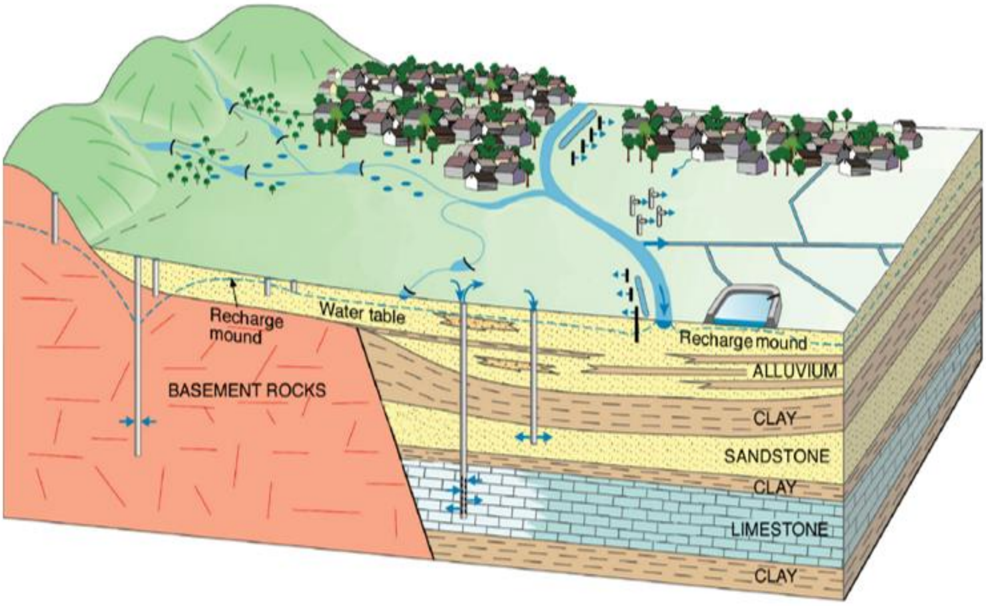

Managed Aquifer Recharge: Overview and Governance

IAH Special Publication

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Managed Aquifer Recharge:
Overview and Governance

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Foreword

The United Nations World Water Development report launched on World Water Day 22 March 2022, has the theme "Groundwater: making the invisible visible." Its executive summary expressed the importance of managed aquifer recharge. "MAR is an integrated approach that allows replenishment of aquifers to complement storage dams and provides a cost-effective alternative that minimizes evaporation and environmental impacts. MAR can also be used to retain unharvested urban stormwater and recycled water, to be made available for productive use when needed. At the watershed scale, MAR can be used to maintain environmental water flows and their availability, creating lags in water discharges to a stream. The application of MAR has increased by a factor of 10 over the past 60 years, but there is still ample scope for further expansion, from the current 10 km^3/year (about 1% of global groundwater use) to probably around 100 km^3/year."

In 2021 UNESCO published a compendium of 28 case studies of exemplary MAR schemes in operation from 17 low to high income countries. This contained a synthesis of their characteristics and evolution, their sustainability as depicted in 9 indices designed for evaluation, and their economics using levelised cost and benefit/cost ratios. Governance arrangements for MAR were found in most cases to be trailing project development. Experience gained at these sites show that failing to provide proponents entitlements to recoverable water and by creating barriers that were unrelated to risk tend to disincentivize MAR projects. Further, water banking arrangements, vital as a climate change buffer, were in place in very few jurisdictions. Therefore, this document was prepared to help water resources planners, managers and regulators to see the range of options available for frameworks and practices to enable and ensure good outcomes.

The International Association of Hydrogeologists in 2002 formed a Commission on Managed Aquifer Recharge (a term coined by its founding co-chairman Ian Gale). IAH publishes this book as a product of cooperation with UNESCO, a founding partner with IAH in the IAH-MAR Commission and in other initiatives, and with the National Ground Water Association (USA).

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Preface

The Groundwater Project (https://gw-project.org) requested a foundational book on MAR and William (Bill) Alley of the USA-based National Ground Water Association was charged with assembling a writing team. He drew on the International Association of Hydrogeologists Commission on Managing Aquifer Recharge (IAH-MAR), and it was decided to give an overview of MAR and the governance arrangements that guide the way that the quantity and quality of water is managed in MAR operations. This book shows why water managers need a sound technical basis in hydrogeology and in natural and engineered water quality processes to achieve effective, sustainable and safe MAR operations.

"Groundwater governance comprises the enabling framework and guiding principles for management of groundwater in line with society's goals." (UN FAO and World Bank Group, 2015). There is a good understanding of the need for effective governance of groundwater and conjunctive use (Villholth et al 2018), as evidenced by too many examples of overexploitation and pollution of groundwater. MAR is seen as one potential solution and its well-planned use has resulted in very positive outcomes. However, its inappropriate use can also cause problems. While some countries have documents to guide the use of MAR, and thereby facilitate exemplary MAR projects and programs, until now there has been no international overview of the wide range of governance arrangements for MAR. These are needed to address both water resources policies and groundwater quality protection.

The book is organized in three main sections, each written by a team of authors:

- Section 1 gives an overview of purposes, types, source waters, advantages and challenges, essential requirements, and stakeholder involvement. MAR is at the interface of surface water and groundwater management and draws on good scientific and communication skills to make progress.
- Section 2 focuses on less-studied elements, namely innovative policies and regulations, which need to be soundly based to underpin the viability of MAR. This is intended to be of prime interest to water resources planners or managers, and lays out a framework that can be used in both developing and advanced jurisdictions and will allow, and even encourage, MAR to be implemented.
- Section 3 takes a parallel track focused on water quality management for health and environmental protection from a variety of starting positions and capabilities. This is fundamental to managing risk and to sustainable MAR operations, including the management of clogging and recovery efficiency.

Acknowledgements

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- Thomas Grischek, Professor for Water Sciences, University of Applied Sciences Dresden, Germany
- Karen Villholth, Coordinator of GRIPP, International Water Management Institute, South Africa
- Richard Evans, Principal Hydrogeologist, Jacobs Group, Melbourne, Australia
- Manuel Sapiano, CEO Energy and Water Agency, Malta
- Everton de Oliveira, Director, HIDROPLAN, São Paulo, Brazil
- Lauren Bartels, MSc student, University of Nevada, Reno, USA
- Eileen Poeter, Emeritus Professor, Colorado School of Mines, Golden, Colorado, USA

We are grateful to John Cherry for encouraging this work, and for Amanda Sills and Connie Bryson of the Groundwater Project for their oversight of review. Due to changes in GWP objectives for its book series occurring after successful review and revision of the manuscript, this book is published by IAH, in concert with UNESCO and NGWA, and with the agreement of GWP, recognizing that the book fills an identified gap. It is freely accessible and contains Exercises and Solutions to assist its use as a learning resource.

