelaide's northern region by integrating stormwater, groundwater, wastewater and drinking water systems to provide sustainable water supply resources. WNA was coordinated by a Regional Subsidiary formed by neighbouring local government areas, the Cities of Salisbury, Playford and Tea Tree Gully, in partnership with the Australian and SA State Governments and private industry. WNA delivered 18 integrated stormwater ASR projects across the three Council areas, with the theoretical capacity to harvest up to $5\text{x}10^6$ m^3 per year, and a dedicated non-potable, purple pipe, reticulation network. Salisbury alone added 2 Mm^3 supply capacity and the realisation of this capacity is increasing, as the economic case for expansion of the reticulation network to reach new customers becomes viable.

Potential expansion of customer base: Aquifer Storage Transfer and Recovery (ASTR) and Managed Aquifer Recharge and Stormwater Use Options (MARSUO) research projects

CSIRO and City of Salisbury collaboration on MAR spans over two decades and has delivered two major research initiatives addressing the long-term sustainability of urban stormwater MAR; the Aquifer Storage Transfer and Recovery (ASTR, 2003-2010) and

Managed Aquifer Recharge and Stormwater Use Options (MARSUO, 2010-2014) projects. ASTR, a key sub-project of WNA, considered the potential for stormwater recycling via the aquifer for drinking water supply. This project, while ultimately not an economically viable proposition for a recycled water operation in a competitive environment, successfully demonstrated that urban storm water could be cost-effectively treated to drinking water standard [5, 6]. MARSUO built on this by assessing the technical, social and economic feasibility of stormwater use for a range of uses (irrigation, domestic non-potable, potable), with and without MAR. These research projects provide science to underpin expansion of the uses for, and customer base for alternate water supply [7].

Capacity expansion: Whites Road/Daniel Avenue Reserve MAR project

In 2009, Salisbury secured funding under the Australian Government's Water for the Future - National Water Security Plan for Cities and Towns' program to focus on a large scale 'bottom of catchment' treatment scheme. The site, designed with CSIRO and University of SA input, was intended to be a large-scale MAR applied research site for both waste water and stormwater. Unfortunately, the intended collaborative research project, titled 'A Brilliant Blend' was not supported by SA Water, the State Utility responsible for drinking water and waste water services. The site has now been integrated into the MAR network (capacity 1.0×10^6 m^3) and Salisbury continues to explore opportunities to develop the potential of this site with expansion of stormwater harvesting from the Dry Creek and Little Para catchments and/or integration with an industrial waste water re-use scheme being evaluated.

Capacity expansion through technology: Water for the Future Unity Park Biofiltration project

With funding support from the Australian and State governments, this project demonstrated the application of 'small footprint' biofiltration options that could pave the way for widespread application in urban areas across Australia, where space is limited for large wetland-based stormwater treatment options. The project, which won a Stormwater Industry Association (SIA) National Infrastructure award in 2014, demonstrated clever utilisation of available land, with the harvest site 3 km away from two treatment wetlands and eleven bio-filters. The wetlands and biofilters are an integral part of a community park. The ASR storage well-field (9 wells) is a further 3 km away, located in the verge of a major arterial road. The distribution pumping station is in the re-purposed 'backyard' of a factory.

Integrated urban water management: Water for the Future Cobbler Creek/Bridgestone project

Over the last 20 years, Cobbler Creek Catchment (a sub-catchment of Dry Creek) has undergone significant urbanisation which has dramatically altered the stormwater flow regime of the creek, resulting in serious erosion and bank instability. The urbanisation has resulted in a large increase in annual runoff from the catchment, providing an opportunity for stormwater harvesting (contributing to the capacity in the Parafield ASR scheme). This 2016 project has resulted in an improved management regime for the Cobbler Creek recreation park, reduction in erosion and sediment runoff issues from the catchment, reduced localised flooding issues and has significantly offset drinking water demand. This was a collaborative project, with National Parks, Friends of Cobbler Creek Community Group, the City of Tea Tree Gully, the Natural Resources Management Board and the City of Salisbury engaging to deliver the best possible outcome. The scheme incorporates a large flood control dam, located in the Cobbler Creek National

Park, which controls flows from the modern Golden Grove housing development. The site has also become an important research site for a licenced groundwater desalination plant with permits to discharge brine to the lined stormwater drainage network. Trials are focused on reducing the cost of brackish groundwater desalination and evaluating the impact of brine discharges on the constructed wetlands. The high-quality desalinated water is sold to local industry and a cemetery, thus expanding the customer base for the alternative water supply.

14.3. Environmental sustainability

A network of constructed wetlands and MAR schemes harvest, treat and store urban stormwater to provide a sustainable alternative water supply and reduce pollutant loads to the marine environment. Benefits provided by this integrated approach to stormwater management include:

- Flood protection for property - this remains Council's highest priority
- Contribution to the overarching goal of a sustainable urban environment
- Restoration of local habitat and increased biodiversity – e.g. Greenfields wetland provides a habitat for over 180 bird species, including several rare species
- Protection of the downstream Barker Inlet, an estuary of the Gulf St Vincent and the largest fish breeding nursery in South Australia
- Natural treatment of stormwater, enabling a low-cost treatment option for community use
- An alternative water supply for industry, supporting economic development
- Creation of attractive landscape features, provision of areas for recreation
- Facilitation of research and development
- Opportunities for environmental education and awareness
- Employment opportunities and community volunteer engagement.

Environmental sustainability of the MAR network is addressed specifically through compliance with the Australian MAR Guidelines, which requires comprehensive management of health and environmental risks [4] and is a condition of regulatory requirements. The target aquifers for Salisbury's MAR network are typically composed of limestone and contain brackish groundwater, with total dissolved solids around 2000 mg/L. Therefore these aquifers' environmental values are not considered to include drinking water supplies and predominantly they are too saline even for irrigation use. Groundwater flow modelling [e.g. 5] is undertaken in scheme planning and reviewed on a five yearly basis to ensure the scheme can be operated within safe operating pressures and without adverse impacts on other groundwater users. The average injected and recovered volumes indicates that <80% of injected water is recovered. Water quality monitoring is also undertaken in planning and regularly during operation to ensure injected and recovered water quality meets target values.

Research at Salisbury has provided knowledge which can be applied more broadly for environmental sustainability. Further understanding has been provided on the potential of urban stormwater as a drinking water supply resource [6-8]; an assessment of the reliability of urban stormwater supply under variable climate, which revealed that impervious urban areas are more resilient to climate change than pervious rural catchments [9]; and of the potential for natural treatment of pathogens [10, 11], nutrients [12] and organic chemicals [13] in the aquifer to reduce the need for engineered water quality treatment. The levelised unit energy cost for pumping for injection and recovery in stormwater ASR has previously been reported at 0.10 kWh/m^3 (<3% unit energy cost for desalination) [14].This estimate did not include energy costs for water treatment or embodied energy in existing infrastructure. Energy intensity for the Salisbury MAR network is estimated at 0.06 kWh/m^3 for injection, 0.14 kWh/m^3 for extraction and 0.30 kWh/m^3 for distribution. Distribution energy requirements include pumping and the embodied energy of the purple pipe network. Dandy *et al*. reported energy savings of 0.5-1.6 kWh/m^3 for water supplied by stormwater MAR for irrigation or drinking water supply, when compared to traditional supply for Adelaide (River Murray or desalination plant) [15]. This accounted for embodied energy of existing infrastructure.

14.4. Cost and benefit considerations

The City of Salisbury has an integrated approach to managing all water resources across the City in order to maximise the 'water benefit' to the community. The capital cost (capex) of Salisbury Water's MAR network is AUD $52M, and the average annual operating cost (opex) is AUD $3M. Council has established an internal business, Salisbury Water, to manage sales of all recycled water to its own parks and gardens service, industrial users, schools and other institutions and new residential subdivisions. Based on the average annual volume of water recharged to and recovered from the aquifer (Box 1), the monetary benefit attributed to annual water sales is AUD $5M.

The MAR network was supported through Australian (AUD $28M) and State (AUD $6M) government initiatives to secure urban water supply, in conjunction with a loan from City of Salisbury (AUD $22M), which is expected to be repaid within 5 years. All major projects, since 2001 have been subject to rigorous business case evaluation prior to proceeding to securing funding.

The community, homeowners and industry all benefit from the security of a reliable, fit for purpose water supply, at lower cost than drinking water, provided by Salisbury's MAR scheme. Community benefits include high quality irrigated sports fields and the amenity of 'green' public open space. The constructed wetlands used to harvest and treat the urban stormwater have also become important passive recreational sites for the community.

While there has been no economic cost benefit analysis of the entire Salisbury scheme cost benefit analysis has been undertaken for twelve configurations for stormwater use, encompassing public space irrigation, residential non-potable supply and drinking water supply in part of the Salisbury scheme, in the Parafield catchment. Eight of the twelve configurations assessed included MAR. Public open space irrigation using MAR had the lowest levelised costs (from $0.98/m^3), which reflects the scheme as operated [15]. The relative cost of MAR compared to the lowest cost alternative (using the existing mains water drinking water supply for irrigation (\$2.43/ m^3) [15]), gave a benefit cost ratio of 2.5:1. A multi-criteria analysis (MCA) was used to assess environmental and social costs and benefits [15]. This assessment included the net present value (NPV), for reducing supply from a fully allocated water resource with a tradeable value (River Murray). This also demonstrated savings in greenhouse gas release due to avoiding pumping River Murray water to a height of 500 to 700m to reach Adelaide's drinking water storages, with an energy and greenhouse gas intensity equivalent to that of seawater desalination. There was also a shadow value in relation to reduced stormwater discharge of nitrogen and suspended solids to the Gulf of St Vincent, where costs of alternative measures with equivalent effect to reduce loss of seagrass were known. Public support and public trust was substantially higher than for either pumping from the River Murray or for seawater desalination [7, 16].

14.5. Social sustainability: regulations and community engagement

Salisbury Water reports to a Governance Board with both internal (Council) and external members who can provide technical, commercial and legal oversight to the business. The Board advises the City CEO, who is accountable to the community-elected Council and ensures that the Council/Community objectives are met in an efficient and professional manner. Community objectives were initially focused on the marine environmental impact, urban aesthetics and sustaining high quality sports grounds. Increasing awareness of urban heat and other public health issues is now seeing a much greater community demand for 'greening' of the City.

MAR schemes in South Australia are regulated under the *NRM Act 2004*, and the *Environmental Protection* (EP) Act 1993, the *Public Health Act 2011* and *Development Act* 1993, where applicable. The City of Salisbury Project Management Manual ensures all major project phases are undertaken in accordance with the *Development Act*. The Australian MAR Guidelines require a comprehensive risk-based assessment and management of health and environmental risks and underpin the management of water quantity and quality in relation to MAR in each jurisdiction [4]. Stormwater MAR schemes in metropolitan Adelaide are authorised by SA EPA under the Environment Protection Act to discharge stormwater to underground aquifers. Licences are available in a public register and licence conditions include recharge locations, maximum recharge volume per year, water quality criteria for source water, contingency planning, water quality monitoring and reporting requirements and approval of a MAR Risk Management Plan developed in accordance with the Australian MAR Guidelines. A comprehensive assessment of externalities is encompassed within the risk-based framework of the Australian MAR guidelines [4] and has been reported for the Salisbury MAR scheme by Page *et al* [20].

Risk-assessment and management of Salisbury's MAR network includes assessment of injected stormwater and recovered water quality against relevant water quality guideline values [3, 17]; determining supplemental treatment requirements prior to use [6]; aquifer characterisation and solute transport modelling to optimise recovery efficiency of water at suitable quality for the intended use [5]; establishment of appropriate operational trigger values for use in risk-management [18]; and evaluating the potential for biofilm and sediment formation in pipe material receiving stormwater [19].

Community involvement through consultation and education processes are essential components of risk management in accordance with the Australian Guidelines for Water Recycling, including the MAR Guidelines [4] and Stormwater Harvesting and Reuse Guidelines [2]. For example, a risk management plan for Salisbury's Parafield scheme [20] documents various communication pathways including personal communication, customer agreements, information sheets, electronic and print media.

Public awareness of the Salisbury MAR network is very high with regular exposure in local and State media. The City of Salisbury host Natural Resource Management (NRM) Sustainability Education staff who facilitate education programs in local schools. Salisbury Water staff also conduct regular tours for technical visitors and support a wetland volunteers' group in providing community group tours.

Focus group and web surveys have reported a high level of public acceptance for stormwater use in third pipe residential and drinking water supply [16].

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Case Study 15: Recharging floodwaters to depleted aquifers for irrigation in the Ganges Basin, India

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15.1. Background and motivation

India lies within a region disproportionately affected by climate- and water- related risks, with severe associated consequences for the national economy and its population [1]. Excess intense monsoonal rainfall regularly causes devastating floods, whilst deficits cause catastrophic droughts. The average economic impact of floods in India over recent decades is estimated to be more than US$ 1 billion per year with 22 million people affected. The corresponding figures for drought is put at US$ 62 million per year and 25 million people affected [2]. Resilience to both drought and flood is diminished by widespread groundwater exploitation, which affects around 31% of the administrative units in the country [3]. Rising water demand combined with clear signs of increasing climate variability due to climate change combined with rising water demand have greatly exacerbated water insecurity nationally [4].

India's long and proud traditions in MAR have been biased towards the more drought-prone and socioeconomically depressed parts of the country. More humid, flood-prone areas have received limited attention [5,6]. With the rapid expansion of groundwater use in recent years, so too, distinct signs of depletion have also emerged even in these areas [3].

There is a clear need for pragmatic, cost-effective, socially inclusive and scalable solutions to lessen the impacts of recurring and worsening cycles of floods and droughts and growing groundwater depletion [7]. *Underground Transfer of Floods for Irrigation* - or simply "UTFI" [16] - is one such solution that serves to redress spatial and temporal mismatch between water availability and demand at the river basin scale. UTFI focuses on recharge of excess wet season flows into aquifers to strengthen resilience of groundwater dependent communities [7-10]. It is also a novel twist on existing modalities of MAR. Implementation takes place at the local level and is replicated across suitable locations within a basin so as to achieve the desired cumulative effect in mitigating floods and in boosting groundwater reserves over wider areas.

This case study presents a synthesis of the learnings gained from initiating and testing UTFI at the pilot scale within the Gangetic Plain in India. In so doing, it outlines the challenges, gaps and ways forward for knowledge and capacity enhancement that could help facilitate more wide scale implementation in India and potentially similar settings elsewhere.

Box 1: Salient features of the UTFI pilot

Location: Jiwai Jadid village, Uttar Pradesh, India (28.784 N, 79.202 E)

Design: 10 recharge wells (25-30 metres deep) drilled into base of village pond (75m x 35m) situated adjacent to an irrigation canal

Commencement of operation: Commissioning in 2015 followed by trialling from 2016 to 2018 and advancing to operational mode from 2019

Quantity of water recharged: 26,000-62,000 m^3/year

End use: Village water supply (irrigation & domestic)

Source of water: Pilankhar minor canal – sourced from a tributary of the Ramganga river

Aquifer: Surficial fine-medium Quaternary alluvium

Type of recharge: Well recharge method (through gravity)

Main advantage: Reduce flood risk and enhance groundwater storage to boost resilience to droughts

Site management: Project partners with local community during 'trial mode' and later transferred to the District administration during 'operational mode'

15.2. Conceptualisation and implementation

Piloting and implementation of emerging new technologies such as UTFI should involve thoughtful planning and staged development to minimise any potential risk. The sequence of staging ideally followed may be broadly categorized as: (i) large-scale mapping of UTFI prospects; (ii) local-level site identification and verification; (iii) pilot-scale testing and evaluation to establish proof-of-concept; and (iv) outreach and advocacy to facilitate scaling up [9].

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[16] UTFI was formerly referred to as "Underground Taming of Floods for Irrigation"

This case study focuses mainly on the on pilot-scale demonstration and testing phase. Selection of the pilot trial site at Jiwai Jadid village in India was based on a detailed selection process including regional mapping of site suitability at the basin scale [10] followed by local verification through surveys of actual biophysical conditions and interactions to gauge the level of support of the local community, as the primary beneficiaries of the intervention, before proceeding with piloting [7]. A degree of care was taken to avoid selecting sites where obvious signs of pollution from industrial sources was evident.

Jiwai Jadid is situated on the Upper Gangetic Plain in the district of Rampur in western Uttar Pradesh (Figures 1, 2). Groundwater provides the main source of domestic and irrigation water in the village and throughout the district. Available observations for the period from 2004 to 2014 show that groundwater levels across the district have been declining at rates ranging from <0.01 to 0.7 m/yr [11]. As a result, four of the six sub-district units (blocks) are categorized as ‘highly overexploited’. Annual abstraction within Milak block, where Jiwai Jadid is located, is estimated to be 81% of total recharge. In recent years the village has been inundated by monsoonal flooding in 2010, 2013 and 2015 [11].

Piloting focused around the use of village ponds due to highly constrained land availability brought about by high population density and intensive year-round cultivation for rice and wheat. Community-owned village ponds are nowadays largely abandoned as the dominant source of irrigation water has switched from ponds and canals to privately-owned groundwater wells. In 2015 a pond in the village was rehabilitated and converted to a pilot structure. A total of 10 recharge wells, each 150 mm in diameter, were drilled through the base of the pond down to depths of 25 to 30 meters where strata is comprised of fine to medium sand layers occasionally intersected by clay lenses. This upper unconfined aquifer is the source for much of the groundwater pumping in the area. Water is siphoned into the pond from an adjacent small irrigation canal which receives river flows from a tributary of the Ramganga river. Raw water is pre-treated by sedimentation within the pond and by gravel-filled tank beds constructed around each of the recharge wellheads before recharging by gravity to the aquifer. The stored surface water is recovered via existing domestic and irrigation wells in the local area. An upper 6 to 7 meter blanket of heavy clay soil precludes surface-based recharge methods being applicable in this case. A suite of 9 piezometers at locations around the structure enable the close monitoring of groundwater level changes around the pond.

Pilot operations were conducted over three years from 2016-18 that followed initial short-term testing during the latter stages of the 2015 monsoon. Desilting of the gravel filter beds was performed on an annual basis, whilst manual desilting of the pond base and of the recharge wells using an airlift pump around every second year.

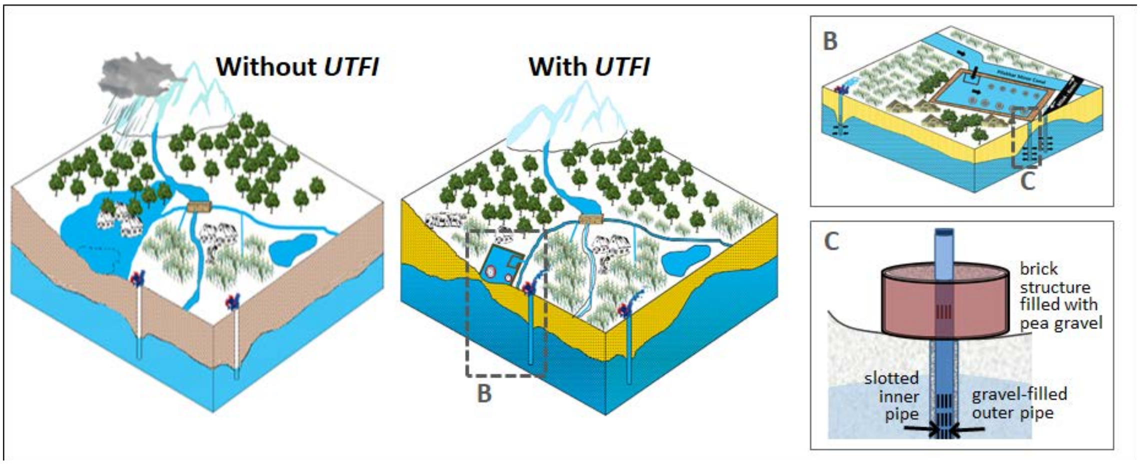

Figure 1.
Schematic representations of the implemented design and functioning of the pilot UTFI system. Source: Adapted from Pavelic et al. (2015) [23]


(Photo credits: IWMI)

Figure 2.
View of the pilot site before (left) and after (right) construction in 2015. © IWMI

15.3. Environmental Sustainability

15.3.1. Water quantity

The volumes of water stored each monsoon ranged from 26,000 to 62,000 m^3 over recharge durations ranging from 62 to 85 days, giving an annual hydraulic loading rate from the pond of 10 to 24 metres. The two-fold inter-annual variation is a function of duration and intensity of rainfall; depth to watertable (which controls local hydraulic gradients); quality of the recharge water; and frequency and extent of de-clogging operations [12]. Intra-annual declines in recharge rates were observed as a result of gradual siltation of the filters and wells from turbid water (total suspended solids values ranged from 50 to 1,000 mg/L), combined with the reduced hydraulic gradients as watertables rose over the course of the monsoon due to rainfall-induced recharge.

Groundwater level mounding and extent due to recharge was limited due to the target aquifer's high permeability and unconfined conditions [11]. Peak mounding was observed to be 0.8 metres or less and most clearly evident at the beginning of the season when recharge rates were highest. Furthermore, periodic pumping from nearby wells to meet the crop water demands for paddy rice caused difficulty in delineating responses to recharge mounding. The volumes recharged through UTFI were estimated to range from 2 to 4% of the total recharge at the village scale [12]. Whilst the contribution to groundwater stocks of the village are modest, they could be further enhanced if the two other ponds within the village were retrofitted for recharge.

15.3.2. Water quality

Surface water and groundwater quality monitoring showed mixed results. Selected constituents, including fluoride, nitrate, arsenic and chromium were not detected at levels that are of concern relative to the Indian drinking water standards (Table 1). In contrast, faecal coliforms, lead, mercury and TDS did periodically exceed the standards. Arsenic in the recharge water and groundwater did not exceed the 'maximum permissible' standard of 50 μg/L [17], but regularly exceeded the more stringent 'acceptable' standard of 10 μg/L [13]. Faecal coliforms exceeded the standards in 100% of recharge water samples and between 89 to 100% of groundwater samples, including those piezometers located farthest from the pilot site where any potential impacts from recharge operations are not expected. Lead and mercury were commonly detected at levels higher than the standards in both the recharge water and the groundwater. TDS levels exceeded the standards in up to 17% of recharge water samples and up to 42% of groundwater samples.

Microbial pollution of groundwater is not altogether surprising as wastewater is poorly managed in the village (e.g. pit latrines are used in dwellings). Community ponds serve as disposal sites for wastewater from open drains servicing the village. Tens of thousands of industries (e.g. textiles, steel fabrication, paper and pulp, wooden furniture, leather and sugarcane mills) deemed moderately to highly polluting by the Central Pollution Control Board are distributed throughout the Ramganga basin [14]. There is considerable evidence to show that pollution of soil and water across the Ramganga basin is widespread [15,16]. Industrial activities situated upstream of the site would be the most likely source of the elevated concentrations of specific metals observed. The data suggests that contamination of groundwater due to salinity, microbes (coliform bacteria) and some heavy metals had already been present in Jiwai Jadid village prior to pilot commencement.

Water quality is an area that warrants careful scrutiny. Whilst the UTFI intervention has introduced constituents of concern to the aquifer, it has also helped to reduce the concentration of heavy metals in groundwater by dilution and thereby reduced toxicological exposure to the local inhabitants. Thus, the pilot has not caused net detrimental harm. Targeting shallow aquifers polluted by local and upstream sources is appropriate in this context. These results also highlight environmental issues on a larger scale than could explored in a pilot study. There is a need for a wider examination of catchment-wide landuse planning and pollution control measures within the basin. The Gangetic Plain contains extensive groundwater resources, and thus careful planning is needed to avoid recharging waters of impaired quality into deeper aquifers less affected by anthropogenic activities. When scaling up UTFI, baseline monitoring of source water and ambient groundwater should be part of the site selection process to ensure major water quality issues are avoided.

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[17] applicable in the absence of alternative water sources

Table 1.
Percent exceedance of recharge water and groundwater relative to Indian drinking water standards. The range of exceedance values represents the variation between years.

Parameter	N[1]	Standard [2]	Recharge Water Exceedance (%)	Groundwater Exceedance (%)
pH	141	6.5-8.5	0	0
Total dissolved solids (mg/L)	141	500	0-17	24-42
Fluoride (mg/L)	123	1	0	0
Nitrate (mg/L)	57	45	0	0
Faecal coliforms (MPN/100mL)	36	0	100	89-100
Arsenic (µg/L)	54	10 / 50[3]	100 / 0	93-100 / 0
Chromium (µg/L)	54	50	0	0
Iron (µg/L)	54	300	0	0-28
Lead (µg/L)	54	10	0-100	0-10
Mercury (µg/L)	54	1	67-100	67-83

[1] total number of surface and groundwater samples analysed
[2] [13] Bureau of Indian Standards (2012)
[3] both the acceptable limit of 10 µg/L and maximum permissible limit of 50 µg/L are used

15.3. Ecosystem services

UTFI has the potential to enhance a range of ecosystem service benefits such as flood control, groundwater recharge and dry season water availability. Some of these benefits are difficult to establish reliably at the scale of a pilot trial and may be better quantified through broader basin scale modelling studies [17]. For the case where 20% of the mean outflow from the Ramganga river basin (6,000 Mm^3) is recharged through a distributed arrangement of UTFI structures, modelling shows that groundwater level declines and flood frequency could be substantially reduced, and baseflow to rivers and streams enhanced. On the basis of the trial results, it is estimated that around 25,000 village ponds would need to be converted to achieve 20% reduction. Across Rampur district alone where mapping has taken place there are no fewer than 1,800 ponds, indicating high potential for scaling up within the basin.

15.4. Costs and Benefits

The capital cost for replicating the pilot, non-inclusive of research-related costs, is $US 11,500 (₹ 800,000). Annual maintenance costs are estimated to be $US 1,400 (₹ 100,000) [18]. The estimated levelised cost of water recharged is $US 0.048 (₹ 3.4) per m^3. Estimates of the UTFI attributed agricultural output are based on the average recharge volume of 45,000 m^3/yr of which 75% is withdrawn for agriculture and the remaining 25% retained in the aquifer to support environmental flows. The quantity of irrigation water is sufficient to irrigate 9.6 hectares of wheat during the rabi (winter) cropping season with an irrigation water requirement of 350 mm. Gross economic returns to farmers are $US 315 (₹ 22,000) per hectare [19]. The total benefits from an agricultural production viewpoint alone are larger than the operating costs with a benefit cost ratio of 1.34:1.

15.5. Social Sustainability

Acceptance of UTFI by local communities and government authorities is an essential prerequisite for sustainability. The local context, as reflected in the socio-cultural setting and institutional frameworks determine which, and to what extent, communities perceive and gain benefit from UTFI. Piloting provides a tangible way for these stakeholders to be meaningfully informed about UTFI and to strive for convergence between their expectations and reality. Site visits and Open Days helped demystify how UTFI functions, how benefits are derived, and how it can be best managed. A key milestone was achieved through the integration of annual maintenance of the system into a national flagship program for guaranteed rural employment (Mahatma Gandhi National Rural Employment Guarantee Scheme, MGNREGS). This involves community participation in regular maintenance tasks, paid through the government. The institutional arrangements have evolved as the barriers to a well-functioning and sustainable system have been identified and incrementally addressed. Initially site management was handled by the project team working closely with community leaders, together with field support by local villagers. As UTFI was demonstrated to perform effectively, management was handed over to the district authorities after appropriate training was provided to government personnel to manage the system and liaise with the local community to ensure the site is operated and managed appropriately.

Earlier attempts to achieve village-level self-governance of UTFI faced numerous insurmountable challenges relating to resourcing and risk and was subsequently abandoned. These challenges were interpreted as a sign of the weak institutional environment in the village [20]. Women's groups are not active in the piloted area. There is minimal participation of women in decision making, site selection and other interactive processes, reflecting their limited degree of inclusion in agriculture in the village, and perhaps more broadly, deeply entrenched social and cultural barriers to participation [21, 22]. Women largely perceive UTFI as a men's domain and consequently few women would be willing to engage. For example, women would not help to maintain the infrastructure, even if there were financial incentives in place and existing rules around caste were to allow this.

15.6. Upscaling UTFI

The value of UTFI is most apparent when implemented at scale. Some success in the planning for scaling up has emerged in the piloted district. UTFI has been formally recognized by the Government of India and is included in the so-called District Irrigation Plan for Rampur with budget allocations under the national flagship program, PMKSY ('Pradhan Mantri Krishi Sinchayee Yojana' which translates to 'Prime Minister's Irrigation Program'). The plan allows for a total of 50 sites with a capital investment of US$ 1.2 million (₹ 7.5 crore) over a time-frame of 5 to 7 years. The geographic focus is on the sub-districts categorized as having most critically overexploited groundwater, as recharge to enhance groundwater storage is a higher priority than flood reduction in this part of the Ganges Basin. Opportunities to scale up have been facilitated through close engagement and support provided by high level officials within the district and by having a project team engage closely with the district nodal agency of PMKSY.

Over the long term, successful mainstreaming of UTFI into policies and planning hinges upon continued progress along both research and development pathways to ensure the technical knowledge and institutional capacity to implement and manage UTFI are put in place.

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Case Study 16: Soil aquifer treatment system to protect coastal ecosystem in Agon-Coutainville (Normandy), France

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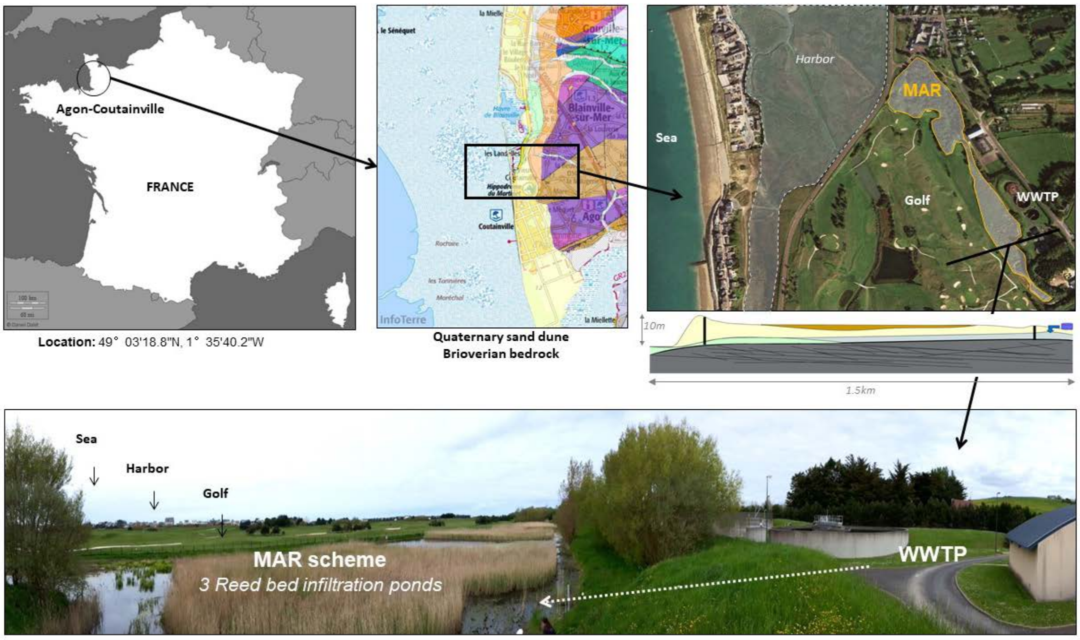
16.1. Introduction and origins from concept to implementation

A Soil Aquifer Treatment (SAT) scheme has been implemented in Agon-Coutainville for more than 20 years and sustainably integrated within the municipal wastewater treatment system for 13 years [1]. The Agon-Coutainville commune is located in France in Normandy, along the West coastline of the English Channel, between the Hague pointe, and the bay of Mont Saint Michel and is 10 km from Coutances (Figure 1).

16.2. Motivation, conceptualization to implementation

The commune, with an estimated population of 2,800 residents (INSEE, 2015), is one of the oldest seaside resort of the Manche department and the location of the largest production of shellfish in France. The preservation of the coastal ecosystem, and the associated sanitary stakes are essential for local economy and has to be fully integrated to the ongoing development of residential areas, tourism and shellfish aquaculture. Subject to a large tidal range, the groundwater resources are prone to salinization in this coastal area, resulting in a superficial hydraulic area with low capacity for water supply.



Operator: SAUR company

Commencement of operation: 2005 with the actual form

Quantity of recharged water: 2000 m^3/day (500 to 5000 m^3/day)

Main advantage: improved water quality discharged to the habitat of shellfish production and bathing activity

Design: activated sludge pre-treatment, 3 infiltration ponds with reed bed, 5 observation wells, 5 online monitored wells (salinity, temperature, water level)

Source of water: urban/municipal wastewater

Aquifer: shallow sand dune coastal aquifer (Quaternary)

Type of recharge: infiltration ponds flooded by gravity

End use: Environmental purposes

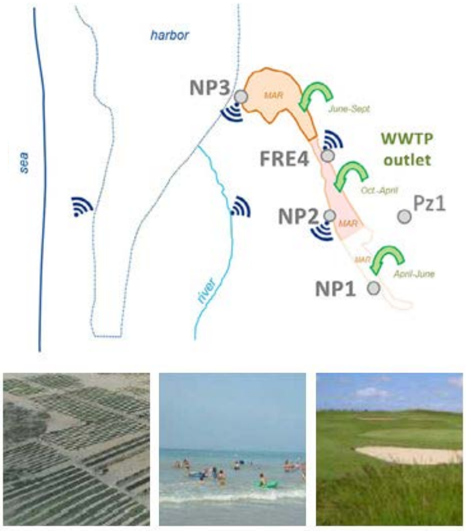


Figure 1.
Layout of MAR-SAT scheme in Agon-Coutainville.
Source: Own elaboration; Photos © Géraldine Picot-Colbeaux

Sustainable water management has to take the seasonal variation of the population and the irrigation needs of the backshore golf courses into consideration. In addition there is a need to adhere to environmental regulations (eg.French Coastal acts) and an ambitious water quality target, in spite of financial constraints (requiring a minimal cost system). To face this demanding challenge and to preserve the estuary ecosystem in Agon-Coutainville, the SAT system has been considered as locally more efficient and sustainable than the conventional direct discharge system to surface water (river or sea).

The integrated system relies first on the engineered treatment by an activated sludge process within the Waste Water Treatment Plant (WWTP) composed of pre-screening, pump station, buffer tank, rotating screen, oil and grit separators with sand classifiers (separator tanks), two aeration tanks (4000 m^3), a 470 m^2 clarifier, a treated water counting canal. The WWTP treats and infiltrates via the SAT system ~2,000 m^3/day varying from 500 to 5000 m^3/day depending on seasons and holidays. During winter, flow is significantly higher because the WWTP also receives rainwater. Based on an estimated accommodation structure of about 35,300 population equivalent, the Agon-Coutainville WWTP has a maximal capacity of BOD5 treatment up to 2,120 kg/day. The urban treated wastewater flows by gravity to one of the three infiltration ponds outside the WWTP. Once in the infiltration ponds, treated wastewater infiltrates through the reed beds to recharge the coastal aquifer composed of a 2 to 10 m layer of Quaternary sand. The three infiltration ponds are alternatively flooded during the year (Figure 2): flooding of the southern infiltration pond from June to September; flooding of the central infiltration pond from October to March; and flooding of the northern infiltration pond from April to May.

Figure 2:
Central infiltration pond: a) flooded; b) dry. © Géraldine Picot-Colbeaux

16.3. Environmental Sustainability

16.3.1. Groundwater quantity

The completed monitoring within the AQUANES project shows a significant rise (0.5 – 1 m) of the water table in the shallow sand dune aquifer mostly downstream of the infiltration pond. However, no flooding or seepage was observed to nearby surface depressions.

Although water reuse is currently not allowed, one potential application of water reclaim through the SAT system would be for irrigation purpose of the golf course during the dry season (from April to October). Such alternative water supply for the golf would require a minimal quantity approximated to 300 m^3/day or equivalent to 64,200 m^3/year, based on the current irrigation use (pumping of 30 m^3/h x 10 h/day x 214 day). The reported amount of infiltrated water during the dry period is around 250,000 m^3/year (average infiltration of 1,175 m^3/day, minimum of 1,040 m^3/day and maximum of 1,280 m^3/day recorded between 2006 and 2019. Hence, golf course irrigation could take up 26 % of seasonal infiltrated water.

Results from a multidisciplinary investigation were merged into a decision support tool developed to identify the most favourable zone with respect to water quality within the shallow sandy aquifer for irrigation use. Thus, freshwater production potential zone of the aquifer is identified including Managed Aquifer Recharge (MAR) which improves buffering against saline intrusion in dry years and large tides.

16.3.2. Groundwater quality

To assess water quality improvements of the SAT system, wastewater is collected and analysed at the inlet of the WWTP (before treatment), at the outlet (after treatment) and after the SAT system from five observation wells in the shallow sandy aquifer (NP1, NP2, NP3, FRE4, Pz1, see Figure 1). The observation wells are located at a distance of 20-30 m from the discharge pipes. The SAUR operator performed a long-term monitoring with respect to infiltrated flow rate (continuous monitoring for 20 years) and water quality (discrete sampling for 13 years). The monitored parameters were defined based on governmental regulation for water discharged from the WWTP outlet (Table 1) and the Groundwater Framework Directive (GWD: Directive 2006/118/EC) for groundwater downstream to the infiltration ponds (Table 2). Such approach aims to ensure that the groundwater composition fulfills environmental quality constraints at the outer part of the infiltration ponds [2, 3].

At the WWTP outlet, the long-term monitoring (750 to 900 analyses) confirms that 99% of the water samples follow the quality guidelines for most of the regulated inorganic and organic substances for the last 13 years (Table 1). There is one notable exception for phosphorus (Ptot) and the five days biochemical oxygen demand (BOD5) concentrations, for which 86% and 16% of the samples collected exceed the regulated threshold value, respectively.

Table 1.
Quality assessment of the water discharged at the WWTP outlet based on the French regulation and prefectoral decrees[18]. Dataset retrieved from the long-term monitoring (2006-2019)

Parameters	Threshold values[19]	Number of analysis required per year	Total amount of analysis from 2006 - 2018	% of samples above threshold value
Suspended solid (mg/L)	25	52	612	0.3
BOD5 (mg/L)	25	24	305	15.7
COD (mgO2/L)	90	52	621	0.3
Ntot[20] (mg/L)	15	24-12	292	0.7
NH_4 (mg/L)	10	24-12	316	1.6
Ptot (mg/L)	2	24-12	305	86.0
E. Coli (cfu/100ml)	-	24-12	313	-
pH	6 - 8.5	24-12	354	0.3
Temperature (°C)	25	12-6	938	0.1

Table 2.
Quality assessment of the groundwater monitored downstream to the SAT system based on the GWD (Directive 2006/118/EC). Dataset retrieved from the long-term monitoring (2006-2019)

Parameters	Threshold values for groundwater	Number of analysis per year	% of samples above threshold value
NH_4 (mg/L)	1-4 mg/l	12-14	35 - 2
NO_3 (mg/L)	50-100 mg/l	12-14	0-0
NO_2 (mg/L)	0.2-0.5 mg/l	0	-
Cl (mg/L)	200-250 mg/l	12-14	20.8 – 15.5
E.Coli (cfu/100ml)	250-1000 (cfu/100ml) [21]	12-14	7.8 - 2.9 (0 since 2015)

At the outlet of the SAT system, the groundwater significantly reaches concentrations below the recommended threshold values. Among the set of regulated parameters, the chloride concentrations, related to the natural tidal cycle, is higher than 250 mg/l for a minor part of the dataset. However, this trend affects only a single observation well. Ongoing monitoring provides the assurance that the risks are sufficiently managed and the groundwater quality meets the government's site-specific water quality requirements. Nevertheless, the number and the type of parameters useful for assessing the water quality could be optimized or completed.

An innovative and multidisciplinary monitoring performed within the H2020 AquaNES project (2016-2019) [3], which focuses on 1) the spatial salinity monitoring for detecting freshwater bubble generated by the SAT system and 2) proposing improvements to the current

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[18] Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment

[19] Prefectoral decree n°00-1000-IC - 01.AOU.2001 and Prefectoral decree n°04-1824 – 17.FEV.2005

[20] include nitrate NO_3, nitrite NO_2, ammonium NH_4 and N-kjeldhal

[21] Maximum admissible values for reuse of water used for Aquifer Recharge by percolation (indirect recharge) from Frame Handbook, (Polesello et al., 2018; adapted from DEMEAU, 2011).

monitoring systems. Field water sampling campaigns and tracer tests were conducted for a better understanding of the SAT efficiency using classical chemical measurements, and innovative approaches including online system monitoring device. Such device are dedicated to measurement of the groundwater level and characterisation of the extent of the MAR fresh water bubble and the seawater intrusion in the coastal sand dune aquifer (SMD [5], [6]). The number and the type of parameters useful for assessing the water quality has be optimized or extended to large set of the parameters including physico-chemical measurements (pH, Eh, temperature, salinity) and quantitative analyses (total amount of 75 elements of major and trace elements, pharmaceuticals compounds and organic and inorganic carbons).

The collected data further confirm that the SAT scheme results in further reduction in salinity (P50 Cl: 550 mg/L for WWTP Outlet, 125 mg/L in observation wells), concentration of Escherichia Coli (E.Coli) up to 2.5 order of magnitude and concentrations of regulated nutrients (e.g. NO_3, Ptot) up to one order of magnitude (Figure 3). Micropollutants, mostly discharged from the WWTP, generally displayed higher (median) concentrations in treated wastewater (WWTP Outlet), exceeding the recommended Environmental Quality Standards (EQS) ([GOW], [WATCH LIST]) for carbamazepine (CBZ) and diclofenac (DIC) (Figure 4). The SAT system, combined with the natural recharge, significantly reduce the concentrations of contaminants of emerging concern such as benzotriazole, CBZ and DIC concentrations (three of the 35 CECs monitored), which overall decline below the recommended threshold values defined by the EQS (Figure 4). The decrease of concentrations is likely due to the combined effect of dilution of the treated wastewater in the aquifer and biogeochemical reactions (sorption and/or degradation).

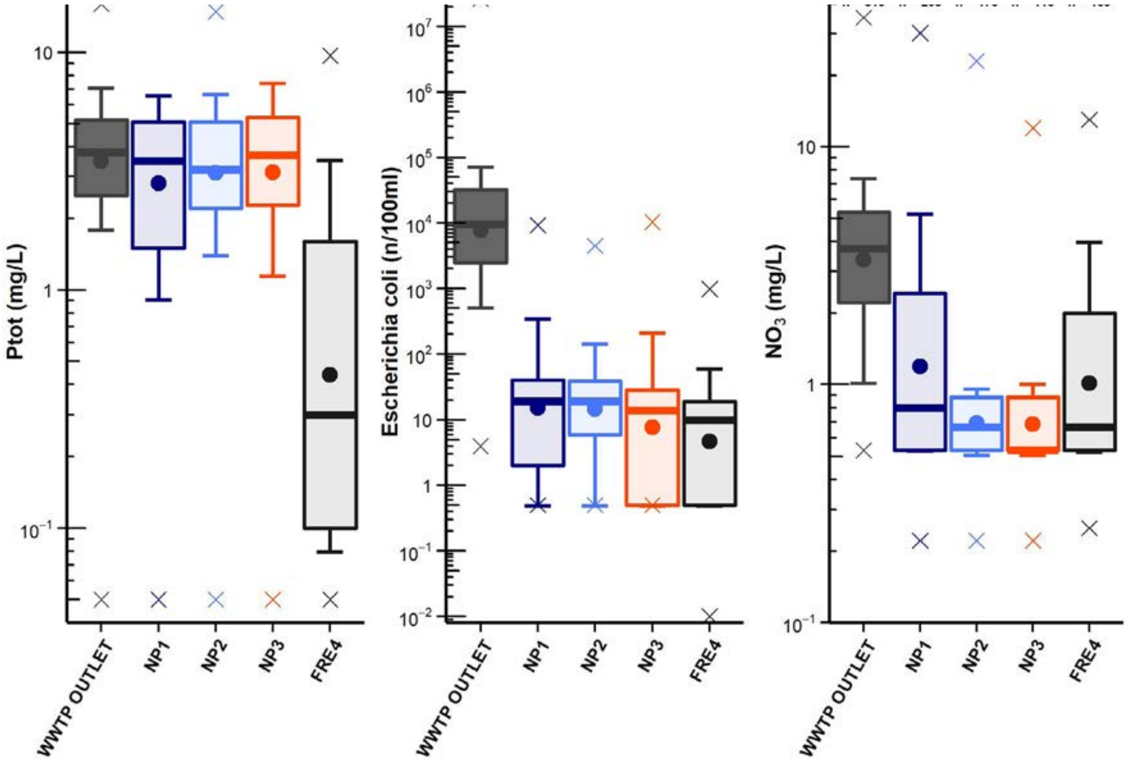

Figure 3.
Concentrations of regulated nutrients in effluent from the WWTP outlet and in groundwater for observation wells NP1, NP2, NP3 and FRE4 (see Figure 1).
Source: Own Elaboration

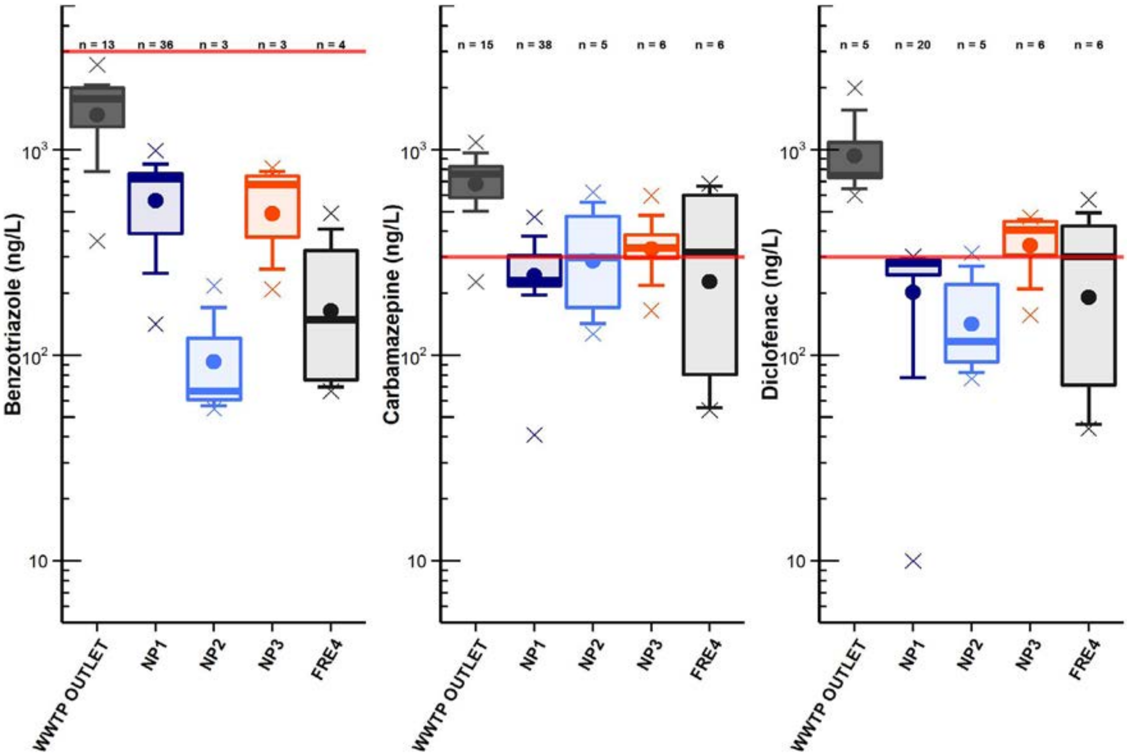

Figure 4.
Concentrations of three organic chemicals of emerging concern at the WWTP Outlet and in groundwater from observation wells NP1, NP2, NP3 and FRE4 (see Figure 1). The red lines indicate the recommended Environmental Quality Standards (EQS) ([GOW], [WATCH LIST]).
Source: Own Elaboration

The WWTP of Agon-Coutainville combined with SAT system is considered as beneficial for seawater quality when compared to the other WWTP systems where the reclaimed water is generally directly discharged in the surface water and regarded as an environmental contamination source along the seashore. From the current knowledge [3], the mean travel velocity, estimated to 1.8 m/day, results in a mean residence time of about two weeks to flow from infiltration ponds to the downstream observation wells. In broader context, the SAT allows bio- and geo- chemical reactions in the soil and the sand aquifer and thus could improve groundwater quality down-gradient depending of the distance of the natural outflow (1 month to 2 years). Although a general decrease of concentrations was characterized for many regulated substances, the respective extent of the ongoing dilution process and the biodegradation process for nutrients, E.Coli and micropollutants is not yet well defined in the SAT system. The value of the SAT system in Agon-Coutainville will be demonstrate during the next EVIBAN research project.