Dedication

This book is dedicated to five individuals who devoted their careers to the advancement of managed aquifer recharge (MAR) worldwide and to informing and teaching others about this suite of methods.

Herman Bouwer led pioneering inter-disciplinary scientific and engineering research on MAR for over 42 years at the U.S. Water Conservation Laboratory in Phoenix, Arizona, USA. This included studies of soil aquifer treatment of treated sewage effluent and groundwater mounding beneath infiltration basins. He wrote many papers and a book, taught courses, and is acclaimed for his contribution to water management and research and training. He passed away on July 28, 2013.

Ivan Johnson worked as a hydrogeologist with the USGS[2] from 1948-1979, and subsequently as a consultant when he initiated and was scientific convenor of the first two international conferences on MAR in 1988 and 1994. He encouraged UNESCO[3] to develop an interest that helped form what became the IAH[4] Commission on MAR. He was also very active in land subsidence studies around the world. He passed away on August 31, 2011.

Ian Gale had a long career with the British Geological Survey, where his interest in MAR led to the first MAR project in the United Kingdom, and subsequent MAR studies and projects in India and the Middle East. He was a founding co-chair of the IAH Commission on MAR in 2002 through to his retirement in 2011. Ian was the first to coin the term "managed aquifer recharge" in 2002. He authored a foundational UNESCO-IAH document "Strategies for MAR in semi-arid areas". He passed away on August 13, 2017.

Devinder Chadha chaired the Central Ground Water Board, India where he was an immensely powerful advocate of recharge enhancement. He secured national investment worth several billion American dollars in a myriad of small- to modest-scale schemes to increase water security via several government programs in rural and urban areas. He was also active in research and university teaching, and served senior roles in IAH and other associations, until his death in December 2020.

Edwin Lin in his 20 years with Todd Groundwater, after postgraduate studies in Australia, focused on understanding and solving technical issues and managing numerous MAR investigations and projects in California, USA, rising to Principal Hydrogeologist. Gracious and highly respected by staff and clients, he also mentored junior staff on technical aspects of MAR. While in the prime of his career, Edwin passed away on November 15, 2020.

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[2] United States Geological Survey

[3] United Nations Educational, Scientific and Cultural Organization

[4] International Association of Hydrogeologists

1 Basic Concepts of Managed Aquifer Recharge

Authors: William Alley, Peter Dillon and Yan Zheng

1.1 Introduction

Managed aquifer recharge (MAR) is defined as the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit (Dillon et al., 2009). It is a water resources management tool that encompasses a wide variety of water sources, recharge methods, and storage management practices. MAR has a long history and is likely to see increased use as growing populations create greater demand for water and as a strategy to adapt to increased variability of water supplies due to climate change. Figure 1 shows an example of how MAR can be adapted to a local situation.

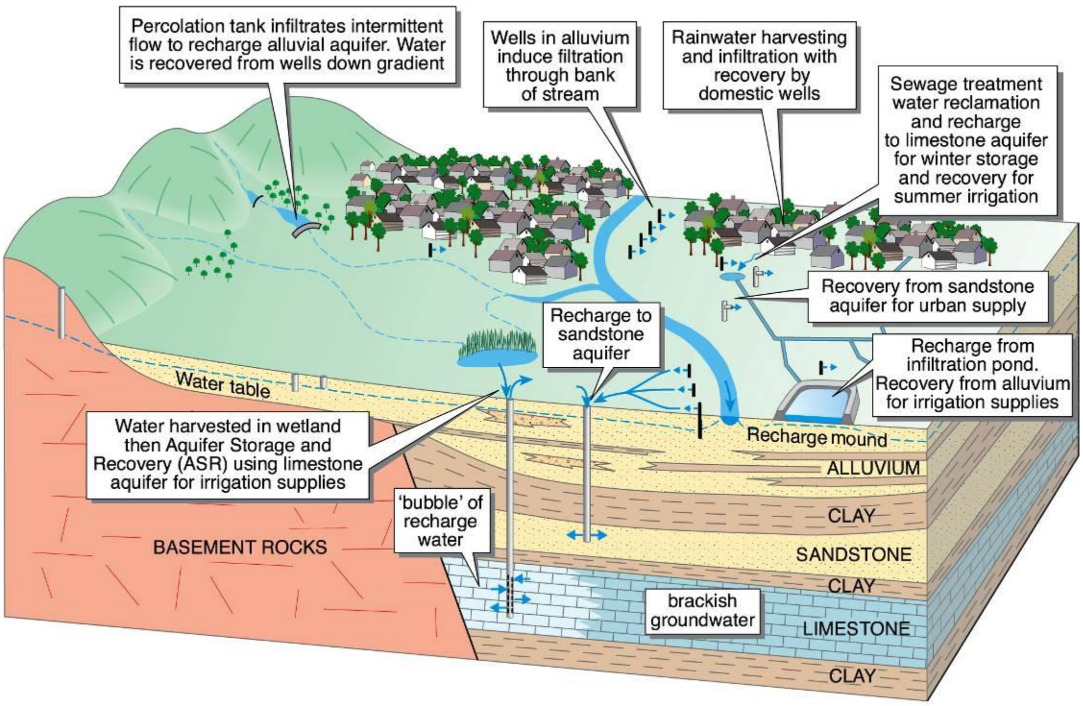

Figure 1 - Managed aquifer recharge is adapted to the local situation, and is usually governed by the type of aquifer, topography, land use, and intended uses of the recovered water. This diagram shows a variety of recharge methods and water sources making use of several different aquifers for storage and treatment with recovery for a variety of uses. An understanding of the local hydrogeology is fundamental to determining options available and the technical feasibility of MAR projects. Recharge shown here occurs via wells, percolation tanks, and infiltration basins (adapted from Gale, 2005, with permission).

As a "managed" process, MAR should consider the value of the recharged water, its impacts on groundwater quality, and protection of human health and the environment. *Purposeful recharge* is an important part of the definition of MAR. Managed aquifer recharge includes only recharge enhancement that is an intentional attempt to manage groundwater availability and quality as part of the process (Table 1). Recharge from irrigation, leakage from water mains, and unintentional recharge caused by vegetation clearing are not considered MAR. MAR also excludes recharge for disposal purposes, such as septic tank leach fields. Water storage underground in abandoned mines or natural caverns is also not considered MAR.

Table 1 – Categories of recharge enhancement, only one of which is recognized as MAR. This relates to its primary goal to purposefully recharge the aquifer and also conveys the ability to quantify recharge enhancement through monitoring.

Unintentional Recharge Enhancement (incidental)	**Unmanaged Recharge (for disposal)**	**Managed Recharge (for recovery)**
• Clearing of deep rooted vegetation, or soil tillage • Spate irrigation • Leakage from water pipes and sewers • Irrigation deep seepage • Spraying herbicides	• Stormwater drainage wells and sumps • Septic tank leach fields • Mining and industrial water disposal to sumps	• Streambed channel modifications • Bank filtration • Water spreading • Recharge wells • Reservoir releases • Soil aquifer treatment • Rainwater harvesting

Recharge water may be stored in a wide spectrum of confined and unconfined aquifer types, from unconsolidated alluvial deposits to karstic and fractured rocks. Recovery is typically achieved through wells, but in some cases by means of natural discharge of the water to surface water bodies. Recovered water may be used for drinking water, irrigation, cooling, industrial processes, and environmental purposes, among other possibilities.

In many aspects, MAR is the modern version of the term artificial recharge. The two are not equivalent, however, as artificial recharge does not necessarily imply a managed process. The terminology has evolved, and the term artificial recharge, as used in some older regulations and guidelines, is gradually becoming superseded.

1.2 Purposes of MAR

Managed aquifer recharge is being successfully implemented worldwide for various interconnected purposes (Pyne, 2005; Dillon et al., 2019; Zheng et al., 2021). Among these are:

1. *managing water supply*: MAR is commonly used to address imbalances in supply and demand. This may occur with respect to seasonal timeframes (e.g., recharge during wet seasons and recovery during dry seasons), interannual timeframes (e.g., drought mitigation), or emergency uses (e.g., for fire fighting, or loss of water supply during hurricanes or earthquakes);
2. *meeting legal obligations*: MAR may be used to help meet legal obligations, such as downstream water rights or compact agreements;

3. *restoring/protecting aquifers*: MAR may be used to restore or prevent further declines in groundwater levels, control saltwater intrusion, or halt land subsidence;
4. *maintaining minimum flows and levels:* MAR may be used to maintain minimum flows in streams and rivers or minimum levels in lakes;
5. *flood mitigation*: use of stormwater for MAR may contribute toward flood protection;
6. *water quality enhancement and protection*: MAR may be used to manage or improve groundwater and surface water quality or control contaminant migration;
7. *water reuse*: MAR is increasingly used to manage reuse of treated wastewater, often for irrigation and potable purposes; and
8. *ecosystem restoration and protection*: examples of the use of MAR for ecosystems include restoring or maintaining wetlands and protecting endangered species and their habitat.

Managed aquifer recharge is often connected with the concepts of sustainability, conjunctive use, and demand management (Dillon and Arshad, 2016).

Groundwater sustainability can be defined as development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental or socioeconomic consequences (Alley and Leake, 2004). For sustainable management of a groundwater resource, demand ultimately needs to be managed to balance the recharge, whether it be natural, managed or incidental. A recent review by Owen (2021) found no agreed framework and little appetite among regulators for managing natural recharge when land use is changed or incidental/unintentional recharge occurs. Hence managing demand and MAR are the two tools used by water managers to influence the groundwater balance over time. Water quality also needs to be protected for groundwater resources to be sustainable. In Chapter 3 of Zheng et al. (2021), six environmental and three social sustainability indicators were developed specifically for MAR schemes. These innovative governance instruments protect the security and quality of water supplies and groundwater-affected ecosystems, and give assurance to the community on the fairness and transparency of regulations.

Conjunctive use is the coordinated use of surface water and groundwater to optimize their combined use, and minimize potential undesirable physical, environmental, and economic effects of relying on only one or the other (Evans and Dillon, 2019). In practice, conjunctive use involves relying more on surface water when it is available during wetter years - including to recharge groundwater - and relying more on groundwater during dryer years and droughts. MAR is often (but not always) part of conjunctive use of surface water and groundwater. MAR augments groundwater with available surface water and acts alongside conjunctive use of surface water and groundwater to sustain water supplies and achieve groundwater and surface water management objectives such as protection of ecosystems as shown in Figure 2.

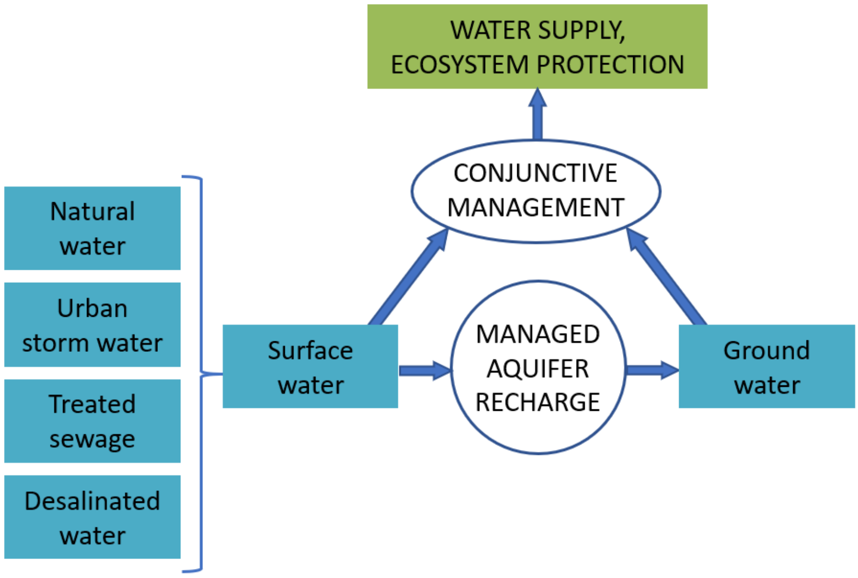

Figure 2 - Roles of managed aquifer recharge and conjunctive use in integrated water resources management (from Dillon and Arshad, 2016).

Demand management can take many forms, including more efficient use, education, fiscal policies, and changing priorities in water use. Figure 3 demonstrates how MAR can be coupled with demand management and conjunctive use to bring an overexploited aquifer back into hydrologic equilibrium.