16.3.3. Energy Intensity and Environmental Benefits

The energy requirement of the WWTP has been monitored since 2007 and estimated to a mean value of 0.938 KWh/m^3. Because transfer of WWTP effluents to the infiltration ponds results from gravity phenomenon, the energy requirement is considered as null. The energy requirement for groundwater monitoring is estimated to 1.3 KWh per year and considered insignificant. The global WWTP-SAT system's energy requirement is therefore estimated to c.a. 0.938 KWh/m^3. The potential needs for irrigating the surrounding golf, mostly for pumping groundwater at 4-5 m of depth at a rate of 30 m^3/h, results in a 0.07 KWh/m^3 requirement.

No specific monitoring on the catchment has been dedicated yet for assessing the change in ecological flow due to the MAR scheme.

16.4. Cost and benefit considerations

The initial investment relies mainly on the land surface acquisition required for the infiltration ponds, the pipe installations to connect the WWTP to the ponds, and the observation wells (drilling and equipment costs). In the description of this initial investment, we exclude the cost referring to the preliminary environmental assessment (geological, hydrogeological or chemical) and stakeholder meetings which are necessary conditions for identifying the steps to be taken. The initial capital costs (when the wastewater treatment plant was built, e.g. before the 90s') is not easily disseminated through human generations and would require further historical research in the owner archive or municipalities 'archive.

The capital costs into land acquisition has been estimated based on an actual and local land cost of US$270/m^2. With a total infiltration surface area of 35,000 m^2, i.e. three reed bed infiltration ponds, the SAT system would have an initial land cost of US$9,450.0K. The capital cost of the five observation wells is US$8.5K and for the 600 m of pipes and manual valves is estimated to US$60.0K. The initial investment including land surface acquisition, pipe installation and observation wells is around US$9,500.0K.

As the MAR system in Agon-Coutainville is based on gravity for flooding the three ponds, the overall cost of operation is around US$20.0K/year, and dedicated to:

- reed bed maintenance (cutting cost),
- monthly groundwater sampling for five observation wells (5 x 12 = 60 samples),
- monthly groundwater analyses (NO_3, NO_2, NH_4, P_{tot}, Cl, E.Coli) x 60 samples.

The levelised cost of recharge under the scheme is estimated to be US$1.10 per cubic metre.

On a short-term perspective, the next innovation recommended for this site will focus on adaptation of SAT to meet the seasonal irrigation needs (April to October) for the nearby golf course (pumping 30 m^3/h during 10 h/day). Such action will require research on the full integration of the evolution of the groundwater salinity and its impact on the nutriment recycling under pumping conditions created by indirect reuse from the aquifer.

16.5. Social Sustainability

In France, there is neither centralised governance for managed aquifer recharge (MAR) practice nor French guidelines dedicated to MAR system. While water suppliers want to implement SAT systems an investigation study needs first to be applied and approved by prefectural authorization, most often in the context of preventing saline intrusion or to meet the need of seasonal water demand as required depending on climatic conditions. According to the European Water Framework Directive (WFD), the good status of the water bodies affected by a MAR system must be preserved.

In the case of Agon-Coutainville, the first issue would be to protect the coastal area and avoid discharge of the WWTP secondary effluent to the river, harbour or ocean. The Prefect issues the permit granting infiltration of the secondary effluent of the WWTP, establishes a specific monitoring program of the groundwater after the SAT system (5 observation wells) with a committee dedicated to follow the program, and evaluates it regarding the groundwater quality results. A specific prefectural order was signed in 2001 and completed with other orders for each modification of WWTP-SAT operation (for example, in 2003 enhancement of the WWTP and SAT system to increase the water treatment to 35,300 inh.eq. compared to the prior 10,000 inh.eq.) and regulation [7,8]. Signatories rallied for managing this authorization are mayors, vice-prefect of the department of Manche, directors of the Direction Départementale des Affaires Sanitaires et Sociales, Direction Départementale de l'équipement, Direction Départementale de l'agriculture et des forêts and then the director of the Direction régionale de l'environnement. The document details all the operational and alert conditions in terms of monitoring parameters (type, number, location and frequency of each analyse).

The WWTP-SAT operator has to inform stakeholders in charge of water policy, aquatic environment, the health agency (ARS) and water agency (Seine-Normandie) by:

- communicating the results 4 times a year for regulated parameters as described in the prefectural order;
- communicating immediately each noncompliance when results of water analysis are higher than the threshold value, and for each incident;
- reporting methodology, operations, internal organisation;
- reporting a yearly synthesis of the global results and efficiency of the system.

Mechanisms for community engagement included:

- Showing adults and school children WWTP and SAT installations and operations;
- Showing WWTP metadata on the french sanitation database [9];
- Advertising in community newspapers and providing media releases;
- Presenting at community forums;
- Facilitating access to the data and the WWTP-SAT site for research experiments and studies.

Acknowledgments

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Case Study 17: Intentional infiltration using irrigation canals to sustain Central Platte River ecology and irrigation

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17.1 Introduction

The Platte River stretches for 1,400 km, with a drainage basin of 230,000 km^2 in Central Nebraska, USA. The river flow is primarily snowmelt from the Rocky Mountains as it travels through semi-arid high plains. Hydraulically connected surface waters and underlying aquifers define the typical hydrogeologic setting of the Platte River Valley. The hydraulically connected nature of the Platte Valley system provides opportunities to re-distribute and re-time water supplies that support over 60,000 ha of irrigation. This particular project focuses on four surface water irrigation canals that have historically provided passive conjunctive management opportunities, and currently provide irrigation water and managed aquifer recharge. In 2015, these canals were rehabilitated for multiple purposes, including surface water irrigation, re-timing of excess flows to reduce flood risk, and aquifer recharge. Groundwater underlying the canals is hydraulically connected to the Platte River via the alluvial aquifer, thus ensuring that groundwater recharged from the canals eventually contributes to base flow that is essential for maintaining groundwater-based irrigation and drinking water supply, as well as critical instream flows for multiple endangered species that rely on river habitat, especially during times of drought. Between 2011 and 2018 over 49 million cubic meters (Mm^3) of surface water were diverted into three major canals, resulting in 11.11 Mm^3 of average groundwater recharge annually [1]. It is estimated that 1.8 Mm^3 (16%) was also returned to the Platte River as base flow [2] [3] [4].

The project is a partnership of the locally-organized private irrigation canal companies, the regional government agency Central Platte Natural Resources District (CPNRD), and State of Nebraska Department of Natural Resources (NeDNR). Additional funding was also provided by the Nebraska Environmental Trust, a state grant agency that uses lottery proceeds to fund projects that improve the natural resources of Nebraska.

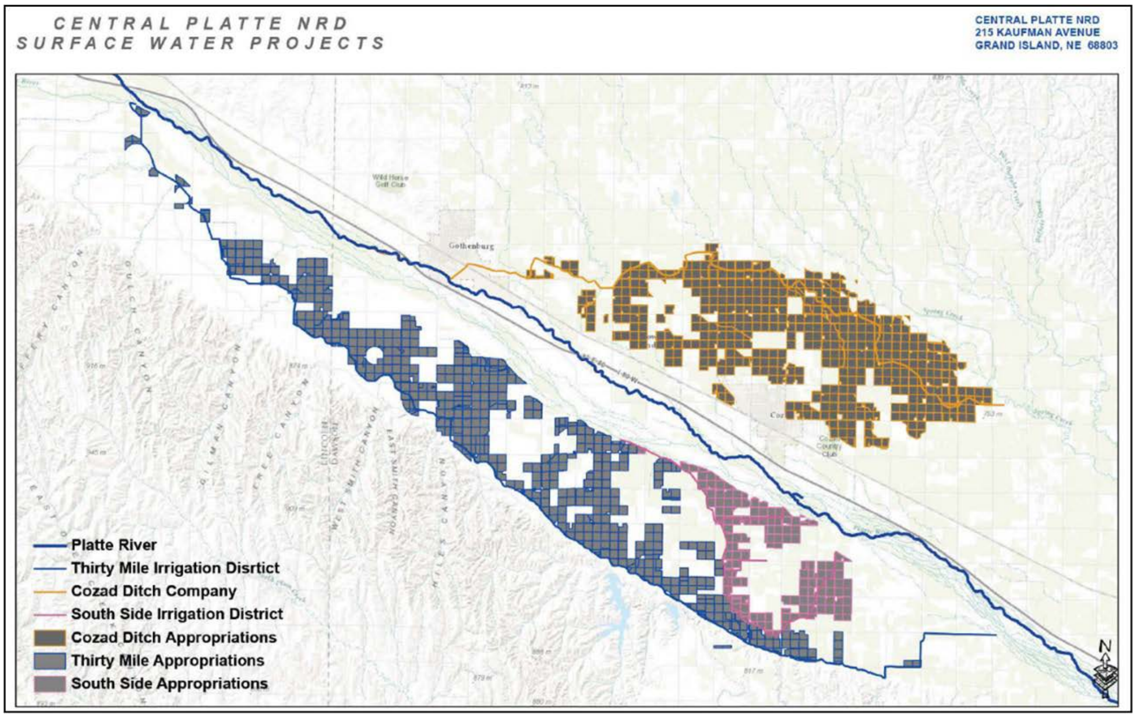

Figure 1.
Map of Central Platte managed aquifer recharge locations. Source: Own Elaboration

17.2. History of the project

The Central Platte Valley has an average annual rainfall of 910 mm. Irrigation has been used to enhance yields since the late 1800s, first using surface irrigation from a series of privately managed canal companies and later through groundwater pumping from the alluvial and High Plains aquifer. This water system also provides the drinking water for the residents of Central Nebraska. The relatively abundant supply of both surface and groundwater sources has led Nebraska to develop and irrigate more land than any other state in the USA. Most of Nebraska's irrigated land produces maize and soybeans. This has led to increasing pressure on the water supplies, leading to various conflicts and legal battles. Nebraska is also under pressure from several interstate compacts to mitigate streamflow depletion caused by groundwater pumping in order to protect habitats for endangered species and/or ensure adequate surface water supplies for downstream users (Platte River Cooperative Agreement/Platte River Recovery Implementation Program (PRRIP)[5]. These challenges have led to multiple strategies to manage the water system, including water allocations, restructuring reservoir agreements, reduction of irrigated land and aquifer recharge projects.

Nebraska's Natural Resources Districts, the Nebraska Department of Natural Resources (NeDNR), private irrigation districts and canal companies have increasingly turned to managed aquifer recharge (MAR) as a means to maintain functional linkages between groundwater and surface water supplies, while making use of excess flows and potentially damaging floodwaters. The Central Platte Natural Resources District (CPNRD) is a local-government entity responsible for the management of groundwater, while the NeDNR is responsible for surface water administration. This piece-meal legal management structure necessitates that multiple management entities cooperate to either build or manage any water project. The projects were funded through a partnership of CPNRD, NeDNR, private canal companies, and the Nebraska Environmental Trust.

The canals were in major disrepair after nearly a century of providing irrigation; however, the groundwater recharge provided by the leaky canals was still essential to mitigate groundwater declines from groundwater irrigation, as well as provide accretions to baseflows. So, in 2011, CPNRD approached the canal companies to negotiate a new way to store water in the aquifer and increase flows to the Platte River through rehabilitating the canals and diverting excess river flows.

CPNRD and the local canal companies first negotiated purchases or leases to form irrigation districts, an official political sub-division. Inter-local agreements were then signed for the continued maintenance and delivery of surface water for both irrigation and groundwater recharge. The projects were then approved by the NeDNR for excess flow water rights so that the partners can use the canal in the non-irrigation season to hold diverted excess Platte River flows when available. The rehabilitation portion of the projects included new water control structures and monitoring equipment, clearing undesirable vegetation, re-grading surfaces, and installing bank protection.

The project benefits current and future local farm families who use irrigation, rural households and communities that use the aquifer for drinking water, and wildlife that uses the river by helping to maintain adequate aquifer supplies. The agencies involved use a public stakeholder input process throughout project development, hold monthly public meetings, and provide project updates through print and digital media.

(1925): Diversion Point. Canal has been in place and diverting water for 120 years.

(2012): Channel overgrown with trees and channel in disrepair.

(2014): Channel at headworks holding water as designed.

Figure 2.
Historical photos of canals used in the Central Platte MAR. © Brandi Flyr

17.3. Indicators of Environmental Sustainability:

Groundwater quantity

The Central Platte MAR has been providing alluvial aquifer recharge and subsequent river returns since 2011. These returns vary depending on annual climate and crop water use. The diversions and returns back to the river are measured and MODFLOW is used to estimate recharge (Figure 3). The thousands of wells in the area are not metered, therefore it is not known how much was extracted. Groundwater levels have risen across most of the project area since the inception, even with an extreme drought in 2012 (Figure 4).

The recharge project site lies within the critical habitat reach of the Platte River Program, which is a species recovery program for the least tern, piping plover and whooping crane. River returns contribute to each species streamflow targets.

Year	Diversion (Mm^3)	Recharge (Mm^3)	River Return (Mm^3)
2011	23.72	20.09	1.27
2012	1.75	0.00	0.00
2013	9.30	5.28	0.77
2014	1.42	0.00	0.00
2015	15.61	11.18	1.66
2016	21.64	11.96	2.25
2017	12.16	10.19	3.10
Total	**85.59**	**58.69**	**9.05**

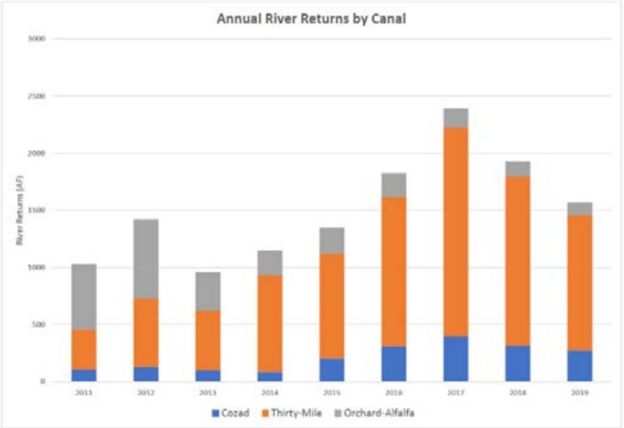

Figure 3.
Annual diversion, recharge, and river returns. Source: Own Elaboration

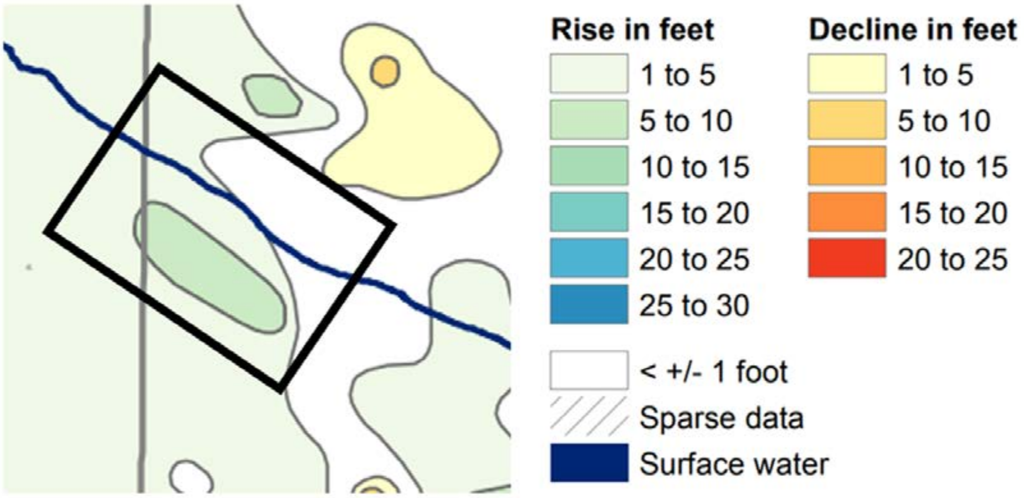

Figure 4.
Groundwater-level change in project area (black box) from spring 2008 to spring 2018.
Source: [6]

Groundwater quality

Platte River water being used for recharge is considered supporting its recreational, agricultural, and aquatic life uses in the project area. Groundwater nitrate testing in the project area has found 90% of the wells below 7.5 mg NO_3-N/l with only one sample exceeding the safe drinking water standard of 10 mg NO_3-N/l. [7]

Energy requirements

As a passively operated MAR system, there are negligible energy requirements to infiltrate, with the only energy uses being monitoring & operating the flows and gates. To recover the water, it would need to be pumped the same with or without the MAR project, so there are no additional energy requirements. Additionally, because the ground water table is only 1-2 meters below the surface, energy requirement for groundwater pumping is nearly the same as that of pumping water out of the canal.

17.4. Economic Costs and Benefits:

The canal rehabilitation was for both irrigation and MAR, and all three canals were completed under the same contract, therefore 50% of total costs were assigned to MAR. All values are in U.S. Dollars.

Capital costs		**Average Annual Project outputs (2015-2017)**	**(Mm^3)**
Total Design & Construction Cost	$14,426,113	Water diverted	16.47
Portion Assigned to Recharge	$7,213,056	Water infiltrated	11.11
Project preparation	$4,849,997	Water for river return	2.34
Construction: water conveyance	$2,363,059		
Annual Operating costs			
Labor	$9,156		
Management and maintenance	$10,780		
Total	**$19,936**		

The levelised unit cost of infiltrating water to the aquifer is estimated to be US$0.044/m^3 while the levelised unit cost of water returned to the river is estimated to be US$0.212/m^3.

Monetary benefits of the Central Platte MAR can be assessed by comparing the value of irrigated agriculture production or land valuation. As this watershed is considered over-appropriated (more users of water than is sustainable), the assumption can be made that many of the irrigated crop fields would have to become non-irrigated if it were not for the MAR. On average, this portion of Nebraska requires 230 mm of supplemental irrigation. If the 11.11 Mm^3 were not available in the aquifer, that would result in the loss of irrigation on 4,830 ha. In 2018 in Central Nebraska the average yield for irrigated maize 15.1 metric tons/ha (225 bu/ac) while the average non-irrigated production was 10.1 metric tons/ha

(150 bu/ac) [8]. Assuming a market price of $138 U.S./metric ton ($3.50/bu), this leads to an average annual value increase of $690 U.S./ha. With the project providing irrigation to 4,830 ha, its annual value is $3.33 million U.S. dollars. The levelised cost of annual infiltration is about US$0.5 million which implies a benefit cost ratio of 6.7:1.

The impact of irrigation on land values provides an alternative perspective on the benefits of the Central Platte MAR. In 2018, non-irrigated land in Central Nebraska was on average $6,793/ha, while irrigated land was valued at $15,833/ha, due to expected crop yield differences, a ratio of 2.33:1 [9]. The additional land value caused by the transformation of 4830 ha from non-irrigated to irrigated land is $43.7 million dollars.

There are also several external benefits that are hard to monetize, including improvements in water quality, drinking water supply, flood storage, and wildlife.

17.5. Social sustainability:

Governance

Local irrigation districts are local government entities, formed around surface water boundaries, with a locally elected board, who set taxes and fees, and hire staff to manage canals that provide surface water to member irrigators. Nebraska's NRDs are the entities primarily responsible for groundwater management, under the state's conjunctive use law. They have sole authority to regulate groundwater extraction and to enforce violations of district rules and regulations. The districts are governed by democratically elected boards of directors and managed by teams of technical staff. The NRDs are given taxing authority to provide financial security. District boundaries are based on watershed boundaries, with 23 in the state of Nebraska. The state fully supports local governance by the NRDs. The NeDNR is a state agency responsible for registering groundwater wells and permitting induced groundwater recharge in the state as well as overseeing surface water quantity and water rights under prior appropriation law. Surface water and groundwater quality (point-source pollution) is monitored by the Nebraska Department of Environment and Energy, while the NRDs are responsible for groundwater quality related to nonpoint source pollution. Surface water rights for the canals were established 1894-1927, the MAR project does not affect these rights.

This scheme is organized under the local Central Platte Integrated Management Plan (IMP), the basin-wide Platte River IMP, and the inter-state PRRIP. In instances where surface water and groundwater are hydrologically connected and fully or over-appropriated, the NRDs are required by NeDNR to develop a local IMP for surface water and groundwater, and many of the river basins have voluntarily created their own regional IMPs. The inter-state PRRIP is the result of the Platte River Cooperative Agreement between Nebraska, Wyoming, and Colorado to manage endangered species habitats in the Platte River Basin. The program's mission is to increase streamflow in the Platte River in the hope of improving habitats for endangered fish and bird species.

The agencies involved use a public stakeholder input process throughout development of IMPs, PRRIP, and the MAR projects. These included monthly public meetings and providing project updates through print and digital media.

30-year inter-local management agreements were negotiated between MAR project owners:

- Water appropriations will be leased from private Irrigation Districts to the CPNRD who are MAR project owners.
- 50% leased interest in real and personal property
- 50% leased interest in water delivery system, including operations & maintenance

Externalities

Local and Basin-wide IMPs address the impact on surface and groundwater resources and ecosystems and annual monitoring is conducted by NeDNR and NDEE. [7][10] PRRIP does annual monitoring of target endangered bird and fish species and preliminary results indicate that numbers have increased since PRRIP began their conservation efforts [11].

In the Great Plains region, climate change is expected to increase extreme events in the form of both increased potential for flooding and drought events. These MAR projects increase resiliency through storage and re-timing of excess flows.

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Case Study 18: Achieving water supply reliability at Hilton Head Island, South Carolina, USA

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18.1. Introduction

Treated drinking water is seasonally stored in an Aquifer Storage Recovery (ASR) well during winter months in a deep, brackish, semi-confined limestone aquifer. The stored water is recovered annually to help meet peak seasonal water demands during summer months, requiring only restoration of a disinfectant residual prior to distribution. Stored water is also utilized during emergencies such as loss of water and electricity during hurricanes, providing water supply reliability. Operation began in October 2013, achieving original ASR objectives and substantially reducing water supply costs to meet peak demands. Approximately 40 ASR wells are operational in South Carolina.

18.2. History of the project

Hilton Head Island is located on the coast of South Carolina, very close to Savannah, Georgia. Geologically it is close to the outcrop of the Floridan Aquifer, which begins in a channel at the north end of the island. Historically, springs in the sea floor discharged large quantities of fresh water that enabled sailing ships to replenish their drinking water supplies while remaining offshore. In recent decades, heavy regional groundwater production has reversed the direction of groundwater flow, causing saltwater intrusion beneath Hilton Head Island. The Floridan Aquifer extends southward several hundred kilometers to the southern tip of Florida, becoming deeper and increasingly brackish to saline. Beneath Hilton Head Island, the aquifer is comprised of an Upper Floridan Aquifer from about 30 m to 80 m depth which is semi-confined above and below and is karst limestone. This producing interval was originally fresh but is now experiencing relatively rapid saltwater intrusion. A deeper, karst limestone interval known as the Middle Floridan Aquifer occurs from about 156 m to 175 m and is brackish, semi-confined above and fully-confined below. This interval is utilized for ASR storage at Hilton Head Island.

Almost all the 12 original freshwater wells in the Upper Floridan limestone aquifer have been lost to saltwater intrusion, caused by decades of heavy pumping on the mainland. Saltwater intrusion continues, as a result of which remaining freshwater wells on the island are expected to become saline during the next few decades. Hilton Head Island is a popular, residential/tourist area that has experienced rapid growth since the 1980s and is challenged to provide a reliable, sustainable water supply. Three brackish water supply wells have been constructed, producing water from the Middle Floridan limestone aquifer for treatment at a reverse osmosis desalination plant that produces 15,000 m^3/d. This is supplemented by drinking water supplied from the mainland, purchased at approximately half of the normal wholesale cost during offpeak (winter) months and stored in an ASR well in the same aquifer utilized for brackish water supply, but at a distance of 4.4 km. The well is known as the Royal James ASR well. It has a 390 mm inner diameter PVC well casing. Static water level is 1.3 m below sea level, with about 0.3 m tidal variability. The stored water is recovered from the same ASR well during summer months to help meet peak demands, adding 8,000 m^3/d to the drinking water supply. During 2016 when Hurricane Matthew caused severe regional damage, including loss of the local power supply and road access, water supply was sustained by pumping from the ASR well, which was equipped with an emergency engine generator and fuel supply. The volume stored and recovered annually is 1 Mm^3, typically stored during October to March and recovered during May through September. Operation commenced in 2011 and has continued successfully since then. Based upon that success, two other ASR wells have been constructed on Hilton Head Island, operated by the South Island Public Service District since 2014. Seven other ASR wellfields with a total of 40 ASR wells are operational in South Carolina, some for almost 30 years.

Hilton Head Island ASR

Location: 32° 14′ 35.36″ N; 80° 44′ 01.79″ W. Elevation 2.5m. Hilton Head Island length about 20km. Width up to 8 km.

Water Source: Drinking water from reverse osmosis brackish water desalination plant on the island and from imported water transmission pipeline from mainland

Type of aquifer: semi-confined, limestone artesian aquifer containing brackish water (chloride 685 mg/l). Transmissivity: 418 m^2/d (4,500 ft^2/d) Storage Coefficient: 0.0001

End use: drinking water to meet peak and emergency water demands

Type of recharge: Aquifer Storage Recovery (ASR) well, utilized for both recharge and recovery

Scale: 0.95 Mm^3 recharged/recovered annually (store October to March; recover May to September)

Year Commenced: September 2011

Owner: Hilton Head Public Service District, the service area for which covers the northern third of the island

Unique Features: Purchase of imported water from regional water supplier on mainland at approximately half cost during winter months when supply is plentiful and marginal unit costs of water production and transmission are low. Imported water is blended with water from the reverse osmosis plant, stored in the ASR well, and then recovered from aquifer storage during summer months when peak demands are very high, or during emergencies. Drinking water is stored and recovered in a brackish aquifer. The same volume stored is recovered each year, meeting drinking water standards. Inner casing is PVC. A buffer zone of drinking water effectively separates the stored drinking water from the surrounding brackish groundwater. (HHPSD (2020) [1], Pyne (2013) [2]).

Figure 1.
Well ASR-1 at Royal James, with pump, motor, wellhead piping, equipment shelter for electrical and SCADA controls, disinfection and emergency engine. © David Pyne

This was an emergency water supply effort due to the failure of the District's most productive water supply well due to saltwater intrusion. A collaborative effort of the HHPSD (Owner), ASR Systems (Consultant), contractors (well drilling, well equipping, SCADA), and the State Regulatory Agency (SC Department of Health and Environmental Control) enabled construction and placing the ASR well online in 26 months, a record short time. Funding was provided by the Owner.

The ASR project success has led to construction and operation of two more ASR wells at the south end of Hilton Head Island, for South Island Public Service District (SIPSD), following shutdown of the first of their freshwater supply wells due to saltwater intrusion. The SIPSD ASR wells are essentially the same design and operation but the well casings are larger inner diameter PVC casings (530 mm) set to slightly greater depths than for HHPSD.

The project beneficiaries are the residents and visitors to Hilton Head Island, who have a demonstrated reliable water supply from diverse sources, including ASR, meeting all drinking water quality standards and at reasonable cost. There are no particular considerations for women, other than that ASR Systems LLC, the design engineering company, is a registered Women Business Enterprise. The Chief Executive Officer (CEO) is Emily W. Black, a professional civil engineer.

18.3. Sustainability

Groundwater quantity

Water levels are below sea level due to excessive groundwater withdrawal about 30 km away in Georgia which has resulted in the lowering of groundwater levels (~ 7 m depth) to below sea level, causing sea water intrusion. However, groundwater quantity is not a significant factor for this project. This is a seasonal storage project, not long-term water banking. There is no net annual change in water level in this aquifer. The purpose is to meet seasonal peak demands from storage. Based on >6 years of daily data, the ASR wells inject on average 1 Mm^3/yr. This water is then recovered during summer months over about 120 days, with the amount ranging from 0.9 to 1.1 Mm^3/yr. So, the ratio of injected and recovered water is about 1 on an annual basis. There are two monitoring wells, one about 100 m away in the Middle Floridan Aquifer (the storage aquifer) and one at the base of the Upper Floridan Aquifer, about 30 m away. Water level and water quality data is collected periodically and reported annually to the State Regulatory Agency. The storage aquifer is semi-confined, not fully confined. Well interference with the desalination wells was a concern but they are too far away to have any adverse effect. There is a self-imposed limit on recovered volume of about 1.0 Mm^3/yr. Any more than that and vertical movement through the overlying confining layer during recovery months would cause chloride to be excessive, or the need to reduce the recovery flow rate.

Groundwater quality

Ambient groundwater quality is steadily deteriorating due to saltwater intrusion. Thirty-five years ago groundwater from the Upper Floridan aquifer was 100% of the local drinking water supply. Thirty-five years from now it is likely that the Upper Floridan aquifer will have been almost completely lost to saltwater intrusion and will increasingly become a significant source for brackish water desalination. The Middle Floridan aquifer will likely become an underground reservoir for ASR storage, supplementing its use for brackish water desalination to the extent that adequate separation distance can be maintained between brackish water supply wells and ASR wells so that short-circuiting does not occur. Original monitoring was comprehensive, addressing many water quality constituents that were of interest. This was subsequently scaled back as results were repetitive. Chloride is currently the primary indicator constituent. Monitoring of ASR recovered water quality since 2011 indicates no exceedance of water quality standards during recovery. This is also the case for the source water, which is treated drinking water.

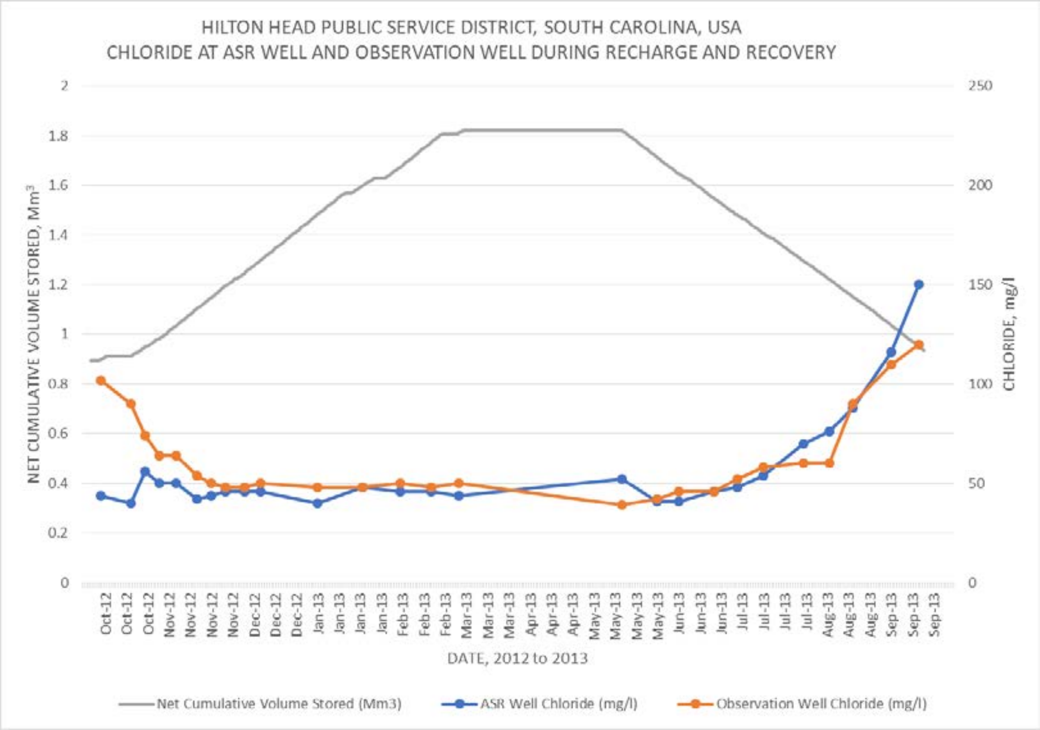

Figure 2.
Graph showing typical water quality response during a one-year period. The top line is cumulative volume stored during the year, including a 0.91 Mm^3 (240 MG) buffer zone. The bottom two lines show chloride concentration at the ASR well and at the storage zone monitor well, 100m away. Source: Own Elaboration

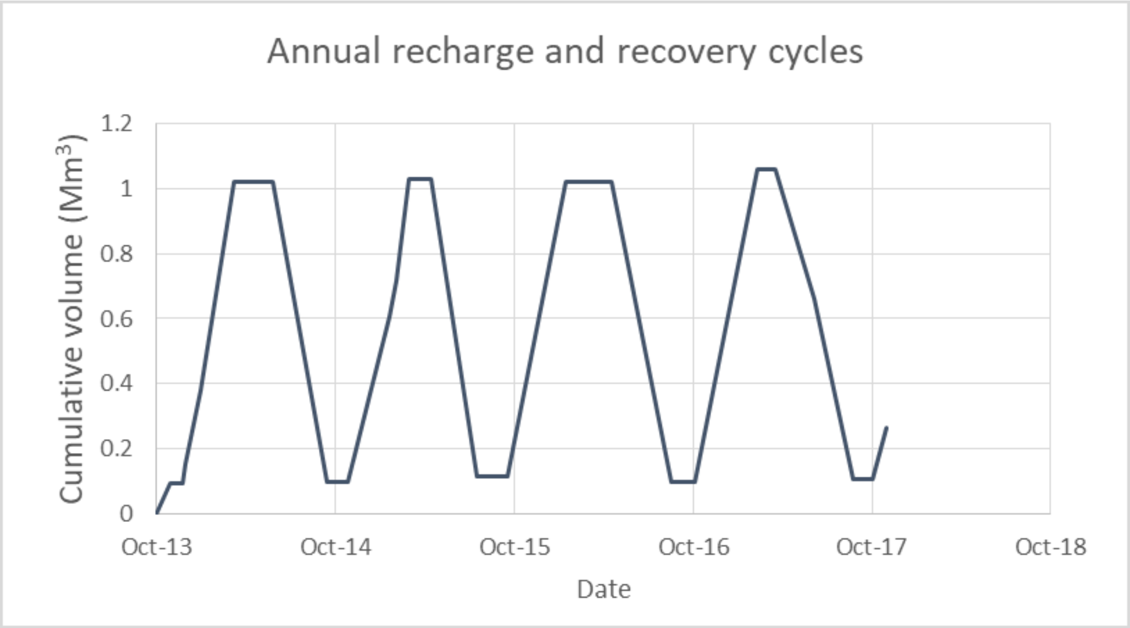

Figure 3.
Net Cumulative Storage Volume, 2013 to 2018 for Hilton Head Public Service District ASR Well. Source: Own Elaboration

The difference between the cumulative volumes stored during Figure 2 (cycle testing) and Figure 3 (routine operations) is that the buffer zone volume was hidden from operating records, thereby reducing the motivation for operators to continue pumping the buffer zone after the stored water volume has been recovered each year. Native groundwater choride concentration was 685 mg/l.

Although further studies are desirable, environmental benefits may include carbon sequestration because TOC reduction typically occurs during ASR storage, particularly when the original water source is surface water. One of the HHPSD water sources that supplies the water for ASR storage is the Savannah River. Also, the footprint for ASR facilities is very small considering the large volume of water stored, as might be compared with a surface reservoir or an aboveground tank. Between May to September 2018, 0.96 Mm^3 (254 MG) was recovered to the distribution system, with energy consumption costing US$27,282. Assuming a reasonable energy cost of US$0.10 per kWh, this would equate to 273,000 KWh. Unit cost would have been about 0.3 KWh/m^3. Energy requirements for water storage underground are small compared to energy requirements for desalination of brackish groundwater ~1 KWh/m^3 to meet comparable peak demands. All wastewater is treated and recycled for irrigation purposes.

18.4. Costs and Benefits

Capital cost for construction of ASR well and wellhead facilities, including engineering services plus construction, totalled US$1,796,679 and was completed in 2012. A transmission pipeline to get seasonally available drinking water to the site for recharge added about US$2,000,000 since the local distribution system piping conveyance capacity was inadequate. Initial formation of a buffer zone of 0.9 Mm3 (240MG) to separate the stored drinking water from the surrounding brackish groundwater in the storage aquifer cost about US$144,000 There were no land acquisition costs since the well site was on property owned by HHPSD. Total capital investment in 2011 to 2012 was therefore about US$3.941M.

Annual operating cost for 2018 included the following:

Water purchase during winter months	$ 226,919
Pumping costs (transmission, storage and recovery)	$ 27,282
Restoration of disinfection residual after recovery	$ 15,935
Total	**$ 270,136**

The Hilton Head scheme is set up to meet peak summer demands and emergencies, by engaging in seasonal storage and recovery. In this instance the unit capital cost for providing reliable recovery capacity per day is an appropriate metric for assessing cost. Previous ASR studies have shown this to range from about US$0.13 to US$0.53 per litre/day of recovery capacity (US$132 to US$530/m^3/day). A typical unit cost for planning purposes would be about US$0.33 per litre/day (US$330/m^3/day). For Hilton Head, the unit capital cost was US$0.49/litre/day (US$490/m^3/day), but about half of this cost was for local distribution system pipeline improvements to get water to the ASR well for storage.

Average annual volume of water recharged to aquifer storage and recovered from aquifer storage is the same, 0.95 Mm^3 (250 MG). The total recovered volume is supplied to water users for potable purposes. The value of the water recovered and distributed each year at typical retail water rates is about US$817,680 for average tier times. One measure of the benefit cost ratio (BCR) for the project would be the ratio between the total annual cost for amortisation and operations and the annual value of water recovered and distributed. This gives a BCR of 1.93 using the assumptions made by the project managers (3% discount rate 50 year life) and a BCR of 1.50 using the standardised assumptions used in this publication (5% discount rate 30 year life). An alternative measure of value would be the cost to purchase from the mainland the same volume of water at peak summer rates instead of low winter rates. That would be about $446,400 however that option would probably entail several million dollars of additional capital costs for a parallel transmission pipeline to convey the additional water to the island during peak summer demand periods. Another alternative would be to expand the desalination plant capacity from 15,000 to 22,700 m^3/d (4.0 to 6.0 MGD) and rely totally on local brackish water supplies. This would tend to exacerbate both vertical and lateral salt water intrusion while also increasing the gradient between ASR well storage and brackish water wellfield pumping, thereby decreasing ASR recovery efficiency. A preliminary estimate of the associated cost is US$6.3 million, assuming US$0.79/litre/d (US$3.00 per gallon per day) of additional treatment capacity, including additional supply wells, brine disposal and associated infrastructure.

ASR is far more cost-effective, typically with capital costs at least 50% lower than construction of treatment and transmission facilities sized to meet peak day demands. Furthermore ASR storage takes place during winter months when the price of water is low and recovery takes place in summer when the price of water is higher (Pyne 2005 [3]).

There are no known "external third parties" in this case. Beneficiaries are those who benefit from having a reliable, sustainable, water supply.

18.5. Sustainability

Governance. The USA and the State of South Carolina have well-established laws, policies and rules governing "Underground Injection Control (UIC)," originally enacted by EPA in 1981 pursuant to federal legislation passed in 1975. Rule interpretations have evolved with time, and vary state-by-state, however most states are supportive of recharging aquifers and storing high quality water underground that meets or exceeds drinking water standards.

The ASR regulatory approval process was well-established and involved two steps, including submittal of planning and final engineering design documents for regulatory agency approval to begin construction, and a final approval to begin operations after submittal of final construction documents plus proof that the recovered water met drinking water standards. The commissioning stage extended over a period of several weeks, including preparation of an Operations and Maintenance Manual; conducting an Operator Training Program; startup of operations; adjustment of operating procedures to match well initial hydraulic response to recharge, recovery, backflushing, trickle flow during extended storage periods, and shutdown. South Carolina is very supportive of ASR. There are now 8 ASR wellfields in South Carolina, one of which has 26 ASR wells.

HHPSD holds monthly public meetings. Annual reports on ASR are filed with the state agency and are publically available. Public awareness of the ASR program is probably highest among island residents who understand the seriousness of the salt water intrusion challenge, and the need for a reliable, sustainable water supply. Visitors to the island, particularly during the summer, are probably unaware that they are drinking and bathing in water recovered from seasonal storage in ASR wells, blended with water from other sources.

Externalities. There are no known externalities impacting the HHPSD ASR program. Looking more broadly, supportive externalities are increasingly common, including concerns about declining groundwater levels, saltwater intrusion, subsidence, sea level rise, unreliable and emergency water supplies, etc. Adverse externalities are rare. Opposition to ASR has been in a few areas of Florida where ASR has been purposefully confused with deep well injection of treated wastewater into much deeper, saline aquifers. This confusion was subsequently shown to be intentionally stirred up by lawyers for their own pecuniary interests, a practice that was stopped through public disclosure of the legal strategy. In one area (eastern North Carolina) opposition to ASR was based on the demonstrated presence of PFAS (a persistent flame retardant and suspected carcinogen) in all drinking water sourced from the Cape Fear River. (It was also found in rainfall and occasional other water supply wells). In response to public pressure, stored water in a local ASR well was then pumped out and discharged to waste, just prior to Hurricane Florence in 2018. The regional water system then failed due to hurricane damage, as did the regional power supply and road access. Their ASR well had an emergency generator and fuel supply, but unlike Hilton Head, no water remaining in storage. ASR opposition in Florida from 2001 to 2013 was based on concerns about arsenic mobilization caused by ASR storage, however that was shown to be easily controllable through inexpensive operational measures (initial formation and maintenance of a buffer zone around the stored water) that had already been demonstrated successfully from 1981 to 2001. That issue has now subsided, and there is strong support for storing water underground through ASR wells and recharge wells. Benefits include raising groundwater levels, helping to control subsidence, preventing salt water intrusion, achieving water supply reliability, meeting peak demands, saving money, and many other benefits. There have been no unacceptable adverse effects resulting from ASR operations at Hilton Head Island.

Acknowledgements

We acknowledge those individuals at Hilton Head Public Service District who have guided ASR program development since about 2010. They include; Richard Cyr, former General Manager (recently-retired), Bill Davis (Operations Manager); and Lee Barnard (Laboratory Manager). We also acknowledge the many Board members of HHPSD during this period who have continued to support the District's ASR program.

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Case Study 19: The Serchio River bank filtration for drinking water supply in Sant'Alessio area of Lucca, Italy

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19.1. Introduction

The River Bank Filtration (RBF) scheme along the Serchio River in Sant'Alessio (Lucca, Italy; Figure 1) supplies drinking water continuously with good chemical quality. An average yearly volume of 16 Mm^3/year (in the last four years; source GEAL SpA) is delivered to about 300,000 inhabitants of the cities of Lucca, Pisa and Livorno (Italy [1], with the surrounding areas mainly being agricultural or peri-urban/rural. RBF is by far the most common Managed Aquifer Recharge (MAR) scheme in Italy, even though it is not formally recognized as such by government authorities who do not appear to acknowledge that groundwater extraction is sustained by induced recharge through the river bank and is not entirely from natural recharge, or ambient groundwater.

Box 1: Salient features

Location: 43°51'42.00"N, 10°27'56.00"E to 43°51'18.00"N, 10°30'19.00"E
Operator: GEAL SpA (Water Utility)
Design: 12 vertical wells located between 30 m and 100 m from the river reach complemented by a river weir for raising surface water head by about 1.5 m
Commencement of operation: 1967
Quantity of water abstracted: 16 Mm^3/year
End use: domestic (drinking) water
Source of water: Serchio River
Aquifer: Holocene coarse sand and gravel overlain by silty surficial cover
Type of recharge: Natural and Induced RBF
Main advantage: sustainable abstraction of high quality and quantity of groundwater by RBF
Distribution: to 300,000 residents of Lucca, Pisa and Livorno

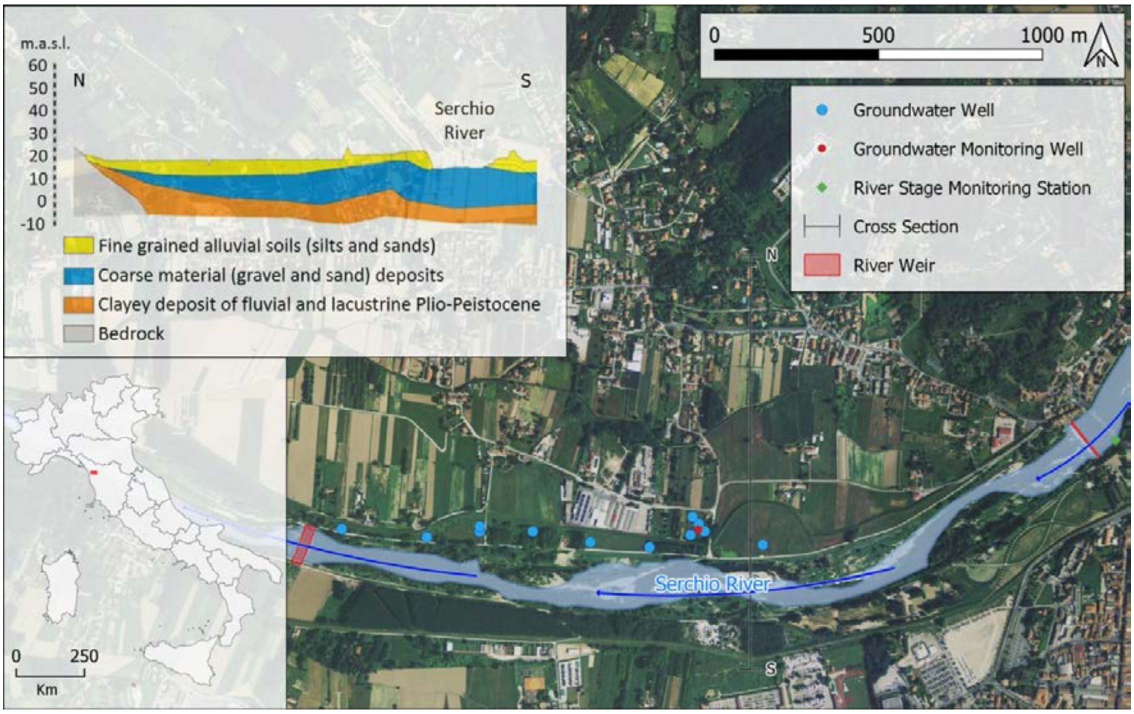

Figure 1.
Layout of the Serchio River bank filtration scheme in Lucca, Italy.
Background image rt_ofc.2k10 - OFC 2010 2k col Ortofotocarta anno 2010 proprieta' Regione Toscana. Dettaglio 1:2000. Licence CC3.0

Figure 2.
The Serchio River in the area of the Sant'Alessio river bank filtration scheme.
© Rudy Rossetto

19.2. Motivation, conceptualisation and implementation

Since the 1960s, the Sant'Alessio area along the Serchio River (Figure 1 and Figure 2) was deemed suitable for groundwater abstraction for drinking water purposes. Four vertical wells were set in operation in 1967 about 100 m away from the Serchio River to supply the north western households of the Lucca town with about 100 l/s or about 3.1 Mm^3/ yr [2]. During the 1980s hydrogeologic investigations funded by Lucca Municipality were carried out to define aquifer flow dynamics and yield [2]. These studies highlighted the presence of a highly yielding sand and gravel aquifer capable of providing up to 400 l/s or 12.6 Mm^3/ yr, hence suitable to supply the towns of Pisa and Livorno about 20 km and 40 km away, respectively. These two towns were facing water scarcity issues; the first because of limited abstractions permitted to preserve the Pisa Leaning Tower, and the second due to missing resources of adequate quality. In 1988, an Expert Commission was formed, with members nominated by the regional Authority (Regione Toscana) to evaluate the impact of RBF: 1) of increasing abstraction over the aforementioned 400 l/s; 2) setting in operation a river weir, about 1 km downstream the Sant'Alessio bridge, in order to raise groundwater head in the Sant'Alessio area.

Following a procedure similar to that of an environmental impact assessment, the Commission's evaluation was positive, showing barely any impact of the abstractions and an increase in aquifer storage due to the weir. This led to the construction of eight new vertical wells with depth ranging from 20 m to 25 m along the right bank of the River installed at distances between 35 m and 80 m in late 1980s and early 1990s (Figure1) to reach a total of about 500 l/s or 15.8 Mm^3/yr supply capacity. The river weir was completed in 1997 (Figure 1 and Figure 3).

Figure 3.
The Sant'Alessio weir on the Serchio River. © Rudy Rossetto

At present, the Sant'Alessio well field is managed by GEAL SpA, a private-public partnership company that manages the area's water distribution and wastewater treatment, supplying directly to the city of Lucca and delivering water through a 1 m diameter pipeline to the water utilities managing water supply to the towns of Pisa and Livorno. The abstracted groundwater is of such good quality that is only treated with sodium hypochlorite before delivery.

19.3. Environmental sustainability

19.3.1. Groundwater quantity

In the EU co-founded FP7 MARSOL project (*Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought*; www.marsol.eu), a series of research and demonstration activities took place. They are described in Deliverable 8.4 [3]. These activities allowed to better characterize the hydrodynamics and hydrochemistry of the Serchio River RBF scheme and to gain insight on its reliability as a safe and continuously available source of water. Previous studies had defined the main hydrogeological characteristics of the Sant'Alessio plain, but had never gone in details on the hydrodynamics and hydrochemistry of this very important freshwater resource.

In particular, non-invasive high definition characterization following the UFZ MOSAIC approach [4] gathered information on the stratigraphy and the hydrodynamics within the river-aquifer-well system. The MOSAIC concept is to use a combination of existing methods such as drilling, geophysical measurements and water level and quality analyses. In addition, innovative investigation methods which produced quantitative data on hydraulic conductivities and dual-tracer tests identified very high groundwater flow velocities, in the order of m/day, at the river/aquifer interface.

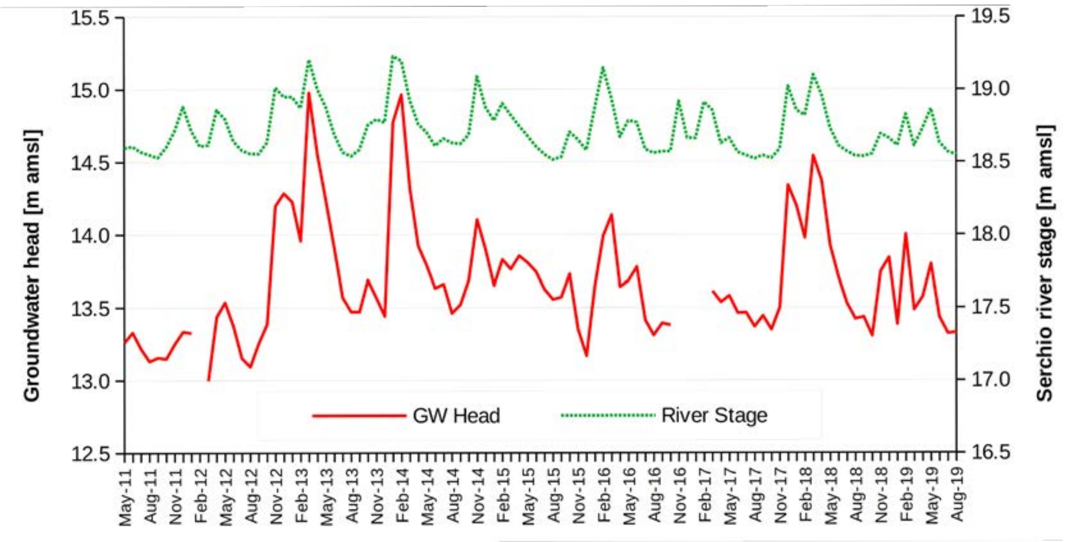

Figure 4.
Monthly groundwater head data at the Sant'Alessio piezometer and Serchio River stage at the Ponte di Monte San Quirico monitoring station from April 2012 to July 2019 (data courtesy of Servizio Idrologico Regionale – Regione Toscana). The location of the piezometer and the Serchio River monitoring station is marked in Figure 1.
Source: Own elaboration

From the point of view of water quantity, the scheme is reliable as the river/aquifer connection ensures that there is no excessive drawdown. A piezometer in the well field shows a direct relationship with the Serchio River head (Figure 4), with the range between the maximum and minimum groundwater head no larger than 2 m between 2012 and 2019 (Figure 4). The amount of water recharged is estimated to be on average 13.6 Mm^3/year (according to a dual end-member chemical tracer mixing model), this is 85% of the total amount of water abstracted ~ 16 Mm^3, so 2.3 Mm^3 of abstracted groundwater comes from ambient groundwater. Ecological concern may be potentially relevant in drought years, when the Serchio River discharge may drop below 6 m^3/s, the minimum flow requirement set by the River Basin Authority per the Water Framework Directive; EU 2000. During dry summer seasons in 2007, 2012, and 2017, the flow has been lower than this threshold. However, thanks to the presence of the Sant'Alessio weir, peak summer season water needs are met and drawdown in the aquifer is kept small. The peak abstraction rate is ~8% of this required baseflow rate. It should be pointed out that during the last few years the river discharge in the summer period, is artificially increased through the regulation of flows released by some dams for hydropower production placed in the middle-upper part of the basin [5].

19.3.2. Groundwater quality

Serchio River water quality is monitored three to four times each year by Regione Toscana Environmental Protection Agency (ARPAT). The chemical status of the Serchio River in the reach crossing the Lucca town area is at present not categorized according to the requirements of the Water Framework Directive [6]. However, before entering the Lucca plain, the river runs through a semi-natural area with few inhabitants and with little anthropogenic pollution so the surface water quality is considered suitable as a raw water source for producing drinking water supplies in bank filtration schemes.

Results of groundwater quality monitoring conducted since the 1990s confirm that, apart from the high removal of pathogens and turbidity, all inorganic parameters are within the limits of the Italian drinking water standard over the last 15 years. In late 1990s and early 2000s, the herbicide terbuthylazine was detected in surface and groundwater, contaminating the abstraction wells. While contamination was initially suspected to come from agricultural activities in the fields adjoining the MAR scheme, river contamination was found to be the cause of groundwater contamination [7] during the EU co-funded LIFE SERIAL WELLFIR project [8]. The presence of terbuthylazine in surface water, at levels one order of magnitude higher than those in groundwater, was attributed to its use by the paper mill industry for algal control, with subsequent discharge of effluent into the Serchio River. Hence, the need for a proper understanding and monitoring of the MAR scheme arose for the first time. Communication activities run during the above-mentioned EU LIFE SERIAL WELLFIR project led to mitigation of this contamination in surface water and then in the abstracted groundwater. At present, the Serchio MAR scheme is threatened by untreated wastewater running in ditches in the area adjoining the well field. However, GEAL SpA is currently upgrading the wastewater collection system to reach also the Sant'Alessio area.

Physical and chemical water quality data were collected during the FP7 MARSOL project via discrete and continuous monitoring methods in surface water and in groundwater by means of six dedicated multi-level piezometers. The data gathered revealed that the overall geochemistry of the Serchio scheme shows homogeneous Ca-HCO$_3$ hydrochemical facies for most of the samples (i.e. surface water and groundwater). The different sources of water contributing to the water cycle were identified, thanks also to trace elements (eg. Lithium) and water stable isotope analyses, ($\delta^{18}O$ and δD). The tracers show that the Serchio River provides most of the groundwater recharge in the Sant'Alessio area, with the Serchio River water fraction ranging from 96% (using Lithium as a tracer) to 82% (using Chloride as a tracer). Dissolved oxygen is very high in surface water (average 9.2 mg/L), while, although diminishing, still shows oxidizing conditions in groundwater (1.7 to 5.7 mg/L). Dissolved organic carbon concentration in surface water is low (generally about 1 mg/L) and is well below 1 mg/L in groundwater. Monitoring of contaminants of emerging concern (pharmaceuticals) shows that while they are present in surface water on the order of ng/L, only a few were detectable in some of the wells (i.e. carbamazepine, clarithromycin, ibuprofen) at levels one order of magnitude lower than those in the river water [9] provided explanations of the pharmaceutical mass removal during bank filtration.

During FP7 MARSOL, high-frequency monitoring proved to be useful for the daily management of the RBF scheme. The S-CAN Spectrolyser probe based on spectrometer analysis (www.s-can.at) was tested for monitoring the organics in groundwater in the wellhead protection area, since the Implementation of the probe for monitoring the surface water quality proved to be difficult for logistic reasons. Early warning was set to detect pollution events related to organics (especially using DOC and UV254 parameters) in groundwater. During the tested period no events were detected. Subsequently, groundwater monitoring is run in some wells every two weeks, but generally monthly.

19.3.3. Energy intensity and environmental benefit

The main benefit provided by the Serchio MAR scheme is related to the availability of a large volume of good quality groundwater all year round. At this River Bank Filtration scheme, processes are very effective in completely reducing the presence of harmful substances during the path from the surface water to groundwater wells [10] proposed a risk assessment methodology to evaluate the risk of failure of MAR schemes in the Mediterranean region considering technical and non-technical constraints, based on expert criteria. The results on perception of risks for the Serchio RBF scheme (18 %) was the lowest among the sites considered in the analysis. This was attributed to the fact that the scheme has been in operation since 1967 with technical expertise to maintain the facility, therefore the technical risks were low. However, the results of the analysis also demonstrate that, as contaminants are present within the MAR scheme area due to human activities, a high-frequency monitoring system both for surface- and groundwater complemented by an alert system is required.

The energy requirement for this RBF scheme is estimated to be between 0.374 and 0.977 KWh/m^3 depending on the abstraction point of abstracted groundwater, averaging 0.676 KWh/m^3.

19.4. Cost and benefit considerations

Based on the above-mentioned design, within the FP7 MARSOL project a cost analysis was performed [11]; this is here reviewed and updated based on the following experience of the authors. Cost estimates are either referred to the actual expenditures occurred during previous project design and execution on the same facility, or descending from a conceptual design of the works.

On this basis, the cost for drilling and installing the 6 multi-level piezometers is 20,000 €, and the cost for the 7-point Wireless Sensor Network (including sensors plus one gateway) is 50000 €. The costs for constructing the 140 m-wide weir on Serchio River is 2,895,478 €[22]. The investment costs for each 300 mm abstraction well supplying water to Lucca is 150,000 € (total 5 wells), that for each 500 mm abstraction well supplying water to Pisa and Livorno is 250,000 € (7 wells). The cost for testing, developing the aquifer model, and the Decision Support System is 250,000 €.

Table 1.
Investment cost and asset value (modified after Balzarini and Furlanis, 2016)[11].

Facility	Unit	Quantity	Unitary Cost €/Unit	Investment €	Asset €
Piezometers	Sum	1	20,000	20,000	20,000
Wireless Sensor Network	Sum	1	50,000	50,000	-
River Weir	m	140	20,682	2,895,480	2,895,480
⌀300 mm Well	No.	5	150,000	750,000	415,000
⌀500 mm Well	No.	7	250,000	1,750,000	1,155,000
DSS Development and Testing	Sum	1	250,000	250,000	-
Total				**5,715,480**	**4,465,480**

The license fee for the abstracted groundwater amounts to 298,000 €/y.

The energy cost is 775,000 €/y, the labour cost is 251,700 €/y.

The cost for Operation and Maintenance (O&M) is estimated in 140,000 €/y, including 5,000 €/y for maintenance of the monitoring system.

It is assumed that the full implementation of the program will take 2 years; the useful life for the works is 30 years (except for the river weir, whose useful life is 50 years with a constant depreciation rate). The levelised cost of water supply from the scheme is estimated to be US$0.138 per m^3.

The analysis proven to be financially sustainable thanks to revenues guaranteed by distributing the water to the town of Lucca and providing it to the water utility of Pisa (Acque SpA) and Livorno (ASA SpA) in 30 years: the project does not run out of money since the sources of financing match or overcompensate disbursements year by year and the cumulated net cash flow is always positive.

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[22] Value obtained actualizing the costs encountered in 1990 (3 billion Italian Liras) by considering the inflation rates till date.

The scheme was also compared to an alternative, that water is directly abstracted from the river. This implies that the water supply is not continuous as the users would not receive any water during the 35 days of the year in which the river flow might be lower than MEF. Storing water to cover these 35 days-demand would require a huge volume (1.51 Mm^3). The building of such a reservoir, depending in the first instance on its feasibility, would require between 6 and 10 M€, an amount to be precisely defined during the project design phase. Hence this solution is deemed unviable. Additional disadvantages are related to the need to fully treat the surface water, due to its quality, then requiring investments for the water works for intake of surface water, the treatment scheme and, finally, higher additional treatment costs (due to the large variability of the quality of surface water, i.e. in first instance related to turbidity).

19.5. Social sustainability

MAR is authorised in Italy by the DM 100/2016 [12]. This piece of regulation details all of the steps needed to get an authorization to design, to set-up, and to operate a Managed Aquifer Recharge plant. However, as previously mentioned, RBF is often not recognized as a MAR technique because the hydraulic connection between the surface water body and the aquifer is often disregarded. The Serchio RBF scheme was then authorized via Environmental Impact Assessment (EIA) for large groundwater abstractions as per EU EIA Directive (EU 2011) [13] and following amendments. More in general, following DM 100/2016 [12], permitting of MAR is granted in Italy through a two steps approach by submitting a preliminary project and a following executive one, the latter to be presented after one year of hydrological and hydrochemical monitoring, including risk considerations. Upon approval, a high frequency monitoring system (for quality and quantity of the recharging and the recharged bodies) must be in place complemented by an early warning system.

The Serchio scheme has not been conceived following public consultation and no institutional agreements are in force. Following the terbuthylazine contamination event, an agreement was signed by the relevant stakeholders involved in water resource management for defining the wellhead protection area. This document, while paying attention to potential land-sourced contamination, again disregarded the hydraulic connection between the Serchio River and the aquifer and did not foresee any measure to monitor potential contamination events driven by the river water quality.

In order to inform the water managers and authorities on the importance of a dedicated management and monitoring of the Serchio RBF scheme, the FP7 MARSOL project developed a Decision Support System (DSS) to demonstrate the benefits of switching from un-monitored/un-controlled (although intended) artificial recharge to MAR [14]. An Operational and Contingency Plan was then presented based on high-frequency monitoring, an early warning system, and a series of modelling applications aiming at:

- defining the well-head protection areas for the Sant'Alessio well field by outlining isolines at selected times (10, 20, 30, 45, 60, 90, and 180 days as required by the Italian national legislation; D.Lgs. 152/2006; Figure 5);

- inferring expected concentration in the Serchio River for a particular pesticide, in relation to duration of pollution events, likely to cause pollution events at the RBF well field managed by GEAL spa.

Results show that the availability of a reliable and solid operational monitoring protocol based on high frequency monitoring is essential to foresee potential pollution events on time and to have the time to set in place remedial actions at a plant providing water to about 300,000 persons. This will finally allow to complement the MAR initial concept of intended recharge to that of intended and controlled recharge, increasing the reliability of the MAR scheme.

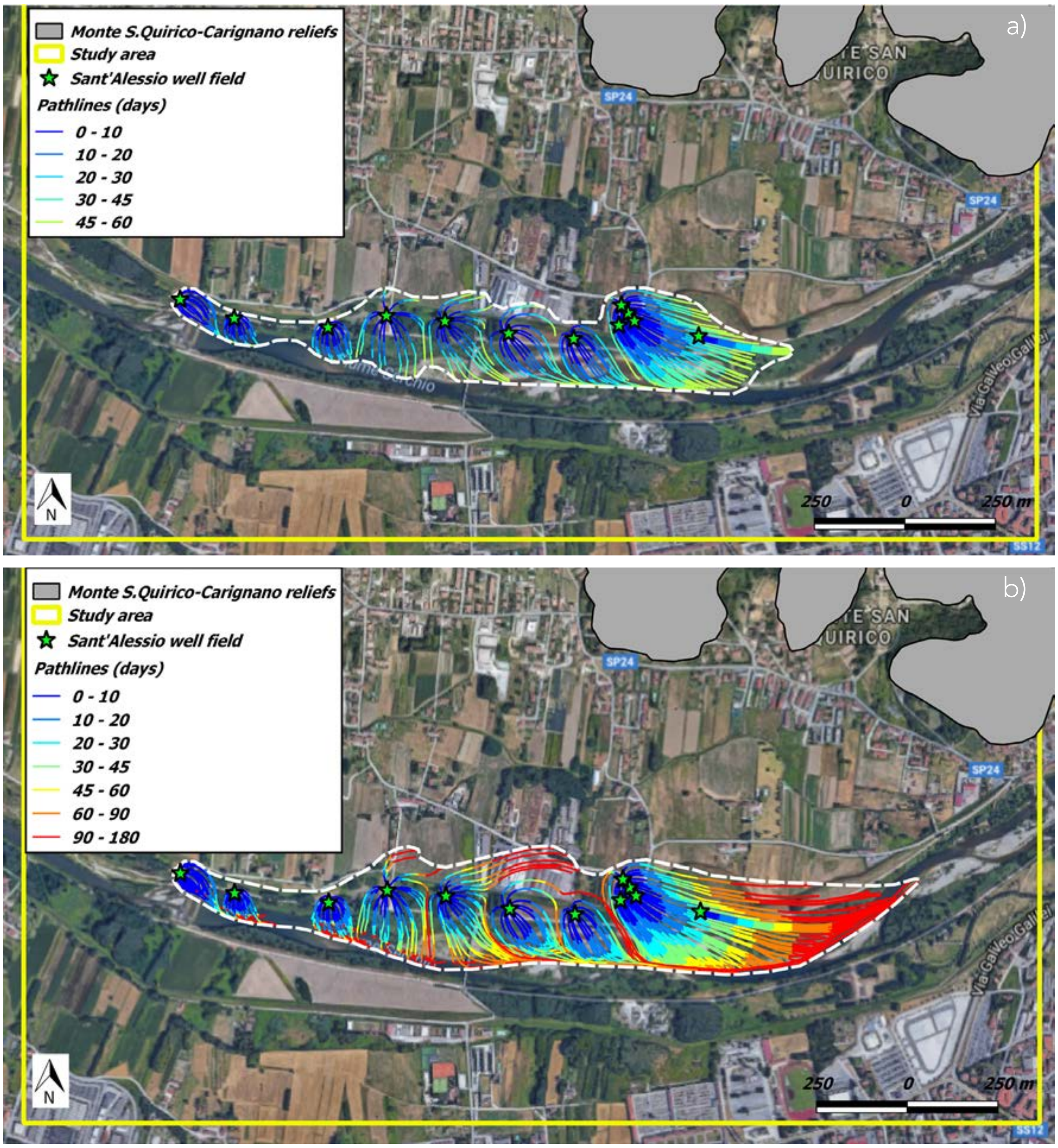

Figure 5.
Inner (a) and Outer (b), well-head Protection zone envelopes proposed based respectively on 60-days (a) and 180-days (b) isochrones.
Background image rt_ofc.2k10 - OFC 2010 2k col Ortofotocarta anno 2010 proprieta' Regione Toscana. Dettaglio 1:2000. Licence CC3.0

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Case Study 20: Sustainable and year-round drinking water production by riverbank filtration in Haridwar, India

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20.1. Introduction

The riverbank filtration (RBF) scheme in Haridwar by the Ganga River and Upper Ganga Canal (UGC), consisting of 22 caisson wells, is operating sustainably for > 50 years [1,2] (Figure 1; Box 1). A consistent removal of ≥ 4 $\log_{10}$ (≥ 99.99 %) of pathogens (Total Coliforms and *E. coli*) has been observed since monitoring commenced in 2005 [1–6]. RBF removes turbidity by ≥ 2.5 $\log_{10}$ during monsoon, when the Ganga has a turbidity in the range of 100–744 NTU [2–6]. The RBF scheme effectively meets peak water demand during religious gatherings when > 1 million bathe in the Ganga and UGC.

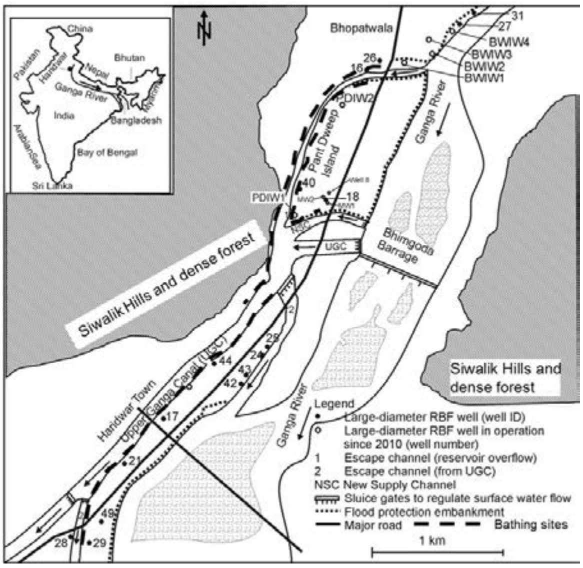

Figure 1.
Layout of RBF scheme in Haridwar.
Source: [7]

Box 1: Salient features of RBF scheme

Location: 29°56.351′N, 78°09.378′E to 29°59.219′N, 78°11.761′E

Operator: Uttarakhand Jal Sansthan (UJS/ Uttarakhand State Water Supply Organisation)

Design: 22 caisson (10 m diameter) wells located between 3 m and 320 m from river / UGC

Average depth to water table: 1–6 m

Commencement of operation: 1965

Quantity of water abstracted: 22 Mm^3/year

End use: domestic (drinking) water

Source of water: Ganga River & groundwater

Aquifer: medium–coarse Pleistocene alluvium

Type of recharge: natural and induced RBF

Main advantage: sustainable abstraction of high quality and quantity of water by RBF

20.2. Motivation, conceptualisation and implementation

Haridwar is considered as one of the seven holiest places of Hinduism. The city receives an average of 50,000 pilgrims on normal days and 150,000–300,000 persons on semi-festive days, with 1–8.2 million on specific religious / festive days (e.g. Kumbh, Ardh Kumbh and Kanwar Melas) and on certain new moon days throughout the year [8]. In addition to this variable temporary population, a permanent population of > 310,000 persons has to be supplied with drinking water [7].

Ensuring drinking water supply in Haridwar is a challenge for the water supplier UJS due to:

- the city's year-round dynamic water demand,
- large-scale public bathing in the Upper Ganga Canal (UGC) and Ganga River,
- high turbidity in river water in monsoon,
- discharge of overland surface runoff and partially treated to untreated wastewater and
- the absence of source-protection zones around wells.

The above factors imply that the removal of pathogens during water treatment for drinking water production is a crucial aspect. Considering these factors and other land-use constraints, the water supply of Haridwar is predominantly based on RBF and groundwater abstraction.

Piped water supply was first introduced in Haridwar in 1927 with groundwater abstraction [9]. Realising the benefit of the natural availability of large quantities of water of improved quality from wells located near riverbanks compared to direct use of river water [10], the first RBF caisson well (#16, Figure 1) was constructed in 1965 in order to cater to the needs of the growing infrastructure and pilgrims. From 1980 to 1998, 15 more wells were constructed and another six new wells commenced operation in 2010, taking the total number of RBF wells currently in operation to 22 [2]. Subsequently a risk-based assessment and management study in accordance with the Australian Guidelines for Managed Aquifer Recharge (MAR) was conducted for the RBF scheme in 2013/2014 [2,11]. Accordingly, the study provided the first internationally reported staged approach to managing risks associated with RBF systems. And it found that the risk to human health mainly from turbidity and *E. coli* in Ganga water was high, if Ganga water were to be used directly as a source of raw water for drinking.

20.3. Environmental sustainability indicators

20.3.1. Water quantity and ecological flows

High quality pre-treated RBF water abstracted for urban drinking water production, relatively stable well-yield and sufficient flow of source water (Ganga River) make the scheme in Haridwar sustainable year-round. These statements are supported by groundwater flow modelling investigations, which advocate the environmental benefits of achieving sustainable water levels by siting RBF wells on Pant Dweep (Figure 2, [7]). These wells exhibit normal seasonal changes in response to river water levels. Groundwater is the main source for drinking and irrigation in other parts of Haridwar urban area and the district further away from the Ganga and UGC (and not covered by RBF scheme). With more than 4,389 government-owned groundwater abstraction wells and 90,605 private wells, the groundwater level is reported to be decreasing steadily as a result of which it has attained a critical status [14]. In contrast, the environmental benefit of RBF wells is that they are located in an area where a natural flow between the Ganga and UGC occurs, such that the aquifer is naturally recharged, sustainable abstraction by the RBF wells is ensured and no long-term lowering of the groundwater table in the area of the RBF wells occur [7].

Figure 2.
View of *Pant Dweep* island, on which four RBF wells are located, surrounded by the Ganga (background) and UGC (foreground). Photo facing East with Ganga and UGC flowing South/right. © HTW Dresden

The mean portion of bank filtrate abstracted by the RBF scheme (mean of 22 wells) is around 70% (remainder being ambient land-side groundwater), which amounts to a total bank filtrate volume of 15.4 Mm^3 per year (70% of abstracted water quantity by RBF scheme; box 1). Considering a mean discharge of the Ganga in Haridwar of 24,500 Mm^3 per year [23], the annual volume of bank filtrate abstracted accounts for $< 0.1\%$ of the Ganga's mean annual flow. Thus there is no environmental impact by the RBF scheme on the Ganga's flow.

The energy consumption per m^3 of recovered water by RBF in Haridwar is 0.16 KWh.

20.3.2. Water quality

Water quality monitoring of the RBF scheme has been conducted since 2005. Bacteriological indicator counts (total coliforms and *E.coli*), turbidity, major ions and instant field parameters have been monitored monthly continuously at least for one year during the periods 2005–2006, 2012–2013 and 2016–2018. Inorganic chemicals, including salinity, nutrients and metals, have been monitored during these periods too, albeit less frequently. The data was compared to the Indian and German standards for drinking water and the WHO guidelines [20,21,22]. The mean total coliform (TC) and *E. coli* counts in the Ganga water were in the range of 7,824 (non-monsoon) to 119,650 MPN/100 mL (monsoon) and 4,298 (non-monsoon) to 48,650 MPN/100 mL (monsoon) respectively. The mean TC and *E. coli* counts for all 22 RBF wells monitored during the period 2005 to 2013 were in the range of <2 to 1,600 MPN/100 mL (mean of all wells 179 MPN/100 mL) and <2 to 93 MPN/100 mL (mean of all wells 30 MPN/100 mL) respectively. Occasional exceedances of the Indian Drinking Water Standard [20] limits of 0 MPN/100 mL for TC and *E. coli* were observed in most wells, thereby necessitating post-treatment by disinfection. The investigations confirm that, apart from the high removal of coliforms and turbidity, all inorganic parameters are within the limits of the standards and guideline values [1–6,12,13]. The mean dissolved organic carbon (DOC) concentration in surface water is low and generally in the range of 1–2 mg/L (maximum 3.5 mg/L) and < 1 mg/L (maximum 1.6 mg/L) in RBF well water [12,13]. This in turn is attributed for the very low formation of disinfection by-products [5]. Occasional monitoring of mainly polar organic micropollutants (OMPs) shows that only a few pharmaceutical and personal-care product OMPs (e.g. sulfamethoxazole and triclosan) were detectable in some RBF wells, albeit in low concentrations (11–143 ng/L) [12,13].

20.4. Social sustainability indicators

20.4.1. Regulatory framework

There are no specific legally binding standards or regulatory framework for RBF in India. However, the «Guidelines on Bank Filtration for Water Supply in India» [24] published in 2019 provide internationally accepted best-practise guidelines, including on health risk assessment consistent with the WHO's Water Safety Plans and with the Australian Guidelines for Managed Aquifer Recharge. In Haridwar, the water supplier UJS is responsible that the quality of water supplied by the RBF wells meets the limits defined in the Indian Standard for Drinking Water [20]. Source water quality i.e. Ganga River is regularly monitored by the Central Pollution Control Board and Uttarakhand State Pollution Control Board.

20.4.2. Permit granting process

Permits are required mainly for procuring land for the construction of RBF wells. In general, permission has to be obtained by the water supply organisation from the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, to obtain land to build the well. If the well is constructed on land not belonging to the MoEFCC, permission has to be sought from the landowner. Furthermore, generally permission to drill a well has to be obtained from the state ground water board under the jurisdiction of the Central Ground Water Board of the Ministry of Water Resources, River Development and Ganga Rejuvenation.

20.4.3 Institutional framework and public and stakeholder participation

As of 2018 in India, there is no uniform policy or a specific technical framework for planning a RBF site. However, there are various frameworks and scientific works that support (directly or indirectly) the use of RBF in India and to which the development of RBF can be anchored [25]. These include, but are not limited to, the National Water Policy [26], Indian Standard Guideline for Artificial Recharge to Groundwater [27] and the Master Plan for Artificial Recharge [28]. In context to development of RBF in India at a state-level, the Department of Drinking Water of the Government of Uttarakhand issued a government order (GO) in March 2006 wherein specific natural treatment technologies for drinking water supply such as RBF and the use Koop wells for small-scale RBF schemes specifically designed for rural water supply should be encouraged by water supply organizations working in Uttarakhand. From a policy and an administrative perspective, the issuance of such a GO significantly simplifies planning aspects of RBF schemes for the water supply organization. As the provision of drinking water is a subject of state governments under the Constitution of India, a suitable approach can be selected to integrate or anchor RBF into various water supply infrastructure development projects at a state level [25]. Taking the RBF scheme in Haridwar and the development of new RBF schemes in Uttarakhand (2010 onwards) as examples, recommendations for strengthening the institutional framework and public and stakeholder participation for RBF have been derived [29,30].

20.5. Cost and benefit considerations

On one hand UJS fulfils social aspects such as meeting its obligation to provide high quality drinking water for very low tariffs (free of cost through public standposts) to the residents and pilgrims in Haridwar, of which many are poor, women and/or live in temporary structures. Thereby the fundamental constitutional right to water of everyone in Haridwar is ensured [15]. On the other hand, the revenues are insufficient to cover the operational cost for the production of drinking water [16]. Based on information provided in [15], the capital cost (capex) of constructing one typical caisson RBF well is around USD 112,000 (INR 8 million). The average total operating cost (opex) of drinking water production by RBF in Haridwar, including a debt service of 20% and depreciation of 2% on the capex for a RBF well, is expected to be around USD 0.09 per m^3 (INR 6.18 per m^3).

Although the capex for a deep vertical well of the same capacity that would abstract 100% groundwater is cheaper at around USD 92,000 (INR 6.5 million) per well, the environmental benefits of RBF in Haridwar outweigh the alternative of only groundwater abstraction (section 3, [15]). Furthermore, there are savings in operation costs (energy costs) due to lower drawdown and quality issues as the pumped bank filtrate has lower salinity and hardness. The focus lies on the fact that the RBF scheme is a sustainable supplement to groundwater-based supply and an alternative to direct surface water abstraction [1]. A surface water abstraction system followed by conventional treatment has never been considered by the authorities for the city because on one hand cost of building a conventional water treatment plant based on surface water abstraction would have incurred an extremely high capital cost and on the other hand, planners and engineers already recognised in 1965 that large quantities of naturally pre-treated water can be obtained by RBF [15].

20.6. RBF demonstration site

In 2005 the RBF well 18 on *Pant Dweep* island was equipped with two monitoring wells (Figure 3). Wide-ranging civil engineering works, including intensive well-cleaning and construction of a sanitary seal and a boundary wall to create a well-head protection zone, were conducted. Detailed hydrogeological and water quality investigations commenced same year. The results of the investigations are on display at the well. Consequently, a steady transfer of technology and know-how on different aspects of RBF-based water production to UJS and other water supply organisations in India has also been achieved. During regular training courses, workshops and conferences conducted on RBF in nearby Roorkee and Dehradun, excursions have been organized to well 18 nearly every year since 2006. These excursions have enabled scientists, water resources engineers and managers, students and policy and decision makers to acquaint themselves with RBF.

Figure 3.
RBF well 18 and monitoring wells at demonstration site. © HTW Dresden

A major milestone as a result of these activities was the formal recognition as a RBF demonstration site by the UNESCO IAH Managed Aquifer Recharge Network in 2009. Feedback received from water supply / resource engineers and managers, who participated in these excursions to well 18, highlights the usefulness of RBF demonstration sites for greater visibility of RBF and for improving technology transfer. Thus at least one RBF demonstration site should be developed in the state where RBF can be applied.

One of the crucial issues in India for year-round safe drinking water from RBF schemes is to achieve a robust and sustainable disinfection [17]. A potential solution tested within the *AquaNES* and *NIRWINDU* projects at the RBF demonstration well 18 was the coupling of inline-electrolysis pilot-plants (to RBF wells) for stand-alone decentralized disinfection of water for rural water supply with a capacity to disinfect ~20 m³/day [5,18] and a medium-capacity plant to disinfect around 1,600 m³/day [19]. Both plants show that no total coliforms and *E. coli* were present in the produced drinking water (after disinfection by inline-electrolyses). Therefor both systems are potential solutions to achieve continuous and robust disinfection, with the system for rural water supply mature to be implemented in a real scenario [5].

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Case Study 21: The Arizona Water Banking Authority: The role of institutions in supporting Managed Aquifer Recharge

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21.1. Introduction and background

In 1996, the legislature in the U.S. state of Arizona established the Arizona Water Banking Authority (AWBA) to further several policy objectives, including: fully utilizing Arizona's entitlement to Colorado River water; facilitating interstate banking arrangements; and creating a supplemental "firming" supply for future Colorado River shortages. In 2006, the AWBA's role was expanded to help settle historic water rights claims by American Indian communities [1].

Since its creation, the AWBA has utilized Managed Aquifer Recharge to store nearly 5,600 million cubic metres (Mm^3) of surface water from the Colorado River and achieved several of its stated policy objectives [2]. The success of the AWBA can be traced to factors that include: local political consensus; a large temporary water supply; favorable hydrogeology; supportive regulations; public funding; and institutional innovation [3].

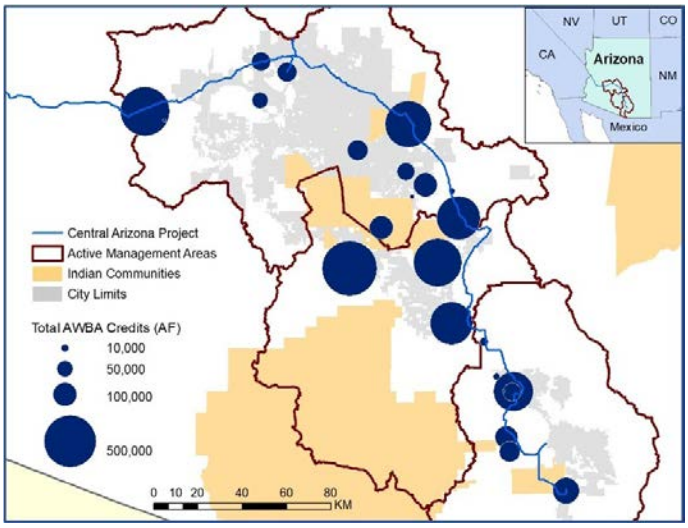

Figure 1.
Location of storage by AWBA.
Source: Own elaboration

Box 1 Summary of AWBA

Arizona Water Banking Authority

Location: Arizona, USA

Established: Legislation in 1996, with first operations in 1997

Source of Water: Colorado River water via the Central Arizona Project

Storage through 2018: 5600 MCM

Types of recharge: Spreading basins.

Arizona is located in the southwestern region of the United States and has an arid and semi-arid climate. Water supplies include in-state surface water, groundwater, and water from the Colorado River, which is shared with six other states and the Republic of Mexico. More than half of Arizona's 3,454 Mm^3 annual allocation of Colorado River water is delivered to the central and southern portion of the state through the Central Arizona Project (CAP), which consists of pumping plants and an aqueduct that spans 540 km. CAP water is delivered to a variety of municipal and agricultural users, as well as indigenous American Indian communities. Those users have priority access to CAP water, but there has also been CAP water available on a year-to-year basis for others, including the AWBA.

21.2. Institutional setting

The MAR activity undertaken by the AWBA is regulated by the state of Arizona, acting through the Arizona Department of Water Resources. ADWR has extensive regulatory authority related to groundwater rights in the areas where CAP water is delivered, including the ability to issue fines for violations. ADWR also administers a comprehensive system of permits, monitoring, annual reporting and accounting related to MAR that was instituted pursuant to laws passed by the Arizona legislature beginning in the mid-1980s [4]. To demonstrate hydrologic feasibility, recharge projects require groundwater modelling, pilot phase operations, and permits that have a fixed duration along with annual and cumulative volumetric limits [5].

To facilitate MAR techniques, and in recognition of the extensive and largely unconfined alluvial aquifers in much of the state, Arizona adopted a flexible, mass-balance approach to MAR accounting. This includes the future right to recover (i.e., pump) 95% of the volume that was stored; the ability to recover almost anywhere within the regional aquifer system; and the ability of the recovered water to retain the legal character of the stored water. After detailed calculation of losses, ADWR issues Long-Term Storage Credits to account for this activity, and these credits underpin water banking in Arizona.

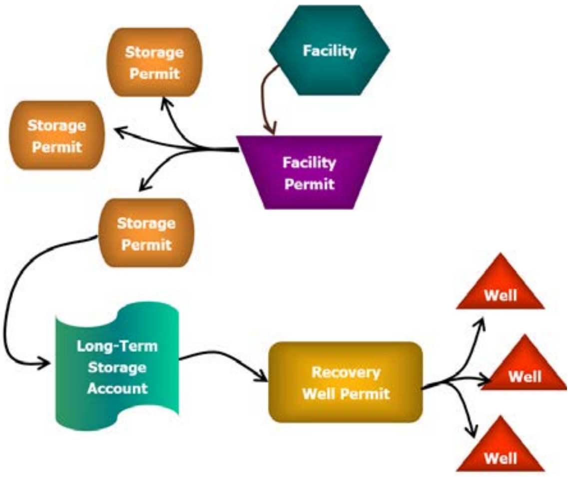

Figure 2.
MAR permitting in Arizona, simplified. Source: Own elaboration

The development of large-scale MAR capacity for CAP water began immediately prior to the formation of the AWBA, including a large project involving spreading basins next to a normally dry reach of the Salt River in the Phoenix metropolitan area [6]. In the southern portion of the state, MAR capacity was developed in "State Demonstration Projects" that were funded primarily with property taxes, and projects funded by the City of Tucson. These projects are situated in areas with an initial depth to groundwater ranging from 30 to 140 m, with infiltration rates often greater than one meter per day, and adjacent to the CAP water delivery system. ADWR requires extensive modelling and testing before full operations of the spreading basins, and then daily calculations of losses due to evaporation are performed. Throughout the early 2000s, the number and capacity of recharge projects increased, and there are now 20 projects that can directly store CAP water, with a permitted annual capacity of 865 Mm^3 [7]. In addition, nearly all irrigation districts that receive CAP water have also received ADWR-issued permits, (892 Mm^3/yr), that allow credits to be earned for CAP water that is used in lieu of groundwater pumping.

21.3. Environmental sustainability

Without the water stored by the AWBA, the aquifers of central and southern Arizona would be under greater current and future stress. Extensive and regular groundwater level measurements have confirmed the rise in water levels associated with water banking [8]. ADWR has an extensive monitoring program, including both automated and field measured water levels. Statewide groundwater data are available online [9]. There are also specific water level monitoring requirements for MAR facilities [10]. MAR-specific water level monitoring includes both Alert Levels and Operational Prohibitions if water levels rise too close to land surface. While some of the benefit of that stored water will diminish as water is recovered—expected to occur in the coming decades—some of the benefits are durable. In particular, the availability of AWBA credits diminishes the likelihood that cities that are eligible for AWBA credits would seek a waiver from the State that would allow them to pump groundwater unsustainably during times of shortage [11].

The AWBA's activity fits within a broader adoption of MAR in Arizona. The aquifers of the central and southern part of the state are well suited to MAR, and for many years the available supply of CAP water has exceeded the annual demands of the users with long-term rights to the supply [12]. This temporary mismatch has created an opportunity for water banking by a number of entities, including the AWBA. From the year 2000 through 2009, the AWBA stored an average of 342 Mm^3 per year [13].

Much of the MAR activity in Arizona is being pursued as a supplemental supply for times of shortage, but other examples include the use of MAR as pre-treatment for potable distribution and blending with local groundwater to manage water quality. For instance, the City of Tucson has developed 234 Mm^3 of annual capacity through spreading basins. In 2018, 76 Mm^3 was stored and recovered in the same year, and an additional 76 Mm^3 was stored for the long-term [14].

Figure 3.
Superstition Mountains Recharge Project. ©Central Arizona Project

MAR facilities in Arizona are required to routinely sample water quality in monitor wells adjacent to spreading basins. The quality of the source CAP water is also regularly monitored, and easily meets most nationally established drinking water quality standards [15]. Initiation of recharge operations can be accompanied by a mobilization of nitrate and other constituents, but long-term monitoring has confirmed this is a short-term phenomenon [16].

Delivery of Colorado River water to central and southern Arizona via the CAP system is energy intensive (1.23 KWh/m^3 to 2.16 KWh/m^3) due to the large elevation change (300 m to 700 m), though additional lift to recharge basins typically minimal. The energy requirements for recovery wells varies by location, but reported pumping energy for irrigation wells in the central portion of the state range between 0.48 KWh/m^3 and 0.91 KWh/m^3, with costs of $US 0.02/m^3 to $US 0.04/m^3 [17].

21.4. Economic costs and benefits

The AWBA has access to several revenue sources, including a tax on the value of all property, fees paid by groundwater pumpers, interstate funds, and legislative appropriations. Through 2018, the AWBA has expended $US 393 million to purchase and store water, and it holds 5311 Mm^3 of storage credits [18]. In 2019 dollars, those expenditures equate to $US 490 million, for an average cost of $US 0.092 per m^3 recharged [19].

It is possible to value the AWBA credits based on market transactions. In addition the credits held by the AWBA, there are approximately 9000 MCM of credits held by others [20], including cities, American Indian communities, and private companies. While most of those credits are held for later use by the storers, some are available for purchase and a market with a number of transactions has emerged [21]. Average purchase prices in 2017 and 2018 were in excess of $US 0.20 per m^3 [22], which suggests that the in-place value of the AWBA's accrued credit balance may exceed $US 1.1 billion USD, and a benefit-cost ratio of 2.17:1.

The value of this public investment is further supported by an economic impact study of the Central Arizona Project and the Colorado River water it delivers [23]. The study authors estimate a $US 1 trillion benefit to Arizona's economy between 1985 and 2010. By ensuring full utilization of that supply, and improving the reliability of it during shortages, the AWBA contributes to that value.

In addition to the direct economic value of the AWBA's activity, water banking has played a prominent role in the economic messaging of the state. State leaders have touted the role of the AWBA and water banking to allay concerns from the public and investors about the security of the water supplies for urban areas [24].

21.5. Social sustainability

The AWBA supports a number of broad social objectives, and its operations and decision-making have multiple points of oversight and transparency.

Arizona's legal entitlement to Colorado River water has been the subject of decades of contention with neighboring states, and protecting it is a point of broad political consensus in Arizona. In the early 1990s the supply was not fully utilized, and the AWBA had two important roles in the interstate context—fully utilizing Arizona's entitlement, thus denying California access to Arizona's underused portion, and partnering with Nevada to store water in Arizona for later delivery, through exchange [25]. Those two factors placed Arizona in a more favorable position in subsequent negotiations over the management of the Colorado River.

The AWBA also assisted in settling historic surface water rights claims by American Indian communities. By agreeing to use MAR to increase the reliability of certain CAP water supplies, the AWBA made those supplies more valuable, which helped in the negotiated resolution of claims by the Gila River Indian Community, White Mountain Apache Tribe, Hualapai Tribe, and others.

To support these policy objectives, the AWBA is staffed by ADWR and governed by a five-member Commission. By state law, the Commission is chaired by the Director of ADWR; one seat is held by the Board President or designee of the CAP; and the remaining three seats represent sectoral interests and are appointed by the Governor of Arizona [26]. The Commission's public meetings are held quarterly, or more often as necessary.

The AWBA produces an Annual Plan of Operation, which details the expected storage and credit purchases for the upcoming year. Draft versions of this document are made available for public comment and are formally considered by local Groundwater User Advisory Councils [27]. Meeting materials, including minutes, and other documents are posted on the AWBA's website (www.azwaterbank.gov). The AWBA is also required to produce an Annual Report detailing its finances and operations, which is submitted to the Arizona Governor and Legislature and made publically available [28].

The goals of social sustainability are also advanced by requirements that prevent MAR facilities from being located in areas that could negatively affect water quality. The Arizona Department of Environmental Quality is responsible for this review, pursuant to a state law that ensures a MAR facility «...is not in a location that will promote either the migration of a contaminant plume or the migration of a poor quality groundwater area so as to cause unreasonable harm or is not in a location that will result in pollutants being leached to the groundwater table...» This standard lends confidence that storage by the AWBA and others is making a positive contribution to regional aquifers.

21.6. Recovery and innovation

The credits held by the AWBA are intended to be managed for long-term use; in many cases 100 years. However, some recovery is anticipated sooner, and cost-effective recovery is a priority for Arizona's water managers [29]. In some cases development of recovery capacity has been more expensive and complex than expected. Fortunately, Arizona's flexible approach to MAR provides a range of recovery methods for using infrastructure and partnerships. Efforts by the AWBA, ADWR, CAP, cities, Indian communities, and others have led to several key legal agreements [30], an overall framework for recovery [31], and innovative partnerships [32]. Some of those innovations have been spurred by the fact that long-term storage credits are a form of marketable water right that can have lower transaction costs or fewer regulatory impediments than leases or other types of water right transfers. And as the name implies, long-term storage credits are ideally suited for banking currently available supplies for the future.

Some factors related to the AWBA are unique to the circumstances in Arizona. However, the AWBA is an important example of how a strong regulatory framework, coupled with public institutions and funding can help support the adoption of MAR on a large scale, and how MAR can achieve broad water management and public policy objectives.

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Case Study 22: Sustainable drinking water supply from riverbank filtration of the Nile for Sidfa, Egypt

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22.1. Introduction

Riverbank filtration (RBF) is a widely used managed aquifer recharge method for water supply using riverbank wells to enhance recharge of river or lake water into aquifer with water quality improvement. In Sidfa City (Assiut Governorate) located in Upper Egypt part of the Nile Valley, a RBF system was constructed in 2004 to supply drinking water year-round to about 30,000 residents [1-5]. Six wells were installed 20 m to 40 m away from the bank of River Nile to abstract groundwater, inducing aquifer recharge by surface water. All 6 vertical wells are installed to a depth of 60 m below ground, with a diameter of 30 cm and a screen length of about 30-40 m that tap the sandy-gravel main aquifer of the Nile Valley (Figure 2).

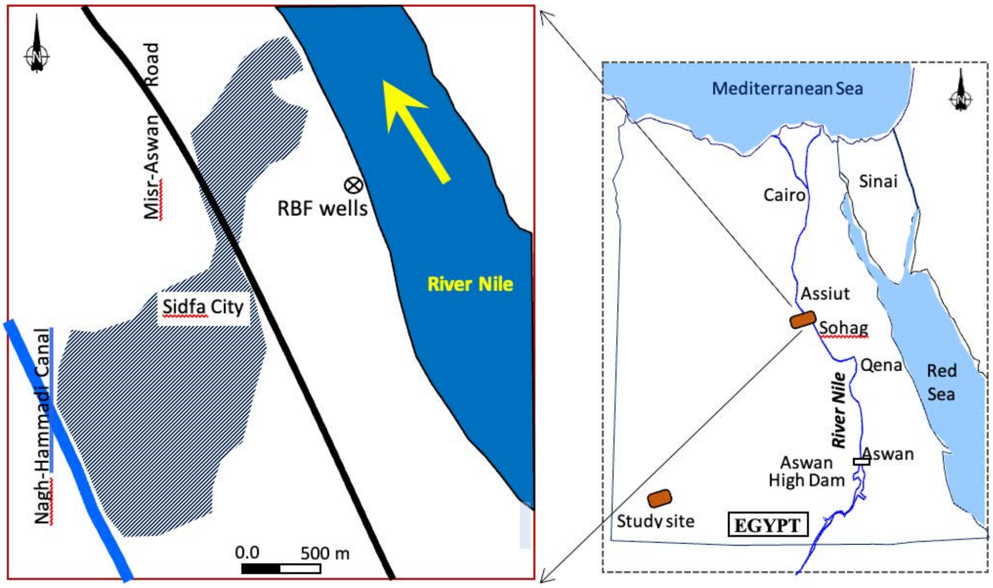

Figure 1.
Layout of the Sidfa RBF system, the oldest RBF in the Nile Valley of Egypt.
Source: Own elaboration. Map (right): © Google Maps

Box 1: Main features of Sidfa RBF system

Location: 26°58.265′N, 31°22.991′E to 26°58.343′N, 31°23.026′E
Operator: Assiut Company for Water and Wastewater (branch company)
Design scheme: 6 vertical wells (30-40 cm diameter), located 20-40 m from Nile
Date of first operation: 2004
Quantity of water abstracted: 2.19 Mm^3/year
End use: drinking water
Source of water: River Nile & groundwater
Aquifer: Semi-confined aquifer of Pleistocene graded sand-gravel alluvium
Type of recharge: Induced Nile water and natural groundwater (RBF)
Main advantage: sustainable abstraction of drinking water by RBF

22.2. Motivation and implementation

Sidfa city is part of the old historical Egyptian civilization in Nile Valley, with small villages scattered all around the main city with agriculture being its main economic activity. The water supply in Sidfa has improved since 1960s [2]. In that decade, residents of Sidfa city were first supplied with piped drinking water sourced from a groundwater wellfield kilometres away from the Nile. However, the abstracted groundwater suffered from iron and manganese problems, typical problem of natural groundwater in Egypt [4-6]. Furthermore, the growth of the city engulfed this wellfield and it became located inside the expanded city; this caused another water quality problem of fecal bacteria from septic tanks [4]. In late of 1990s, the city constructed a "compact unit" that used traditional processes of coagulation-filtration-disinfection to treat the River Nile water. Yet this "compact unit" still could not meet the drinking water demand, with inefficient operation a contributing factor [2]. Thus, Assiut company for water and wastewater initiated and constructed this RBF wellfield near the Nile in 2004. In 2018, Sidfa RBF is operating as a standby supply as needed for the new surface water treatment plant from Nile built in 2018. This because the new surface water treatment plant is constructed to supply the whole region with more than 10 times the capacity of this RBF facility. The RBF is operated to provide necessary drinking water when demand is high and in case of Nile water quality problems that the surface treatment plant cannot operate (i.e. high suspended solids from flash floods events and chemical spills).