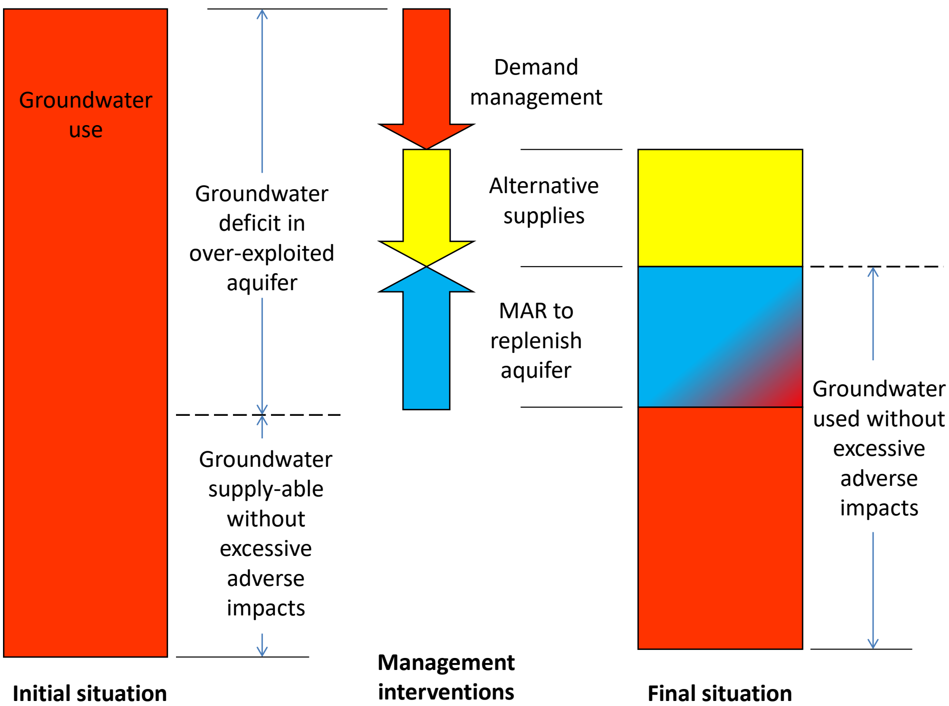

Figure 3 - An aquifer can be brought into hydrologic equilibrium by either reducing extraction or augmenting supplies, either through groundwater replenishment or providing alternative supplies (from Dillon et al., 2012).

1.3 Types of MAR

Many methods can be used to enhance recharge to aquifers. These are shown schematically in Figure 4, and can be broadly grouped as streambed channel modifications, bank filtration, water spreading and recharge wells. Small-scale recharge such as rainwater harvesting use various infiltration methods or wells. Applications are described below.

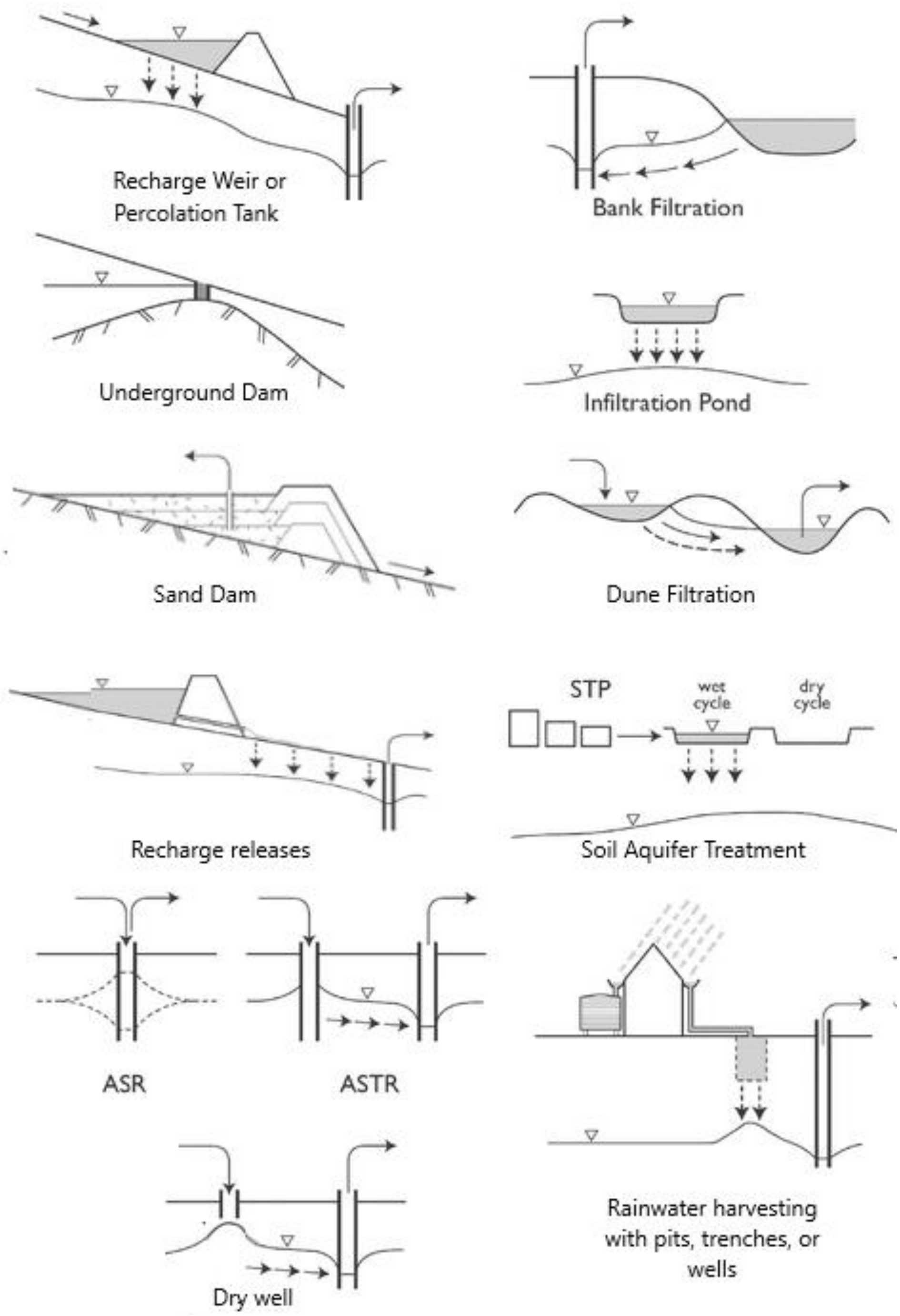

Figure 4 – Schematic of various types of MAR. Many other variations exist. (Redrawn from Dillon et al 2009). (ASR is aquifer storage and recovery; ASTR is aquifer storage transfer and recovery.)

Selection of suitable sites for MAR and choice of method will depend on the hydrogeology, topography, hydrology and land use of the area. It is common to find similar types of MAR projects clustered in the same area due to shared physical attributes. In another area, the methods may be quite different.

Streambed Channel Modifications

Recharge weirs or percolation tanks: dams built in ephemeral streams detain water which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down-valley (very common in India).

Underground dams: In ephemeral streams where basement highs constrict flows, a trench is constructed across the streambed, keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use (e.g. in Kenya).

Sand dams: built in ephemeral stream beds in arid areas on low permeability lithology, these trap sediment when flow occurs, and following successive floods the sand dam is raised to create an “aquifer” which can be tapped by wells in dry seasons (e.g. in Namibia).

Recharge releases: dams on ephemeral streams are used to detain flood water and uses may include slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge (e.g. in South Australia)

Bank Filtration

Bank filtration: extraction of groundwater from a well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovered (very common in Europe).

Water Spreading

Infiltration ponds: involve diverting surface water into off-stream basins and channels that allow water to soak through an unsaturated zone to the underlying unconfined aquifer (very common in Southwest USA).

Dune filtration: infiltration of water from ponds constructed in dunes and extraction from wells or ponds at lower elevation for water quality improvement and to balance supply and demand (e.g. The Netherlands).

Soil aquifer treatment (SAT): treated sewage effluent is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by wells after residence in the unconfined aquifer (common in USA, Israel, Australia).

Infiltration galleries: buried trenches (containing polythene cells or slotted pipes) in permeable soils that allow infiltration through the unsaturated zone to an unconfined aquifer (e.g. Western Australia).

Rainwater harvesting for aquifer storage: roof runoff is diverted into a well, sump or caisson filled with sand or gravel and allowed to percolate to the water-table where it is collected by pumping from a well (e.g. India, USA, Western Australia).

Recharge Wells

Aquifer storage and recovery (ASR): injection of water into a well for storage and recovery from the same well. This is useful in brackish aquifers, where storage is the primary goal and water treatment is a smaller consideration (common in USA, Europe, Australia, Middle East).

Aquifer storage, transfer and recovery (ASTR): involves injecting water into a well for storage, and recovery from a different well. This is used to achieve additional water treatment in the aquifer by extending residence time in the aquifer beyond that of a single well (e.g. in USA, Australia, Europe).

Dry wells: typically shallow wells where water tables are very deep, allowing infiltration of very high quality water to the unconfined aquifer at depth (e.g. Arizona, USA)

Streambed Channel Modifications

In streambeds (also called wadis), surface and subsurface impoundments can be designed to capture or slow down runoff, which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down-valley. These are often low-technology structures, designed to meet local conditions. Recharge weirs have been commonly used.

Bank Filtration

Bank filtration involves pumping groundwater from aquifers that are hydraulically connected to rivers or lakes. The pumping induces seepage from the surface water body into the aquifer and provides filtration of the water as it flows to the water supply well. This is commonly used in alluvial aquifers for natural pre-treatment of surface water, to achieve a high level of resilience against spills, shock loads, floods and droughts compared to direct surface water abstraction, or to prevent excessive drawdown of groundwater beneath large urban centers.

Water Spreading

Water spreading involves the use of ponds or spreading basins to recharge an unconfined aquifer, which is subsequently pumped to provide a water supply or for other purposes. Constructed or natural wetlands may also be used for water spreading. Percolation through the unsaturated zone provides relatively rapid attenuation of some contaminants in comparison with passage through aquifers.

Recharge Wells

Recharge wells are used in situations where the target aquifer is deep, confined, or overlain by low permeability layers. Several different approaches are used, including *Aquifer storage and recovery* (ASR), *Aquifer storage, transfer and recovery* (ASTR), and dry wells as described above.

Small-Scale Recharge

Small-scale options recharge aquifers through collection tanks or sand filters. A common approach is *rainwater harvesting* from roof drainage.

Selection of suitable sites for MAR and the choice of method will depend on the hydrogeology, topography, hydrology and land use of the area. Similar types of MAR projects are commonly clustered in the same area due to shared physical attributes favoring the economics of those MAR types for a given type of source water and MAR purpose (Dillon et al., 2009).

1.4 Source Waters

An aquifer can be recharged with many types of source water, including surface water from rivers or lakes, captured stormwater, treated wastewater, and groundwater drawn from other aquifers or remotely from the same aquifer. Use of desalinated water from seawater or brine is another possibility, although rarely used for MAR. Risk management of water quality and constraints on source water are described in Section 3 – *Considerations for Water Quality Management*.

Most applications of MAR have used surface water due in part to its availability. Requirements for treatment to address the chemical and microbiological quality of natural surface water are normally less than those for stormwater or treated wastewater. For some applications, surface water may be adequate for recharge by itself or with limited treatment.

Stormwater is usually an abundant but sporadic resource, however treatment and storage as a source water for MAR can be challenging. Treated wastewater has advantages in terms of being available throughout the year and in particular during dry periods when demands are the highest and conventional resources are less available. It requires extensive treatment before recharge.

When choosing a MAR site, one must be sure that the quality of the recharge water is compatible with the reactive potential of the aquifer matrix and possibly the vadose zone. This usually means comprehensive investigations during a pilot phase. Water intended for recharge can sometimes contain pollutants, including trace elements, nutrients, pathogens, and contaminants of emerging concern as detailed in Section 3 - *Considerations for Water Quality Management*. Two main issues emerge with respect to the source water used for recharge: the safety of water quality for human health and the environment, and clogging of the recharge facility.

1.5 Overall Advantages and Challenges of MAR

Depending on the situation, MAR can be part of the solution to various issues, including water scarcity, water security, water quality degradation, land subsidence, falling water tables, seawater intrusion, streamflow depletion, and endangered groundwater dependent ecosystems. Water resources management and accounting systems play an important role in securing the benefits that MAR can achieve as described in Section 2 - *Considerations for Water Resources Planning and Management*. Nevertheless, MAR has suffered from a general lack of awareness of its utility and misperceptions about its costs and risks. Numerous international initiatives in recent years have aimed to make MAR technology more widely accessible by demonstrating the long-term positive effects on groundwater resources and other economic, social and environmental benefits (Zheng et al., 2021).

MAR infrastructure has several advantages compared to dams. Among these are lower capital costs, avoidance of evaporation losses, prevention of problems with algae or mosquitoes, and location in proximity to areas with high water demands. A key advantage is that MAR projects are scalable, allowing for staged implementation. They often start as smaller pilot or demonstration projects. While spreading basins sometimes require large amounts of land, MAR generally results in less loss of prime valley floor land than surface reservoirs, and rarely results in any population displacement.

Whereas reservoirs can instantaneously store large volumes of surface water until they fill, the rate of recharge of MAR schemes is constrained by the permeability of porous media. Although evaporation is minimal, other losses may occur in the aquifer. Mixing in a brackish aquifer can result in a much lower volume of water that is recoverable for intended uses. Water from MAR requires a level of treatment appropriate for its uses and risks. Both pretreatment of recharge water and treatment of recovered water are often necessary.

A feature of dams is undisputed entitlement to the stored water under an agreed plan for water sharing, but initially entitlement may be less clear for water stored underground. A common challenge is the need to ensure that the intended benefits of recharge will be realized when needed. This is particularly important when the water is to be stored for long periods of time.

In addition to storage benefits, MAR can provide subsurface treatment benefits (see Section 3 -*Considerations for Considerations for Water Quality Management*), particularly those projects that involve water percolation through the vadose zone. In some areas, MAR has the capability to make use of brackish aquifers that could not be directly used for water supplies.