22.3. Environmental sustainability

The RBF system was proven to be efficient [2], with induced recharge providing the scheme with sustained and sufficient water [7-10]. Monitoring of groundwater head in abstraction wells showed no decline after 10 years of operation, although they were almost 3-4 m below original head due to pumping. The advantage of RBF wells is the hydraulic connection between the Nile and aquifer and the continuous local induced recharge of the aquifer by the Nile water (caused by pumping) and recharge of irrigation water into the natural groundwater portion [11]. The water level in the River Nile is controlled by the Aswan Dam Egypt with planned decrease in January each year. In the normal situation, River Nile is a receiving water body in the Nile valley floodplain due its lower water level than the groundwater head in the Nile aquifer.

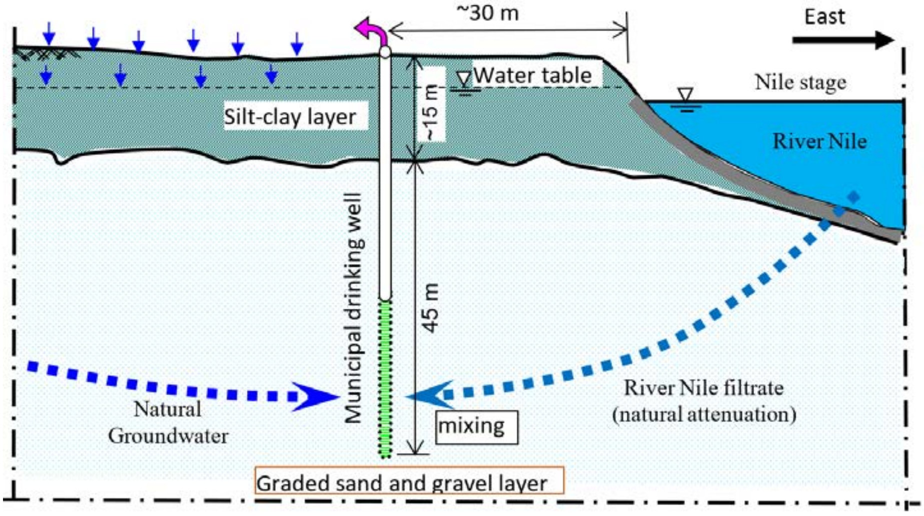

Figure 2.
Hydrogeological cross section of MAR-RBF study case, Sidfa city . Source: [2]

The RBF system has supplied acceptable quality of drinking water to Sidfa residents throughout each year since 2004. Monthly monitoring of recovered water by Assiut Company for water and wastewater has found that the water meets the Egyptian drinking water quality standards (http://extwprlegs1.fao.org/docs/pdf/egy83626.pdf). Potential contaminants present in river water are filtered and attenuated via different mechanisms during its percolation and movement into wells [12-17]. Water quality results of Sidfa RBF for three discrete events in March-April 2016 are given in Table 1. RBF effectively removes turbidity and fecal coliforms of induced recharge from the Nile to be lower than allowable limits. The induced recharge also dilutes the dissolved ion concenctarions of the native groundwater. The water quality of RBF supply wells is compared with both the Nile water, the natural ambient groundwater and drinking water standards in Table 1.

There are two reasons for the water quality improvement. First, there is natural attenuation and filtration of the soil-aquifer system. Second, there is a mixing between ambient groundwater and the induced bank infiltrated water. For Sidfa RBF system, the estimated Nile water infiltrated into pumping wells, applying mass conservation principal, is about 70% [2]. The high percentage of infiltrated Nile water plays a key role in RBF performance because the chemical quality of the Nile water is in general better than that of the ambient groundwater (Table 1).

Table 1.
Water quality of Sidfa RBF

Parameter (mg/L or mentioned)	River Nile {Ave. (SD)}	RBF: supply wells	Ambient Groundwater	Standards of Drinking water
pH	7.70* (0.1)**	7.75 (0.02)	7.8 (0.04)	6.5-8.5
Turbidity (NTU)	6.7 (0.75)	0.5 (0.15)	0.3 (0.14)	1.0
TDS	150 (6.10)	250 (5.60)	530 (5.50)	1000
Hardness (CaCO3)	110 (2.40)	161 (2.60)	247 (3.00)	500
Fe	0.05 (0.01)	0.07 (0.01)	0.27 (0.40)	0.3
Mn	0.07 (0.02)	0.11 (0.03)	0.33 (0.20)	0.4
Ca	24 (1.60)	28 (1.00)	45 (1.70)	-
Mg	16 (1.30)	22 (1.00)	31 (1.70)	-
K	4.6 (0.50)	5.0 (0.40)	6.1 (1.20)	-
Cl	20 (1.00)	24 (0.80)	37 (1.20)	250
SO^4	24 (2.20)	38 (1.50)	71 (2.20)	250
NO^3	3.2 (0.70)	7 (1.30)	22 (2.50)	45
PO^4	0.8 (0.12)	1.0 (0.20)	1.1 (0.22)	-
Total coliform (cfu/100ml)	970 (10.00)	1.0 (0.30)	0.8 (0.70)	2
E-Coli (cfu/100ml)	225 (5.45)	0.0 (0.02)	1.0 (0.70)	Not allowed

* =average value, ** =standard deviation (for all values in the table), March-April 2016

The energy requirement for this RBF scheme is estimated to be 0.3 KWh/m^3 of abstracted aquifer water. The surface water treatment plant for drinking water supply has higher energy intensity due to the need for removal of high concentrations of suspended solids, turbidity, microorganisms and other impurities as shown in Table 2.

22.4. Cost and benefit considerations

Table 2 shows the main components of capital and operation costs of the RBF system for a case of small Nile city in Egypt (10 thousands capita) with comparison to other treatment options [18,19]. The other two options are 1) to use deep municipal wells with problems of groundwater quality (iron, manganese, fecal coliform) with coupled treatment unit. 2) to use Compact Unit to treat surface water to drinking standards. Table 2 indicates that the total cost of RBF system in Nile Valley aquifer, Egypt is much lower than the current two methods (tens of times lower). The environmental impact and fingerprint is another advantage of RBF compared to alternatives. The quality of produced water from the RBF system in Nile aquifer is acceptable for drinking with no further treatments, but disinfection is required to protect the distribution system.

For RBF option, the capital cost (capex) of constructing one typical vertical well is about US$19,000 (EGP 320,000). The levelised unit cost is estimated to be US$0.038 per m^3 and the average annual operating cost (opex) of drinking water production by the RBF plant is estimated to be about US$0.03 per m^3 (EGP 0.52 per m^3).

Table 2.
Comparison of capital and operation costs for RBF scheme and other alternatives.

Method	Capital Cost		Operation Cost			Total cost
	pumps&wells	*treatment units*	*power supply*	*coagulant*	*disinfection*	
Compact Unit (Nile water)	4	full treatment units	2 low +2 high (4) pumps	needed	vital	High cost
Municipal wells	2+wells	Fe &Mn removal and Disinfection	2 submersed pumps	No	needed	Medium cost
RBF technique	2+wells	No	2 submersed pumps	No	needed	Very low cost

Note: Work force is neglected because it is almost same for all options; Disinfection is needed for all options before water enters the distribution system (doses are different).

22.5. Social sustainability

The most closely related regulations for this RBF system are; (1) the supplied water meets the Egyptian drinking water quality standards and (2) the drilling permits are required for vertical groundwater wells beside the banks of Nile. Sidfa RBF system is in compliance with the two regulations. The community in Sidfa was engaged during the construction phase of this site which was accessible for visitors. During the operation phase, community in Sidfa may be engaged through following up the water quality results throughout both the reports from the operation company of the RBF site and the office of Ministry of Health in Sidfa.

22.6. Upscaling potential in Nile valley

Most of the Egyptian cities are located on the banks of Nile which makes RBF an attractive water supply option [19,20]. The advantages are:

- Low capital and O&M costs
- Absence of or minimal addition of chemicals (i.e. coagulants)
- Reduction or absence of disinfection by-products
- No sludge production or generation of hazardous waste stream, i.e. filter wash
- Degradation, rather than sequestration or concentration, of some contaminants
- Robustness over a wide range of operating conditions and water qualities
- Protection against shock loads from flash floods and ship accidents in Nile

These benefits of RBF have received the attention of decision makers in Egypt [19]. The implementation of RBF in Nile valley may be applied as follows:

1. Standalone vertical wells, or followed by post-disinfection treatment.
2. Pre-treatment for surface water treatment plants to improve intake water quality and to reduce disinfection by-products.
3. Integration with existing surface water treatment plant to provide emergency supply in case of accidental pollution or high-suspended solids during flash floods events of the Nile.

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Case Study 23: Intentional flooding of rice fields and payment for ecosystem services in Kumamoto, Japan

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23.1. Introduction

In this novel and integrated MAR approach, an offsetting scheme under the concept of payment for ecosystem services (PES) is used to enhance groundwater recharge along the Shirakawa River in Kumamoto Prefecture, Japan [1] (Figures 1, 2 and 3). The scheme gives a cash incentive to farmers who pond their abandoned rice fields for groundwater recharge. For a specified period of the year, the fields undergo intentional inundation in order to enhance the recharge of the underlying aquifer. In turn, major stakeholders reliant on a steady supply of groundwater down-gradient, such as the Kumamoto City Waterworks and Sewerage Bureau and some private sector businesses, have agreed to pay the farmers as an offset for their groundwater abstraction.

23.2. Motivation, conceptualization and implementation

Kumamoto City (390 km^2), located on the island of Kyushu, Japan is renowned for its pristine and plentiful groundwater, which supplies 100% of the water requirement of the entire city population of over 738,000 as well as partial requirements of other sectors (agriculture and industries) around the city [1]. Of the total 107 million cubic meters (Mm^3) groundwater extracted for the city in 2015, domestic water supply was the largest user, accounting for 72%, while agriculture accounted for 12% and industry, 16% [8]. The average annual rainfall is 1990 mm (1980 - 2010) [5].

Groundwater has come under increasing pressure from growing water demand [4]. Increasing abstraction, combined with a decline in recharge due to urbanization and changing farming practices were responsible for declining groundwater levels [2].

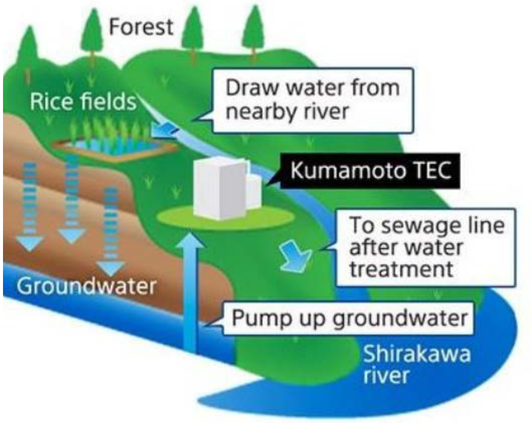

Figure 1.
Conceptual diagram of the Kumamoto MAR scheme. Source: [2]

Figure 2.
Location of Kumamoto, Japan.
Source: [3]

Box 1: Salient features of the recharge scheme

Location: 32°58’29.63”N, 130°51’42.25”E to 32°43’12.56”N, 130°36’25.63”E

Operator: Private sector, Kumamoto City Waterworks and Sewerage Bureau, farmers, local agricultural association

Design: No special design involved; relies on surface infiltration through abandoned rice fields (636 ha/month in 2018) and replenishment of downstream aquifers supplying Kumamoto City

Commencement of operation: 2004

Quantity of water abstracted (as offset): 14 Mm^3/yr

End use: Domestic and industrial

Source of water: Shirakawa River and local streams

Aquifer: Mainly volcanic pyroclastic deposits, primarily confined [4,5,6,7]

Type of recharge: Infiltration basins (rice fields)

Main advantage: Secured water supply for Kumamoto City and surrounding areas

Figure 3.
Rice fields used for groundwater recharge (colored squares) along Shirakawa River in Kumamoto Prefecture. Source: Midori Network Ookiku

Groundwater experts and researchers, mainly from local universities, played a pivotal role in establishing the technical feasibility and viability of such a managed aquifer recharge (MAR) scheme. A sound understanding of the hydrogeology, pinpointing major recharge areas to the deeper confined aquifer in and around the previous rice fields, high potential recharge rates in the rice fields (100-200 mm/day) due to the nature of the subsurface (volcanic pyroclastic deposits), groundwater modelling studies, and regular monitoring of water level changes at observation wells indicated the feasibility of the MAR scheme [4,9]. In addition, the national legislation allowed for MAR, because laws governing groundwater are scattered and do not clarify the recharge aspect in detail, except that it should not affect water quality (under pollution control laws).

23.3. Success of payment for ecosystem services for managed aquifer recharge

A MAR scheme using PES as a financial instrument was conceptualized and fully implemented in 2004, after extensive consultation with stakeholders. An offsetting scheme in which major groundwater users (Kumamoto City Waterworks and Sewerage Bureau and some private industries) agreed to pay farmers for flooding their rice fields under specified conditions. The farmers had to flood their fields during the months of May to October, the wettest months and the normal cropping season of rice. The rest of the year, they were allowed to grow crops on 'dry' fields [3]. The scientific basis developed through field investigations and modelling assessment, such as by groundwater experts at Tokai University, provided recharge estimation, which served as verification for the private sector. This helped establish a standard payment rate, based on equivalent flooded area per month (hectares per month [ha/month]) as a unit. Farmers were paid JPY 11,000 (about US$100), JPY 16,500 (US$150) and JPY 22,000 (US$200) for ponding a 1,000 m^2 rice field for 1, 2 and 3 months, respectively. Offsetting was a win-win option, because the farmers could get direct cash payments, while the city and the private sector could offset their groundwater abstraction in a transparent manner. The PES for groundwater recharge was attractive for a mostly aging rice farming community facing the impacts of declining rice consumption and falling market price for rice.

The MAR-PES scheme has been fully functional since 2004, when the Kumamoto Technology Centre of Sony Semiconductor Co. (Kumamoto TEC) and Kumamoto City started paying the farmers [10]. The scheme then gradually expanded to include other private sector firms (such as fruit farms, and the biomedical and beverage industries). The number of participating farming families increased from 298 in 2004 to 472 in 2011 (Figure 4) [10].

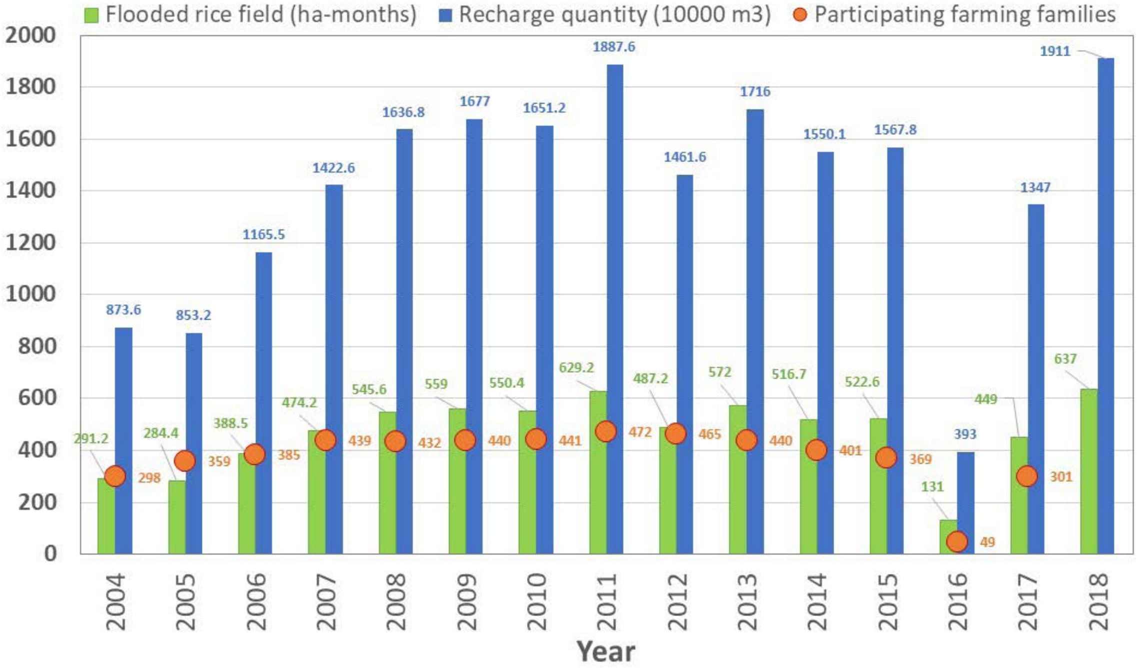

Figure 4.
Annual development in flooded rice field area, recharge quantity, and participating farming families (2004-2018). Note, the values are low in 2016 due to the impact of a major earthquake. Source: [8, 10, 11]

The recharge area has more than doubled from 291 ha-month in 2004 to 637 ha-month in 2018. An estimated 211 Mm^3 cumulatively, or 14 Mm^3 annually on average, was infiltrated under the recharge scheme during the 15-year period (2004-2018) (Figure 4) [10]. In recent years, flooded fields have offset on average around 2 Mm^3 and 12 Mm^3 of the annual groundwater abstraction for industries and Kumamoto City water supply, respectively [10]. This is about 13% of total water demand for the city. This indicates that the MAR-PES scheme accounts for only part of the recharge and the abstraction happening in the greater Kumamoto Region (2014 km^2) [12]. The proportion of the recharge from the MAR scheme is estimated to be 2.3% of the total recharge in the region, which is estimated at 600 Mm^3/yr [12], which may replenish both the unconfined and confined aquifers.

23.4. Environmental sustainability

Groundwater quantity

Groundwater levels have been regularly monitored since 1986. Analysis of time series since 1990 has revealed a gradual recovery of natural spring discharge to Lake Ezu, southeast of Kumamoto City, which previously saw a steady decline [4,11]. Annual mean increases in groundwater level in the deeper confined aquifer, which is the primary source for abstraction, correspond with wet years throughout this record (Figure 5). The very slight long-term increasing, or at least stabilizing, trend observed in groundwater table is consistent with the additional recharge from the MAR scheme constituting a small percentage of total recharge, supported by additional recharge due to improved forest management [3], although the latter portion of recharge is not quantified. Furthermore, groundwater abstraction has been curtailed by successful water demand management (see below).

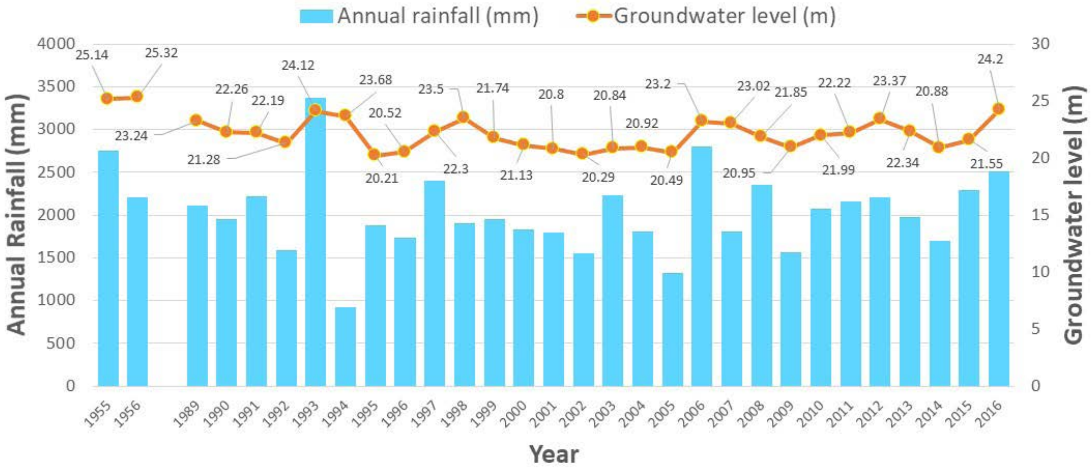

Figure 5.
Changes in groundwater level (1955-2016) in the primarily confined volcanic pyroclastic aquifer used by Kumamoto City (mamsl). Source: [8, 10, 11]

Groundwater quality

There is no water purification plant in Kumamoto City unlike in other Japanese cities. Groundwater drawn from wells in the confined aquifer is only treated with a minimum amount of chlorine as required by Japanese law before being supplied to households [1].

However, since the early 2000s, elevated concentrations of nitrate have been detected in the shallow and confined groundwater, some above the WHO upper limit of 10 mg nitrate-N/L (Figure 6). This is of growing concern [4,5,11,13]. The contribution to nitrate contamination from recharge in the ponded rice fields was found insignificant in a previous study [11], while another simultaneous study found that maximum nitrate concentrations are found in upper recharge areas [5]. The source of nitrate is likely from chemical or organic fertilizers though more research is needed [3]. Concentrations were found to decrease along the flow paths in the groundwater in both shallow and deep aquifers, attributed primarily to dilution and to a lesser extent denitrification. Denitrification was inhibited due to high dissolved oxygen levels even in confined systems, except for a smaller hotspot area, where denitrification was efficient due to different sedimentology, higher organic content and reduced oxygen conditions [5]. Combining the observation that agricultural intensification in the area (primarily livestock farming) happened since the 1970s [5], with an estimated residence time in the aquifer of 25-30 years to reach the abstraction wells [5], gives an uncertain picture of the future prospects and risks of nitrate contamination [5].

For the protection of groundwater quality due to agricultural activities, the First Kumamoto City Nitrate-Nitrogen Reduction Plan was introduced in 2005 to deal with contamination of nitrate in groundwater from livestock as well as chemical fertilizers [3,4]. Since it is an urban environment, there are also other threats to the groundwater quality, like volatile organic compounds [3], but these are not associated with the MAR scheme.

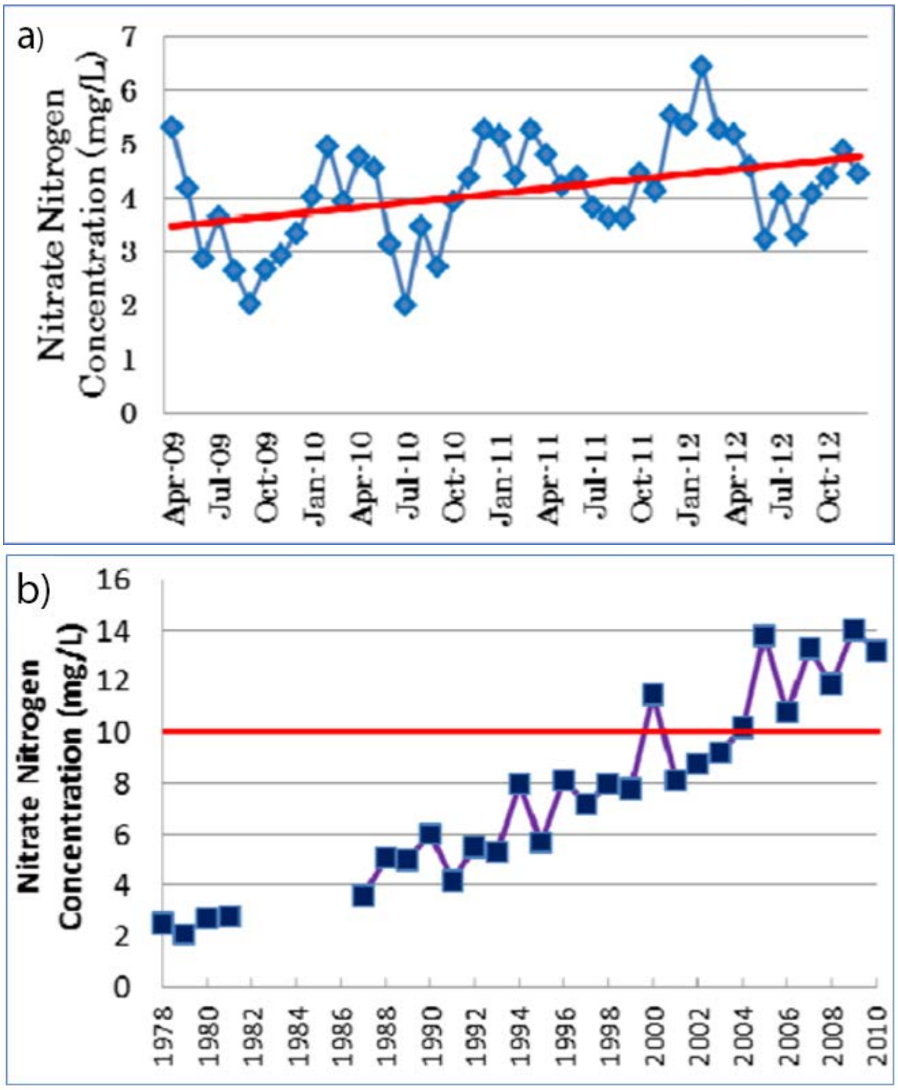

Figure 6.
Nitrate concentration of (a). spring water in the Lake Ezu downstream (2009-2012), and (b). an upstream observation well (1978-2010). Source: [11]

Energy intensity

Accurate assessment of the groundwater-energy nexus is hard in the present case, because not all of the recharged and abstracted groundwater is contributed from the MAR scheme. Depending on the depth of pumping, the energy use intensity was reported in the range of 0.3-1.2 kWh/m^3, while for every 1 m increase in lift an estimated 0.0044 kWh/m was needed for pumping groundwater to the surface [6]. From this assessment, it is inferred that the role of MAR-PES to maintain the groundwater level has positive but nominal impacts on the energy cost for water supply for the city.

23.5. Cost and benefit considerations

There are no substantial costs involved in the physical design and infrastructure of the scheme, as it relies on the infiltration capacity of existing rice fields. The major cost on the side of the city water utility and involved private sector is the payments to the farmers. So far (until 2017), the PES scheme has paid over 5 million US$[23] to the farmers (Figure 7). On an annual basis, it amounts to around US$0.36 million for a total of around 378 farming families and 388 ha-month. Based on the estimated average annual recharge of around 14 Mm^3, average per unit cost for recharge based on the payments was US$0.026 /m^3. Although this adds to the cost for the water utility and involved private sector, the paid amount is still below the average annual budget of around US$0.45 million/yr secured for the PES scheme so far. The sound financial state indicates the financial viability and further scope for expanding the scheme.

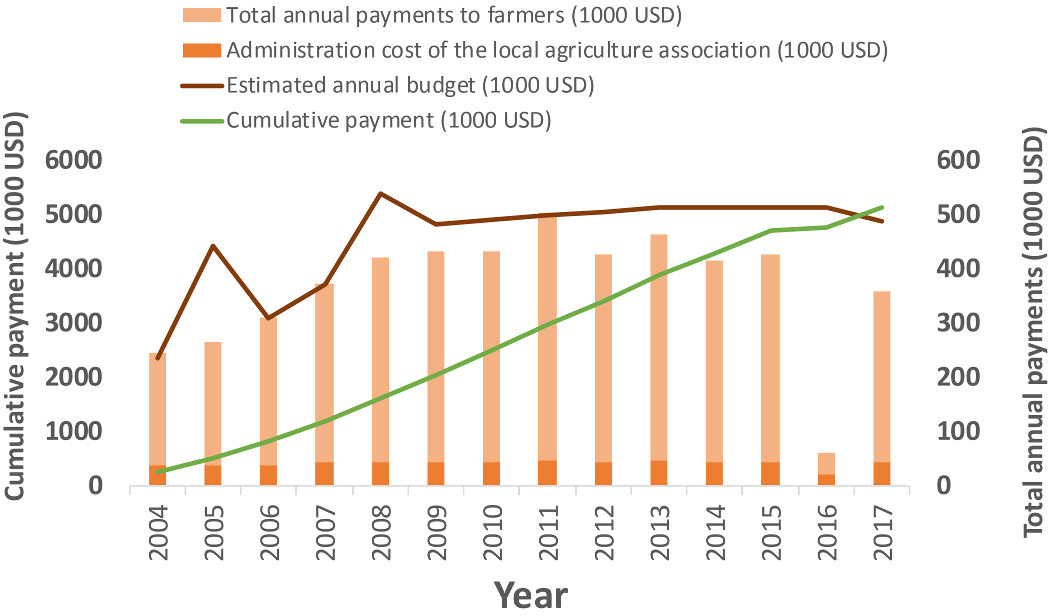

Figure 7.
Summary of payments made under the MAR-PES scheme to the farmers and budget (2004-2017). Administrative cost refers to the overhead associated with the operation and management of the PES conducted by the local agricultural association as a mediator. The administrative cost is deducted from the total payments received from the utility and private sectors participating in the scheme prior to paying the farmers. Source: [8,10,11]

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[23] Based on 1 US$ = 110 JPY with reference to 2018 January rate in www1.oanda.com. Same rate is used throughout.

If Kumamoto City had extracted water for its water supply directly from rivers running through the city, capital costs for dam and waterworks construction for the present demand (0.3 Mm^3/day) would be several billion US dollars [13]. The city is taking advantage of the subsurface to enhance the quality of the water supply as a critical nature-based solution [13].

From the farmers' viewpoint, the payment (around US$925/yr per family) is a good motivation considering the aging farming community and high market risk for growing and selling rice. However, this is generally not the only income for the farmers. Though the success of PES depends on the compliance of farmers flooding for the agreed time, the farmers can opt to continue farming when market for rice or other agricultural commodities is better. In addition, farmers can use their land for the rest of the year for farming once their flooding contract is over. So, the opportunity cost due to lost farming can be partially offset by the flooding contracts.

As for the water utility and private sector, the MAR scheme helps minimize the negative impacts of declining groundwater storage caused by their abstractions, e.g. in terms of increasing pumping costs [11]. Increased pumping costs due to decreasing head levels were estimated at 61.4 million JPY (US$ 0.54 million) over the period 1982–2003, or approximately US$25,000/yr [6]. This is less than one tenth of the costs to the scheme for the utility/private sector. So, while there is an economic incentive to farmers, there is a net cost to utilities and the private sector. The most important factor here is the environmental sustainability issue as well as aspects of city and corporate social responsibility [3].

23.6. Social sustainability

One of the important success factors of this MAR-PES scheme is sound operation and management (Figure 8). The structure of the PES has to be transparent in order to develop trust between involved parties. In this context, the coordination role played by the local agricultural association, known as Midori Network Ookiku (MNO), which is overseeing the operation and management of the PES scheme, is crucial. The MNO, which is normally involved in irrigation management, mediates between providers and buyers of the ecosystem services and enters into a formal contract with each farmer before each flooding season. The MNO monitors the flooding condition in each field, keeps a record (e.g. taking pictures, Figure 9), and prepares a report on the results. Under the contract, farmers are also required to report the conditions in their fields at the beginning and end of the flooding season. The MNO can terminate the contract with farmers failing to comply with the flooding contract and automatically remove them from the payee list. Based on the seasonal monitoring and the reports by farmers, the MNO prepares a technical and financial report and submits it to the participating buyers (city water utility and private companies) for their review. After review, the buyers sanction the requested fee (PES and administrative cost) to the MNO, which then transfers the payments to eligible farmers' bank accounts.

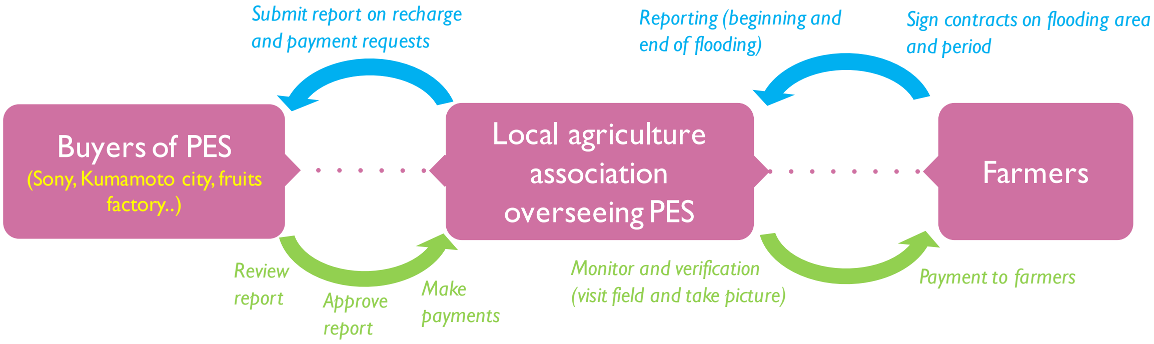
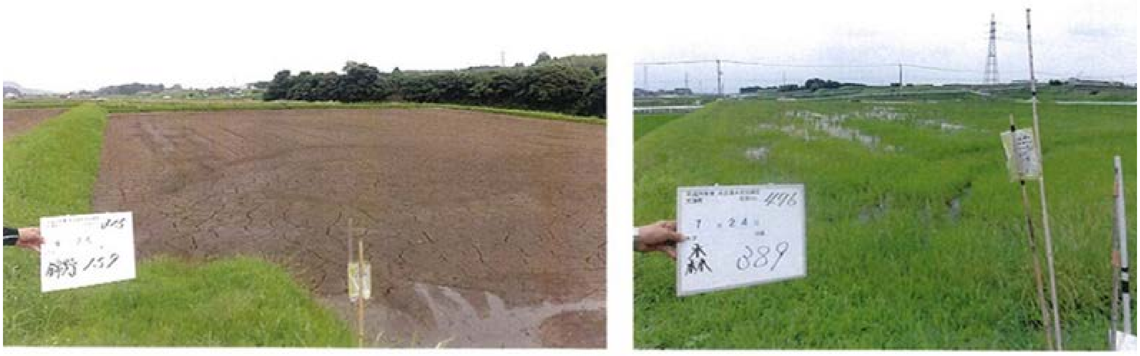


Figure 8.
Management process of MAR-PES scheme. Source: Own elaboration

A) Farmer's field qualified for PES payment



B) Farmer's field unqualified for payment

Figure 9.
Flooding of converted paddy fields. A sign is placed in every field showing the period of flooding and verified as qualified (A) or unqualified fields (B) for payment (photos credit: © Midori Network Ookiku)**.**

Strong interest and support from many stakeholders in Kumamoto City over the past 15 years is a testimony to the success of the MAR-PES scheme. It has received positive response from the city government, the universities, Kumamoto Groundwater Foundation, farmers, industries and local non-profit organizations (NPOs). Managed groundwater recharge is now one of the key water management priorities of the city. As an example, the Kumamoto City Water Source Forest Development Policy 2004 acknowledged the role of upper catchment forests in contributing to groundwater recharge and flows of major rivers, and the prefecture maintains a forest area of 800-900 ha upstream of the city [3,9,14].

Furthermore, groundwater quantity and quality issues are broadly covered under the "Declaration of the Groundwater Preservation City" established in 1976, "Kumamoto City Groundwater Preservation Ordinance" from 1977, and "The First Kumamoto City Nitrate-Nitrogen Reduction Plan" from 2005. The "Kumamoto Ground Water Foundation" was established in 2012 to protect groundwater and sustainable groundwater management. At the national level, the Basic Law on Water Cycle in Japan (2014 Act No.16) requires any intervention on water resource development to consider the whole water cycle. Active participation of farmers, city-wide campaigns to protect groundwater and reduce water demand, "Wakuwaku Water Saving Club", "Forest Volunteers", and "Gift of water" [3] and information sharing on the web are other initiatives contributing to awareness on sustainability of groundwater resources in Kumamoto.

The development of a thorough scientific understanding of the groundwater system by experts and researchers, mainly from local universities, a financially viable PES model, corporate social responsibility and tourism incentives, and the participatory approach among implementing partners and the general public were the key factors for the success of the scheme. As a result of the city's initiatives in water resource conservation, Kumamoto City won the "10th Japan Water Prize (Japan Water Prize Committee)" in June 2008 and the 2013 edition of "Water for Life" UN-Water Best Practices Award [3,11]. While groundwater contamination due to the MAR scheme seems limited due to the relatively small areal extent and small contribution to overall recharge, it is relevant to consider pollution risk from future activities or potential new sources to protect the aquifers across all recharge areas such as through appropriate land use and safe waste disposal practices.

Acknowledgements

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Case Study 24: Storm water and wastewater reuse by MAR at Atlantis, South Africa to enhance resilience to drought

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24.1. Introduction

The town of Atlantis, situated approximately 50 km north of Cape Town, is presently located within the city and houses 1.8% of the estimated 4.42 million inhabitants of the city [1]. Commissioned in 1980, the MAR scheme at Atlantis consists of two 'inland' recharge basins for infiltrating the blend of storm water runoff, mainly from the residential and commercial areas, and the treated domestic wastewater [2] (Figure 1; Box 1). In addition, a set of three "coastal" recharge basins are used for the infiltration of treated industrial wastewater and storm water from the industrial area for preventing seawater intrusion in the coastal zone. The storm water collection system consists of a series of nine connected detention basins designed for peak flow reduction. Four of these are in the residential area and the remainder in the industrial area. Domestic and industrial effluents, but not the storm water, are treated in separate wastewater treatment works and the secondary treated wastewater is polished in separate maturation ponds before discharging into the 'inland' and 'coastal' recharge basins, respectively. Currently, the MAR scheme is an integrated component of the Atlantis Water Resource Management System (Figure 2), having played a significant role during the 2016 drought.

The effluents from both the domestic and the industrial sewage treatment works are passed through separate maturation ponds for polishing before infiltration into the aquifer via the respective basins. Finally, groundwater abstracted from the Witzand Wellfield, located downstream of the 'inland' recharge basins, is softened by ion exchange and chlorinated before being pumped to the city as public water supply (domestic and industrial).

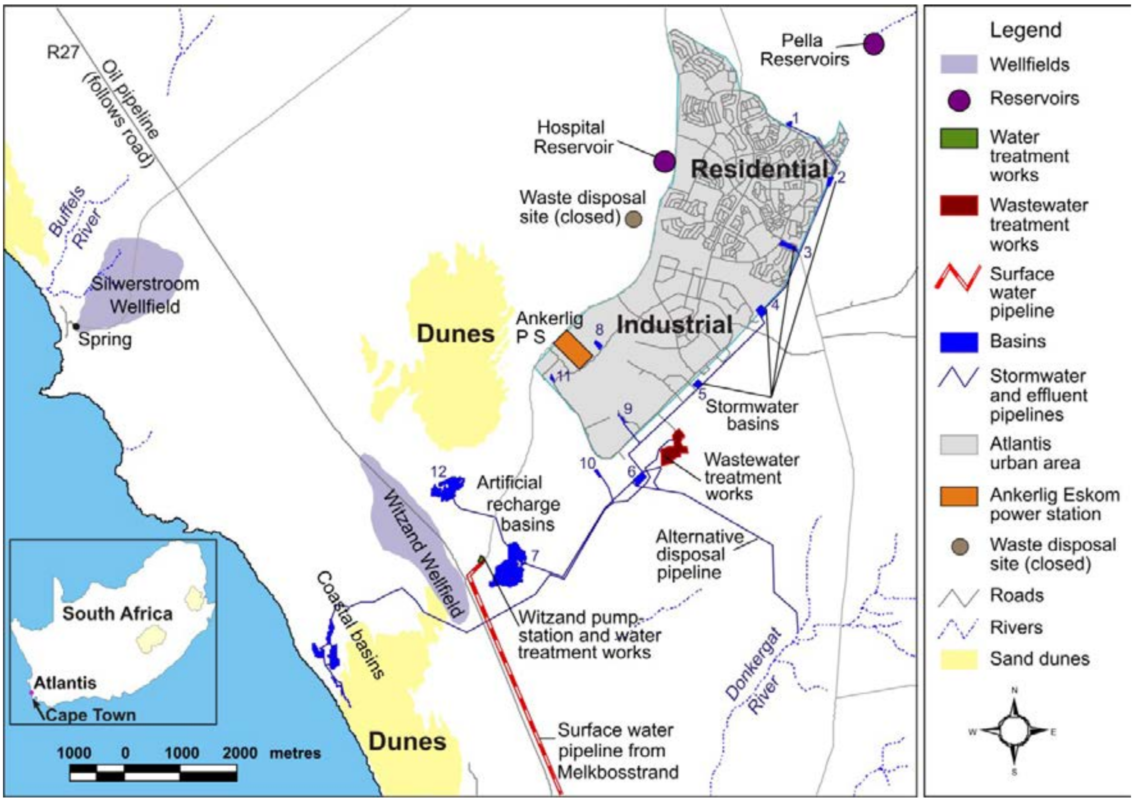

Figure 1.
Layout of MAR scheme in Atlantis. Source: [2]

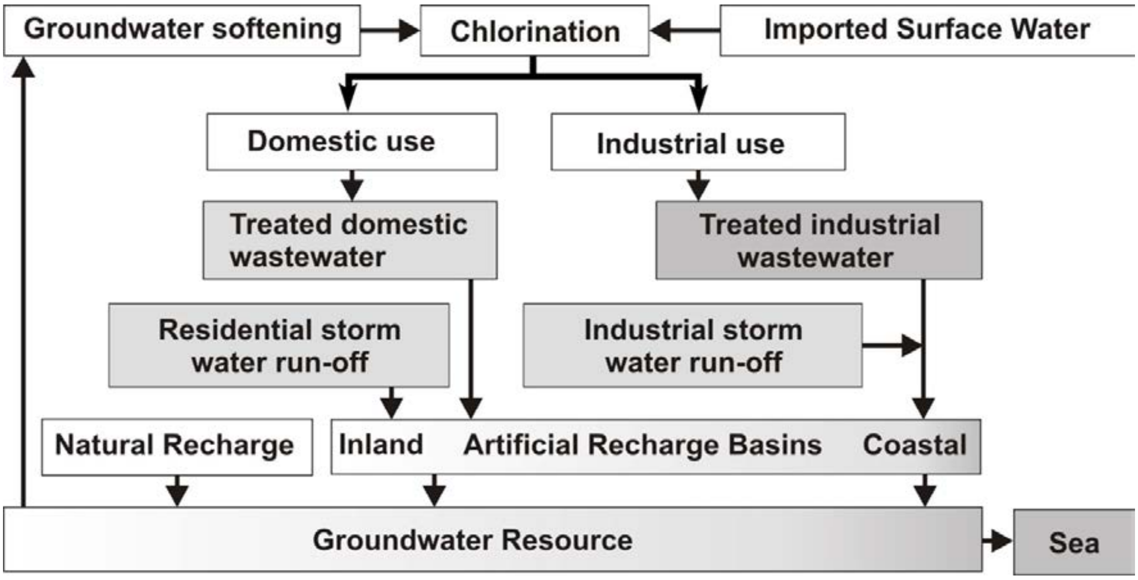

Figure 2.
Schematic layout of the Atlantis Water Resource Management System. Source: [3]

Box 1: Salient features of Atlantis MAR scheme

Commencement of operation: 1980

Location: 33°31.205′S, 18°21.285′E to 33°39.198′S, 18°30.577′E

Operator: Bulk Water Branch, Water and Sanitation Department, Informal Settlements, Water & Waste Directorate, City of Cape Town

Design: Two inland recharge basins located up-gradient of the Witzand wellfield; Basin #7 (treated domestic wastewater and storm water base flow); Basin #12 (peak flow storm water);

Mean MAR volume: 5.442 Mm^3/year

Coastal Basins: treated industrial wastewater and noxious trade area storm water runoff

Mean MAR volume: 1.305 Mm^3/year

Maximum quantity of water abstracted (1992): 5.5 Mm^3/year

End use: Public water supply

Source of water: Treated domestic wastewater, urban storm water runoff

Aquifer: Fine to medium grained sand (Cenozoic)

Type of recharge: Infiltration basins

Main advantage: Sustainable reuse of treated wastewater and urban storm water by MAR; coastal salinity control.

24.2. Motivation, conceptualisation and implementation

Figure 3.
Permanent structure damming the Silwerstroom Spring for abstraction of water.
Photo: © chapter co-authors

Atlantis is situated along the semi-arid west coast of South Africa. In the mid-seventies, when the development commenced in this so-called economic growth point, the Silwerstroom Spring in the far north-western part of the area was the only known freshwater source (Figure 3). The development was politically motivated, as the so-called "Coloured" people were moved from the city to the Atlantis area, and the Divisional Council of the Cape (DCC) had to take care of the town planning, funding, and construction. They built a collection weir and a small water treatment plant at the spring from where the water was pumped to the town. The Silwerstroom wellfield (Figure 1) was developed in an area up-gradient of the Silwerstroom Spring. Further groundwater development followed, primarily from the Witzand Wellfield, but at the time, this resource was considered a temporary supply until a 70 km pipeline could be built to bring surface water from the nearest river system to the development. Meanwhile the DCC decided against marine wastewater disposal as they became aware of the successful pilot MAR studies in the Cape Flats [4], and saw an opportunity to augment the limited groundwater resources at Atlantis by recycling the wastewater while also incorporating the storm water runoff generated due to the large impervious areas in the town area. As a result, the 70 km pipeline was never built, but in 1998, a connection was established to the Cape Town water supply. This was due to the drop in wellfield groundwater levels in the mid-1990s for a variety of reasons (Table 1).

The sequence of events in the development of the MAR system is set out in Table 1. Over the years, several modifications were made to the system mainly due to water quality considerations [5]. Initially, Basin #7 was the only MAR facility but the basin started overflowing in 1986 due to the high winter rainfall and a further recharge basin was initiated. Basin #12 was constructed in 1994 in an area down gradient of the non-vegetated dunes (Figure 1) where high quality natural groundwater occurs. There was an increase in alien vegetation especially after the construction of the basin and an exceptionally good rainy season. Woodcutters remove the alien vegetation for firewood.

Table 1.
Atlantis water infrastructure development timeline

Date	Action	Motivation
1980	Recharge Basin #7 constructed	Introduction of MAR up-gradient of wellfield
1980	All treated wastewater and urban storm water runoff recharged	Recycling for supply augmentation
1986	Diversion pipeline constructed to Donkergat River	Discharge of treated wastewater not suitable for MAR
1986	Wastewater recharge terminated; treated effluent discharged to Donkergat River; all storm water recharge continues	Industrial effluent quality (especially DOC and trace metal content)
1987	Storm water system connected to Donkergat River discharge	Discharging poor quality storm water base flow when needed
1988	Closure of Atlantis Solid Waste Disposal Site (ASWDS)	Aquifer pollution threat: 5 km up-gradient of wellfield
1988	Commissioning of separate domestic WWTP; only storm water recharge	Treated domestic wastewater considered suitable for MAR
1988	Construction of coastal recharge basins; only test filling of first basin	Intended for treated industrial wastewater and industrial area storm water runoff
1989	Basin #7 dried out and cleaned in late summer; residential storm water recharge resumed	Removal of fine surface deposits; improving infiltration capacity
1989	All wastewater treated in domestic WWTP; effluents to Donkergat River	Refurbishment of industrial WWTP
1992	Treated domestic wastewater and residential storm water recharge resumed	Completion of refurbishment of industrial WWTP
1994	Construction of Recharge Basin #12; high flow - low flow separation unit	Most good quality storm water peak flow piped to Basin #12 for MAR; Base flow with treated wastewater directed to Basin #7 for MAR
1994	EIA undertaken for Witzand Farm	Environmental and aquifer protection needs
1995	Basin #12 in use (winter rainfall)	Mostly good quality peak flow storm water
1998	Pipeline connecting Cape Town (surface) water supply to Atlantis	Augmenting Atlantis supply due to extended MAR interruptions during construction work
1999	Rehabilitation of production boreholes	Clogging due to iron biofouling
2011 - 2020	Pilot study of in situ Fe and Mn removal followed by field testing	Treatment intended to prevent iron biofouling of production boreholes
2016 - 2018	Extended drought with low rainfall and drastic demand management	Lack of water supply
2018	Extensive renovation of Atlantis water supply, including additional boreholes	Renewal of infrastructure for augmenting groundwater supply as insurance against drought

Initially, all wastewater was treated at a single wastewater treatment works, but by 1986 water quality considerations (i.e. high DOC and trace metals) necessitated exclusion of the industrial effluent for recycling via MAR. After this, treated domestic wastewater was only reintroduced into the MAR system in 1992 after completion of the new domestic wastewater treatment works (Figure 4) and refurbishment of the older works for treating the industrial effluent.

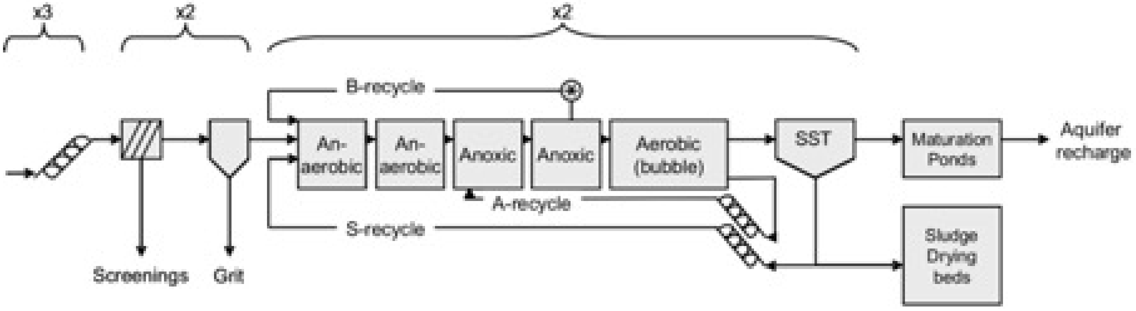

Figure 4.
Schematic diagram of upgraded domestic wastewater treatment plant at Atlantis [3]. Three parallel Archimedes screws lift the wastewater into the plant and from the screens and grit removal the system is doubled up to the sludge settling tank. A series of three maturation ponds do the final polishing.

Basin #12 is located in an area with relatively dense vegetation between the non-vegetated dune area and the Witzand wellfield, which has low salinity groundwater. The new basin provided the opportunity to separate low salinity peak flow storm water runoff from the base flow which also includes treated wastewater. The purpose of infiltrating the lower salinity water is to maintain the high quality of the water in that part of the aquifer between the dunes and the wellfield (Figure 5).

Figure 5.
Recharge Basin #12 in August 2007, after a major rainfall event. The basin is mostly dry and fills only when there is sufficient peak flow storm water. Photo © chapter co-authors

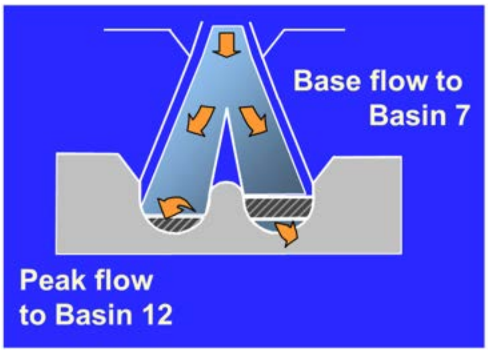

Figure 6.
Peak and base flow separation weirs.
Source: Own elaboration

An innovative weir system, allowing over flow and under flow, achieves separation of peak storm flow from base flow (which includes treated domestic wastewater) in the MAR input system (Figure 6).

Iron clogging of the production boreholes caused a gradual decline in the groundwater abstraction and once the connection to the Cape Town surface water supply was made in 1998 surface water gradually became the main supply source for Atlantis. Only when the drought started in 2016 and surface water resources were virtually depleted, re-drilling of production boreholes took place and groundwater abstraction increased (Table 2). The effect of the drought extended from 2016 to 2019 and possibly even later as water restrictions were still in place in 2019.

Table 2.
Atlantis water supply sources

Year	Surface water imported	Witzand wellfield (MAR)	Silwer-stroom wellfield	Total supply	Groundwater use
	Mm³/yr	Mm³/yr	Mm³/yr	Mm³/yr	%
2013/14	5.280	0.979	0.252	6.511	18.2
2014/15	5.853	1.001	0.222	7.076	17.1
2015/16	5.513	1.445	0.201	7.158	23.2
2016/17*	4.386	1.655	0.119	6.160	29.5
2017/18*	1.580	2.587	0.580	4.747	67.1
2018/19*	2.512	1.854	0.640	5.005	50.2

* Demand reduced due to water restrictions

The characteristics and functions of the various infiltration basins vary considerably (Table 3). The infiltration rates may be overestimated as the exact distribution of the recharged water is unknown.

Table 3.
Recharge facility characteristics and function [2]

Facility	Area (ha)*	Thickness of unsaturated zone (m)	Recharge volume Mm³/yr	Infiltration rate (mm/day) **	Recharge water source
Basin #7	28.3	1.5		32	Treated wastewater & base flow
			5.442***		
Basin #12	16.8	4.5		23	Peak flow & treated wastewater
Coastal Basins	12.5	10.5	1.305	43	Industrial wastewater & urban runoff from industrial areas

* Total basin area when full; Basin #12 is mostly dry and only fills after major rainfall events
** Rate based on total basin area (derived from modelling)
*** Joint infiltration volume in Basins #7 and #12 (estimated for period 2003 - 2013, Table 4)

24.3. Environmental sustainability of MAR scheme

24.3.1. Groundwater quantity

Water levels near the MAR facility show a seasonal trend due to the winter rainfall (Figure 7). Following the discontinuation of wastewater recharge in 1986, a steady decline in water level is observed closer to the wellfield in the early 1990s. Domestic wastewater recharge resumed in 1995 but due to the deficit caused by over abstraction the situation only improved towards 1999 when surface water importation from the Cape Town water supply provided relief (Table 1). At this stage the Cape Town water supply system reached

Melkbosstrand which is only 12 km from the Witzand pump station and Atlantis also formed part of the City of Cape Town.

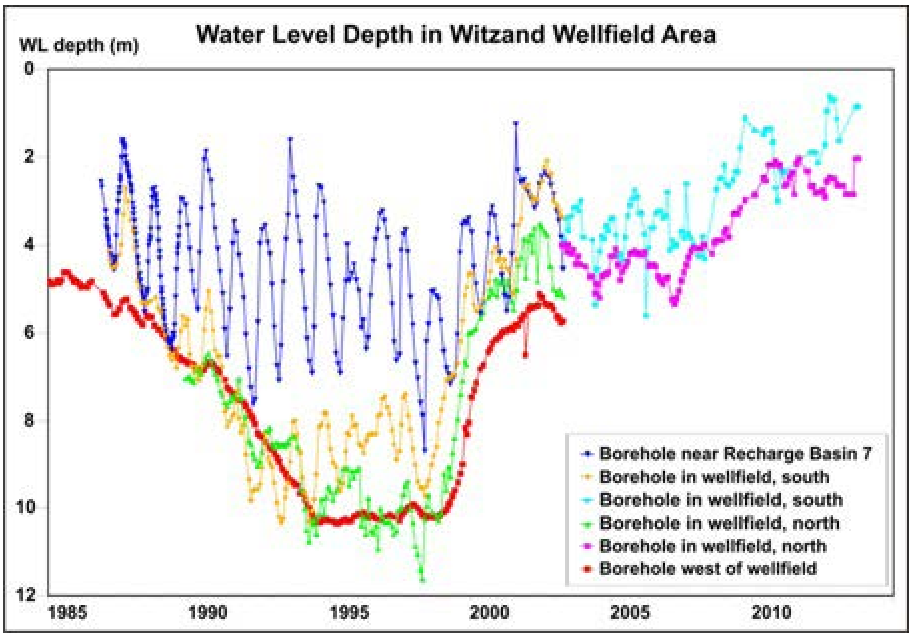

Figure 7:
Water level configuration between Recharge Basin #7 and the Witzand wellfield area - Source: Own elaboration

The annual recharge volumes to the inland and coastal recharge basins are shown in Table 4.

Table 4.
Recharge volumes to the inland and coastal recharge basins

Year	Domestic wastewater Mm^3/yr	Storm water Mm^3/yr	*Total Recharge to Basins #7&#12 Mm^3/yr	Witzand wellfield abstraction Mm^3/yr	Industrial wastewater to CRBs Mm^3/yr
2003	1.237**	3.69	3.557	2.057	1.039
2004	2.225	4.45	5.335	2.092	2.062
2005	2.086	4.86	5.626	1.951	1.446
2006	2.158	4.06	4.868	2.205	1.411
2007	2.180	5.28	6.170	2.410	1.430
2008	2.136	5.23	6.056	1.370	1.362
2009	2.265	5.92	6.895	0.750	1.386
2010	2.469	3.69	4.789	0.526	1.233
2011	2.625	3.89	5.165	0.680	0.948
2012	1.625**	5.23	5.545	1.390	0.730
2013	no data	7.09	5.850	0.834	no data
Average	2.101	4.854	5.442	2.057	1.305

*Treated domestic wastewater and storm water to Basins #7 and #12; Recharge volumes were adjusted for rainfall and evaporation

**Incomplete data

Treated domestic wastewater and residential storm water runoff are recharged into Basin #7 and Basin #12 but the exact distribution between the two basins is unknown. The Witzand wellfield is located down gradient of the MAR basins and benefits directly from MAR. Therefore, only abstraction from the Witzand wellfield is shown in Table 4 for comparison with the recharge volumes. It is evident that there is an annual surplus over the period shown. This was due to the decline in abstraction as a result of the clogging of production boreholes and the relative ease of importing surface water from the Cape Town supply system as Atlantis now formed part of the city. The very high water levels in the wellfield area from about 2008 to 2013 are reflected in Figure 7 and explained by the limited groundwater abstraction [Table 2].

24.3.2. Groundwater quality

The sandy nature of the Atlantis aquifer makes it particularly susceptible to pollution, and therefore protection of the main recharge area, which specifically includes the non-vegetated dune area is of the utmost importance. The establishment of a nature reserve in that area contributed significantly to the protection of the aquifer although it only covers the central area and Basin #12 at this stage. A logo was developed for the aquifer to draw public attention to the importance of the aquifer and its protection [6] (Figure 8). The logo depicts raindrops falling on the bare dunes while the flowers (Protea spp) are typical for the natural vegetation in the area. The 1700 ha area is called the Witzands Aquifer Nature Reserve [7].

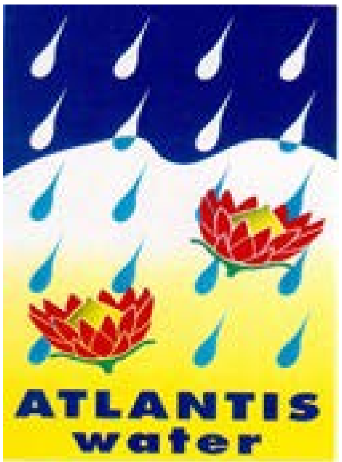

Figure 8.
Logo for aquifer.
Source: [6]

Protection zones for both wellfields equating to a groundwater travel time of ten years were delineated using the groundwater model constructed for the aquifer [8].

The natural groundwater is hard due to the presence of calcrete and shelly material in the aquifer, and for this reason the ion-exchange softening plant forms part of the groundwater treatment system. The low calcium content of the recharged wastewater causes a gradual decrease in the calcium concentration in the abstracted water despite further leaching of calcium from the aquifer [9]. Softening will nevertheless have to continue as some parts of the wellfield area are not affected by MAR and still yield hard water. The freely available calcium in the groundwater is assumed to be the most important factor in the removal of phosphate by precipitation.

From a water supply point of view the general inorganic chemistry of the water supply at Atlantis is of key importance due to the salinity and hardness of the groundwater. The locations of the sampling points are shown schematically in Figure 9. Sampling point S0 refers to raw sewage and is only of importance for the study of pharmaceutical compounds.

An intensive water quality study was carried out in 2007 to 2008 and detailed results for inorganic chemistry, trace metals, pharmaceutical compounds, bacteria and viruses were reported [3]. The results showed that the maturation pond effluent (S2) is sodium chloride water which is chemically very similar to the secondary effluent (S1). Inspection of the data shows that only the nitrate decreased slightly during the residence in the maturation ponds. The urban storm water (S3) has a slightly different composition with a little less sodium and chloride but slightly higher calcium, magnesium, and bicarbonate. The blend of maturation pond effluent and storm water used for recharge in Basin #7 is sampled at S4. As the water progresses through the subsurface past sampling point S6 to the nearest production borehole (S8) both calcium and bicarbonate increase to some extent. These changes together with the slight increase in sodium and chloride are ascribed to the dissolution of calcium carbonate from the aquifer and blending with slightly more saline groundwater. The lower salinity parallel flow path from Basin #12 runs past observation point S7 to the closest production borehole (S9) in the wellfield. In this case calcium and bicarbonate also increase but both sodium and chloride decrease due to blending with low salinity natural groundwater [3].

Sodium and chloride levels in the groundwater blend (S10) are similar to those at the production borehole S8 but higher than at production borehole S9. The blend also has a significantly higher calcium and bicarbonate content and this represents the impact of the natural groundwater in the aquifer which is unaffected by artificial groundwater recharge and relatively hard. After softening (and chlorination), calcium, magnesium, and particularly bicarbonate are significantly lower (S12). During use in the town the sodium, chloride and sulphate concentrations increase notably when considering the treated domestic effluent (S1) and in comparison with the final chlorinated water (S12) [3].

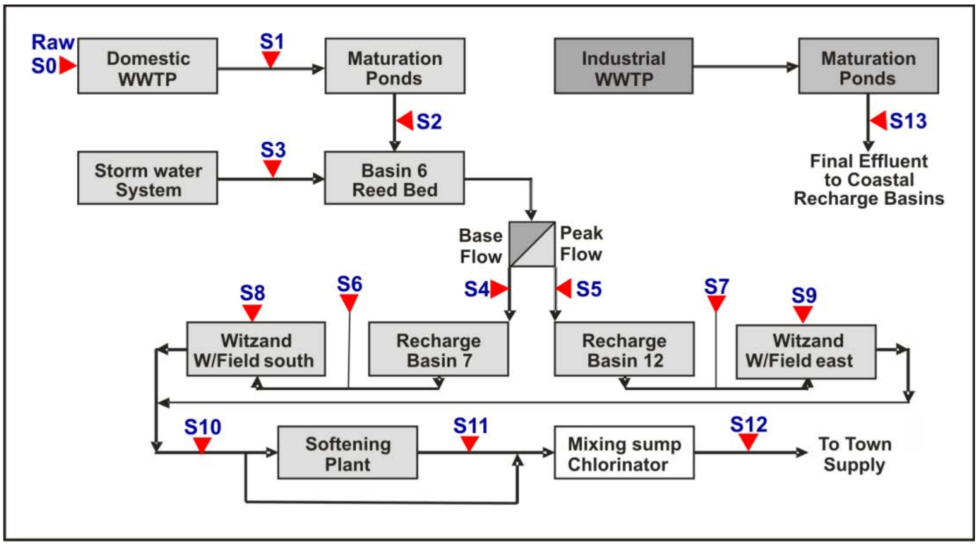

Figure 9.
Schematic layout of the Atlantis system showing the sampling points.
Source: Own elaboration

The bacterial counts (Colony-forming units/100 mL) at the various points in the system illustrate the importance of the subsurface passage as a safety barrier in the system (Figure 10). It was found that not only the indicator organisms follow this pattern, but also that the pathogens, including viruses, follow a similar pattern of log-reductions to provide the necessary safety margins for the recycling system.

The wastewater and storm water inputs to the system as well as the production boreholes nearest to the recharge basins were sampled for organic micropollutants. A total of twelve of these compounds were detected in the domestic wastewater secondary effluent while nine were detected in at least one of the production boreholes at nanogram per litre levels. In the wastewater some compounds reached the microgram per litre level. The compounds included antibiotics, antiepileptic and psychoactive drugs, compounds used as contrast media, and anti-inflammatory medication in the group of "acidic compounds". As these compounds occur at very low levels triplicate samples were taken but this limited the number of sampling points as four SPE extractions are required on each sample plus blanks and spiked samples to increase confidence limits [3].

The trace organic compounds and pharmaceuticals showed a significant decrease through the treatment system and the subsurface passage [3]. Tests indicated that trace organic carbon compounds are effectively removed and diluted to such an extent that the nanogram levels remaining were well within internationally accepted norms [10]. It is, however, possible that the situation may be changing over time, particularly due to the low water use as a result of the recent drought, and the monitoring program may need expansion for certain (non-monitored, but possibly critical) emerging contaminants.

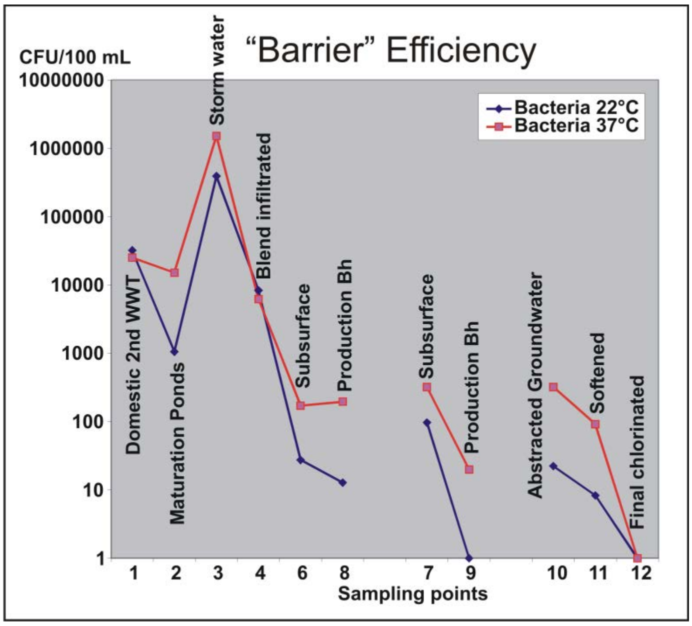

Figure 10.
Bacterial counts (Colony-forming units/100 mL) in the MAR system showing CFU numbers in secondary treated domestic wastewater, also after the maturation ponds, in the storm water system, the aquifer, after softening, and in the final chlorinated town supply.
Source: Own elaboration

A preliminary study using ^{35}S as tracer was carried out in an attempt to determine the residence time of the artificially recharged water but conflicting results jeopardised the study and a follow-up study could not yet take place [11].

24.3.3. Energy intensity and risk management

The Witzand wellfield is situated on the coastal plain at an elevation of approximately 50 m above sea level while the storage reservoirs serving the town of Atlantis are above 180 m elevation which requires lifting the water some 130 m, adding significant pumping costs. For example, over the period of one week from 30 August to 5 September 2019 (both dates included), the quantity of water pumped from the Witzand Water Treatment Plant to the town of Atlantis amounted to 72,607 cubic metres. This is consisted of a blend of 64.5% surface water and 35.5% groundwater from the Witzand wellfield. The abstracted groundwater is a blend of MAR and naturally recharged groundwater. The total power consumption for the same week amounted to 129,574 kWh. This is equivalent to ~ 1.8 kWh per cubic meter of water. It is worth noting that it largely reflects the energy intensity of lifting groundwater at least 130 m for distribution from the town reservoirs unrelated to MAR.

Production borehole clogging due to iron and manganese presents serious problems and tests are being carried out to precipitate the iron in-situ and upstream by oxygenation [12]. The principle, which is similar to the Vyredox process, was proven in trials at a production borehole and presently further research is being carried out to get full-scale design criteria. The occurrence of iron is a natural phenomenon in the aquifer and does not relate to the MAR process.

Chemical spills in the industrial area or malfunctioning of the wastewater treatment works is possible. However, in 1986 when it was decided to stop recharging the industrial wastewater in the inland basins, a diversion pipeline was constructed to the nearby Donkergat River for disposal of the treated effluent (Table 1). This option is still available as an emergency discharge route when required due to poor water quality. In 1987 the main storm water pipeline was also linked to this outfall (Table 1).

Other pollution threats to the aquifer include leachate from the waste disposal site approximately 5 km NE of the wellfield. It was closed in 1988, but is still being monitored [13]. Further, an oil pipeline runs along the R27 route (Figure 1) past the Witzand wellfield. An emergency response plan is in place, but a regular monitoring programme is still needed.

The Ankerlig Power Station presently runs on diesel fuel and spillage in this area up-gradient of the wellfield could threaten pollution of the water supply (Figure 1).

A risk management plan was developed based on the 12 elements of the Hazard Assessment and Critical Control Point (HACCP) system as recommended in the literature [14]. Four critical control points were identified for regular monitoring. A semi-quantitative risk estimation and consequence analysis led to the compilation of a risk matrix for ranking risks of all hazards identified.

The Atlantis MAR scheme is relatively robust and consistently yielding good quality water, but nevertheless a series of 21 further changes have been recommended for increasing its efficiency and longer term viability [15]. These include among other things the redesign of Basin #7 to allow for sub basins that will facilitate wetting and drying cycles for more efficient quality improvement; constructing a bypass for treated domestic wastewater in order that it does not blend with poorer quality storm water in Basin #6; redesign Basin #6 into a proper reed bed for efficient treatment of storm water. Recharge basin maintenance only received attention once when Basin #7 was cleaned in 1989 by scraping and removing the top 15 cm of the basin floor, especially in depressions.

24.4. Cost and benefit considerations

The Atlantis MAR scheme provided a novel and economically viable solution for a local water supply in the early days of the development, which fulfilled the immediate goal. Groundwater exploitation and recharge provided a coherent solution to water supply and wastewater and storm water runoff recharge at a lower cost than alternative engineering options, such as the originally intended construction of a 70 km pipeline for importing surface water and a marine wastewater and storm water outfall. The eventual much shorter connection to the Cape Town water supply would not have been possible in 1980 but in 1998 Atlantis formed part of the City. The experience in the 1990s when no treated wastewater was recharged showed the importance of MAR to prevent the significant drop in the water table [Figure 7] to the detriment of the aquifer.

In the recent drought (2016-2018), the value of the local water supply was proven again as the area was once more becoming largely independent of the limited supply of the Cape Town Metro (Table 2). It was even planned (but not yet implemented) to export water from Atlantis to augment Cape Town water supply.

The coastal recharge basins are generally wet and attract numerous birds and other wild life serving as a significant environmental benefit for the Koeberg Nature Reserve located between the coast and the R27 route. The inland basins are not easily accessible to the public.

24.5. Social sustainability

The two primary acts that govern artificial recharge projects in South Africa are the National Water Act (No. 36 of 1998) and the National Environmental Management Act (No. 107 of 1998). Other legislation and local by-laws also apply to the Atlantis MAR scheme which protects the resource. These include:

- National Environmental Management: Biodiversity Act (Act 10 of 2004)
- National Environmental Management: Protected Areas Act (Act 57 of 2003)
- Water Services Act (Act 108 of 1997)
- National Heritage Resources Act (Act 25 of 1999)
- Local City of Cape Town by-laws

The National Department of Water and Sanitation is the regulatory authority and further to the act has developed strategies which are aligned with the relevant legislation.

- National Water Resource Strategy (2004)
- National Groundwater Resource Strategy (2016)
- Artificial Recharge Strategy (2007)

These strategies aim to develop new water sources in situations of increasing water scarcity, actively pursue the protection and conservation of water resources and achieve sustainable resource utilisation through appropriate water resource governance.

Furthermore the scheme complies with the South African National Standards for drinking water quality (SANS 241) limits which ensures safe drinking water to the town. The SANS 241 limits are guided by the World Health Organization Guidelines. The National Water Act and the relevant strategies enforce monitoring of the resource. A Water Safety Plan has also been developed for the scheme. The plan draws on many of the principles and concepts from other risk management approaches (e.g., ISO (ISO 9001 and ISO 22000), the multiple-barrier approach, and HACCP (as originally used in the food industry) (WHO, 2004). The City of Cape Town Municipality is responsible for the implementation of the Water Safety Plan.

The current Atlantis MAR scheme does not require a permit (referred to as a Water Use Licence) in terms on the National Water Act (No. 36 of 1998) as it is permissible as a continuation of an existing lawful use (under section 22 of the Act). The optimisation of the MAR scheme as well as the expansion of the Atlantis Water Resource Scheme will however require a water use licence as it triggers activities listed (a, c, e, and i) in Section 21 of the National Water Act.

Institutional arrangements for public and stakeholder consultation took place through meetings with the Atlantis Management Committee, which acted as an advisory body to the Divisional Council of the Cape. Concerns by the community were never raised regarding the fact that treated wastewater was being recharged into the groundwater. Some concerns regarding the hardness of the potable water were however raised as it caused geysers and kettles to build up deposits of calcium. This led to the establishment of the Witzand Softening Plant. Initiatives were taken to involve the community, and educational awareness programmes were carried out to make schools aware of the unique water supply system. Informal arrangements with various institutions (e.g. universities, municipalities, World bank, etc.) are still in place.

Currently, a Monitoring Committee is being established which will include internal and external stakeholders who are directly or indirectly affected by the entire Atlantis Water Supply Scheme. The Monitoring Committee is a vehicle for effective participation, consultation and dialogue to discuss, debate and share interests and positions regarding the scheme with the intention of reaching consensus for consideration by the relevant authorities and technical operators.

Acknowledgements

The central role Mr J. A. Clark, Engineer of the DCC, acting as a champion for the development of the MAR system is gratefully acknowledged. Also Mr P. B. King, Chemist of the DCC, played a pivotal role in the design and operation of the water and wastewater treatment plants and had a passion for the system as a whole. The planning and construction of the Atlantis town infrastructure was done by the consulting engineers Liebenberg and Stander of Cape Town. Knight Hall Hendry (Pty) Ltd was responsible for environmental matters and also arranged for the design of the logo.

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Case Study 25: Water recycling with Managed Aquifer Recharge in sand dunes of St-André (Koksijde) as one of the multiple safety barriers for drinking water to Veurne area, Belgium

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25.1. Introduction

Between 1980 and 1990, the demand for drinking-water increased from 3.8 to 5 million m³/year (Mm³/yr), exceeding the capacity of the dune water catchments of the Intermunicipal Water Company of the Veurne area (IWVA). It was decided in 1990 that alternatives should be developed. Artificial recharge of the unconfined aquifer of the dunes of St-André (situated in Koksijde) was the selected solution. Effluent from a nearby wastewater treatment plant was selected as the source water for recharge (Van Houtte and Verbauwhede, 2005) [1].

The scheme, based on the multiple barrier approach, became operational in 2002 (Figure 1). At the Water Production Center (WPC) Torreele, the effluent, approximately 3 Mm³/yr, is treated using ultrafiltration and reverse osmosis. In St-André, this water is infiltrated in a pond of 500 m length and abstracted using wells screened between 8 and 12 m depth (Figure 2). The average residence time in the aquifer amounts to 55 days and this groundwater is treated using aeration and sand filtration for iron removal to comply with drinking-water quality standards.

The scheme resulted in a decrease in groundwater extraction elsewhere from 3.87 Mm³/yr in 1990 to 1.78 Mm³/yr in 2018 (Figure 3), accompanied by a rise in groundwater levels. The largest share of decrease of groundwater extraction was achieved in the dunes of Cabour and the Westhoek (Figure 3). Not only it has enhanced the natural values of the coastal region, but also will improve resilience to rising sea level due to climate change.

Figure 1.
Areal photograph of water catchment of St-André (Koksijde) with the infiltration pond in the soutwestern part. © IWVA

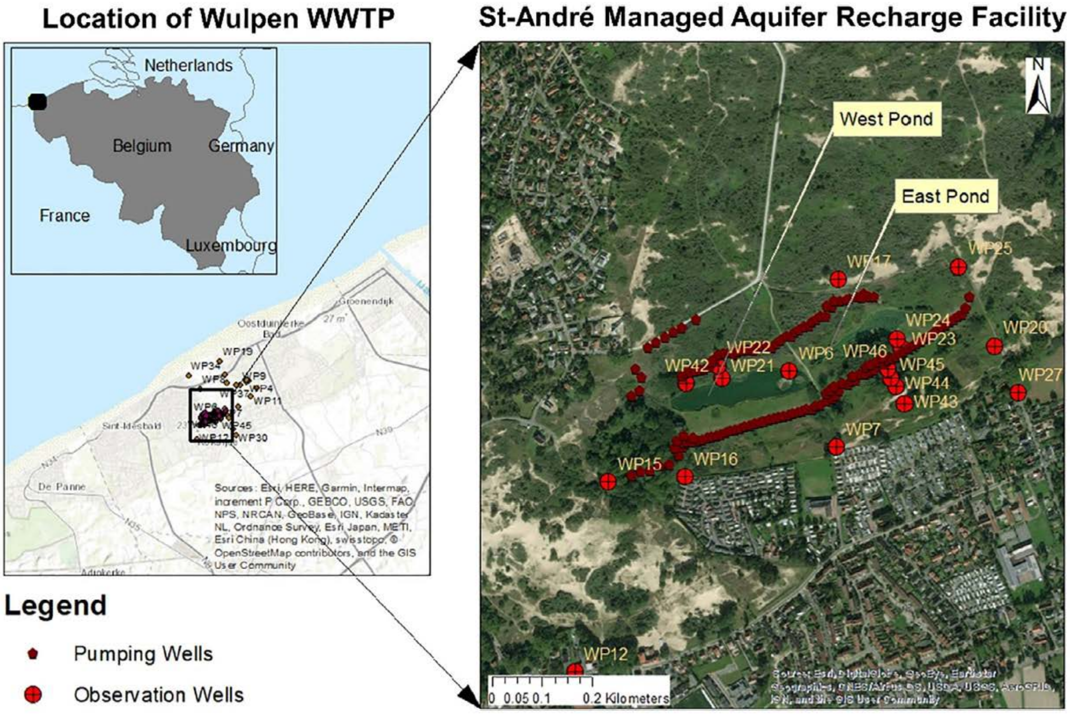

Figure 2.
Managed Aquifer Recharge in the water catchment of the dune aquifer at St-André (Koksijde). Source: Own elaboration; Photos © IWVA

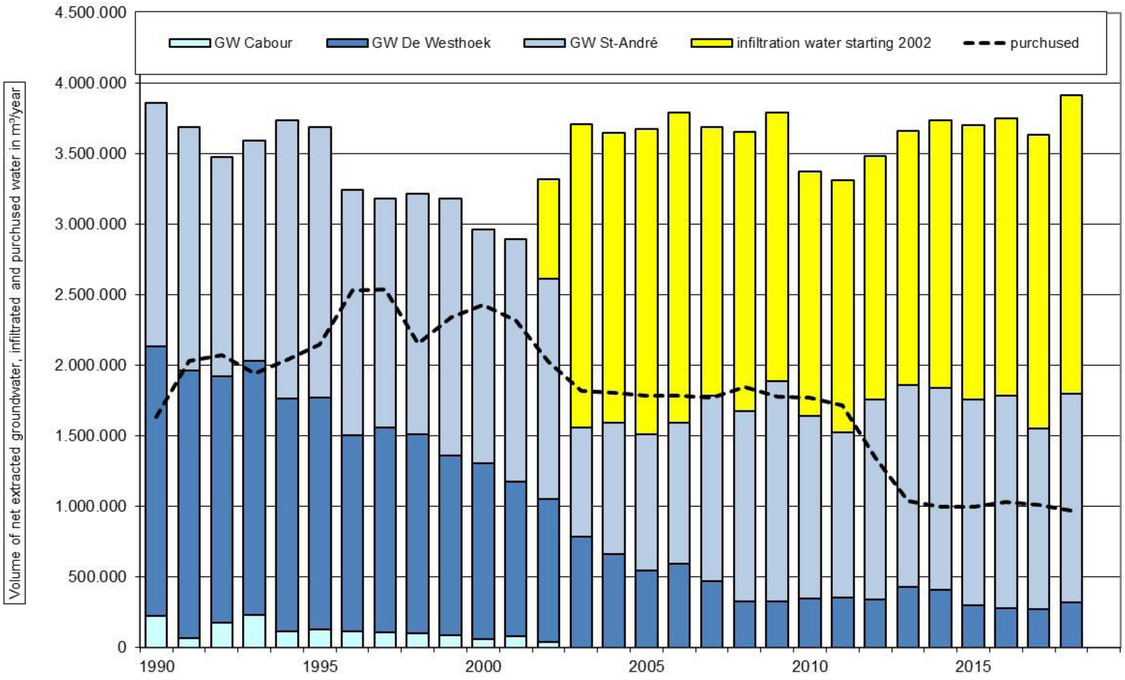

Figure 3.
Annual quantity in m^3/year of groundwater production (three blue bars) and infiltrated water (yellow bar) between 1990 and 2018. Dashed line shows amount of water purchased by IWVA from neighboring companies for the same time period. Source: Own elaboration

Salient Features

Location :	Koksijde, Belgium N 51,06,50 E 2,39,17
Operator :	Intermunicipal Water Company of the Veurne area (IWVA)
Start-up :	2002
Source water :	effluent from wastewater treatment plant of Wulpen, operated by Aquafin
End use :	drinking-water
Design :	treatment of effluent using 5 trains of UF membranes (13,200 m^2) and 2 RO skids (22-11 6” PV configuration); infiltration in the dune aquifer using pond 500 m long with area of 18,200 m^2; extraction with 112 wells
Treatment capacity :	max. 7,000 m^3/d
Investment cost :	7,000,000 euro

25.2. History of the project from its origins

Main drivers for water reuse Despite purchasing drinking-water from neighbouring regions since the 1970s, in summer periods water shortages were common in the area. The dune water catchments reached their maximum capacity and at the same time the ecological interest in the dunes was growing. At the beginning of the 1990s, alternative exploitation methods were studied to remediate the decreasing groundwater levels and to guarantee the current and future water extraction possibilities, resulting in the project for artificial recharge (as it was then called, now known as 'managed aquifer recharge') of the unconfined dune aquifer. As no other year-round sources are available in this area, the IWVA chose wastewater effluent from the nearby wastewater treatment plant of Wulpen as the source for the production of high-quality infiltration water (Van Houtte and Verbauwhede 2013) [2].

Initiation of project and approval process Prior to the development of the MAR scheme, the IWVA conducted pilot tests with infiltration in the dunes of St-André (Van Houtte *et al*. 2012) [3]. These tests were executed in cooperation with the University of Ghent. The IWVA also had preliminary discussions with environmentalist specialists. As a result, at the start of the permitting procedure ecological conditions were taken into account.

Expansion of the project In November 2014, IWVA introduced a novel infiltration technique in an area 60 m south of the existing wells. A well battery was present there until 2002. Infiltration boxes of the type that are used to store rain water, were placed at a depth of approximately 1.6 m below ground level and covered with 1 m of dune sand. A first experiment was 50 m in length, with a width of 4.8 m and a height of 0.66 m (Figure 4, Green object in trench). It was called a 'subterranean infiltration' system and the feed water for the system was the treated effluent of WPC Torreele. The system offered several advantages compared to the existing infiltration system. There is no recontamination due to wildlife or leaf fall and temperatures remain constant compared to the infiltration water leaving WPC Torreele: no cooling down in winter and no heating up in summer. This meant that during colder periods the infiltration capacity of 'subterranean infiltration' exceeds that of conventional infiltration. Based on the positive results the system was expanded in February 2016 to 300 m length (Van Houtte *et al*. 2019)[4].

In December 2018 the western part of the infiltration pond was extended further in length by 100 m. By 2018, the subterranean infiltration system recharges 300,000 m^3/year water (Figure 5, light blue bar). This resulted in an increased infiltration and ratio of approximately 10% in January and February 2019.

In 2019 infiltration was expanded to the eastern part of St-André. In this area the existing canal formerly used to infiltrate the flushing water from the sand filters was converted to an infiltration canal. This extra infiltration capacity of 400,000 m^3/year compensated for a decrease of permitted groundwater extraction by 200,000 m^3/year; and the operation started the second half of March 2019. The expansion resulted in an increase of infiltration of 10% by the end of August 2019 compared to the same period in 2018.

Figure 4 (a)
Construction of 'subterranean infiltration' in water catchment of St-André (Koksijde).
© IWVA

Figure 4 (b)
Extended infiltration pond, January 2019.
© IWVA

The current permitted volumes are shown in the Table 1 below.

Table 1.
Permitted volumes (since July 2018) in water catchment of St-André

	Infiltration capacity (m³/year)#	Groundwater extraction (m³/year)
Western part of St-André	2,500,000 (by subterranean infiltration 300,000)	1,000,000
Eastern part of St-André	400,000	500,000

all infiltrated water can be extracted, so total extraction capacity amounts to the sum of infiltrated and net groundwater extraction

25.3. Environmental sustainability

The MAR scheme of St-André allowed the IWVA to stop groundwater production in its oldest water catchment of Cabour and to limit the extraction in the dunes of the Westhoek (De Panne) to 250,000 m³/year in 2020 (Figure 3), compared to the permitted volume of 1,800,000 into the 1990s. This resulted in an increase of groundwater levels by 4 to 5 meters (Figure 6).

Total groundwater extraction is designed not to exceed 1.4 times the infiltrated volume by the scheme. Groundwater production/extraction in St-André decreased from 1.79 Mm³/year on average between 1990 and 2001 to 1.29 Mm³/year between 2002 and 2018 (Figure 3 light blue bar). Infiltration achieved a maximum of 2.20 Mm³/year in 2006 with an average yearly infiltration of 1.96 Mm³/year (Figure 5). On average, the ratio between total extraction and infiltration was 1.407 times thus close to the designed ratio.

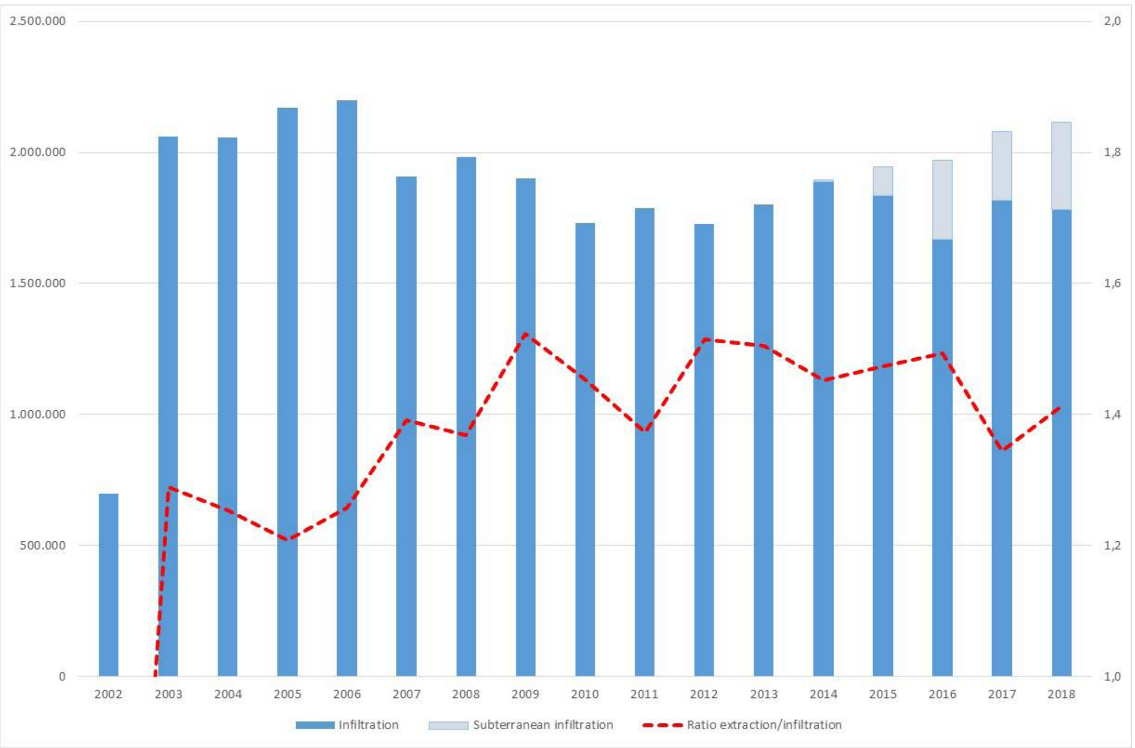

Figure 5.
Yearly infiltration (m³/year, left axis) at St-André compared to yearly ratio extraction/infiltration (right axis). Source: Own elaboration

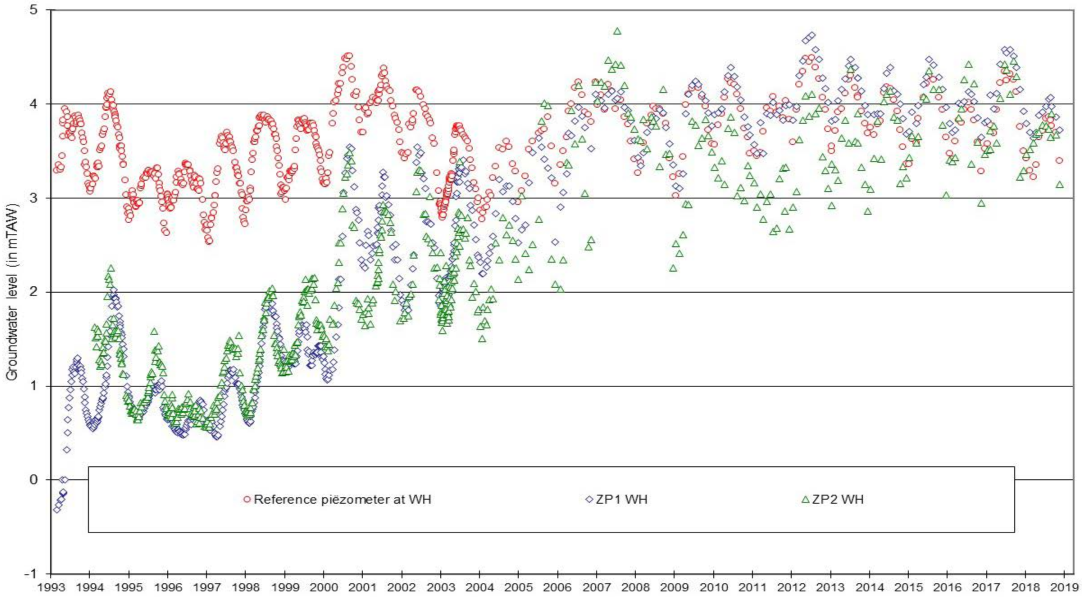

Figure 6.
Evolution of groundwater levels at the water catchment of the Westhoek.
Source: Own elaboration

It is important to note the significance in seasonal variations of recharge rate from the infiltration ponds at MAR facility St-André in Belgium. In winter months, infiltrate rates were usually low therefore extraction to infiltration ratios tended to be higher than those in the summer months primarily attributed to variations in hydraulic gradient and hydraulic conductivity (Sayantan 2018) [5]. The expansion of the infiltration pond and the implementation of 'subterranean infiltration' were meant to increase infiltration rates especially during the colder months. After the completion of the expansion in 2018, the ratio of extracted to infiltrated groundwater decreased to 1.29 in the first quarter of 2019, lower than an average ratio of 1.52 in the period 2014 – 2018 and of 1.76 for the period 2009-2013.

Groundwater quality

Since the inception of the MAR scheme, 39.3% of the distributed water is infiltrated and re-extracted at St-André with no known quality issues. The quality of the source water for infiltration is excellent as demonstrated in various European research projects (Böckelmann *et al* 2009 [6], Ernst *et al* 2012 [7] and Tandoi *et al* 2012) [8]. Ambient groundwater (700 μS/cm at 20°C) has been replaced by infiltrated water, which gains mineral content during passage through the soil. Of the 124 wells operational in 2018, the average conductivity was 327 μS/cm (range: 127 to 928 μS/cm). There is a relation between the electrical conductivity and the distance from the well to the infiltration pond; and this distance varies from 33 to 153 m with an average of 59 m. The extracted water is bacteriologically safe and is treated with aeration and rapid sand filtration to remove iron to below 0.2 mg/L prior to distribution. Iron is the only parameter in the extracted groundwater exceeding drinking-water guidelines. Compared to the quality of the drinking-water prior to the project, the main advantage for the customer is that the hardness is halved.

Recent monitoring of contaminants of emerging concern in the extracted water has detected only benzotriazoles at 0.2 μg/l, below the Flemish guideline value of 4.5 μg/l. Along with benzotriazoles, metformine, due to its prevalence in the environment, is also being monitored quarterly.

Energy intensity and environmental benefits

Approximately 0.1 KWh/m^3 is required to extract and treat the groundwater at the water catchment of St-André. Together with 0.75 KWh/m^3 for treating domestic wastewater effluent prior to infiltration at WPC Torreele, the total energy requirement of this multiple barrier approach is 0.85 KWh/m^3.

Current groundwater extraction is less than 50% of that before the MAR scheme (Figure 3). The rising groundwater level has resulted in wet grasslands emerging around the infiltration pond, with plants like Orchids and Parnassia flourishing in the dunes again. They disappeared over 50 years ago.

25.4. Economic costs and benefits

The IWVA had enough capital to fund the project. It decided to opt for a 10 year maintenance contract. The total investment cost amounted to 7 M€. As both the infiltration capacity and the drinking-water demand decreased, the production of infiltration water declined and consequently the operation and investment cost increased between 2005-11. In 2005 (2.17 Mm^3 produced) the production cost for infiltration water including depreciation was €0.46/m^3. In 2011, for a production just under 1.8 Mm^3, the production cost was €0.64/m^3. Between 2016 and 2018 production averaged 2.06 Mm^3 and the production cost averaged €0.44/m^3. The production cost has fallen recently since most of the investment costs have been depreciated. The levelised cost of infiltration water produced by the scheme is estimated to average US$0.50/$m^3$.

In 2011 the total production cost of 0.64 €/m^3 was still substantially lower than the average cost of purchasing drinking-water from a neighbouring inland area which amounted to 0.79 €/m^3 in 2011 and has now risen to €1.01/m^3or US$1.12. One measure of the benefits of the MAR scheme is the ratio of this alternative cost to the levelised cost of MAR infiltrated water, which gives an estimated benefit cost ratio of 2.23:1.

Comparison of drinking-water price for the customer is difficult as the price structure was changed according to Flemish legislation. However IWVA has a competitive price compared to its colleagues.

The recent investments amounted 0.18 M euros for implementing the ‘subterranean infiltration’ (2014 – 2019), 0.17 M euros for extension of the infiltration pond and eastward expansion of infiltration (2018-2019) and 0.1 M euros for extra (2013) and renewed extraction wells (2019).

25.5. Social sustainability

Authorisation for aquifer recharge or extraction is a regional, thus Flemish matter. The Flemish Environmental Agency (VMM) and the Agency for Nature Conservation (ANB) has a lot of input in permitting so without their consent a permit is not possible. There is no specific regulation for MAR but permitting includes hydrogeological, ecological and environmental evaluation in general. The first permit, from the Flemish authorities, was the result of discussions with an institute and agency responsible for ecological management and nature conservation. In recent re-permitting, IWVA had to discuss and arrange again with this agency. No degradation of natural values could occur.

An Environmental Impact Assessment was mandatory. It included a hydrogeological and ecological study of the area. In the final permit, specific parameters had been set for infiltration water, especially regarding the nutrient content to avoid negative impact on the dunes. For many parameters the standards were even more stringent than those for drinking-water. The most important ecological consideration was that all recharged water should be re-extracted. The permit included a monitoring scheme for the quality of the infiltration water, the groundwater level and quality and the ecological value of the area. Since the start of the project, the IWVA has performed the monitoring dutifully and all requirements have been met. There is no separate risk assessment guideline required for permitting which was based on drinking-water guidelines. But since 2016 risk assessment has become a part of the drinking-water guidelines in Flanders, which is the northern region of Belgium.

The project had a long history before it actually started with the local media regularly reporting on the preliminary plans and the tests [3]. Since the 1970s environmentalists have opposed groundwater extraction from the dune aquifer with hot summers often seeing the area affected by drinking-water distribution problems. As the water reuse scheme, involving groundwater recharge, proposed a solution both to the drinking-water shortage and the environmental objections, the project was accepted by stakeholders and the large majority of the public.

The projects have been well accepted by the public and the stakeholders. Information is the key factor for building trust. Plant visits and public forums were organized by IWVA to present the water recycling facility and its performance. Since the project was implemented its results have been presented to the public. This is done through informative board in the IWVA's visitor's center. In vacation periods guided walks to the infiltration area, which is closed to the public, are organized to inform the local community. Every 5 year a major 'open day' is organized together with Aquafin.

25.6. Conclusion

The combination of water reuse and MAR enabled sustainable groundwater management of the dune aquifer. The project is characterized by:

- securing the water supply for the region with excellent quality;
- enhancing the natural values of the dune area by restoring groundwater levels;
- lowering the risk of saline intrusion even with expected sea level rise caused by climate change;
- using novel infiltration techniques, e.g. 'subterranean infiltration', to enhance infiltration rate during winter months.