Various technical and regulatory challenges occur with advancing the use of MAR. MAR projects require careful hydrogeologic characterizations for water quantity and prudent hydrochemical assessment for water quality. Inadequate knowledge of aquifers can be a significant impediment to MAR. Short- and long-term impacts of MAR systems on both native groundwater and surface water should be considered, including:

1. changes in groundwater recharge, flow, and discharge;
2. the water quality effects of the mixing of source water and native groundwater; and
3. chemical interactions with aquifer materials. Monitoring of groundwater levels and quality is commonly an integral part of MAR risk assessment.

A level of certainty is required for investment in MAR projects to occur. The cost of investigations to achieve sufficient confidence depends on the complexity, level of risk and scale of a project. Simpler projects with low risks are easiest to implement, and experience gained will inform future projects. Similarly, where the source water catchment and recharged aquifer for a MAR project are within the same water management jurisdiction, project governance could be expected to be simpler to implement than if multiple jurisdictions are involved. In the latter case, MAR would be easier to develop if the policies and regulations across those jurisdictions are consistent. Effective implementation of MAR typically calls for integrated water resources management, because MAR involves managing the quantity and quality of both surface water and groundwater.

As part of planning for MAR, costs, energy requirements and associated environmental impacts should be evaluated in comparison to alternative supply systems. Often MAR is most economic and also reduces energy demand compared to alternatives (Zheng et al 2021). If MAR is more economic but uses more energy than the alternative water supply, greenhouse gas emissions targets may be achieved by provisioning renewable energy sources from some of the economic savings of MAR with respect to the most economic alternative that also meets emissions targets.

1.6 Essential Requirements for MAR

The five critical elements for a successful MAR project are:

1. a sufficient demand for recovered water;
2. an adequate source of water for recharge;
3. a suitable aquifer in which to store and recover the water;
4. sufficient land to harvest and treat water; and
5. capability to effectively manage a project.

These are the first things to evaluate when contemplating undertaking a MAR project. These ingredients are essential and are either inherent properties of the location or can be developed through alliances and training. These constitute an entry level assessment, which is just the first step in demonstrating the viability and sustainability of a proposed MAR operation as set out in the 2009 guidelines for MAR from Australia's Natural Resource Management Ministerial Council (NRMMC), Environmental Protection and Heritage Council (EPHC), and National Health and Medical Research Council (NHMRC). These guidelines are referred to frequently throughout this book as NRMMC-EPHC-NHMRC, 2009.

Demand

The volumetric demand for recovered water (within an economic scale) or a clearly defined environmental benefit of recharge is essential for MAR. The purposes for which water will be recovered also need to be defined. Generally, this will provide the revenue stream to pay for the water supply cost elements of the project. In urban areas, the demand for stormwater detention to mitigate floods, improve coastal or receiving water quality, and enhance urban amenity and land value may also contribute revenue streams for MAR projects. For reclaimed water projects, the decline in discharge of treated effluent to water bodies may provide a motivation for investment in MAR. Demand may be steady, seasonal, or solely to secure water supplies during occasional droughts. Environmental benefits may include prevention of saline intrusion, sustaining base flow in streams and protecting wetlands and groundwater-dependent ecosystems. Unless one or more of these elements are present, the project is not a MAR project and rather may be a waste disposal or flood mitigation project without the intention and assured motivation to protect groundwater throughout the life of the project

Source

Entitlement to water to be used for recharge needs to be secured. Firstly, there is a lake, dam, stream, water pipeline, desalination plant, water recycling plant, or other aquifer accessible. Secondly, an entitlement to that water can be obtained, either continually or during intermittent periods of excess, such as during floods and high flows. Generally, this will mean that a catchment water sharing plan is in place, whereby it is possible to gain a legal right to take and use water. If no water sharing plan is in place, whatever customary form of government approval for water use should be sought. Mean annual volume of recharge should exceed the mean annual withdrawal of water with a sufficient margin to build up a buffer storage to meet reliability and quality requirements. Alternatively, recharge may be used to reduce net groundwater extraction below any existing entitlement.

Aquifer

A suitable aquifer is critical for MAR. It must be capable of an adequate rate of recharge (hydraulic conductivity), have sufficient storage capacity (thickness, porosity), and normally be capable of retaining the water where it can be recovered (that is, that it does not discharge so quickly to surface water that the recharged water is lost before it can be used). Low salinity and marginally brackish aquifers are preferred so that mixing with fresh recharge water should still allow recovered water to be fit for use. Maps of aquifer suitability for MAR, if available, will assist in determining the likelihood of one or more suitable aquifers being present at the proposed site. Some methods to produce such maps were reviewed by Sallwey et al (2018) and many examples of maps of aquifer suitability for MAR are found at the IGRAC MAR Portal (2021). Note that further detailed evaluation is needed and the Australian MAR Guidelines (NRMMC-EPHC-NHMRC, 2009) give a degree-of-difficulty assessment that indicates the extent of investigations and management needed to assure that successful MAR operation can occur at the site.

Detention Storage

Open space, or dams, wetlands, ponds or basins are required to detain sufficient water without causing flood damage to enable the target volume of recharge to be achieved. Similarly, space needs to be available for whatever treatment process, if any, is subsequently determined to be required. In established urban areas, space for capture can be a major impediment to stormwater harvesting and ASR (aquifer storage and recovery) wells are commonly used to avoid land requirements of infiltration systems. For recycled water from a sewage treatment plant, generally no additional detention storage will be required at the recharge facility, because the plant will have buffering storage to manage variability of inflows.

Management Capability

Hydrogeological and geotechnical knowledge, knowledge of water storage and treatment design, water quality management, water sensitive urban design, hydrology and modeling, monitoring and reporting are all required to meet governance requirements. Such expertise will be required for the next stage of investigations. A growing number of consultants, water utilities and water resources managers have experience in investigations and design of MAR projects, and training courses (e.g., at ISMAR symposia) are available to enable hydrogeologists and water engineers to gain the necessary knowledge.

1.7 Stakeholder Involvement

Active stakeholder engagement and public education can be critical to the success of a proposed MAR project. This is particularly important for recharge of reclaimed water. Stakeholder involvement can be crucial to identify local priorities and shape the project to local conditions.

A number of aspects promote effective stakeholder involvement. The first is an early start in terms of informing stakeholders about the need for a MAR project. Local stakeholders are often not fully aware of groundwater conditions and management challenges. Many agencies therefore identify and meet with individual stakeholders and stakeholder groups before public meetings. These meetings can be the start of building important long-term relationships and trust. Such relationships help alert agencies to concerns or challenges as they arise.