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Case Study 26: A coastal plain groundwater reservoir in Balisha River drainage basin of Shandong, China

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26.1. Introduction

Balisha River groundwater reservoir of Longkou, Shandong, China is located in the alluvial-proluvial fan of the river's downstream piedmont plain (Figure 1). Longkou is adjacent to Bohai Bay in the northern part of Shandong Peninsula. Constructed in 1990 as a pilot mainly to augment agricultural irrigation supply, an impervious wall of 6,424 m^2 by high pressure jet grouting formed a 756 m long dam with an average depth of 8.5 m (Figure 2), resulting in an underground reservoir with a total storage capacity of 430,000 m^3, of which 360,000 m^3 can be regulated or recovered (Figure 1). The cost of construction per m^3 of water stored is only US$0.10, or 1/2 to 1/3 of that for a surface water reservoir. Since 1992, 600,000 m^3 of water has been abstracted each year for agricultural (95%) and industrial use. A total of 6 groundwater reservoirs have been built following this successful pilot, with more being planned in Shandong Peninsula to enhance water supply resilience through preventing sea water intrusion.

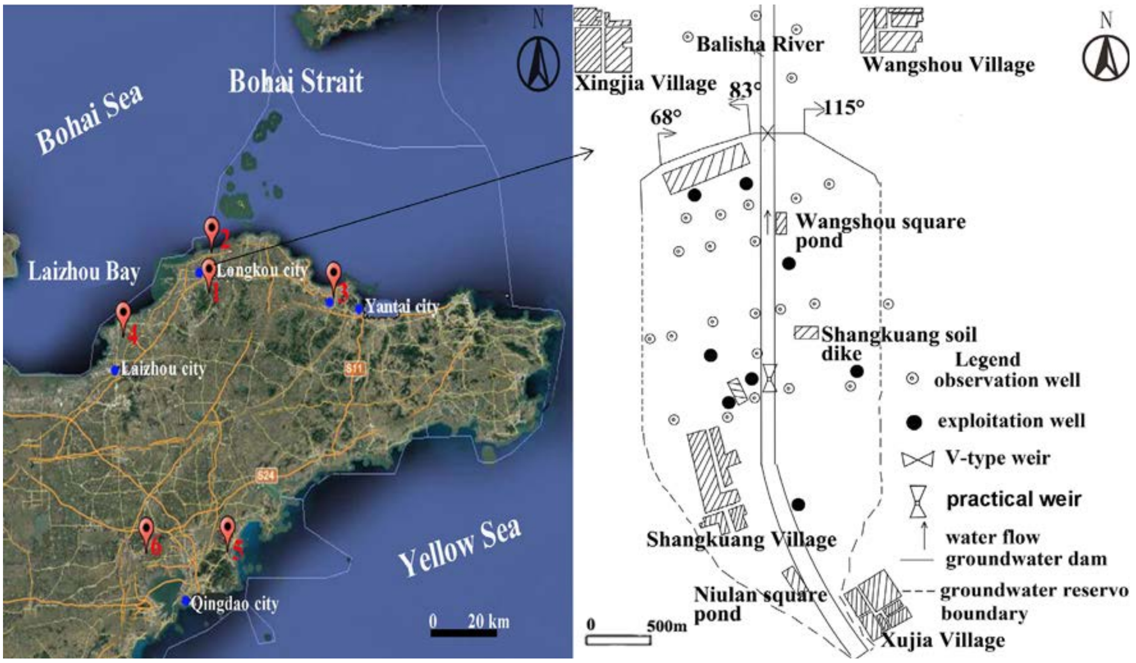

Figure 1.
(a)
Map showing location of 1-Balisha River groundwater reservoir near Longkou, 21 km from the coast, and also 5 others; 2-Huangshui River groundwater reservoir; 3-Dagujia River groundwater reservoir; 4-Wanghe River groundwater reservoir; 5-Shirenhe River groundwater reservoir; 6-Daguhe River groundwater reservoir).
(b) Site map of the Balisha River groundwater reservoir with underground dam in the north.
Source: Qingyang Zheng; Map © Google Maps

Box 1: Salient features of Longkou Underground Dam

Location: 37°28′N-37°31′N, 120°18.5′E-120°19.5′E
Operator: Longkou Water Authority
Design: underground reservoir area is 0.682-0.805 km^2, total storage capacity is 430,000 m^3
Commencement of operation: 1990
Quantity of water abstracted: 600,000 m^3/a
End use: 95% for agricultural irrigation
Source of water: piedmont lateral recharge, rainfall infiltration and river leakage
Aquifer: medium coarse sand with an average thickness of about 5.0 m
Type of recharge: induced recharge
Main advantage: increasing water supply resilience to drought and preventing seawater intrusion

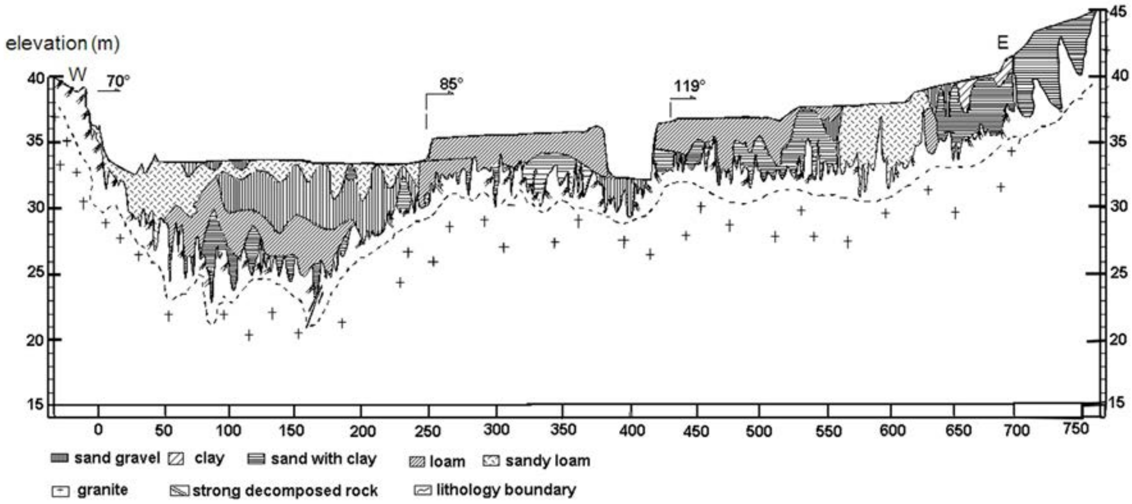

Figure 2.
Hydrogeological cross section along the axis of the underground dam.
Source: Own elaboration

26.2. Motivation, conceptualisation and implementation

Since 1980s, rapid economic development has led to increases in water consumption in Shandong Peninsula, with groundwater over-exploitation in coastal plains causing seawater intrusion. The average annual precipitation is 584 mm. Persistent and frequent drought over two decades (1980-1999) further exacerbated water shortage, resulting in a regional water crisis. Longkou has a coastline of 68 km. By 1990, the areal extent of seawater intrusion has reached 88.7 km^2; of those, 15.75 km^2 is located in the coastal plain [1, 2]. In 9 villages of Longkou with a population of 6,192 and 817 hectare of irrigated farm land, water supply dwindled before the construction of Balisha River groundwater reservoir. Of 8 wells and 5 ponds for supply, only 1 pond (Xingjia) produced water intermittently. All large-diameter irrigation wells installed by farmers dried up. The average annual withdrawal rate of groundwater decreased to <175,000 m^3.

Recognizing the potential of MAR [3, 4], the Water Resources Research Institute of Shandong Province and Longkou Water Authority initiated a pilot project to construct the Balisha River groundwater reservoir in Longkou in 1990. The Commission for Science and Technology of Shandong Province funded an investigation project entitled "Techniques for seawater intrusion prevention through impounding and regulating groundwater by an underground reservoir" based on the premise that an underground dam can intercept subsurface flow to increase storage and to deter the intrusion of seawater. The completed groundwater reservoir consists of four components: a) a subsurface dam; b) aquifer storage created by the dam; c) surface water impoundment to retain runoff for infiltration to increase recharge; d) wells for groundwater extraction. There are some auxiliary works, including a waste water treatment and drainage system, plus surface and groundwater monitoring systems [5]. The underground dam and flow measurement weirs in the Balisha River are shown in Figure 3.

a) b) c)

Figure 3.
a) Underground dam during construction,
b) weir for inflow measurement, and
c) large V-shaped weir for outflow measurement. © Qingyang Zheng

High pressure jet grouting with cement paste was adopted for construction of the dam with low hydraulic conductivity (10^{-5}-10^{-8} cm/s). Site selection not only considered hydrogeological (Figure 2) and engineering geological conditions, but also water storage space, recharge area and quantity [6]. First, watertight granite underlies the entire basin, suggesting that the site is suitable for storage. Second, for the entire catchment with an area of 14.02 km^2, groundwater lateral flow is estimated to be 490,000-560,000 m^3 per year while the groundwater recharge rate through rainfall infiltration over the reservoir surface area is estimated to be 127,000 m^3 per year so the total recharge is 617,000-688,000 m^3 per year [7]. This natural recharge rate exceeds the planned annual extraction rate of 600,000 m^3 per year, even after considering the "loss" due to evaporation, base flow and groundwater flow out of the groundwater reservoir, and without taking into account recharge from irrigation return flow and the river bed. Third, to ensure that the dam is constructed of high quality, a wide range of methods including resistivity survey, isotope non-destructive testing and bounding well excavation leak detection have been used to detect and to prevent leaks.

26.3. Environmental sustainability

Water quantity

The dam has raised the groundwater level in the reservoir area, allowing for the return of base flow in the river. Between 1990 and 1992, groundwater level increase ranged from 7.42 to 8.46 m cumulatively (equivalent to an average annual groundwater level increase of more than 2 m) in 25 observation wells. Installed in 1988, there are 20 wells within the reservoir area and 5 wells outside the reservoir area for monitoring (Figure 1). Before the construction of dam, the recharge coefficient (ratio of groundwater replenishment with respect to rainfall) was 0.140-0.312. After the construction of the dam, the groundwater table rose, the unsaturated zone thickness reduced, and recharge coefficient increased by 13-59% to 0.158-0.476. Hydraulic gradient of the reservoir area was 9.9‰ before and 5.7‰ after construction of the dam. Base flow appeared for the first time in 1990 in the Balisha river that had no flow in 1989. To determine surface runoff and base flow entering the reservoir, a combination of a practical weir (measuring large discharge, Figure 3b) and small flat V-shaped weir (measuring small discharge) was used. To determine the outflow of reservoir and the flow of the entire basin, a large flat V-shaped weir was constructed where the impervious wall intercepts the Balisha river (Figure 3c). For 1990, 1991 and 1992, the annual mean surface runoff was 339,700 m^3, 82,600 m^3, 185,900 m^3; the annual mean base flow was 674,300 m^3, 4,245 m^3, 9,600 m^3, so together the annual river runoff was 1,010,000 m^3, 86,836 m^3 and 186,893 m^3, respectively. The reason that the baseflow was higher than that of the surface runoff in 1990 is because the surface runoff in the upper stretch of the Balisha river has changed to “groundwater” in a rainfall abundant year with even an annual abstraction of 600,000 m^3, and is discharging to the river as baseflow in the lower stretch of the Balisha River. The ratio of the volume of infiltrated water vs recovered water on an annual basis is about 1.0, although the annual recharge is 1.6 to 2.0 times of the storage capacity of the underground reservoir, increasing the volume supplied by 306,000 m^3-419,100 m^3. Energy requirement to recover water is 0.02 KWh/ m^3 based on electricity use to pump water for irrigation.

Water quality

Balisha river water samples and groundwater samples from the same set of 25 observation wells were collected four times in 2008 for analysis. A total of 18 parameters in surface water and 20 parameters in groundwater were analyzed. Thirteen parameters were measured in both surface water and groundwater, including permanganate index (CODMn), volatile phenol, cyanide, Hg, As, NH_4-N, Mn, Cu, Zn, Pb, Cd, pH and CrVI, with 5 parameters (P, F^-, COD, BOD, sulfide) measured only in surface water, and 7 parameters (Fe, $CaCO_3$, Cl-, SO_4^{2-}, NO_3-N, NO_2-N, total dissolved solids) measured only in groundwater. Measurement protocols followed those described in «Water and Wastewater Monitoring and Analysis Method» and are in accordance with the «Surface Water Environmental Quality Standard» (GB3838-2002) and “Quality Standard for Groundwater” (GB/T14848-93).

According to the national environmental quality standards for surface water of China (GB3838-2002) that classifies surface water into 5 categories using 24 basic parameters [8], the Balisha river water data consisted of 18 parameters met the thresholds for Class III, or suitable for agricultural use, although 6 parameters including temperature, O_2, Se, petroleum, anionic surfactant and fecal coliform bacteria were not analyzed. The technical standard for groundwater quality of China (GB/T 14848-93) uses 39 parameters to classify groundwater also into 5 categories [9]. Results of groundwater water quality data with a total of 20 parameters show that NO_3-N in groundwater from 5 monitoring wells outside the reservoir area was 22 mg/L whereas the average concentration from 20 monitoring wells inside the reservoir area was 23 mg/L. Other than NO_3-N, recovered groundwater meets the Class III thresholds defined by GB/T 14848-93, although 19 parameters were not measured, including color, taste and odor, turbidity, visible substances, Al, anionic surfactant, sulfide, Na, total coliforms, colony forming units, F^-, I^-, Se, $CHCl_3$, CCl_4, C_6H_6, C_7H_8, gross a radioactivity, gross α radioactivity. Due to agricultural activity in the region, NO_3-N pollution is not surprising.

There are point source and non-point source pollution risks for groundwater reservoirs. They are managed through a series of pollution prevention measures in accordance to the "Law of the People's Republic of China on the Prevention and Control of Water Pollution" and the "Regulations on Safety Management of Reservoir Dams". Specifically, industrial and mining activities in the upper reaches of the Balisha river are prohibited.

Regulatory framework

Clearly defined and transparent regulatory framework for MAR was not available even after the project was completed. It is not until 2017 the Chinese Government released a technical standard document GB/T 35580-2017 entitled "guidelines for water-draw and utilization assessment on construction projects" [10]. This guidance document strengthened the requirement for the water intake permit system, and called for governmental departments of water resources to further integrate science into decision making. For example, a water balance calculation is now required before any water intake permit is issued. A hydrogeological survey is often conducted for groundwater resource utilization projects to ensure access to water by all stakeholders, with environmental impact assessment of abstraction and discharge of water [11]. Although this guideline is intended for all types of water resources infrastructure projects, it is important to note that the quantity and quality of source water and groundwater of all MAR projects are now required to be regularly monitored.

Permit granting process and community engagement

Permission to implement the Longkou pilot project was granted by the Commission for Science and Technology of Shandong Province. Because the dam is underground, no new land acquisition was necessary except for monetary compensation to the farmers for temporary land use during project construction phase.

There were no systematic institutional arrangements for public and stakeholder consultation when the project was implemented. Now the technical guideline for environmental impact assessment of construction project (HJ2.1-2016) [12] has this requirement.

26.4. Cost and benefit analysis

The total capital investment in 1990 was RMB 540,000, including RMB 105,000 for installation of the monitoring wells and RMB 435,000 for construction of the dam. With an annual water supply of 600,000 m^3, the capital cost of water is only RMB 0.9 per m^3. With an annual operation and maintenance cost ranging from RMB 56,450 to RMB 62,000 between 1990 and 2020, the O&M cost of water is RMB 0.09-0.1 per m^3. The dam is designed to last 30 years, and the annual depreciation rate is 7%. The levelised cost of additional water is estimated to be very cheap at US$0.042 per m^3.

The groundwater reservoir increased supply from 100,000-175,000 m³/yr to 600,000 m³/yr, resulting in an expansion of irrigated area with an increased agricultural output of 917,000 kg, or equivalent to RMB 641,900 assuming the sale price of the agricultural products of RMB 0.7 per kg. About 5% of the 600,000 m³ water was supplied for industrial activities primarily consisted of small private enterprises with an estimated industrial output of RMB 885,700. Combined, the agricultural and industrial outputs increased to RMB 1,527,600. In industry, the annual gross benefit value of water supply increased by RMB 88,570, which is calculated at 10% of sharing coefficient; and the annual net benefit of water supply is RMB 13, 285, which is calculated at 15% of the gross benefit value. In agriculture, the annual net benefits of water supply is RMB 160,475, which is calculated at 25% of the gross benefit value (RMB 641,900). So, the annual water supply net benefit of industry and irrigation are RMB 13,285 and RMB 160,475, respectively, and the total net benefit of water supply is estimated to be RMB 173,750. The aforementioned values are for the annual water supply of 600,000 m³.

At the same time, water benefit value is RMB 0.28 per m³ under the condition of annual water supply of 600,000 m³, and the actual water supply cost is RMB 0.09-0.1 per m³. Therefore, the ratio of benefit to cost is in the range 2.3 to 3.1.

26.5. Upscaling Potential

The coastal region of China has a high population density to begin with. Like Longkou, many coastal plains have witnessed rapid economic development that led to increasing water consumption over the last three decades. Although large cities often turn to water diversion and transfer from major rivers over long distances to meet their rising water demands, this option is not practical for most smaller cities and towns where groundwater use has been historically significant. The success of the Balisha pilot demonstrates that a groundwater reservoir is an effective measure to intercept and regulate surface water flow and groundwater storage, and to expand water supply and prevent seawater intrusion.

The methods established at Balisha has been applied for construction of 5 more groundwater reservoirs in Shandong Peninsula, namely, Huangshui River (31,090,000 m³/yr) in Longkou city, Wanghe River (31,940,000 m³/yr) in Laizhou city, Dagujia River in Yantai city, Shirenhe River (3,000,000 m³/yr) and Daguhe River in Qingdao city.

In coastal plains with little relief, groundwater reservoirs offers several advantages over surface water reservoirs. First, it requires neither valuable land nor relocation of villages. Second, water loss due to evaporation and leakage is significantly less. Third, the supply is year round and more resilient to drought. Fourth, capital investment is halved. One disadvantage of groundwater reservoirs is that prevention and control of pollution is more difficult than for surface water reservoirs. To address this, it is recommended that regulations governing groundwater reservoir protection should be formulated by the local legislative chambers, with funding to support pollution control measures and water quality monitoring.

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Case Study 27: Large-scale Managed Aquifer Recharge for drinking water production in a semi-arid karst region, Jordan

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27.1. Introduction

The Wala reservoir is located in Jordan about 40 km south of the capital Amman and recharges a regional karst aquifer. Since its construction in 2002, a strong increase in groundwater level has been observed in a downstream wellfield, which is used throughout the year to supply water to local residents. Most of the recharge from the reservoir takes place by natural lateral infiltration and minor volumes by controlled injection through 8 recharge wells. The wellfield comprises 16 active pumping wells, which were already drilled and tested between 1989 and 1992, and between 1999 and 2005. Additional wells of lower yield can be found along the wadi (Figure 1).

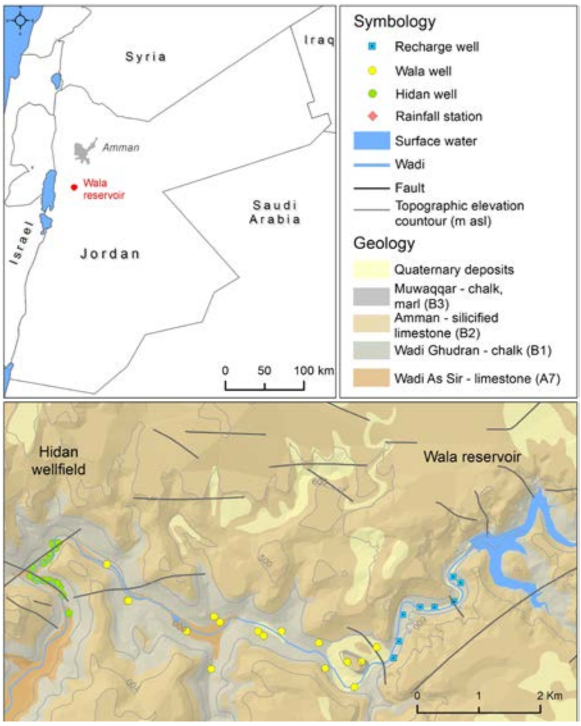

Figure 1.
Location and Layout of MAR scheme at Wadi Wala, (modified after Xanke et al 2016 [1]

Box 1: Salient features of Wala reservoir

Location: 31°34’05.01 N, 35°48’16.00 E to 31°33’58.58 N, 35°43’49.00 E

Operator: Ministry of Water and Irrigation (MWI), Jordan Valley Authority (JVA), Water Authority Jordan (WAJ), Amman, Jordan

Design: 42 m high dam with 9.3 million cubic (Mm^3) storage volume, 8 recharge wells, 16 abstraction wells

Commencement of operation: 2002

Quantity of water abstracted: 11.7Mm^3/yr

End use: domestic (drinking) water and irrigation

Source of water: Surface runoff & groundwater

Aquifer: Upper Cretaceous limestone, moderately karstified

Type of recharge: natural and injection

Main advantage: sustainable abstraction of high quality and quantity of water

27.2. History of the project

The semi-arid Jordan is facing the challenge of natural water shortage, population growth and the associated increase in water demand. Since most aquifers are exhausted by overexploitation, the development of water resources in recent decades has increasingly concentrated more on rainwater harvesting and promotes also managed aquifer recharge (MWI 2016a,b) [2,3]. Among numerous surface reservoirs, the Wala dam was constructed between 1999 and 2002 by the Ministry of Water and Irrigation (MWI) with the main purpose of flood water storage during winter and the unique property of aquifer recharge for the supply of the Hidan wellfield 7 km downstream. The main criteria for the construction were the sustainable use of the wellfield, the control of the unused rainfall runoff and the avoidance of damage to the wadi caused by flash floods. The water from the wellfield is mainly directed to the city of Madaba (located halfway to Amman) and its suburbs and supplies around 184,000 people with drinking water. Smaller quantities of groundwater are taken from the scattered Wala wells along the wadi (Figure 1) and used for local domestic and irrigation purposes (<4%). The Wala MAR project plays an important role in regional water supply and is widely accepted by the population especially by local farmers and Bedouins who benefit from the constant availability of water for domestic use, agriculture and livestock farming. Due to the high input of sedimentation load, the original storage volume was reduced from 9.3 to 7.7 MCM in 2012, leading to a reduction of the infiltration rate and an increase of overflow events (Xanke *et al*. 2015) [4]. The removal of sediments by dredging or flushing is difficult because access to the reservoir is insufficient and the outlet of the dam is already covered and blocked by sediments. Therefore, the Ministry decided to increase the dam by 15 meters to a total storage capacity of 25 MCM to lower the risk of dam overflowing and to optimize the storage of rainfall runoff. This measure will significantly increase lateral infiltration and considerably extend the life time of the reservoir. However, the effects of increased infiltration on groundwater cannot yet be predicted but will certainly lead to stronger groundwater seepage into the wadi.

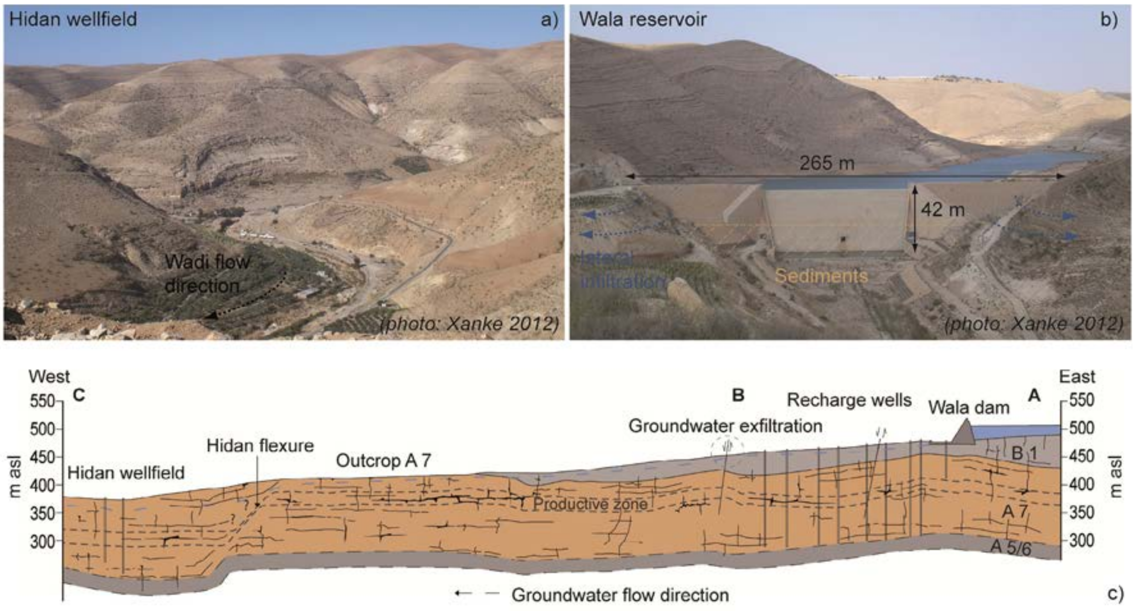

Figure 2.
a) View at the Hidan wellfield and b) the Wala reservoir at normal water level (2012).
c) Schematic geological profile along Wadi Wala with the location of the recharge wells and abstraction (Xanke et al. 2015) [4]. Source: Own elaboration; Photos © Julian Xanke

27.3. Environmental sustainability

Even before the reservoir was built, the local geological characteristics led to natural groundwater seepage into the wadi, resulting in almost year-round sparse surface runoff. As a result, numerous natural pools have been formed along the wadi course, home to a diversity of flora and fauna. With the construction of the reservoir, the dropped groundwater level has increased again and thus ensures a constant groundwater seepage, which benefits these local groundwater dependent ecosystems. However, the accessibility of surface water and vegetation makes the valley also a popular recreation area and watering place for sheep and goat herds. Both circumstances aggravate the protection of the wellfield, which endangers a sustainable water supply.

Precipitation in Jordan is highly variable, both in its temporal occurrence and its intensity, visible in the changing annual infiltration at the Wala reservoir (Figure 3). About 136 Mm^3 of surface runoff were stored in the period from 2002 to 2012 of which 74.1 Mm^3 was recharged. Compared to the 129 Mm^3 pumped in the same period, this corresponds to a contribution of 57% of the natural groundwater contribution by the catchment, which is indicated also by isotopic studies. This results in an average infiltration of around 6.7 Mm^3 and an average of abstraction of around 11.7 Mm^3 per year (Xanke *et al*. 2015) [4]. The average energy used for groundwater abstraction is 1.18 KWh/m^3, derived from the average electricity tariff in Central Jordan of around 0.07 JOD per kWh (NEPCO 2017) [5] and average pumping costs per m^3 of around 0.08 JOD for the Wala pumping station for the period from 2014 to 2018. This value almost corresponds to the value of 1.02 KWh/m^3 stated by Busche and Hayek [6]. They also found a reduction potential of energy consumption to 0.9 KWh/m^3 by replacing the pumps with higher quality ones at Wala station, which would lead to cost and energy savings and a reduction in CO2 emissions. The latter is currently around 7,700 tonnes per year on average for the Wala station, assuming Jordan's CO_2 emissions of 675g per produced KWh (Hussein 2016) [7].

Daily water level and evaporation measurements at the reservoir allow the surface inflow into the reservoir and the infiltration into the aquifer to be determined precisely. Since 1994 the groundwater level has been measured monthly at a 60 meter deep observation well in the center of the wellfield (Figure 1). The seasonal fluctuations registered up to 2001 are due to different abstraction volumes in the winter and summer months. After the start of the infiltration from the reservoir in 2002 a large increase in the groundwater level was observed. A significant decrease in infiltration with subsequent lowering of the groundwater level occurred in 2008, where the reservoir dried up, and in 2012. A numerical assessment by Xanke *et al*. [1] verified that this groundwater level decrease can be mainly attributed to changes in wellfield operation, with increased pumping from shallow wells, and to minor parts to the slightly increased annual groundwater abstraction with the simultaneous decrease in infiltration from the reservoir. This means that even during a few dry years with low infiltration from the reservoir, the drinking water supply can be ensured without significantly reduce the abstraction rates at the wellfield.

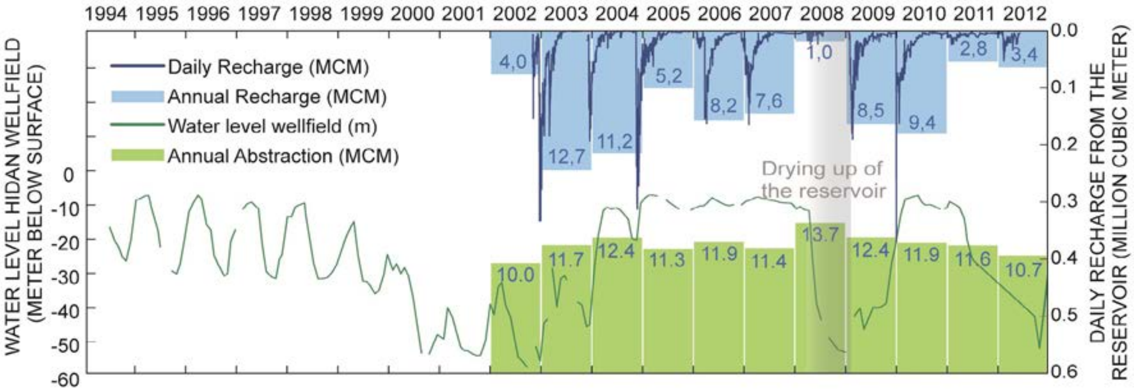

Figure 3.
Infiltration from the reservoir and groundwater abstraction in comparison to water level fluctuations in an observation well at the wellfield (modified after Xanke et al.) [4].

In general, the local groundwater is calcium and bicarbonate dominated and meets Jordan's drinking water quality standards (MWI 1997) [8] with salinity values up to 1,200 and 1,400 µS/cm respectively in the wellfield and in the Wala wells. Periodic deterioration in water quality occurs mainly during precipitation in winter, when floods reach the wellfield and quickly infiltrate through cracks and fissures. Then, turbidity and contamination by faecal bacteria often make the groundwater unusable for several days to weeks (Xanke *et al*. 2017) [9]. This not only interrupts the water supply but also causes economic losses. Therefore, water quality parameters are regularly observed at the reservoir and the wellfield by the Jordan Valley Authority (JVA) and the Water Authority Jordan (WAJ), respectively. Measured parameters are mainly temperature, pH, electrical conductivity, turbidity, major ions and coliform bacteria, as well as chlorophyll at the reservoir. The intervals between the measurements are usually one month (reservoir), sometimes longer (wellfield) or every few days, especially during and after rain events. An intrinsic karst vulnerability (Figure 4a) and risk map was elaborated by Xanke *et al*. [9] and adapted to regional characteristics considering the separation of the Hidan wellfield catchment (inner zone) and the reservoir catchment (outer zone) by the Wala dam and the interaction of surface water and groundwater. Both maps provide the basis for an adapted protection zone concept (Figure 4b) for a more sustainable operation of the MAR plant.

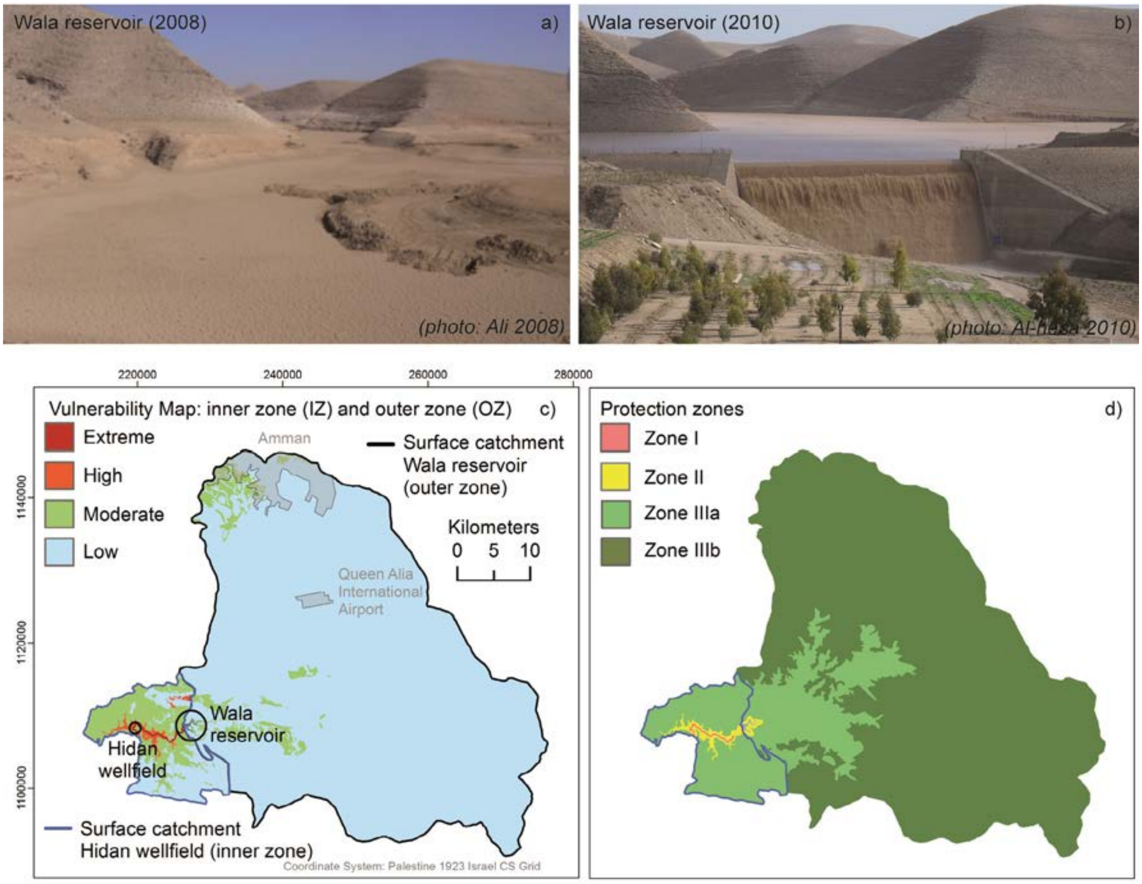

Figure 4.
a) Vulnerability map and
b) the derived protection zones for the wellfield and the reservoir [9].
Source: Own elaboration.

27.4. Economic costs and benefits

Data on investment costs are only available for the dam, but not the wellfield, as it was continuously expanded since the late 1980s. Therefore, its investment costs were calculated by using data from Al Qadi *et al*. [10], who estimated the drilling costs for two replacement wells at Wadi Al Arab wellfield in northern Jordan, a similar karst setting. Data for operation and maintenance (O&M) costs for both the reservoir and the wellfield are available on annual basis, but for different periods. Thus, the overall assessment is based on capital costs and annual O&M investments of the Wala dam for 2012 and the wellfield for 2014 to 2018. The further distribution and treatment of the water to Madaba is not included in the cost evaluation of the MAR facility. Likewise, possible construction costs for a 15 m increase of the dam of about 28 million JOD are not taken into account.

The capital expenditures (capex) for the Wala dam were 24 million JOD whereof 80 % was funded by a loan from the Arab Fund for Economic and Social Development (AFESD) and 20% were covered by the Jordanian treasury, while the capex for the wellfield is derived from Al Qadi *et al*. [10]. Their estimated drilling costs correspond to about 500 JOD per meter, which seems plausible since the drilling costs for shallow wells in unconsolidated sediments range between 140 and 350 JOD per meter (Steinel 2012) [11]. At Hidan wellfield, there are 16 active production wells and two observation wells at depths between 100 and 200 metres, all drilled into limestone. The total depth of all wells (18) is approximately 2,300 metres. Together with the costs for the site mobilization of 5,000 JOD per well (Al Qadi *et al*. 2017) [10], the total investment costs for the wellfield amount to about 1.24 million JOD.

O&M costs for the reservoir include labour and operating costs and sum up to about 0.13 million JOD per year. Wellfield O&M data include labour, operation and pumping costs and add up to an average of 0.103 JOD per m^3 of abstracted groundwater for the considered period from 2014 to 2018. With the annual average abstraction volume of about 11.7 MCM, the annual O&M costs for the reservoir and the wellfield amount to about 1.34 million JOD. Taking into account the gross domestic product (GDP) index for 2012 and 2016, investment and operating costs, a discount rate of 5% and an assumed life time of the MAR facility of 30 years (for consistency with other studies, but possibly overestimated based on siltation rate) the levelised cost per m^3 recovered water are 0.27 JOD or US$0.39.

When the estimated cost of recovered water (0.27 JOD) as compared with the value of water indicated by current average water tariff of 1.92 JOD (WAJ 2019) [12] this implies a benefit-cost ratio of about 7:1.

The calculations show that the annual operating costs for the reservoir are almost independent of the amount of infiltration, but the costs for the wellfield strongly depend on the amount of abstracted groundwater. Taking into account the current average water tariff and average the annual operating costs, the added value of the average annual groundwater abstraction amounts to around 21.2 million JOD (US$30M). Although the profits are very variable and strongly dependent on the amount of abstracted groundwater, they still show a significant surplus.

27.5. Social sustainability

Water availability in Jordan is an important factor for sustainable economic and social prosperity, especially in the context of water scarcity, population growth and climate change. Therefore, the government also promotes the application of new technologies and techniques, such as managed aquifer recharge. Steinel [11], who developed a first guideline for MAR implementation in Jordan, remarked that there are still no clear standards and institutional frameworks in Jordan for planning, implementing and operating of such facilities. There are currently only a few examples of purposeful implementation of flood water storage and aquifer recharge, such as the Wala reservoir, but these are often poorly managed. However, the hydraulic anisotropy and heterogeneity of karst aquifers is a particular challenge for the application of MAR and requires a comprehensive understanding of the hydrogeological system and an adapted management concept. Due to the different governmental responsibilities of reservoirs and groundwater issues, there are as yet hardly any uniform, comprehensive reports and data management, which hinders the coordinated operation of the Wala reservoir and the wellfield. In addition, the infrastructure is often in an inappropriate condition (Figure 5) to ensure a clean drinking water supply, often also endangered by anthropogenic or animal activities (Figure 5a) in delineated protection zones or by natural extreme events such as flash floods (Figure 5b).

Figure 5.
a) poor protected well in the Hidan wellfield surrounded by a sheep herd.
b) flooded Hidan wellfield after heavy rainfall. © Julian Xanke

It is recommended to enforce the implementation of the adapted protection zones and their restrictions on land use and settling at the Wala MAR site, to elaborate solutions to reduce the sedimentation rates in the reservoir and to further improve the operations and data management for both reservoir and wellfield. A general recommendation is made to further integrate MAR into regional water management and to strengthen it through a clearer legal framework for implementation and operation. However, under the current regional framework the Wala-MAR plant is operated and maintained in a relatively sustainable manner throughout the year. Due to the large storage capacity of the reservoir and the distance to the wellfield, dry periods can be bridged which supports sustainable economic and social development in the region.

Acknowledgements

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Case Study 28: Aquifer Storage and Recovery of treated waste water from a sugar factory for drought resilient irrigation supply in Dinteloord, the Netherlands

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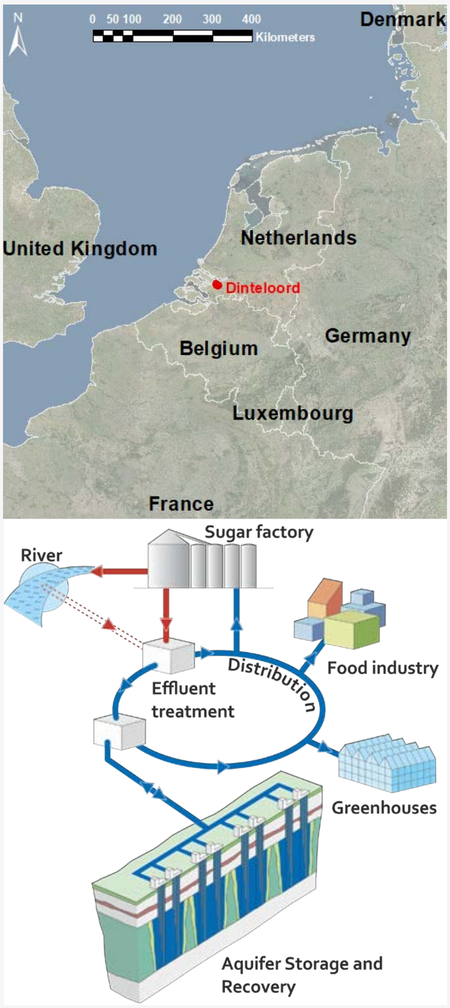
28.1. Introduction



Box 1: Salient Features of Dinteloord recycled water ASR

Location: 51°37’28.63N, 4°24’14.84E

Operator: Cooperation Nieuw Prinsenland U.A.: a cooperation of greenhouse farmers in a 2.6 km^2 area, with support of Allied Waters SALutions

Commencement of operation: commissioning 2015; full scale operation 2018

Quantity of water abstracted: 300 000 m^3/year

Capacity: injection = 60 m^3/h with automated backflushes, recovery = 200 m^3/h

End use: irrigation in modern greenhouses, setting strict limits for water quality

Source of water: Effluent from a waste water treatment of a sugar factory. Treated by UF and RO prior to injection

Aquifer: unconsolidated fine estuarine sands with clay layers (Pleistocene)

Type of recharge: well injection (8x) in an aquifer storage and recovery well field

Main advantage: sustainable abstraction of high quality and quantity of water by ASR

Unique: Combination of centralized system for treatment, storage, and distribution of waste water for reuse by a group of greenhouse owners requiring an impeccable water quality (microbiologically safe, sodium <0.1 mmol/l ; 2.4 mg/l)

Distribution: 5 km long loop with a 200 m^3/h capacity to supply extra water to the greenhouses’ rainwater basins.

Source: Own elaboration; Map © Google maps

The continuous availability of high-quality freshwater is vital for the greenhouse horticulture industry. However, this was not readily available at the Agro- and Foodcluster Nieuw Prinsenland in Dinteloord (The Netherlands). Waste water from a neighbouring sugar factory provided an alternative freshwater source from September until the end of January. One problem remained: where can the water be stored during periods of surplus for later use in periods of drought? Aquifer storage and recovery (ASR) suitable for application in brackish groundwater proved logical and economically attractive. A full-scale ASR reuse system (8 wells) was installed in 2017 and is supplying greenhouse farmers and the neighbouring sugar factory with a maximum of 300,000 m^3 of freshwater per year.

28.2. History

In Dinteloord, a modern greenhouse area Nieuw-Prinsenland (260 ha) was developed. The region is located in a salinizing coastal area without a significant external freshwater supply. Aquifers in the wider area are already stressed due to over abstraction for drinking water supply, agriculture, and industries. Ensuring availability of very high-quality (sodium <2.4 mg/l) water, required for greenhouse irrigation, was a major challenge. Rainwater collected at greenhouse roofs and stored in aboveground basins forms the basis for the irrigation water supply, but cannot ensure sufficient water to overcome years with prolonged periods of drought.

Waste water reuse was found to be the key solution to deal with water scarcity [1]. In Dinteloord, a sugar factory produces large volumes of wastewater between September and January, and provides the irrigation water source for the greenhouse sector. The wastewater is treated and purified to high-quality irrigation water by using ultra-filtration and reverse osmosis. It is crucial to bridge the temporal mismatch between availability (Sept-Jan) and demand (April - August) at the Dinteloord site, and safeguard water quality via aquifer passage [2]. Aquifer storage and recovery (ASR), a form of MAR comprised of injection and recovery of water via wells, offers a solution.

Multiple partially penetrating wells were installed to counteract buoyancy induced recovery losses [3,4] by injecting mainly in the lower half and recovering mainly at the upper half of the approximately 20 m thick target aquifer. The ASR-system had a commissioning stage and started with just one (pilot) well in 2015 (AW1: having 2 well screens in the upper half and 2 in the lower half), with a second well added in 2016 and well number 3 and 4 in 2017. It has been in full operation (8 wells; Figure 1) since 2018, and provides up to a maximum 300,000 m^3/yr of irrigation water, with a maximum supply capacity of 200 m^3/h [4,5]. It was capable of preventing water shortage in the extremely dry summer of 2018.

This water supply system was initiated by the Horticultural Development Organisation (TOM) of Brabant. The feasibility assessment, design, piloting, permitting, supervision, and monitoring and evaluation was done by Allied Waters. Funding of the realization came from the greenhouse owners themselves: they were obliged to invest in the system when buying the land and became shareholders of the cooperation, and thereby co-owners and beneficiaries of the installation. Additional research on the performance of the system in the pilot phase was funded by the Dutch Ministry of Economic Affairs and Climate under the flag of TKI-water technology [6]. In order to raise public awareness and support upscaling of the system, the scheme was embraced in the EU-project SUBSOL [7]. In this project, participatory technology assessments were executed with stakeholders. Experiences were collected in a Technical and Economical Guide [5]. In 2018, the project was awarded a nomination for the Dutch Water Innovation Prize, yielding national attention for the scheme.

Figure 1.
ASR well field, situated along a creek (2018). © Koen Zuurbier

28.3. Environmental sustainability

The main environmental benefits are found in the preventing net abstraction of groundwater, which would result in rapid salinization in this area due to the presence of shallow brackish-saline groundwater and the reduced infiltration of rainwater due to drainage of agricultural land and greenhouse roofs. Thanks to ASR, there is no need to exploit the scarce and poor quality surface water in summers, which would otherwise lead to a reduced availability for agriculture and nature in the area and a firm need for chemicals and energy to treat the water.

The required target storage volume (TSV) to meet demands once all greenhouses are at full scale is 300,000 m^3 and was based on a detailed water balance model using precipitation and estimated water demand time series. In dry years, this volume will be abstracted and consumed, and it may take 2 years to again reach this TSV (Figure 2). Since commissioning, 262,000 m^3 has been injected and 104,000 m^3 (40%) was recovered (Figure 3), which was sufficient as greenhouses were still under construction and water demands were low. In 2021, the TSV should be attained to meet the full demands. A high frequency, automated electrical conductivity (EC) real time monitoring is used to assess salinization; the recovery is stopped when EC exceeds 0.2 mS/cm.

Groundwater level has been recorded every 30 minutes since 2015 in the vicinity of the ASR well field to monitor the phreatic groundwater table as well as the head in the target aquifer. From year to year, groundwater heads were found to be stable, although there are variations induced by stages of injection and recovery.

In terms of water quality, the injected water is demineralized via UF and RO thus has had no exceedance relative to the drinking water standard of the Netherlands. For the recovered water, sodium level should be maintained to below a maximum allowable concentration of 2.4 mg/L for irrigation. In 2017, 80% of the abstracted water met this requirement. In 2018, this was 100%. Based on groundwater modelling using SEAWAT, it is predicted that eventually >95% of the injected water can be recovered within the sodium limits [4]. Monthly monitoring of recovered water has found that Fe (~ 1 mg/l) and Mn (~0.6 mg/l) concentrations are slightly elevated upon recovery as a consequence of mineral interaction (mainly carbonate dissolution), but due to aeration and settlement in the aboveground basins upon recovery, this did not result in operational problems. In the first years, a decreasing trend in Fe and Mn mobilisation was found (Figure 4).

The energy requirements is 0.13 KWh/m³ for injection and 0.29 KWh/m³ for recovering and distributing groundwater. The latter can be completely supplied by solar panels on the roof of the pumping stations when there is sunshine. Around 0.1 KWh/m³ is used for other purposes than pumping (electronics, heating, ventilation). The total energy intensity for aquifer storage and recovery is thus 0.53 kWh/m³. This excludes the required energy for pre-treatment (UF and RO), which adds another 1 kWh/m³ before the water can be injected.

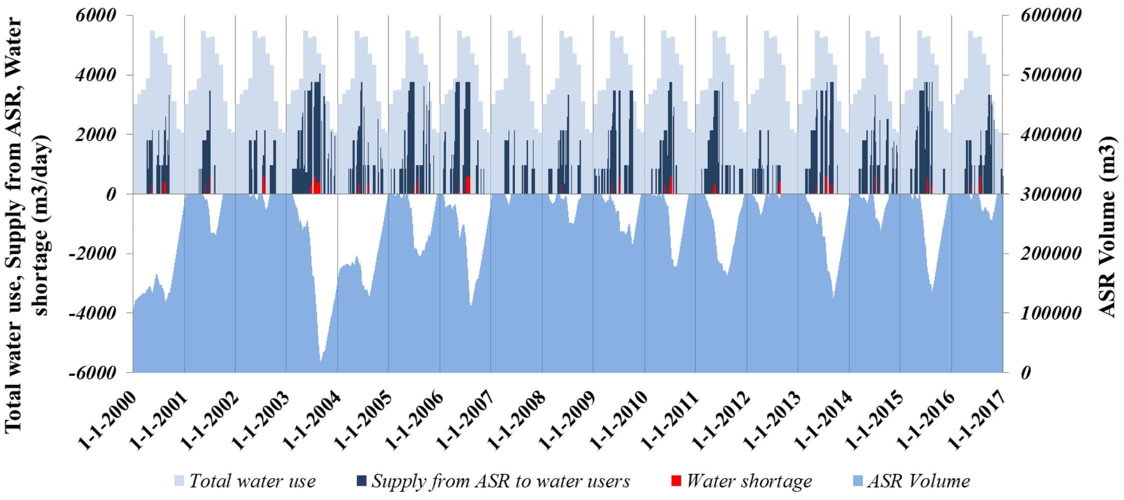


Figure 2.
Injection and recovery based on water balance model. Moments of ‘water shortage’ indicate moments when ASR cannot supply sufficient water to maintain rainwater basins at a level of 40%. There is no real shortage. Source: Own elaboration

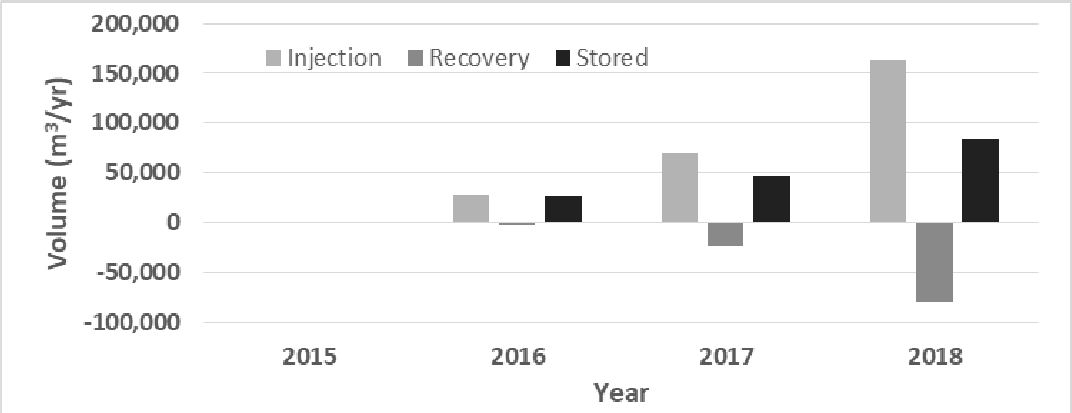


Figure 3.
Injection recovery and net storage per year (as per December 31). Source: Own elaboration

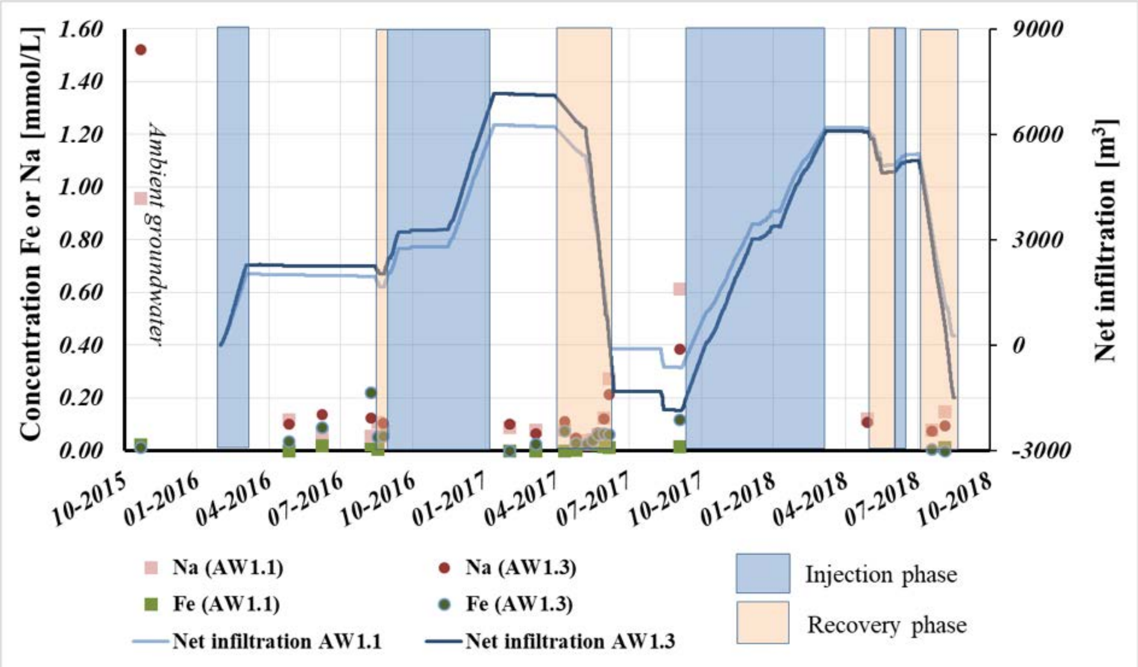


Figure 4.
Sodium (Na) and Iron (Fe) concentrations and operation at two well screens of AW1, including the net injection (injection minus recovery for every well).
Source: Own elaboration

28.4. Economic costs and benefits of ASR in Dinteloord

In Table 1, the most important economic and operational parameters are assembled with regards to the ASR system. This excludes the costs of the treatment of the waste water, which is required to reach the strict water quality standards in the first place. The estimated levelised cost of water recovered from storage is US$0.76 per m³ (€0.69) based on these parameters or US$95,000 (€86,250)/yr. This was compared to the alternative form of storage, which was aboveground storage, which has a higher risk of water quality deterioration. Two locations were considered:

- In the greenhouse areas, meaning 0.1 km² could not be used for crop production;
    - Cost price would be 3.09 €/m³: additional costs would be 300,000€/yr (+448%)
- Outside the greenhouse area, buying at least 0.1 km² of currently agricultural land;
    - Cost price would be 1.06 €/m³: additional costs would be 46,250 €/yr (+35%)

The yearly savings by choosing ASR as a storage solution are therefore substantial and sum up to 0.9 to 6.0 M€ during the lifespan of the system, while having a higher certainty of water quality conservation especially when it comes to microbiological quality. The MAR project has a Benefit Cost Ratio (BCR) of 1.4:1 compared with the next best alternative of buying additional land for water storage outside the greenhouse area. The main economic benefit is made by the limited spatial footprint: there are virtually no costs for land and otherwise occupied land can be used for high-value crop production. Additionally, various parts of the system (piping, wells) can normally be used for a much longer period (up to 50 years).

The proof of cost-effectiveness was crucial in the decision to go for ASR. Not taken into account was the fact that a small part of the water will be lost to the aquifer, where it will improve the ambient groundwater quality. The same holds for the lower impact of the ASR in the landscape (Figure 1) with respect to a (large) aboveground storage basin.

Table 1.
Economical and operational input parameters.

Parameters	Value	Unit
Lifespan of the ASR-system	20	years
Total Capital costs:	1,004,963	€
Piping, cables, data connections	125,833	€
Well drilling	76,000	
Pumping station	88,000	
Well equipment	477,590	
Pre-injection (not recovered)	24,640	
Consulting	100,000	
Re-investments during lifespan	112,900	
Operational costs	20,250	€/year
Yearly maintenance	1,500	€
Yearly monitoring	5,000	
Yearly evaluation	5,000	
Energy costs	8,750	
Average annual water injection	125,000	m^3/year
Average annual water recovery	125,000	m^3/year
Maximal annual water recovery	300,000	m^3/year
Required maximal volume to supply	300,000	m^3

28.5. Social acceptability and organisation

Using wastewater from one party for later use (after aquifer storage) by a second party involves clear agreements between the different parties involved. In Dinteloord, all parties were organised to operate and administrate the entire water system, and responsibilities have been distributed (Figure 4). The greenhouse cooperation, including its eight members, has a central role as owner and main end user of the water system. Veolia is operating the wastewater treatment system, while the cooperation's director and Allied Waters operate the ASR-system. Codema is the engineering company that constructed the ASR-system and is responsible for its maintenance. Allied Waters was involved with the design, permitting and development of the ASR-system. Allied Waters is also responsible for monitoring and evaluation of the ASR-system's performance and the impact on the surrounding water system, and is consulting partner for the cooperation and the Water authority Brabantse Delta, manager of the local surface water system. Suiker Unie provides wastewater but is also end user of the treated water. The Province of Brabant was the permitting agent for the ASR system, which requires permitting under the national Water Act [9] that is applicable for all MAR projects in the Netherlands. Neighbouring land owners are informed via a special committee.

The maximum volume of fresh water that can be recovered by ASR and supplied to the users may vary every year. Each spring, KWR estimates the recoverable freshwater volume, upon which the director of the cooperation distributes the water over the users. The recovery rate is limited to 200 m^3/h, i.e. 1 m^3/h per hectare of greenhouse area. The minimum guaranteed supply rate for each user is based on this rate and their greenhouse area. Users with a lower water demand can transfer their rights to users with a higher demand. These transfers must be communicated to the director, which executes the billing. The costs are covered by a pay-per-use system through the price of a cubic meter of water (Figure 5).

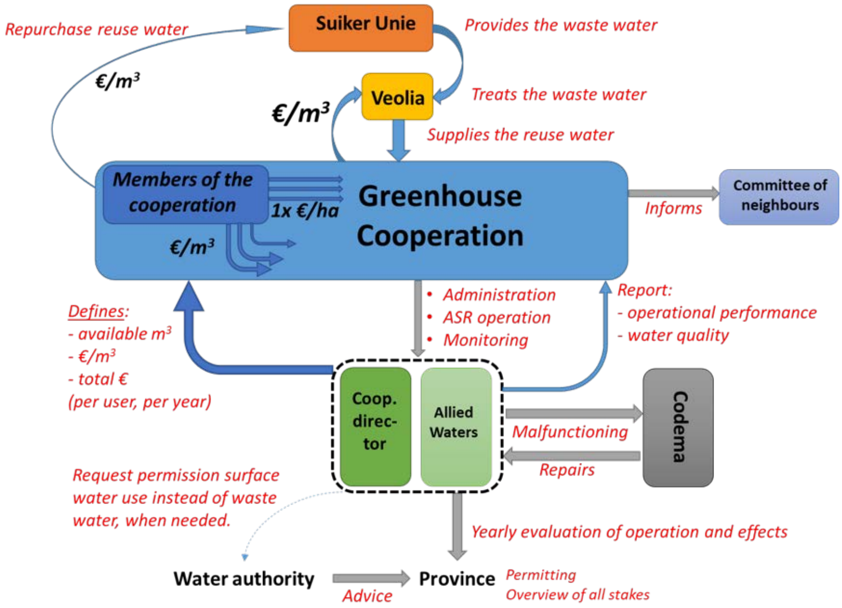


Figure 5.
Organogram of the Dinteloord wastewater reuse system including ASR.
Source: Own elaboration

Acknowledgements

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Dutch Ministry of Economic Affairs and Climate (TKI Watertechnology)
EU Horizon 2020: SUBSOL (grant agreement No 642228)

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Section III. Appendices

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Appendix I. Information template for documenting a MAR case study

This Appendix is adapted from the guide originally provided to authors of case studies published in this book, and has been updated based on discussions with authors during the editing process and on the advice of editors. This presents a recommended approach to documenting future case studies, if this compendium were to be expanded.

The guide below contains an outline of the expected content and length of case studies. Each should contain five sections (I-V): I. title and metadata; II. history of project from conceptualization to implementation; III. environmental and social sustainability; IV. economic costs and benefits; V. other vital information. All should be supported by quantifiable evidence.

Each section contains numbered questions or points to be addressed. Please attempt to answer each question with at least one sentence, and provide evidence if you can. Finally, provide more information about the most important aspects of your MAR case.

I. Title and metadata

1. Name of scheme
2. Authors' names and affiliations (should include owner /operator of scheme)
3. Project metadata: Presented as a box containing facts (max 1p) – e.g.: Location, source of water, type of aquifer, end use, type(s) of managed aquifer recharge (e.g. streambed structures, riverbank filtration, basins, wells), current average volume of water recharged and recovered (m^3/yr), year commenced, who owns and manages the project, what is unique about this project, an interesting photo or helpful diagram or map.

II. History of the project from its origins to implementation. (~ 1p)

4. Motivation and objective
    a. Key water issue(s) tackled by the project
5. How was the project initiated
    a. Which organisations got involved?
    b. Who funded the project?
    c. What were the stages of development?
6. What was the approval process ?
    a. Describe any commissioning stage?
7. Has the project been revised or expanded?
    a. What were the key phases/changes and why?
8. Who are the project beneficiaries ?
    a. Are there targeted beneficiaries, or at least considerations, for e.g. women ?
9. What is the public awareness of and appreciation for the project
10. If possible provide a photo (historical or present) or graph

III. Environmental and Social sustainability (~ 1-2 p):

11. What are the project's environmental benefits? – e.g. see the six environmental indicators defined in Table 3 of Chapter 3 (Assessment of environmental and social sustainability for Managed Aquifer Recharge Schemes). These have headings as follows:

12. Groundwater quantity

- **a.** Monitoring of groundwater levels or pressures demonstrates acceptable changes over 10 years, or more than 3 years with high likelihood of maintaining resource integrity
- **b.** The ratio of volume of infiltrated water vs recovered water on an annual basis, or to what extent is the project banking water to mitigate future drought?

13. Groundwater quality

- **a.** Describe the water quality monitoring and evaluation undertaken
- **b.** Exceedance rate based on time series monitoring of recovered or ambient water quality parameters with respect to acceptable values of water quality parameters for the intended uses
- **c.** Exceedance rate based on time-series monitoring of source water quality parameters with respect to acceptable values of water quality parameters for the intended uses

14. Ecosystem services

- **a.** Change in ecological flow (m^3/yr) or storage (m^3) in ecosystems needing protection identified in a catchment water management plan or similar
- **b.** Change in peak flow (m^3/s) at a relevant average return interval for MAR intended for flood mitigation

15. Energy and greenhouse gas considerations

- **a.** Energy requirements in KWh per cubic meter of recovered water, including source water treatment, recharge, pumping, monitoring and treating recovered water, solving clogging and low recovery efficiency issues.

16. Governance

- **a.** Clearly defined, transparent regulatory framework for MAR, preferably one that requires monitoring of resource integrity
- **b.** Permit granting process is based on sound risk assessment aimed to protect human and environmental health
- **c.** Systematic institutional arrangements for public and stakeholder engagement, preferably with regular publicly available reports of scheme outcomes.

17. Broader considerations

- **a.** Impact on surface water resources and ecosystems are acceptable as determined in a sound catchment water management plan or similar
- **b.** Ecosystems requiring protection are identified and protected by project as evident by monitoring
- **c.** No unacceptable seepage, waterlogging, discharge from artesian wells or unintentional inter- aquifer mixing occurs

IV. Economic costs and benefits (~ 1p):

18. Financial costs in local currency

- **a.** Capital cost
    - **i.** If possible, provide a breakdown of capital costs into land, construction, other (attach more detailed breakdown, if available)
- **b.** Annual operating cost in the most recent year available
    - **i.** If possible, provide a breakdown of operating costs into water, energy, monitoring, other (attach more detailed breakdown, if available)

19. Project outputs (required to calculate the levelised cost of water supplied from the MAR scheme. Please, specify the years used to calculate the annual average)

- **a.** Average annual volume of water recharged to aquifer
- **b.** Average annual volume of water recovered from aquifer
- **c.** Average annual volume supplied to users

20. Monetary benefits of the MAR scheme - use whichever approach is appropriate in your case;

- **a.** If the main benefit is additional water supply, estimate monetary value of additional supply (either annual supply or reserve supply for drought years) by one of following methods:
    - **i.** volume of water recovered or supplied multiplied by the price of water - in theory the best way to estimate the value of additional water, but often impossible because water is supplied at rates that do not reflect its full economic value;
    - **ii.** the cost of recovering or supplying an equivalent amount of water of similar quality by the next cheapest supply option. It should be possible to apply this method to most MAR schemes;
    - **iii.** In the case of water for agriculture or industry, additional supply can be valued by the net benefit (revenue minus cost) of additional production made possible by the additional water supply;
- **b.** If the main benefit is an improvement in water quality, to meet a specified standard, as might be the case in a bank filtration system or a MAR scheme using recycled stormwater or wastewater, the benefit can be valued by the costs of the next cheapest alternative water treatment facility.

21. Specify any important external costs and benefits taken into account in the decision to choose a MAR scheme, and/or that have arisen during scheme implementation. External costs and benefits are costs and benefits that are not met by the scheme owner/operator including impacts on third parties, the receiving aquifer or other environmental assets.

22. Attach copies of any available cost effectiveness or cost benefit analysis of the scheme.

V. Other vital information

If anything vital about the scheme has not been said – include it in this section

Acknowledge those who have provided information, and scheme founders/donors if appropriate.

Insert reference list with reports and papers with web links where relevant.

Appendix II. Characteristics of Case Studies

No.	Author ref.	Case study location	Country	"High Upper Middle Lower Middle in-come"	Continent	Coordinates	Rainfall at MAR site (mm/yr)	Type of MAR*	Geological formation/aquifer used for MAR	Confined or unconfined aquifer	Source of water	Pre-treatment**	Post-treatment	End use of reharged water	Rural or urban scheme***	Size of scheme****	Volume of water recharged (m3/yr)	Volume of water abstracted (m3/yr)
1	Ahmed et al.	Khulna	Bangladesh	L	Asia	"22.6674 89.5128"	1700	RW	Coastal plain, shallow-brackish, unconsolidated fine to medium grained sand	Unconfined to semi-confined	Pond water (surface runnoff)	Sand filtration	None	Regular and emergency domestic water supply	R	S	640	200
2	Artimo et al.	Virttaankangas, Loimaa	Finland	H	Europe	"60.9833 22.6333"	632	WS	Quaternary sand/gravel esker formation	Unconfined	River water	Floatation and sand filtration	Disinfection with UV and chloramine	Public water supply	U	L	22 800 000	22 300 000
3	Chávez et al.	San Luis Rio Colorado, Sonora	Mexico	UM	North America	"32.3923 -114.8152"	554	WS	Quaternary alluvial deposits	Unconfined	Reclaimed water	Secondary treatment: lagoon and later lagoon plus constructed wetland	None	Primarily irrigation	U	M	10 500 000	1 260 000
4	Dashora et al.	Udaipur, Rajasthan	India	LM	Asia	"24.6333 74.2000"	665	ICM	Fractured/weathered granitic hard rock	Unconfined	River water	None	None	Irrigation and drinking water	R	S	779 000	779 000
5	de los Cobos and Luyet	Vessy, Geneva	France/Switzerland	H	Europe	"46.1817 6.1702"	950	WS	Silty-sandy gravel of glacial and fluvioglacial deposits (Wurm)	Unconfined	River water and groundwater	Sand filtration, chlorination	Chlorination	Public water supply	U	M	9 000 000	14 000 000
6	Elkayam et al.	Shafdan, Rishon LeZion	Israel	H	Asia	"31.9613 34.7643"	550	WS	Pleistocene-age coastal environment rocks, dominated by calcareous sandstone and interbedded by conglomerates, silt, and clay layers	Unconfined	Reclaimed water	Secondary treatment	None or chlorination	Irrigation	R	L	130 000 000	145 000 000
7	Fernández Escalante and San Sebastián Sauto	El Carracillo, Segovia, Castilla y León	Spain	H	Europe	"41.2920 -4.2900"	430	ICB/WS/RW	Sandy Quaternary aquifer (dunes) and alluvial at the bottom of palaeobasins	Unconfined	River water	Stagnation/decantation of suspended particles, sand/gravel filtering	None	Irrigation	R	S	2 420 000	2 400 000
8	Grischek et al.	Hosterwitz, Dresden, Saxony	Germany	H	Europe	"51.0222 13.84758"	592	BF	Quaternary alluvial deposits	Unconfined	River and groundwater	For IB: Coagulation, sedimenation, filtration	Aeration, GAC absorption, chlorination	Public water supply	U	L	24 500 000	26 300 000
9	Higginson et al.	Perth, Western Australia	Australia	H	Australia	"-31.7843 115.7770"	733	RW	"Interbedded sandstones, siltstone and shale (Leederville: early Cretaceous, Yarragadee: Jurassic) "	Confined	Reclaimed water	Ultrafiltration, reverse osmosis, UV disinfection	Aeration, coagulation, sedimentation, filtration, chlorination, fluoridation	Public water supply	U	L	28 000 000	28 000 000
10	Hutchinson and Woodside	Orange County, California	USA	H	North America	"33.7175 -117.8311"	355	ICM/WS/RW	Unconsolidated terrestrial and marine sediments	Confined and unconfined	River water, stormwater, reclaimed water and reservoir water	Sediment removal ponds	Chlorination	Public water supply and irrigation	U	L	148 000 000	148 000 000
11	Jadhav et al.	Baramati, Maharashtra	India	LM	Asia	"18.2282 74.4561"	504	ICM	Medium coarse	Semi-confined	Rain and river water	River bed filtration	None	Various	R	S	273 000	564 473
12	Jones et al.	North London	UK	H	Europe	"51.6253 -0.0584"	738	RW	Cretaceous chalk and Palaeogene sands	Confined	River water	Ozone treatment, sand filtration, GAC absorption, chlorination	Ozone treatment, sand filtration, GAC absorption, chlorination	Public water supply, drought or other emergency supply	U	S	7 200 000	3 300 000

Water banking?	Water banking or environmental goals (if recharge > recovery)	Number of beneficiaries	Volume of water per beneficiary (m3/yr/capita)	Gender/equity considerations	Year commenced	Significant phases	"Owner/ Manager/ Operator"	Funder	Implementer	Email of corresponding author	Website
440	To reduce salinity and arsenic concentrations	160	1	Women-led user committee for site mnagement	2009	"2011: increase in number of recharge wells 2015: handed over to community with partial support 2019: fully handed over to community"	Built on a private land/ site managed and operated by the User Committee	UNICEF	Dhaka University (DU) and Department of Public Health Engineering (DPHE), GoB with technical support from Acacia Water Netherlands	kmahmed@du.ac.bd	http://gripp.iwmi.org/natural-infrastructure/water-quality-2/a-nature-based-innovative-and-low-cost-solution-for-disaster-resilient-drinking-water-supply-in-coastal-bangladesh/
500 000	Controlling aquifer drawdown	300 000	74	N/A	2011		Turku Region Water Ltd.			aki.artimo@turunseudunvesi.fi	"https://www.youtube.com/watch?v=Vul2vG3wG5Q https://www.turunseudunvesi.fi/en"
9 240 000	Initially partial aquifer recovery from historical depletion	74 000	17	N/A	2007	2017: Construction of Cucapá wetlands	Organismo Operador Municipal de Agua Potable Alcantarillado y Saneamiento (OOMAPAS)	BANDAN-BEIF (construction of IBs)	Organismo Operador Municipal de Agua Potable Alcantarillado y Saneamiento (OOMAPAS)	APalmaN@iingen.unam.mx	"https://link.springer.com/article/10.1007/s40899-017-0196-2 http://www.aguaysaneamiento.com/ays/notas_66/estudio_lagunas.html"
-	No	9 000	87	Women benefit same as men from irrgataion and more than men from reduced water carrying	1995	2014: monitoring of 4 check dams commenced. More check dams constructed frequently - almost doubling in 2017 alone	Gram Panchayat (Village Council)	Watershed Development Program, Government of Rajasthan	Block Development Agency (Panchayat Samiti)	"prahladsoni.baif@gmail.com dashora.yogita@gmail.com"	www.marvi.org.in
-5 000 000	No	200 000	70	N/A	1980	"1980: full operation 2015: rehabilitation of sand filtration basins of the recharge plant"	Industrial Services of Geneva (SIG)	Canton of Geneva	Canton of Geneva, SIG	gabriel.deloscobos@etat.ge.ch	"https://link.springer.com/article/10.1007/s12665-014-3575-0 https://www.ge.ch/document/eau-video-nappe-du-genevois"
-15 000 000	No	About 170 registered farmers	852 941	N/A	1977	"1977: Soreq-1 (235 d) 1987: Yavne-1 (240 d) 1988: Yavne-2 (180 d) 1996: Yavne-3 (187 d) 2003: Yavne-4 (163 d) 2006: Soreq-2 (66 d)"	Mekorot, Israel National Water Company	Mekorot, Israel National Water Company	Mekorot, Israel National Water Company	"nido@mekorot.co.il relkayam@mekorot.co.il"	http://aquanes.eu/Default.aspx?t=1673
20 000	Wetlands, springs, and sand-pits converted into artificial wetlands	" 700 direct 3 000 indirect "	649	Socio-economic benefits from agriculture and food value chains. Approximately 80% of workers in major processing plant (total 800 people) is women.	2003	"1999: early studies 2003: MAR began 2005: second phase and enlargement of MAR canals 2014: third phase started and still pendant of approval by River Basin Authorities"	"El Carracillo Irrigation Community "	"Ministry of Agriculture, Spain Junta de Castilla y León (Regional Government)"	"Tragsa Group Spain Junta de Castilla y León (Regional Government)"	efernan6@tragsa.es	"http://www.marsol.eu/35-0-Results.html http://gripp.iwmi.org/natural-infrastructure/water-storage/the-alcazaren-pedrajas-managed-aquifer-recharge-mar-scheme-in-central-spain/"
-1 800 000	No	544 000	48	N/A	1907	1983: IBs inplemented	DREWAG - water company of the city of Dresden			thomas.grischek@htw-dresden.de	https://de.wikipedia.org/wiki/Wasserwerk_Hosterwitz
-	No	168 000	167	Considerations for equity in the work force of the Water Corporation	2010	"2007-2010: characterization 2010-2012: trial 2017-2019: stage 1 of full scale 2019: stage 2 of full scale"	Water Corporation of Western Australia	Water Corporation of Western Australia	Water Corporation of Western Australia	simon.higginson@watercorporation.com.au	https://www.watercorporation.com.au/water-supply/our-water-sources/groundwater-replenishment
-	Controlling aquifer drawdown	2 400 000	62	N/A	1936	"1936-1948: storm water 1948-present: storm water and reservoir water 2008-present: recycled water"	Orange County Water District (OWCD)	Replenishment assessment paid for groundwater pumped. Pumpers pay.	Orange County Water District (OWCD)	gwoodside@ocwd.com	https://www.ocwd.com/what-we-do/groundwater-management/
-291 473	No	1 268	445	N/A	2011	"2011 to 2015: desilting of 7 check dams 2014: crop production demo and constrcution of one check dam"	Krishi Vigyan Kendra, Baramati	Ministry of Agriculture, India	Indian Council of Agricultural Research (ICAR)	jadhav_9616@yahoo.co.in	kvkbaramati.com
3 900 000	Emergency supply	500 000	11	N/A	1995	"1995: first operation 2002: scheme expanded 2006: scheme expanded"	Thames Water Utilities Ltd.	Thames Water Utilities Ltd. via regulator-approved business plans	Thames Water Utilities Ltd.	michael.jones@thameswater.co.uk	https://www.thameswater.co.uk/help-and-advice/water-quality/where-our-water-comes-from/north-london-artificial-recharge-scheme

No.	Author ref.	Case study location	Country	"High Upper Middle Lower Middle income"	Continent	Coordinates	Rainfall at MAR site (mm/yr)	Type of MAR*	Geological formation/aquifer used for MAR	Confined or unconfined aquifer	Source of water	Pre-treatment**	Post-treatment	End use of reharged water	Rural or urban scheme***	Size of scheme****	Volume of water recharged (m3/yr)	Volume of water abstracted (m3/yr)
13	Murray et al.	Windhoek, Khomas	Namibia	UM	Africa	"-22.5615 17.0736"	360	RW	Fractured hard-rock (quartzite and schist) aquifer	Predominantly confined	Reservoir water	GAC, chlorination	Blending with treated reclaimed water and surface water from three reservoirs	Public water supply	U	S	3 750 000	3 650 000
14	Naumann et al.	City of Salisbury Council, Adelaide, South Australia	Australia	H	Australia	"-34.7626 138.6457"	460	RW	Tertiary aquifers (T1 and T2) of the Port Willunga Formation, sandy limestone	Confined	Stormwater	Constructed wetland	Chlorination	"Irrigation, non-potable industrial, and household third-pipe supply"	U	S	3 000 000	2 500 000
15	Pavelic et al.	Jiwai Jadid, Rampur, Uttar Pradesh	India	LM	Asia	"28.7794 79.2005"	900	WS/RW	Fine-medium Quaternary alluvium	Unconfined	Storm water (Irrigation canal)	Sedimentation	None	Irrigation and domestic use	R	S	44 000	54 000
16	Picot-Colbeaux et al.	Agon-Countainville, Normandy	France	H	Europe	"49.0552 1.5945"	807	WS	Quaternary shallow coastal sand dune	Unconfined	Reclaimed water	Reed bed infiltration	N/A	Environmental use	R	S	730 000	-
17	Powers et al.	Central Platte River, Nebraska	USA	H	North America	"40.8800 -100.1700"	610	WS	Platte River alluvium	Unconfined	River, wetland and stormwater	None	None	Irrigation and environmental use	R	M	11 110 000	1 800 000
18	Pyne et al.	Hilton Head Island, South Carolina	USA	H	North America	"32.2431 -80.7337"	1 279	RW	Limestone	Semi-confined	Desalinated brackish groundwater and treated river water	Desalination	Chlorination	Peak demand and emergency public water supply	U	S	950 000	950 000
19	Rossetto et al.	Lucca, Tuscany	Italy	H	Europe	"43.8583 10.4854"	1181	BF	Holocene coarse sand and gravel overlaid by silty surficial cover	Unconfined	River water	None	Chlorination	Public water supply	U	M	13 600 000	16 000 000
20	Sandhu et al.	Haridwar, Uttarakhand	India	LM	Asia	"29.9600 78.1700"	1100	BF	Medium–coarse Pleistocene alluvium	Unconfined	River water and groundwater	None	Chlorination	Public water supply	U	M	15 400 000	22 000 000

Water banking?	Water banking or environmental goals (if recharge > recovery)	Number of beneficiaries	Volume of water per beneficiary (m3/yr/capita)	Gender/equity considerations	Year commenced	Significant phases	"Owner/ Manager/ Operator"	Funder	Implementer	Email of corresponding author	Website
100 000	Meeting water demand during times when surface water sources fail due to highly variable climatic conditions	415 000	9	N/A	1997	"1997-2007: studies and testing 2007: change to legislation to incorporate protection of the source 2008-2011: implementation of first drilling phase for deep well large diameter boreholes and installation of recharge infrastructure 2016 - 2017 - Implementation of second drilling phase and the subsequent installation of Phase 1 and 2 drilling to increase abstraction capacity"	City of Windhoek (Groundwater as source owned by the central government)	City of Windhoek, Government of Namibia	City of Windhoek		
500 000	Recreational wetlands, groundwater resource protection in prescribed wells area	" 1 150 direct 140 000 indirect "	18	N/A	1994	"1994-2000: feasibility testing and establishment of customer base 2003-2010: expansion and integration of stormwater ASR schemes through dedicated reticulation network"	Salisbury Water, City of Salisbury	Salisbury Water (internal business established by City of Salisbury), with support from Australian and South Australian funding initiatives and research partners	Salisbury Water, City of Salisbury	joanne.vanderzalm@csiro.au	"http://gripp.iwmi.org/natural-infrastructure/water-quality-2/stormwater-harvesting-via-brackish-aquifers-2/ http://www.salisbury.sa.gov.au/Live/Environment_and_Sustainability/Wetlands_and_Water/Water_Recycling/Aquifer_Storage_Recovery"
-10 000	No	1 814	30	Yes, gender study carried out	2015	"2015-2018: piloting phase 2019 onwards: operational phase"	Panchayati Raj with support from District government	CGIAR Research Programs: Climate Change, Agriculture and Food Security (CCAFS), Water, Land and Ecosystems (WLE)	International Water Management Institue (IWMI)	p.pavelic@cgiar.org	"https://ccafs.cgiar.org/publications/underground-taming-floods-irrigation-utfi-river-basins-south-asia-institutionalising#.XRjX1OgzZPY http://gripp.iwmi.org/natural-infrastructure/water-retention-3/underground-taming-of-floods-for-irrigation-utfi-2/ http://utfi.iwmi.org/"
730 000	Environmental purpose (salinity control), coastal recreational area, coastal shelfish area	Tourists, shelfish economic sector	-	N/A	2001	"2001: implementation of scheme 2005: evolution of infiltration basins"	SAUR company			G.Picot@brgm.fr	"http://aquanes-h2020.eu/Default.aspx?t=1661 http://www.brgm.fr/publication-presse/aquanes-etudier-solutions-traitement-eau-stationagon-coutainville http://www.services.eaufrance.fr/donnees/service/90104"
9 310 000	Constructed wetlands for habitat and canal water for environmental flows	" 8 500 direct 50 000 indirect "	31	N/A	2011	"2011-12: negotiation of agreements 2011-15: construction of projects"	Central Platte Natural Resource District; Multiple Irrigation Districts; Nebraska Department of Natural Resources	"Central Platte Natural Resource District; Multiple Irrigaiton Districts; Nebraska Environmental Trust Resources provides oversight"	Central Platte Natural Resource District; Multiple Irrigation Districts; Nebraska Department of Natural Resources	cpowers@nebraska.edu	http://gripp.iwmi.org/natural-infrastructure/water-storage/managed-aquifer-recharge-mar-in-nebraska/
-	Meeting peak season and emergency water demand	50 000	19	N/A	2013	"2013: beginning of operation 2014: another water supply company took up the ASR approach and now has two wells in operation"	Hilton Head Public Service District	Self-funded	Hilton Head Public Service District	dpyne@asrsystems.ws	https://www.researchgate.net/publication/276242672_Aquifer_storage_recovery_an_ASR_solution_to_saltwater_intrusion_at_Hilton_Head_Island_South_Carolina_USA
-2 400 000	Meeting peak summer season water demand and controlling aquifer drawdown	300 000	53	N/A	1960	1999: weir in Serchio River installed to increase storage	GEAL SpA (Water Utility)	Municipality of Lucca, Toscany Region	Municipality of Lucca, Toscany Region	r.rossetto@santannapisa.it	
-6 600 000	Meeting emergency demands and controlling aquifer drawdown	655 000	34	Water provided at free or reduced cost to socially weaker sections of society and to pilgrims	1965	"1965: first IBF well built 1980-1998: scheme expanded, 15 more wells constructed 2005: systematic water quality monitoring commenced 2009: designated as IBF demonstration site by IAH-MAR commission 2010: scheme further expanded, 6 more wells constructed (total 22 wells) 2016: two pilot plants at IBF well 18 began tests for disinfection by inline-electrolyses "	Uttarakhand Jal Sansthan (UJS - Uttarakhand State Water Supply Organisation)	Government of India, Government of Uttar Pradesh (up to 2000), Government of Uttarakhand (2000 onwards)	Uttar Pradesh Jal Nigam (up to 2000), Uttarakhand Pey Jal Nigam (2000 onwards)	"cornelius.sandhu@htw-dresden.de thomas.grischek@htw-dresden.de"	"http://dss.aquanes.eu/Default.aspx?t=1682# http://gripp.iwmi.org/natural-infrastructure/water-quality-2/riverbank-filtration/"

No.	Author ref.	Case study location	Country	"High Upper Middle Lower Middle in-come"	Continent	Coordinates	Rainfall at MAR site (mm/yr)	Type of MAR*	Geological formation/aquifer used for MAR	Confined or unconfined aquifer	Source of water	Pre-treatment**	Post-treatment	End use of reharged water	Rural or urban scheme***	Size of scheme****	Volume of water recharged (m3/yr)	Volume of water abstracted (m3/yr)
21	Seasholes and Megdal	Colorado River, Central Arizona	USA	H	North America	"33.4484 -112.0740"	204	ICM/WS	Alluvial	Unconfined	River, reservoir and reclaimed water	None	Various depending on scheme	Mainly public water supply during drought	R	L	342 000 000	125 000 000
22	Shamrukh and Abdel-Lah	Sidfa, Asyut	Egypt	LM	Africa	"26.9668 31.3751"	2.5	BF	Pleistocene graded sand-gravel alluvium	Semi-confined	River water and groundwater	None	Chlorination (optional)	Public water supply	u	S	1 533 000	2 190 000
23	Shivakoti et al.	Kumamoto, Kyushu	Japan	H	Asia	"32.8475 130.7344"	1990	WS	Volcanic pyroclastic deposits	Predominantly confined	River water	None	Chlorination	Public water supply, industrial water supply	U	M	14 000 000	14 000 000
24	Tredoux et al.	Atlantis, Western Cape	South Africa	UM	Africa	"-33.5834 18.4251"	445	WS	Fine to medium grained sand (Cenozoic)	Unconfined	Reclaimed water and urban stormwater	Secondary treatment, maturation ponds	Softening by ion exchange and chlorination	Public water supply	U	M	6 747 000	5 500 000
25	Van Houtte and Verbauwhede	Koksjide, Flanders	Belgium	H	Europe	"51.1136 2.6553"	700	WS	Unconfined dune sediments	Unconfined	Reclaimed water	Ultrafiltration and reverse osmosis	Aeration, sand filtration, ultrafiltration	Public water supply	u	S	1 960 000	2 300 000
26	Wang et al.	Longkhou, Yantai, Shandong	China	UM	Asia	"37.4917 120.3085"	584	ICM	Medium coarse sand	Unconfined	Piedmont lateral seepage, rainfall and river leakage	None	None	Irrigation and industrial water supply	R	S	560 000	600 000
27	Xanke et al.	Wala Dam, Madaba	Jordan	LM	Asia	"31.5678 35.8043"	500	WS/RW	Upper Cretaceous limestone, moderately karstified	Unconfined	Stormwater	None	Chlorination (domestic use)	Domestic water supply and irrigation	U	M	6 700 000	11 700 000
28	Zuurbier et al.	Dinteloord	the Netherlands	H	Europe	"51.6246 4.4041"	900	RW	Unconsolidated fine estuarine sands with clay layers (Pleistocene)	Confined	Reclaimed water and stormwater	"Reclaimed water: Ultrafiltration and reverse osmosis Stormwater: slow sand filtration"	None	Irrigation (greenhouses)	U	S	125 000	125 000

Min	204
Max	1 990
Average	756

Min	640	-
Max	342 000 000	148 000 000
Average	28 774 344	21 438 310
Median Value		2 900 000
Total		

*	Main type of MAR	ICM	In-channel modification
		BF	Bank filtration
		WS	Water spreading
		RW	Recharge wells
**	Pre-treatment	GAC	Granular Activated Carbon

***	Rural or Urban scheme	R	Rural	
		U	Urban	
****	Size of Scheme (Mm3/year)	S	Small	0 to 5
		M	Medium	5 to 20
		L	Large	20 to 250

Water banking?	Water banking or environmental goals (if recharge > recovery)	Number of beneficiaries	Volume of water per beneficiary (m3/yr/capita)	Gender/equity considerations	Year commenced	Significant phases	"Owner/ Manager/ Operator"	Funder	Implementer	Email of corresponding author	Website
217 000 000	Water banking for drought response	6 000 000	21	Water supply to tribal communities	1997		Arizona Water Banking Authority (AWBA)	Property tax levied by operator of CAP system; fee assessed by state on groundwater pumpers	Arizona Water Banking Authority (AWBA)	smegdal@email.arizona.edu	http://www.azwaterbank.gov/
-657 000	No	30 000	73	N/A	2004	"2004: full capacity 2018: changed to emergency standby public water supply"	Assiut Company for Water and Wastewater	Government of Egypt		mshamrukh@gmail.com	
-	No	738 000	19	N/A	2004		Private sector, Kumamoto City Kumamoto City Waterworks and Sewerage Bureau, farmers, local agriculture cooperative	Public water utilities and private sectors (payment for ecosystem services)	Local agriculture association, known as Midori Network Ookiku (MNO), overseeing the operation of the PES scheme	shivakoti@iges.or.jp	"https://www.fast.kumamoto-u.ac.jp/gelk/chousei_en.html http://gripp.iwmi.org/natural-infrastructure/water-storage/incentivizing-groundwater-recharge-through-payment-for-ecosystem-services-pes/"
1 247 000	Coastal salinity control	81 200	68	N/A	1980	"1992: domestic and industrial wastewater recharged separately 1994: second recharge basin 2018: extensive refurbishment"	Bulk Water Branch; Dept. of Water and Sanitation; Informal settlements; Water and Waste Directorate, City of Cape Town	City of Cape Town	City of Cape Town	"gideon.tredoux@gmail.com Candice.LasherScheepers@capetown.gov.za"	
-340 000	Coastal salinity control and controlling aquifer drawdown	62 000	37	N/A	2002	"1996-1999 : pilot testing and permitting 2001-2002 : construction 2002: full-operation 2014: upgrade with subterranean infiltration galleries 2018-2019: expansion of infiltration"	Intermunicipal Water Company of the Veurne area (IWVA)	Intermunicipal Water Company of the Veurne area (IWVA)	Intermunicipal Water Company of the Veurne area (IWVA)	emmanuel.van.houtte@iwva.be	www.iwva.be; http://legacywater360.server309.com/
-40 000	Coastal salinity control	6 192	97	N/A	1990	"1988: 20 wells within and 5 wells outside the reservoir area were installed for monitoring 1990: full operation"	Water Resources Research Institute of Shandong Province and Longkou Water Authority	The Commission for Science and Technology of Shandong Province	Water Resources Research Institute of Shandong Province and Longkou Water Authority	stu_wangwp@ujn.edu.cn	There isn't a website that covers the scheme to a certain level of detail and preferably with further refs/links.
-5 000 000	No	184 000	64	N/A	2002	"1999-2002: construction 2002: full operation 2019: increse of the reservoir wall height"	Ministry of Water and Irrigation (MWI), Jordan Valley Authority (JVA), Water Authority Jordan (WAJ), Amman, Jordan	(80 %) Arab Fund for Economic and Social Development (AFESD), (20 %) Jordanian treasury		julian.xanke@kit.edu	https://link.springer.com/article/10.1007/s10040-015-1233-6
-	Coastal salinity control	7	17 857	N/A	2015	2011-2014: inception	Cooperation Nieuw Prinsenland U.A.: a cooperation of greenhouse farmers in a 2.6 km2 area, with support of Allied Waters SALutions	Cooperation Nieuw Prinsenland U.A.: a cooperation of greenhouse farmers in a 2.6 km2 area, with support of Allied Waters SALutions	Cooperation Nieuw Prinsenland U.A.: a cooperation of greenhouse farmers in a 2.6 km2 area, with support of Allied Waters SALutions	Koen.Zuurbier@alliedwaters.com	"http://subsol-data.euprojects.net/ http://gripp.iwmi.org/natural-infrastructure/water-quality-2/asr-coastal-2/ https://www.alliedwaters.com/project/from-sugar-beets-to-tomatoes-sustainable-water-supply-agro-and-foodcluster-nieuw-prinsenland/"

		7	-
		6000000	852941
		553028	31179
		168000	
		12719641	

Appendix III. Summary of Environmental and Social Sustainability Indicators for 28 Cases

A1. MAR cases from high income countries

Case Study 5: A France-Switzerland Transboundary Genevois Aquifer Underground MAR by de los Cobos and Luyet

Annual Recharge: 8×10^6 to 10×10^6 m^3/year; Sustainability Rating: Good (2.4)

To address over-exploitation of the Genevois Aquifer that supplies water for the Canton of Geneva (Switzerland) and the Department of Haute-Savoie (France), transboundary discussions began in 1972 that resulted in the commencement in 1980 a recharge scheme consisted of a water-intake structure in the Arve river, a 340-m long pipe to transfer the water to a water treatment plant with sedimentation, filtration and chlorination units, and finally, a 700-m long pipe to transfer water to a 3-ha underground infiltration area including perforated pipes of a total length of 5,000 m placed at 2 m depth. Monitoring of groundwater table since 1966 demonstrates that the scheme has succeeded in restoring the groundwater level. To maintain a stable water table level, a recharge of 8 to 10 Mm^3/year (infiltrated water) is required to allow for a pumping rate of 12 to 15 Mm^3/year (recovered water), equivalent to about 5% of annual flow of the Arve. The MAR system also brought positive results to overall water quality, especially with regard to its hardness and nitrate content. Systematic monitoring of water quality in accordance to cantonal and federal water regulations has found improvement in hardness and nitrate content and identified a recent perchlorate pollution. In 2015, the energy requirement to infiltrate water at the aquifer recharge plant and to recover water by pumping the wells was 0.61 kWh per cubic meter of recharged water and 0.14 kWh per cubic meter of recovered water, respectively. In addition to abiding the Swiss Federal Law and Ordinance on water protection on MAR, a Franco-Swiss commission in charge of groundwater exploitation regularly reviews the state of the resource according to pumping and artificial recharge. An agreement renewed in 2007, effective January 1, 2008 for 30 years between the communes of the greater Annemasse region, the Genevese communes, the commune of Viry and the State Council of the Republic and the canton of Geneva, succeeded the 1978 arrangement, is a rare example of a transboundary aquifer management agreement. The mean score is 2.1 and 2.8 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow and energy intensity (Chapter 3 Table 5).

Case Study 10: USA California: Orange County Groundwater Basin MAR of Santa Ana River by Hutchinson and Woodside

Annual Recharge: 148×10^6 m^3/year; Sustainability Rating: Good (2.3)

In 1933, the California State Legislature passed the Orange County Water District (OCWD) Act to establish the OCWD with the mission to protect the quantity and quality of groundwater in the Orange County Groundwater Basin that has suffered from over-drafting as early as 1900s and sea water intrusion since 1920s. Starting in 1936, OCWD began using the Santa Ana River (SAR) flow that includes treated waste water and captured storm water to recharge the aquifer through infiltration basins etc. OCWD's MAR system has increased the sustainable yield from a natural yield of the Basin of 123 Mm^3/yr to a sustained groundwater pumping of 370 Mm^3/yr, of which 148 Mm^3/yr is from SAR MAR. Basin storage conditions, with an operating range of 123-617 Mm^3, are determined annually by measuring the groundwater water level in hundreds of monitoring and production wells to ensure that the Basin is neither too full nor too empty. The recharge water and recovered groundwater meets all drinking water standards of US EPA based on required monitoring of the over 200 groundwater production wells. Energy intensity is only 0.05-0.07 kwh/m^3 for infiltration but is 0.3 -0.6 kWh/m^3 for extraction. In addition to the governance framework defined by the 1933 OCWD Act, the Sustainable Groundwater Management Act (SGMA) passed in 2014 prompted the OCWD and several other adjacent agencies to develop a plan that shows the Basin has been sustainably managed for more than a decade. Sustainability rating (Chapter 3 Table 5) is specific to the Santa Ana River component of the OCWD MAR system. The mean score is 1.8 and 2.8 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater level and groundwater quality (Chapter 3 Table 5).

Case Study 17: USA Nebraska: Central Platte River Irrigation Canals MAR for Ecological Flow by Powers *et al*

Annual Recharge: 8.4×10^6 m^3/year; Sustainability Rating: Good (2.4)

In the Central Platte Valley, irrigated agriculture has been in practice since the late 1800s. Under pressure from several interstate compacts to mitigate streamflow depletion caused by groundwater over pumping, Nebraska's Natural Resources Districts, the Nebraska Department of Natural Resources, private irrigation districts and canal companies turned to MAR as a means to maintain functional linkages between groundwater and surface water supplies, while making use of excess floodwaters. In 2011, a project was initiated to rehabilitate irrigation canals and to divert flood water for recharge. Between 2011 and 2017, 85.6 Mm^3 of water was diverted, of which 58.7 Mm^3 of water was recharged, resulting in a rise of groundwater level up to ~ 4 m, and most significantly, 9.1 Mm^3 of water was returned as stream flow. Water quality monitoring did not find major issues, although energy intensity were not estimated but were expected to be low. This scheme is organized under several Integrated Management Plans developed through a public stakeholder input process, with 30-year interlocal management agreements negotiated between all MAR project owners for governance. The mean score is 2.6 and 2.2 by E1 and E2, respectively, with the two experts disagreeing the most on the ratio of volume of water recharged and recovered (Chapter 3 Table 5).

Case Study 18: USA South Carolina: Achieving Water Supply Reliability at Hilton Head Island by Pyne *et al*

Annual Recharge: 1×10^6 m^3/year; Sustainability Rating: Good (1.4)

Hilton Head Island, located along the coast of South Carolina, has lost all of its water supply wells to sea water intrusion due to decades of over pumping of the Upper Floridan Aquifer on the mainland. Aquifer Storage Recovery (ASR) commenced in 2011, targeting the brackish Middle Floridan Aquifer consisted of karst limestone at deeper depth between 156 m to 175 m. Source water is drinking water treated by reverse osmosis in a desalination plant on the island and imported water from mainland. End use is for drinking water to meet peak (summer) and emergency demands. Based on > 6 years of daily data, the ASR wells inject on average 1 Mm^3 of water annually, with all of which recovered during summer months over about 120 days at an estimated energy intensity of 0.3 kWh/ m^3, lower than ~ 1.0 kWh/ m^3 for desalination of brackish groundwater. Monitoring of recovered water quality since 2011 indicates no exceedance of water quality standards. The USA and the State of South Carolina have well-established laws, policies and rules governing "Underground Injection Control (UIC)," originally enacted by the US EPA in 1981 pursuant to federal legislation passed in 1975. The ASR regulatory approval process is well-established and involves two steps. Annual reports on ASR are filed with the state agency and are publically available. The mean score is 1.6 and 1.2 by E1 and E2, respectively, with the two experts disagreeing the most on regulation and permit (Chapter 3 Table 5).