Managers should lay out the case for groundwater management and MAR in terms that are directly relevant to groundwater users. Demonstrating economic benefit of MAR by comparing costs with the best alternative option is desirable. Managers can also build support and trust by involving stakeholders in ongoing monitoring and providing regular and consistent access to data and information.

In addition to key stakeholders, the general public should be informed about the importance and vulnerability of groundwater systems, and MAR as a cost-effective management solution. A public that is knowledgeable of groundwater conditions, management challenges, and alternative solutions is more likely to support MAR. Agencies have developed effective public education campaigns focused on the public at large, including students from kindergarten to senior high school age.

1.8 Opportunities to Exercise Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 1 through 3. Links are provided to each exercise below.

Exercise 1↴

Exercise 2↴

Exercise 3↴

2 Considerations for Water Resources Planning and Management

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2.1 Introduction

For managed aquifer recharge (MAR) to fulfil its potential contribution to effective water resources management and to avoid problems through injudicious applications, water planning and policy must consider the potential benefits and problems related to MAR (Table 2).

Table 2 - The value of good planning and policy is to set a framework that encourages highly beneficial MAR projects and prevents adverse impacts.

Potential benefits of well-planned MAR	Potential problems of poorly planned MAR
• More secure water supplies, especially during drought • Increased efficiency of water management to expand water supplies • Improved quality of water supplies using natural treatment processes • Enhancement or protection of groundwater quality • Protection and enhancement of groundwater-dependent ecosystems • High acceptance by water users and public	• Reduced security of downstream water supplies • Inadequate water for recharge and reduced water supplies downstream • Inadequate capacity for aquifer storage and retention • Adverse changes in groundwater quality impacting pre-existing and potential future groundwater uses • Degradation of groundwater-dependent communities and ecosystems • Clogging leading to inefficient systems and wasted resources • Low acceptance by water users and public

Historically, water resources management authorities have needed to see that MAR is viable in their jurisdiction before they invest resources and effort into planning for and regulating MAR. This normally involves establishing demonstration projects to determine that MAR is physically and economically feasible and that the claimed benefits can be achieved. Once this is done in any catchment or basin, the next step is the development of policy instruments, regulations and incentives to assist in promoting, coordinating and integrating appropriate expansion of MAR in the mix of water management interventions. Policies will need to provide for and articulate the rights of access to source water, rights to recharge, and rights to recover water from aquifers. Regulations should require that MAR operations comply with water quality objectives. Incentives and institutional arrangements that support such governance frameworks would assist in converging the goals of water users and water managers. This is expanded later in Section 2.7 - *Institutional Arrangements and Incentives for MAR* Institutional Arrangements and Incentives for MAR.

Surface reservoirs and MAR slow the movement of water through catchments and basins, giving greater resilience to water supplies. When surface water storage and aquifer storage are accessible and interchangeable, operating these conjunctively maximizes the potential for a resilient water supply. Planning such storages, including the means to bank surface water in aquifers, needs to be carefully done at the catchment and groundwater basin scale, to ensure the benefits are shared widely and that no water users or the environment are disadvantaged by such systems.

Numerous examples of effective policy and regulatory instruments are in use by water resources managers and health and environmental protection authorities in various jurisdictions to ensure that MAR contributes to sustainable benefits and avoids detriment. This section is intended to create awareness of these governance arrangements and assist in the design, adaptation and implementation of instruments where they are currently lacking. Policy architectures are proposed for both developing and developed countries, along with transitioning pathways.

2.2 A MAR Policy Matrix

There are two primary areas of responsibility for water management that in most jurisdictions are managed by different entities in government agencies: water entitlements together with seasonal allocations (in water resources departments) and water quality (in health and environmental protection departments). In some jurisdictions, many government departments may need to be involved (e.g., planning, land use, agriculture, water supply, and pollution control) and functions also shared with different levels of government. However, functional responsibilities can generally be aggregated under one or both categories (quantity and quality). These become entwined because both aspects need to be jointly managed for effective MAR (Table 3), which necessitates collaborative and integrated responses from the various government departments (as concluded by Braune and Israel, 2021). Pioneering MAR projects in any jurisdiction are used by water resources planners and regulators to establish an effective collaborative process and to streamline approvals and incentives in a manner that addresses the requirements of all relevant agencies.

Table 3 - Integrated natural resource management, human health, and environment issues to be addressed for effective governance of MAR (adapted from Dillon et al., 2009).

	Quantity	**Quality**
	Water source and storage entitlements and allocation	Human health and environmental protection
Surface water	• Catchment water allocation plans and surface water entitlements • Environmental flow requirements (including urban stormwater and sewage effluent) • Inter-jurisdictional agreements	• Catchment pollution control plan • Risk management plan for water quality assurance • Aquatic life protection • Invasive species mitigation plans
	Account for surface water - groundwater interaction	Account for surface water - groundwater interaction
Ground water	• Groundwater basin/ aquifer water allocation plan and groundwater entitlements • Resource assessment accounting for groundwater dependent ecosystems • Demand (consumptive use) management • Define and manage recharge entitlements for MAR operations • Define and manage recovery entitlements from MAR operations • Inter-jurisdictional agreements	• Groundwater quality protection plan for recharged aquifer • Water quality requirements for all intended uses of groundwater • Risk management plan for water quality assurance • Review monitoring and reporting of MAR operations for compliance

2.3 Water Resources Planning and Management

A fundamental element of effective water resources management is a plan that accounts for the sustainability of surface water and groundwater. However, the majority of exploited groundwater systems in the world are in sustained storage decline, and in many shallow aquifers water quality is also in decline. This suggests that no plan exists, or that the existing plan does not ensure a sustainable system, or that adherence is lacking. In such places, the benefits of implementing MAR would likely be severely constrained and unsustainable without a plan that includes groundwater demand management. An important role for MAR is for it to be used as an inducement for catchment and basin communities to accept the discipline of demand management (Dillon et al., 2012). In this way the benefits of MAR can be ensured and the level of reduction in demand can be minimized to achieve a sustainable resource. In the absence of a surface water management plan, there is no assurance of a reliable future source of water for recharge.

Around the world, the starting point for many water resources managers is an absence of water resources management plans, so we start this discussion on MAR implementation from that condition. Transitional strategies towards water management plans are then described, before revealing the planning instruments used to regulate and incentivize MAR for effective water resources management that reaps the benefits of MAR and avoids problems.

2.4 MAR in the Absence of Catchment and Basin Water Allocation Plans

In the absence of a water management plan, particularly where water rights are informal and monitoring is weak, there may be no requirement to gain a legal entitlement to water for recharge, nor for recharge or recovery. In catchments where demand for water is small in relation to water availability, MAR may still be needed to improve the quality of drinking water supplies (such as in bank filtration in temperate climates) or increase water security during drought (such as long-term storage of water in aquifers in semi-arid areas, called "*water banking*"). Simple rules for the latter, such as recovering no more than has been recharged (with perhaps a small percentage for the aquifer to cover any losses), may be sufficient to ensure that the MAR activity had no adverse impact on the quantity of water available for other water users.