Case Study 21: USA Arizona: The Arizona Water Banking Authority by Seasholes and Megdal

Annual Recharge: 342×10^6 m^3/year; Sustainability Rating: Good (1.7)

In 1996, the legislature in the U.S. state of Arizona established the Arizona Water Banking Authority (AWBA) that has since used MAR to store nearly 5,600 million cubic meter of Colorado River water by 2018. Several factors have been found crucial: local political consensus; a large temporary water supply; favorable hydrogeology; supportive regulations; public funding; and institutional innovation such as the Long-Term Storage Credits. In recognition of the extensive and largely unconfined alluvial aquifers in much of the state, Arizona adopted a flexible, mass-balance approach to MAR accounting. This includes the future right to recover 95% of the volume that was stored; the ability to recover almost anywhere within the regional aquifer system; and the ability of the recovered water to retain the legal character of the stored water. After detailed calculation of losses, Arizona issues Long-Term Storage Credits that form the underpinning of water banking in Arizona. Although much of the banked water is intended as a supplemental supply for times of shortage, MAR is also used as pre-treatment for potable distribution and blending with local groundwater to manage water quality. Source water for recharge meets drinking water standards. Delivery of Colorado River water to central and southern Arizona via the CAP system is energy intensive (1.23 KWh/m^3 to 2.16 KWh/m^3) due to the large elevation change (300 m to 700 m). Energy intensity to recover water for irrigation in central Arizona is estimated to range between 0.48 kWh/m^3 and 0.91 kWh/m^3. While four indicators (groundwater level, ratio of recharged vs recovered water, regulation, and permit) scored "restorative", the concern is that taking lawfully allocated Colorado

River for water banking has maintained the downstream areas' ecological demise thus the ecological flow indicator was scored "inferior" by E1. The mean score is 1.9 and 1.6 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow, permit and community (Chapter 3 Table 5).

Case Study 9: Australia Western Australia: Perth Groundwater Replenishment Scheme using Recycled Water by Higginson *et al*

Annual Recharge: 14×10^6 m^3/year; Sustainability Rating: Good (1.7)

After a trial between 2010 and 2012, Stage I of a groundwater replenishment scheme commenced in 2017, recharging and abstracting 14 Mm^3 of water annually to two sandstone aquifers. Source water is secondary treated wastewater that undergoes further advanced treatment (ultra-filtration, reverse osmosis, UV disinfection) to produce water that meets the Australian guidelines for drinking water. While geochemical changes are occurring as a result of recharge (buffered pyrite oxidation, sedimentary organic matter mineralisation, trace carbonate (siderite) and crandallite dissolution, feldspar weathering and aerobic degradation of trace organics) no metals or chemical were mobilised above required health guidelines. The energy requirement is estimated to be 2.2-2.5 kWh/m^3 and includes advanced water recycling (UF, RO, and UV), transfer to recharge sites, aquifer recharge, abstraction and treatment via Groundwater Treatment Plant. In comparison, energy requirements for a new desalination plant in Perth are estimated at 4.4-5.1 kWh/m^3. A risk assessment process guided by the Australian Guidelines for Water Recycling; Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge (NRMMC, EPHC, NHRMC, 2009)[12 in References of Chapter 3] was followed. Community attitudes to the scheme have improved with education and positive engagement. Surveys conducted during site tours indicated that support for the scheme increased significantly (approximately 74% to 93%, 2012) once people were better informed about the treatment and management systems and when their concerns had been addressed. The mean score is 1.0 and 2.4 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater quality and community (Chapter 3 Table 5).

Case Study 14: Australia South Australia: Recycled Storm Water for Irrigation, Industrial and non-Potable Use in Salisbury via a Dedicated Pipeline by Naumann *et al*

Annual Recharge: 3.5×10^6 m^3/year; Sustainability Rating: Good (1.9)

The City of Salisbury with over 130,000 residents is located in the Northern suburbs of Adelaide, South Australia. Wetland treated urban storm water is stored via aquifer storage and recovery (ASR) and aquifer storage transfer and recovery (ASTR) in confined, brackish limestone aquifers that is distributed to customers via a dedicated 'purple pipe' network. The distributed water is delivered at 'Dual reticulation for indoor and outdoor use' standard. In the early 1990s, community concerns about polluted urban storm water and wastewater discharging into sensitive coastal environment led the Council of Salisbury to voluntarily set an ambitious goal of treating all storm water through constructed wetlands. Later, the need to irrigate public open space at a reasonable cost motivated commencement of a MAR system in 2004. This MAR scheme took advantage of wetland treated storm water. The average injected volume is 3.5 Mm³/yr while the recovered volume is 2.5 Mm³/yr, indicating that about <80% of injected water is recovered. Regular water quality monitoring ensures injected and recovered water quality meets target values. The levelised energy intensity for injection and recovery in storm water ASR has previously been reported at 0.10 kWh/m³ (<3% unit energy cost for desalination), excluding energy for water treatment and infrastructure (Dillon *et al.*, 2009) [Ref 14 in Case 14], but Salisbury has estimated energy intensity for injection, extraction and distribution (including embedded energy in purple pipeline) at 0.06, 0.14 and 0.30 kWh/m³, respectively. MAR schemes in South Australia are regulated under the NRM Act 2004, and the Environmental Protection (EP) Act 1993, the Public Health Act 2011 and Development Act 1993, where applicable. Public awareness of the Salisbury MAR network is very high with regular exposure in local and State media, plus multiple community engagement channels. The mean score is 1.7 and 2.2 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater quality (Chapter 3 Table 5).

Case Study 28: Netherlands Dinteloord: ASR of Treated Waste Water from a Sugar Factory for Irrigation by Zuurbier *et al*

Annual Recharge: 0.09×10⁶ m³/year; Sustainability Rating: Good (1.3)

To enhance drought resilience of the greenhouse horticulture industry in Dinteloord, the Netherlands, an Aquifer Storage Recovery (ASR) system consisted of 8 wells to recycle treated waste water from a sugar factory for storage in a brackish aquifer during periods of surplus for later use in periods of drought. Between 2016 and 2018, 262,000 m³ has been injected and 104,000 m³ has been recovered, with the rest "banked" for future use. Groundwater levels monitored every 30 minutes since 2015 in the vicinity of the ASR well field were found to be stable, although there are variations induced by stages of injection and recovery. In terms of water quality, the injected water is demineralized via UF and RO thus has had no exceedance relative drinking water standard of the Netherlands. For the recovered water, sodium level is maintained to below a maximum allowable concentration of 2.4 mg/L for irrigation and is achieved through automated monitoring of electrical conductivity to guide extraction. However, monthly monitoring of recovered water has found that Fe (~ 1 mg/l) and Mn (~0.6 mg/l) concentrations are slightly elevated thus requiring aeration and settlement in the above ground basins upon recovery. The energy requirement is 1 kWh/m³ for pre-treatment (UF and RO), 0.13 kWh/m³ for injection, and 0.29 kWh/m³ for recovering and distributing groundwater. Another 0.1 kWh/m³ is used for purposes other than pumping (electronics, heating, and ventilation). The total energy intensity is thus 1.53 kWh/m³. Recycling waste water means high energy intensity so this indicator scored "inferior" by E1. The mean score is 1.1 and 2.2 by E1 and E2, respectively, with the two experts disagreeing the most on energy intensity (Chapter 3 Table 5).

Case Study 2: Finland Turku Region: Managed Aquifer Recharge for Drinking Water Supply by Artimo *et al*

Annual Recharge: 23×10⁶ m³/year; Sustainability Rating: Good (2.8)

Since 2013, the Turku Region Water Ltd. has been using a MAR system to produce drinking water for 300,000 inhabitants in the Turku area. Prior to the MAR system, drinking water produced from nearby rivers and aquifers did not meet the needs of the Turku area, both in quality and quantity. Source water from the River Kokemäenjoki is pre-treated first to remove solid particles before its infiltration through 19 basins into the Virttaankangas sand and gravel esker aquifer. Pumping rates of the 13 production wells are precisely controlled to ensure constant flow paths and residence times to achieve the natural purification of the infiltrated water that is further treated by UV and chloramine disinfection before distribution, while maintaining a ratio of approximate 1 of infiltrated and recovered volume. Decades of monitoring of groundwater table found no undesirable changes outside the MAR operation area. In an area of approx. 20 km² with more than 200 monitoring wells, water levels remain at the natural state in the aquifer with the maximum increase in water level of 4 meters observed next to the infiltration areas. Monitoring of intake river water is automated to avoid harmful substances for example oil spills, with a Water Safety Plan using multiple barriers to ensure safety of the recovered and supplied water with no exceedance. Energy consumption in 2018 for raw water intake, pre-treatment, pumping, water transfer and MAR-process (23 Mm³/a) totaled 14.7 GWh for 23 Mm³ water, or an intensity of 0.64 kWh/m³, close to the average drinking water supply energy use in Finland. The Finnish Supreme Administrative Court (KHO 1883, 13.8.2008) defined a strict framework for the operations and the environmental monitoring of MAR, with an environmental impact assessment and permit granting process of the MAR system completed between 1999 and 2008. This scheme benefits from access to a river with high flow and an aquifer that is well suited for MAR. The mean score is 2.3 and 3.3 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow and source water quality (Chapter 3 Table 5).

Case Study 8: Germany Dresden: River Bank Filtration and Infiltration Basins for Drinking Water Supply at Dresden-Hosterwitz Waterworks by Grischek *et al*

Annual Recharge: 25×10⁶ m³/year; Sustainability Rating: Good (2.5)

Since 1907, Dresden-Hosterwitz waterworks has used river bank filtration to purify the Elbe River water with >100 wells placed at a depth of 5–8 m at a distance of 60–120 m from the river in a Quaternary sand and gravel aquifer. Currently, a small portion of river water is also abstracted, pre-treated, recharged via infiltration basins and recovered from wells near the infiltration basins, which has experienced challenges in extreme flooding. No long-term changes in groundwater levels have been observed due to MAR operations. At maximum water production of 72,000 m³/day, 67,500 m³/day (0.78 m³/s) is infiltrated river water while abstracted ambient groundwater amounts to 4,500 m³/day. Compared to a mean average and mean low discharge of the Elbe River of 329 m³/s and 110 m³/s respectively, the abstraction accounts to less than 1% of the river discharge. Riverbank filtration and aquifer passage after infiltration of pre-treated river water via basins were found to provide very reliable treatment, removal of turbidity, pathogens and organic compounds as wells as high safety against shock loads in the river. However, not all organic micropollutants are removed by natural treatment, thus GAC filtration was added as post-treatment. The energy intensity of the century old technology siphoning wells range from 0.081 and 0.108 kWh/m³ and is 36% to 52% lower than that of modern submersible pumps. An ultrafiltration pilot plant consumes 0.18–0.23 kWh/m³ for bank filtrate, about 28% lower than directly treating river water. While the energy intensity remains about 0.13 kWh/m³, it will increase to >0.3 kWh/m³ once ultrafiltration is at full scale. The guidelines of the German Association for Water and Gas (DVGW) are followed in all technical and operational issues as well as procedures for water quality monitoring and risk assessment. A description of treatment processes and actual water quality data are provided to the public on the web. Because this is a long running scheme that keeps innovating to keep energy intensity from rising too fast, the mean score is 2.1 and 2.9 by E1 and E2, respectively, with the two experts agreeing mostly on all indicators (Chapter 3 Table 5).

Case Study 25: Belgium Veurne Area: Reclaimed Water MAR to Sand Dunes in St-André (Koksijde) by Van Houtte and Verbauwhede

Annual Recharge: 2.0×10⁶ m³/year Sustainability Rating: Good (2.8)

Rising water demands especially summer water shortages motivated waste water reuse, with MAR emerging as the best option investigated in the 1990s. In 2002, effluent treated using ultrafiltration and reverse osmosis began to infiltrate the unconfined aquifer of the dunes of St-André (Koksijde) in a pond of 500 m length, followed by abstraction using wells screened between 8 and 12 m depth. The average residence time in the sand dune aquifer amounts to 55 days. The schemed is further expanded in 2014, using "subterranean infiltration". A recovery of groundwater level by 4 to 5 m that has experienced drawdown prior to the recharge was achieved. An annual average ratio of extracted volume to infiltrated volume of 1.4 between 2002 and 2018 met the design specification because extracted volume includes naturally recharged groundwater that has been replaced by infiltrated water, which gains mineral content during passage through the soil. Of the 124 wells operational in 2018, the average conductivity was 327 μS/cm (range: 127 to 928 μS/cm), lower than the initial ambient groundwater (700 μS/cm at 20°C), with added benefit of halving of the hardness. The extracted water is bacteriologically safe and is treated with aeration and rapid sand filtration to remove iron to below 0.2 mg/L prior to distribution. Iron is the only parameter in the extracted groundwater exceeding drinking-water guidelines. Approximately 0.1 kWh/m³ is required to extract and treat the groundwater at St-André. Together with 0.75 kWh/m³ for treating domestic wastewater effluent prior to infiltration at Torreele, the total energy requirement of this multiple barrier approach to recycle waste water is 0.85 kWh/m³. Although there is no specific regulation for MAR, hydrogeological, ecological and environmental evaluation to meet the Flemish Environmental Agency and the Agency for Nature Conservation (ANB) requirements is necessary for permit granting purpose, including a mandatory Environmental Impact Assessment. Since the 1970s environmentalists have opposed groundwater extraction from the dune aquifer. Therefore this water reuse scheme was well accepted by stakeholders and the large majority of the public, with continued efforts to engage the public through guided walks and open day. Innovation in recharge techniques and systematic management of the aquifer renders a positive rating, with the mean score being 1.9 and 3.8 by E1 and E2, respectively. The two experts disagree the most on source water quality, ecological flow and energy intensity (Chapter 3 Table 5).

Case Study 23: Japan Kumamoto: Intentional Flooding of Rice Fields and Payment for Ecosystem Services by Shivakoti *et al*

Annual Recharge: 14×10^6 m^3/year Sustainability Rating: Acceptable (0.9)

Since 2004, payment for ecosystem services (PES) has been used to incentivize farmers through cash compensation to pond their abandoned rice fields for recharge along the Shirakawa River in Kumamoto Prefecture, Japan. Downstream stakeholders reliant on groundwater have agreed to pay farmers as an offset for their groundwater abstraction amounting to 14 Mm^3/yr on average between 2004 and 2018. Groundwater levels have been regularly monitored since 1986 and appear to be stable, consistent with that MAR is accounting for only 2.3% of total recharge of 600 Mm^3/yr and that there has been demand management of groundwater. Since early 2000s, nitrate at levels > 10 mg/L has been detected in both unconfined and confined aquifers, prompting actions to protect aquifer from livestock sourced pollution. Recharge itself is by gravity, so the energy use intensity in the range of 0.3-1.2 kWh/m^3 is dependent on the depth of wells as in any other groundwater use. The coordination role played by the local agricultural association, known as Midori Network Ookiku, which is overseeing the operation and management of the PES scheme, is crucial. In addition to the “Declaration of the Groundwater Preservation City” established in 1976, “Kumamoto City Groundwater Preservation Ordinance” from 1977, and «The First Kumamoto City Nitrate-Nitrogen Reduction Plan» from 2005, the “Kumamoto Ground Water Foundation” was established in 2012 to protect groundwater and sustainable groundwater management due to the continued threat of groundwater pollution. This mean score is 1.1 and 0.9 by E1 and E2, respectively, with the two experts agreeing mostly.

Case Study 12: UK London: North London Artificial Recharge for Supply During Drought by Jones *et al*

Annual Recharge: 15.6×10^6 m^3/year Sustainability Rating: Good (1.8)

The North London Artificial Recharge Scheme (NLARS) can be traced back to the 1890s following decades of over-abstraction from the confined Chalk aquifer. This led to investigation of the viability of aquifer recharge, via existing wells, to refill aquifer storage, and to restore abstraction yields. The evolution of NLARS into its current form as a strategic component of London’s public water supply occurred in phases in the 1950s and into the 2000s. Now it comprises two wellfields with 48 boreholes and wells to recharge filtered and chlorinated river water, with the potential to provide up to 66×10^6 m^3 of groundwater over a year to supplement reservoir storage, or around 6% of London’s 840×10^6 m^3/year drought water supply capability. Since being commissioned in 1995, NLARS has been used for London’s water supply during drought and dry weather challenges in 1997, 2003, 2005/06, 2011/12 and 2018/19. Both abstraction and subsequent recharge vary significantly, with a mean value for the ratio of volume of infiltrated water to recovered water of 0.36 from 1995 to 2019. Over the last 20 years, groundwater storage has increased progressively, reaching 98% of its maximum practical capacity prior to use in 2018. Monitoring of groundwater quality, and its response to recharge, has demonstrated no significant impact on the stored water or its treatability. The energy intensity is around 0.25 kWh/m³, within the range of 0.1 to 0.3 kWh/m³ for other groundwater supply sources operated by Thames Water. There is a well-established regulatory environmental framework administered by the Environment Agency (EA). For NLARS, an abstraction license and an over-arching operating agreement, plus a series of discharge consents that enable recharge, have been authorized via the Water Resources Act 1991 and Environment Act 1995 by the EA. The mean score is 1.7 and 2.1 by E1 and E2, respectively, with the two experts disagreeing the most on source water quality and community (Chapter 3 Table 5).

Case Study 16: France Normandy: Integrating MAR to Waste Water Treatment System for Coastal Ecosystem Protection by Picot-Colbeaux *et al*

Annual Recharge: 0.73×10⁶ m³/year Sustainability Rating: Good (1.2)

Located in Normandy, the Agon-Coutainville commune with 2800 residents, one of the oldest seaside resort and the largest shellfish production and storage location in France, has integrated a MAR system within its municipal wastewater treatment line since 2005. Effluents from a waste water treatment plant (WWTP), with discharge varying from 500 to 5000 m³/day, floods by gravity into one of the three reed bed infiltration ponds into the coastal aquifer composed of 2 to 10 m Quaternary sand. Only one of the three ponds is flooded at any given time, rotating according to a schedule of June to September, October to Mars and April to May. Monitoring for almost 20 years has found that the WWTP significantly removes organics and microbial contaminants, reaching concentrations below the threshold values for irrigation regulated by the French water reuse standards (Class A) except for E. coli. Bi-annual sampling of five piezometers since 2017 show that In general, the recycled water coming from the WWTP combined with MAR scheme meet the threshold values recommended by government especially E. coli, although there are still a few percentage of exceedance for chloride and ammonia. Groundwater is not recovered at present, although seasonal irrigation use from April to October by a nearby Golf course with a pumping rate of 30 m³/h for 10 h a day, or 64,200 m³/year, is being evaluated. The energy requirement of the WWTP has been monitored since 2007, averaging 0.94 kw/m³. Because transfer of the WWTP effluent to infiltration ponds is by gravity, the energy requirement is taken as 0 kw/m³, with energy requirement for groundwater monitoring estimated to be 0.15 kw/m³. Pumping to irrigate the golf would require 0.07kw/m³. In France, there is no centralized governance of managed aquifer recharge (MAR) practice established and no French guidelines dedicated to MAR. The European Water Framework Directive (WFD) is applicable. A specific prefectural order signed in 2001 and with many other orders provides the regulatory oversight for the MAR system. The mean score is 1.0 and 1.3 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow (Chapter 3 Table 5). With the goal of protecting sensitive marine environment fulfilled, the ecological flow indicator is scored “restorative” by E1.

Case Study 6: Israel Shafdan: Soil Aquifer Treatment of Secondary Effluent for Irrigation in the Negev Desert by Elkayam *et al*

Annual Recharge: 130×10^6 m^3/year Sustainability Rating: Good (1.4)

In water scarce Israel, over 75% of the sewage is "recycled" for irrigation, accounting for about half of its agricultural water use. In most populated area of central Israel is the Dan region, where a plan for agricultural reuse of sewage was developed as early as 1965 by TAHAL (Water Planning for Israel Ltd). On April 20th, 1967 an agreement was signed between the executive branch of the Water Authority (Mekorot National Water Company) and the Dan region association of towns, allowing for a project of soil aquifer treatment to polish effluent from the Shafdan Waste Water Treatment Plant (WWTP) to supply for irrigation use 100 km to the south. The target aquifer is consisted of Pleistocene sedimentary rocks mainly of calcareous sandstone, with a thick vadose zone of 20 – 40 m. Between 1977 to 2017, the total volume of secondary effluent infiltrated was 3,209 MCM while the total abstraction after SAT was 3,661 MCM, with the ratio of the volume of infiltrated water vs recovered water on an annual basis averaged at 0.86 +/-0.10 between 1990 and 2017. Groundwater level monitoring since 1970s indicates that hydraulic head varies between +8 m above sea levels (msl) under the recharge ponds, to about -2 msl in the buffer areas that separate the Shafdan basins from the regional aquifer. Care is taken to maintain positive hydraulic heads of 0.5 to +2 msl near the coast line to prevent sea water intrusion. Results of weekly water quality monitoring of recovered water since 1977 confirm no exceedance of Israeli drinking water standards, with high removal of coliforms, faecal coliform, viruses, turbidity, organic carbon and inorganic parameters (e.g. nutrients, metals) attributed to processes in the vadose zone. The total energy intensity is estimated to be 0.63 kwh/m^3, including pumping effluent to the recharge basin at 0.14 kwh/m^3 and recovering water from the aquifer at 0.49 kwh/m^3 but excluding the WWTP. Several committees with representatives from the Water Authority, the Ministry of Health, the Ministry of Agriculture, the Ministry of the Environment, the Dan region association of towns, the Shafdan operators and local farmers provide oversight to the operation of the Shafdan SAT scheme. Annual report that contains all the operational data and the monitoring program results is available at Mekorot. Although recycling waste water is challenging, the scheme benefits from the protective effects of a thick vadose zone and strong institutional organization. The mean score is 1.2 and 1.8 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater level, the ratio of volume recharged and infiltrated, and energy intensity (Chapter 3 Table 5).

Case Study 19: Italy Serchio River: River Bank Filtration for Drinking Water Supply in Sant'Alessio Area by Rossetto *et al*

Annual Recharge: 13.6×10^6 m^3/year Sustainability Rating: Good (1.4)

The River Bank Filtration (RBF) scheme along the Serchio River in Sant'Alessio supplies about 16 Mm^3/year drinking water with good quality to about 300,000 persons of the cities of Lucca, Pisa and Livorno. The scheme started with four vertical wells in 1967 situated about 100 m away to supply Lucca, then added another eight vertical wells in late 1980s after hydrogeological investigations found a highly yielding (0.4 m^3/s or 12.6 Mm^3/yr) sand and gravel aquifer to also supply the towns of Pisa and Livorno about 20 km and 40 km away, respectively. These two towns were facing water scarcity issues; the first because of limited abstractions permitted to preserve the Pisa Leaning Tower, and the second due to missing resources of adequate quality. Finally, a river weir, about 1 km downstream the Sant'Alessio bridge, was constructed in early 1990s to raise groundwater head in the Sant'Alessio area to enhance supply capacity. The RBF scheme is reliable as there is an excellent hydrodynamic connection between the river and the aquifer. During recent drought in 2007, 2012, and 2017, the Serchio River discharge has dropped below 6 m^3/s, the minimum flow requirement set by the River Basin Authority per the EU Water Framework Directive (2000). Fortunately the weir has helped to maintain the abstraction with minimal drawdown in the aquifer. Results of groundwater quality monitoring conducted since the 1990s confirm that, apart from the high removal of pathogens and turbidity, all inorganic parameters are within the limits of the Italian drinking water standard in the last 15 years. However, there have been and still are known risks of surface water pollution. The energy requirement is estimated to be between 0.374 and 0.977 kWh/m^3 depending well location, averaging 0.676 kWh/m^3. Although MAR is authorized in Italy by the DM 100/2016 following a two steps process, RBF is often not recognized as a MAR technique thus the Serchio RBF scheme was authorized via Environmental Impact Assessment (EIA) for large groundwater abstractions as per EU EIA Directive and following amendments. Needing attention is the pollution risks to source water and including RBF as a recognized MAR technique in Italian regulatory framework. The mean score is 1.2 and 1.7 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater quality, as well as groundwater quantity indicators, energy intensity and regulation (Chapter 3 Table 5).

Case Study 7: Spain Segovia Province: El Carracillo Managed Aquifer Recharge System for Rural Development in Castilla y León by Fernandez Escalante *et al*

Annual Recharge: 2.2×10^6 m^3/year Sustainability Rating: Good (1.6)

Over exploitation of the Los Arenales aquifer that occupies 2,400 km^2 of Castilla y León, Spain with 46,000 inhabitants in 96 villages led to a response by the Spanish Ministry of Agriculture and the Regional Government (Junta de Castilla y León) to initiate MAR demonstration projects in El Carracillo in 2003. The source water draws from a January-April allocation capped at 22.4 Mm^3 from the Cega river, diverted by gravity in a 19.6 km-long aqueduct completed in 2000 which serves to recharge. This aqueduct, plus 17 km of MAR channels, 16 infiltration ponds, 1 RBF, 3 artificial wetlands and14 distribution points, forms the MAR system. Between 2002 and 2015, a total of 31.47 Mm^3 of water has been diverted, although the annual amount varies from no diversion to 3.6 Mm^3. All of this water is assumed to have been recharged at a rate of 2.2 Mm^3/yr, far less than the annual extraction of 8 Mm^3/yr. Fortunately, groundwater level rose from 6.30 m below ground level to 4.00 m below ground level between 2003-2015 based on the annual mean values from all the monitoring wells. Fourteen water quality parameters were tracked at four piezometers, exceedance for nitrate (>50 mg/L) was found at two of them. Recharge relies on gravity so has no energy consumption. Groundwater is pumped from 314 wells and is estimated to have an energy intensity of 0.165 kwh/m^3. The Decreto-Ley 9/1998, of August 28th, approved the constructions of the aqueduct for the "General Interest of the Nation", published on 29/01/1999. The latest water allocation is documented in CHD in 2016, establishing the environmental minimum flow rate for the Cega river, with public consultation and is reviewed every 6 years. Meeting minimum flow remains a challenge, with nitrate pollution needing attention. The mean score is 1.2 and 2.0 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow (Chapter 3 Table 5).

A2. MAR cases from upper-middle income countries

Case Study 26: China Shandong Province: A Coastal Plain Groundwater Reservoir in Balisha River Drainage Basin, Longkou, Shandong for Irrigation by Wang *et al*

Annual Recharge: 0.6×10^6 m^3/year Sustainability Rating: Good (1.3)

Groundwater over-exploitation in coastal plains of Shandong Peninsula has caused seawater intrusion. Diminishing groundwater supply, exacerbated by severe droughts in 1980s, motivated the local government to construct an underground dam to form the Balisha River groundwater reservoir in the alluvial-proluvial fan of the river's piedmont plain. The total storage capacity is 430,000 m^3, of which 360,000 m^3 can be regulated or recovered. The dam has raised the groundwater level in the reservoir area, allowing for the return of base flow in the river. Since 1992, 600,000 m^3 of water has been abstracted each year for agricultural (95%) and industrial use. The ratio of the volume of infiltrated water vs recovered water on an annual basis is about 1.0, although the annual recharge is 1.6 to 2.0 times of the storage capacity of the underground reservoir. The Balisha river water quality measurements consisted of 18 parameters met the thresholds for Class III water, or suitable for agricultural use according to Chinese Government Surface Water Classification. Groundwater quality measurements consisted of 20 parameters suggest that it also meets Class III classification of technical standard for groundwater quality of China (GB/T 14848-93), although nitrate exceedance was pervasive. Energy requirement to recover water is 0.02 kWh/ m^3 based on electricity use to pump water for irrigation. Permission to implement the Longkou pilot project was granted by the Commission for Science and Technology of Shandong Province. Monetary compensation was made to the farmers for temporary land use during project construction phase. Clearly defined and transparent regulatory framework for MAR was not available even after the project was completed. It is not until 2017 the Chinese Government released a technical standard document GB/T 35580-2017 entitled "guidelines for water-draw and utilization assessment on construction projects" that may inform future MAR projects. There were no systematic institutional arrangements for public and stakeholder consultation when the project was implemented. Now the technical guideline for environmental impact assessment of construction project (HJ2.1-2016) has this requirement. Despite water quality concerns and regulatory framework only in place post scheme, the scheme has the lowest energy intensity and a rapid turnover of water in the underground reservoir, making it an efficient storage. The mean score is 1.4 and 1.2 by E1 and E2, respectively, with the two experts agreeing on most indicators (Chapter 3 Table 5).

Case Study 3: Mexico Sonora: Infiltration Lagoons for Agricultural Use of Reclaimed Water in San Luis Río Colorado, Sonora, Mexico by Chávez *et al*

Annual Recharge: 10.5×10^6 m^3/year Sustainability Rating: Acceptable (1.0)

Water is scarce for San Luis Río Colorado (SLRC) city, located in the Sonoran desert bordering the Colorado River (CR) delta with a very low annual mean precipitation of 55 mm. In 2007, effluent treated by a waste water treatment facility constructed in 2005 began to flow into 12 lagoons and to infiltrate an underlying aquifer, with recovered water for agricultural use. Between 2010 and 2019, the annual volume recharged has increased from ~ 7.5 to > 10 Mm^3, or approximately one third of the total volume of water extracted from the aquifer. The groundwater table is said to be 20 m below ground level and has not changed since 2005, although there is no systematic monitoring program. Both the effluent and the recovered water have been monitored for water quality, with no exceedance found for waste water discharge standard (NOM-001), although manganese and chloride exceeded recharge standard (NOM-014). Hydrochemical studies have found almost complete removal of the most common contaminants from the effluent, with 99.99% for removal of fecal coliforms, 98.36% for total suspended solids (TSS) and 98.74% for biochemical oxygen demand (BOD). The energy intensity is consisted of pumping and conveying of wastewater for 5 km at 0.08 KWh/m^3, and for recovering water at 0.175 kwh/m^3. The SLRC scheme played an important role in establishing regulations for MAR in Mexico, with CONAGUA which is the Federal Regulatory and Financial Organism now having the ability to provide regulatory oversight. However, community engagement is still being developed. The mean score is 0.9 and 1.1 by E1 and E2, respectively, with the two experts agreeing on most indicators (Chapter 3 Table 5).

Case Study 24: South Africa Atlantis: Storm Water and Waste Water reuse by MAR by Tredoux *et al*

Annual Recharge: 5.4×10^6 m^3/year Sustainability Rating: Good (1.2)

The town of Atlantis, approximately 50 km north of Cape Town built to house so-called “Coloured” people, commissioned a MAR scheme in 1980 to address diminishing groundwater supply and to prevent sea water intrusion. Today, recharge to over exploited Witzand wellfield has two ‘inland’ recharge basins for infiltrating the blend of storm water runoff and the treated domestic wastewater, allowing separation of low quality base flow from the high quality peak flow by a weir. The two basins recharge on average 5.442 Mm^3/year, the extraction on average 2.057 Mm^3/year at Witzand between 2003 and 2013. Groundwater level rise and fall depending MAR status, alternative supply between 1985 and 2015. Fortunately, the severe decline in mid 1990s has been mitigated after 1999 when Cape Town water reached Atlantis. Water quality testing of the source water to chlorinated and softened supply water demonstrates that bacteria, viruses, trace organic pollutants are effectively reduced, although iron and manganese are found in production wells requiring removal. The Witzand wellfield is situated on the coastal plain at an elevation of approximately 50 m above sea level while the storage reservoirs serving the town of Atlantis are above 180 m elevation which requires lifting the water some 130 m, adding significant pumping costs with an energy intensity of 1.8 kWh/m^3. The two primary acts that govern artificial recharge projects in South Africa are the National Water Act (No. 36 of 1998) and the National Environmental Management Act

(No. 107 of 1998), with other national and local laws applicable. The Atlantis Management Committee conduct public consultation meetings, with a Monitoring Committee being established to further engagement with the community. Although energy is for lifting water and excludes that for treatment of iron and manganese, the intensity is high so it is a minus. The use of two basins for separation of water is a highlight. The mean score is 1.2 by E1 and E2, with the two experts agreeing on most indicators (Chapter 3 Table 5).

Case Study 13: Namibia Windhoek: A MAR Scheme in a Complex Fractured Quartzite Aquifer for Securing Water Supply by Murray *et al*

Annual Recharge: 0.5×10^6 m^3/year Sustainability Rating: Good (1.6)

Namibia is the most arid country south of the Sahara Desert. The City of Windhoek located in its central plateau has an average annual rainfall of only 360 mm with no perennial rivers. By 2050 the population is expected to reach 790,000 from 400,000 in 2019, with an increasing water demand from 28 Mm^3/a now to ~50 Mm^3/yr. Since 2002 numerous water supply augmentation options have been investigated. The Windhoek Managed Aquifer Recharge Scheme (WMARS) in combination with additional direct potable reuse of treated waste water were identified as the most viable alternatives to supplement surface water from three reservoirs (the Von Bach, Omatako and Swakoppoort Dams). The target Windhoek aquifer consisted of faulted and fractured quartzite and schist formations has seen declining water level up to 40 m, making its replenishment an urgent task. Following feasibility tests, recharge began in 2005 with 4 bore holes and expanded to 6 in 2011, bringing recharge capability to 10,000 m^3/day. By 2015, water level in the over-exploited micaceous quartzite aquifer has recovered. Annual recharge is approximately 0.5 Mm^3/yr, while abstraction varies from ~ 0.2 to 5.5 Mm^3/yr depending on wet/dry periods. Source water for injection is treated potable water, when mixed with ambient groundwater with occasional arsenic exceedance, brings the recovered water to meet guideline values. The weighted average of energy intensity for a combination of injection and abstraction is 3.9 kWh/m^3 compare favorably with water transfer and desalination. The City of Windhoek has delineated a development limit line to protect the most vulnerable parts of the aquifer, with an Environmental Management Plan (EMP) also established in 2014.The institutional arrangement is an ongoing process, with agreement between the bulk supply authority (NamWater) and the municipality still been negotiated to secure source water right for storage. The restorative effect on groundwater level that enabled supply during drought are two pluses, although lack of a completed institutional agreement and very high energy intensity are concerning. The mean score is 0.7 and 2.4 by E1 and E2, respectively, with the two experts disagreeing the most on ecological flow, energy intensity and permit (Table 5).

A3. MAR cases from lower-middle income countries

Case Study 27: Jordan Madaba: Wala Reservoir Recharges Downgradient Karst Aquifer for Drinking Water Production by Xanke *et al*

Annual Recharge: 6.7×10^6 m^3/year Sustainability Rating: Acceptable (0.2)

The semi-arid Jordan is facing the challenge of natural water shortage, population growth and the associated increase in water demand. Overexploitation of most aquifers has led to a shift towards rainwater harvesting and managed aquifer recharge. The Wala dam, located about 40 km south of the capital Amman, was constructed between 1999 and 2002 by the Ministry of Water and Irrigation to store flood water during winter and to recharge the Hidan wellfield 7 km downstream. Between 2002 and 2012, average infiltration is about 6.7 Mm^3/yr. Average of abstraction is about 11.7 Mm^3/yr. Monthly monitoring of groundwater level since 2002 has found recovery of groundwater level in the wellfield mostly due to recharge from the reservoir through natural lateral infiltration, with minor amounts from 8 injection wells, although the drying up of the reservoir in 2008 coincided with significantly decline in groundwater table. Water quality parameters are regularly monitored for the reservoir and the wellfield by the Jordan Valley Authority (JVA) and the Water Authority Jordan (WAJ), respectively. Periodic deterioration in water quality occurs mainly during precipitation in winter, when floods reach the wellfield and quickly infiltrate through cracks and fissures. The average energy used for groundwater abstraction is 1.18 kWh/m^3. Although the government promotes MAR, with a guideline for MAR implementation developed for Jordan, it is noted in the guideline that there are still no clear standards and institutional frameworks in Jordan for planning, implementing and operating of such facilities. Under the current regional framework the Wala-MAR scheme is operated and maintained in a reasonably sustained manner throughout the year. Incomplete regulatory framework and serious water quality issues are concerning, with only minor pluses for groundwater level improvement. The mean score is -0.2 and 0.6 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater quality (Chapter 3 Table 5).

Case Study 22: Egypt Sidfa: River Bank Filtration of the Nile River for Drinking Water Supply by Shamrukh and Abdel-Lah

Annual Abstraction: 2.19×10^6 m^3/year Sustainability Rating: Acceptable (0.9)

In Sidfa City (Assiut Governorate) located in the Nile Valley, a RBF system was constructed in 2004 to supply drinking water to about 30,000 residents, replacing groundwater supply wells threatened by contamination. Six wells (depth 60 m) were installed 20 m to 40 m away from the bank of River Nile to abstract groundwater from a sandy-gravel aquifer, inducing aquifer recharge by surface water. In 2018, Sidfa RBF is operating as a standby supply at times of need due to the completion of a new surface water treatment plant. Monitoring of groundwater head in abstraction wells showed no decline after 10 years of operation, although they were almost 3-4 m below original head due to pumping. Monthly monitoring of recovered water by Assiut Company has found that the water meets the Egyptian drinking water quality standards. The energy requirement is estimated to be 0.3 kwh/m³ for one cubic meter of abstracted aquifer water. Drilling permits for vertical groundwater wells were required. Community in Sidfa was engaged during the construction phase of this site which was accessible for visitors. Given its success especially in supplying water with reasonable quality with support of community, it is puzzling why it is replaced by a surface water treatment facility that may have been more costly and less sustainable instead of expansion of the RBF. The mean score is 1.0 and 0.9 by E1 and E2, respectively, with the two experts mostly agreeing with each other (Chapter 3 Table 5).

Case Study 20: India Haridwar: River Bank Filtration for Drinking Water Supply by Sandhu *et al*

Annual Recharge: 15.4×10⁶ m³/year, Sustainability Rating: Good (1.5)

Haridwar is considered as one of the seven holiest places of Hinduism thus needs to supply water for a variable temporary population up to several million on festive days. The scheme in Haridwar by the Ganga River and Upper Ganga Canal (UGC), consisting of 22 caisson wells, has been in operation for > 50 years since 1965. The mean portion of bank filtrate abstracted by the RBF scheme is around 70% with the remainder being ambient land-side groundwater, which amounts to a total bank filtrate volume of 15.4×10^6 m³/yr. Considering a mean discharge of the Ganga in Haridwar of 2.45×10^{10} m³/yr, thus there is no environmental impact by the RBF scheme on the Ganga's flow. Water quality monitoring of the RBF scheme has been conducted since 2005. Bacteriological indicator counts (total coliforms and E.coli), turbidity, major ions and instant field parameters have been monitored monthly at least for one year during the periods 2005–2006, 2012–2013 and 2016–2018. Inorganic chemicals, including salinity, nutrients and metals, have been monitored during these periods too, albeit less frequently. Apart from the high removal of coliforms and turbidity, all inorganic parameters are within the limits of the Indian drinking water standards and WHO guideline values. The energy consumption per m³ of recovered water by RBF in Haridwar is 0.16 kWh. There are no specific legally binding standards or regulatory framework for RBF in India. However, the «Guidelines on Bank Filtration for Water Supply in India» published in 2019 provide internationally accepted best-practice guidelines, including on health risk assessment consistent with the WHO's Water Safety Plans and with the Australian Guidelines for Managed Aquifer Recharge. There are established permit granting processes to procure land through the Ministry of Environment, Forest and Climate Change, and to drill wells from the state ground water board under the jurisdiction of the Central Ground Water Board of the Ministry of Water Resources, River Development and Ganga. As one of longest running RBF scheme that has consistently supplied water with improved quality, minimal ecological flow impact and low energy intensity, the mean score is 1.0 and 1.8 by E1 and E2, respectively, with the two experts disagreeing the most on source water quality (Chapter 3 Table 5).

Case Study 4: India Rajasthan: Streambed Recharge Structures in Dharta Watershed for Agricultural Use by Dashora *et al*

Annual Recharge: 0.779×10⁶ m³/year, Sustainability Rating: Acceptable (0.7)

With the expansion of groundwater irrigation since 1980s, groundwater levels have fallen in the granitic terrain of the Aravalli Hills in Rajasthan, and any streams that were previously perennial became ephemeral. Consequently in the 1990s and 2000s streambed recharge structures, locally known as check dams, were constructed. These were small weirs, generally of concrete, to detain stream water so it could enhance groundwater recharge, and help secure groundwater supplies with a monsoonal climate with a mean annual rainfall of approximately 600 mm. Four check dams constructed between 1995 and 2005 with a combined storage capacity of 469,000 m³ are selected for a hydrological and economic study. Mean annual recharge from the 4 impoundments was 779,000 m³. Monitoring of groundwater table is now undertaken by farmers who have had training and been provided equipment to help decision making with crop planting. The ratio of volume of infiltrated water from the 4 check dams to volume of recovered water on an annual basis varies between 8% and 16%. Water quality analysis of 13 surface water samples and 150 dug wells have identified exceedance of turbidity, pH and fluoride relative to drinking water standards, although for irrigation use, only a few well water samples contained too much salt. Greater attention is warranted on improving the quality of water extracted from dug wells for drinking. These ephemeral streams have lacked base flow at least since 1960s. Restoration of ecological flows is considered of secondary importance to sustaining agricultural crops and farm livelihoods. Check dams recharge water under gravity so there is no ongoing energy cost; there should be energy saving for pumping due to elevated well water level but this is not quantified. There is a voluntary arrangement for farmers to monitor groundwater and self-manage their aquifer through village groundwater cooperatives. The remaining concerns for water quality in terms of human health protection and for food security overtaking ecological flow, even with the efficient storage mechanism of check dams along with positives in groundwater level, permits, community engagement, the mean score is 0.6 and 0.9 by E1 and E2, respectively. The two experts agree on most indicators (Chapter 3 Table 5).

Case Study 11: India Maharashtra: Streambed Recharge Structures with Periodic Desilting to Improve Recharge of Aquifers at Jalgaon Kade Pathar Village, Baramati by Jadhav *et al*

Annual Recharge Increase: 0.078×10⁶ m³/year, Sustainability Rating: 0.4

In the Baramati Taluka of Pune District of the semi-arid Western Ghats of Maharashtra, recharge enhancement structures have been constructed in ephemeral streams since 1968. Local villagers, predominantly women, provided labour for building earthen embankments. By1978 a total of 149 recharge structures in this district had increased detention capacity by 14.7 Mm³ and annual recharge by a larger volume. The claimed benefit by farmers has led to further investment under national programs and by 2019 the number of recharge structures had reached 289. In recent years there has also been considerable coordinated investment in silt removal to maintain elevated recharge from these structures. Again, without hydrological monitoring, the perceived benefits were such that between 2014 and 2019 the Baramati Agricultural Development Trust has desilted an additional 52 check dams from 52 villages. One of the villages is Jalgaon Kade Pathar where 7 old check dams along the small ephemeral Karha River and its tributary, Bedichaodha were silted, reducing water storage capacity by ~40%. Between 2011 and 2013, 55,800 m³ of silt was removed from 7 check dams, increasing water storage by 40% to a total of 195,200 m³. This is expected to increase recharge by at least 40% due to the additional storage capacity and possibly more through likely increase in the permeability of the floor of the check dams. Conservatively estimating annual recharge to increase by 1.4 times the volume of silt removed, increase in recharge would be 78,000 m³/yr. The desilting in each village panchayat (local government) was finalized following a participatory approach through the Village Climate Risk Management Committee (VCRMC), although much remain to be done regarding water quantity and quality monitoring, and consideration of ecological flow that is secondary to food security needs now.

Desilting clearly prolongs the life of the check dams, but due to lack of evidence the sustainability is not rated by E1 so the rating is by E2 only.

Case Study 15: India Uttar Pradesh: Underground Transfer of Floods for Irrigation in the Ganges Basin, India by Pavelic *et al*

Annual Recharge Increase: 0.026 – 0.062 ×10^6 m³/year, Sustainability Rating: Acceptable (0.1)

This case study presents a synthesis of the learnings gained from initiating and testing Underground Transfer of Floods for Irrigation (UTFI) at the pilot scale within the Gangetic Plain in India. Available observations for the period from 2004 to 2014 show that groundwater levels across the district of Rampur in western Uttar Pradesh have been declining at rates ranging from <0.01 to 0.7 m/yr. Thus, in Jiwai Jadid village, 10 wells (25-30 m deep) drilled into base of village pond (75m x 35m) situated adjacent to an irrigation canal to recharge by gravity a Quaternary alluvial aquifer with fine to medium sand were commissioned in 2015. Water is siphoned into the pond from an adjacent small irrigation canal which receives river flows from a tributary of the Ramganga river. Raw water is pretreated by sedimentation within the pond and by gravel-filled tank beds constructed around each of the recharge wellheads before recharging by gravity to the aquifer. The stored surface water is recovered via existing domestic and irrigation wells in the local area. The volumes of water stored each monsoon ranged from 26 to 62 x10^3 m³ over recharge durations ranging from 62 to 85 days. Peak mounding was observed to be 0.8 m or less and most clearly evident at the beginning of the season when recharge rates were highest. Surface water and groundwater quality monitoring showed that faecal coliforms, lead, mercury and TDS did periodically exceed the standards, with arsenic higher than the WHO guideline value of 10 µg/L but lower than the 'maximum permissible' standard of 50 µg/L. A key milestone was achieved through the integration of annual maintenance of the system into a national flagship program for guaranteed rural employment (Mahatma Gandhi National Rural Employment Guarantee Act, MGNREGA). This involves community participation in regular maintenance tasks, paid through the government. However, there are serious water quality and institutional risks, with the mean score being -0.2 and 0.3 by E1 and E2, respectively. The two experts agree on most indicators (Chapter 3 Table 5).

Case Study 1: Bangladesh Khulna: Aquifer Storage Recovery for Coastal Community Drinking Water Supply in Batiaghata by Ahmed *et al*

Annual Recharge: 0.000667×10^6 m^3/year, Sustainability Rating: Good (1.3)

Millions of inhabitants of the southwestern coastal Bangladesh face severe seasonal water shortage despite monsoonal rain during the wet season. Widespread salinity in groundwater and saline intrusion of rivers in the dry season limit the quantity of available fresh water. Since 2010, a communal aquifer storage recovery (ASR) facility has been in operation in Gangarampur Village of Batiaghata Upazila for drinking water supply to 45 families with 160 beneficiaries. The target aquifer had brackish water with electrical conductivity (EC) of 3 μS/cm or approximately 2010 mg/L total dissolved solids (TDS). It has been "replaced" by fresher water (EC ~2000 μS/cm, equivalent TDS 1340 mg/L) sourced from ponds after ~ 6 months of infiltration during rainy season at a rate of ~7 m^3/d. The average infiltration rate is 677 m^3/year while the average abstraction rate is 226 m^3/year. Although ~19% of recovered water exceeded the Bangladesh drinking water quality standard for TDS of 1,000 mg/L (DPHE 2019) [13], this standard is not health based but is based on human taste preference, which is higher in this community due to severe water scarcity. Intermittent water quality testing has confirmed that the recovered water is effectively free from any suspended material and E. coli. Weekly arsenic (As) monitoring based on ITS EconoQuick As test kits between July 2012 and May 2014 also confirm that As is < 10 μg/L, the WHO guideline value. The energy requirement of the ASR operation/infiltration is 0.27 kWh/m^3 to lift water from the pond to the filtration chamber to pre-treat water before recharge. Currently there is no national strategy and/or guideline for construction and operation of MAR systems in Bangladesh. A village User Committee arranges regular monthly meetings to ensure proper O&M and collects water fees. This is the first successful implementation of ASR at pilot scale in Bangladesh and has gained appreciation from diverse stakeholders and is informing the national committee for formulating MAR Strategy and Guideline. The scheme is well accepted by the community so a plus, although the excessive salt in recovered water (despite a freshening of aquifer) and lack of regulatory framework for MAR are concerning. The mean score is 0.9 and 1.9 by E1 and E2, respectively, with the two experts disagreeing the most on groundwater quality (Chapter 3 Table 5).

This publication provides evidence that the **purposeful management of aquifer recharge creates profound economic benefits and ensures environmental sustainability**.

This book is a contribution to the UNESCO IHP studies on Groundwater Resources and Aquifer Systems.

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