However, where water rights are poorly defined or lacking, planning and enforcement is weak and demand for water is high compared to the availability of either surface water, groundwater or both, then establishing a MAR operation could have mixed results, including adverse impacts on downstream water users. There would also be no protection from other users upstream taking more water and rendering a MAR system ineffective through lack of water to recharge. In such circumstances, the motivation for investment in MAR is diminished due to no assurance that the objectives of the MAR system can be met. Under such a laissez-faire approach to governance, upstream water users would have the best access to water and lower risks. While investment in MAR may be useful for those upstream, the potential for detrimental impacts downstream could be significant and undermine the value of such investment and potentially lead to stranded downstream MAR and other water assets.

In both scenarios, a governmental entity has a central role to play. Greater value would be found in government investment in the development of catchment and basin water sharing plans that also accounted for MAR. Examples of early-stage demand management could include restricting the area irrigated by each land holder to an amount that allows all to subsist. In places where communities cooperate for mutual benefit and impose their own sanctions against profligate water use, a government role can be to reinforce the existing cultural practices. It can support these by training farmers in efficient water use practices, providing water measurement and data sharing platforms that can contribute to community decision making, and encouraging construction and maintenance of MAR facilities. This has been shown to be effective in up-catchment villages in fractured rock aquifers of a monsoonal area in north west India (e.g., Maheshwari et al., 2014), in villages in alluvial coastal aquifers in northern Luzon in the Philippines (Dillon et al., 2009), and in groundwater user collectives for irrigation in Castilla y León, Spain (Dillon et al., 2012). These cases are characterized by farmers having mutual concerns based on strong family ties and or religious beliefs that lead to seeking outcomes for mutual good, where water is one of the resources they are accustomed to sharing. MAR is seen as one way of elevating the total village production.

Where water needs to be managed on a larger scale to account for inter-dependencies among people who are unknown to each other, and may even be competitors in produce markets, then government has a larger role. There is a need to assist with monitoring the state of the resource and disseminating this information to help establish an understanding of the limits of the resource and the impacts of current use on sustainability. This leads to consulting on the various means by which the collective use of the resource can be maximized while meeting accepted principles of fairness, equity and sustainability.

Any enforcement measures need to be fair and measurable, include elected community representatives and specify clear mechanisms for dispute resolution and reparation. Similarly, early-stage supply-side management would require equitable sharing in use of the detention volume of dams and recharge structures across the entire catchment. Limiting the number of recharge structures built in each sub-catchment until all sub-catchments have a structure could help give fairer access to water. This would also allow monitoring of water flows and storages to inform further revisions of catchment and basin water sharing plans, and for those plans to be based on evidence of the availability and variability of the resource and the hydraulic impacts of recharge structures.

2.5 Transition Strategies to an Entitlement System

Fundamental elements of good water management include taking measurements to enable reliable evaluation of the state of the water resource, establishing regulations to control construction in streams and construction of boreholes, issuing permits for existing and new structures and subsequently monitoring resource use. In the absence of existing MAR projects and policy instruments, approving a limited number of MAR demonstration projects would assist the local assessment of their effectiveness and impacts and determine the extent to which MAR could contribute to a water management plan. Community engagement and formation of stakeholder consultation processes, such as through existing elected local government or culturally accepted representation, are necessary to define how water sharing arrangements will be instigated and operated and how consumptive pool entitlements will be unambiguously defined to account for existing use, sustainable use, and MAR (Ward and Dillon, 2011). Figure 5 illustrates a transitional pathway to progress from each jurisdiction's current position towards sustainable, transparent, and accepted governance arrangements. This is an ongoing process informed by the growing availability of data and the improved understanding of the water resources, including issues that arise upstream or downstream and all the nuances associated with establishing fully specified and tradeable entitlements.

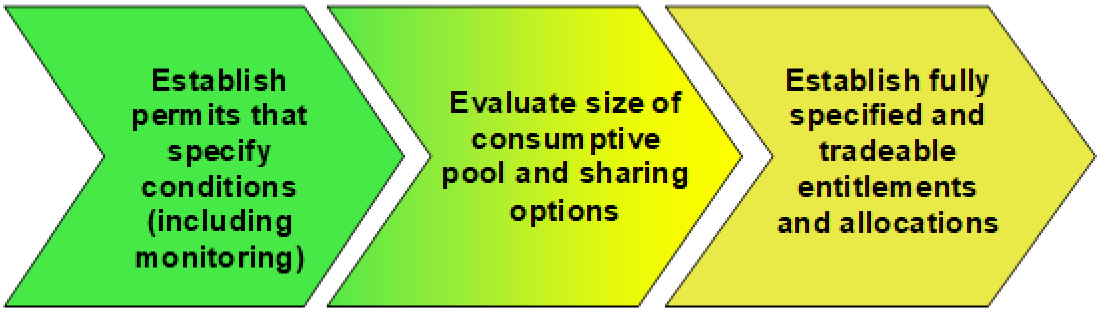

Figure 5 - An example of a pathway for policy implementation from regulation to entitlements that then provides a reliable basis on which to plan the expansion of MAR (from Ward and Dillon 2011).

2.6 MAR Within Catchment and Basin Water Allocation Plans

In an advanced system of management, generally with significant utilization of the available resource, a water resources plan usually identifies:

1. those users who are entitled to a share of the resource;
2. the process by which entitlements are assigned and may be traded;
3. the share of the water resource to which each accredited water user has an entitlement;
4. the method by which periodic volumetric allocations will be assessed, for the catchment or basin as a whole, or for sub-catchments or aquifers;
5. the timing and means by which volumetric share of the resource will be announced;
6. the means of water measurement, accounting, auditing and reporting and legal responsibilities of users and of agencies;
7. the means by which water allocations and entitlements may be traded, by whom and with whom, and under what constraints, including the status of utilization of the available resource; and
8. the requirement for consultation with users over the operation of the plan and for any revisions to the plan at mandated intervals.

Entitlements relate to an individual's right to a defined share of the water resource. A *water entitlement* is a right for a water user to benefit from an agreed share of a defined water resource for a specified period of time. The share is generally defined at one point in time in relation to a sharing arrangement set by the water resources manager following consultation with water users, including, where relevant, the representative for environmental water. The rules, distribution, and administration of entitlements are generally vested with either the state or a community of water users (Ostrom, 1990; Ward and Dillon, 2012; Maheshwari et al., 2014).

Entitlements prescribe the water user's right to access, to withdraw, to exclude, to manage, and to alienate. *Access* represents the right to physically enter the resource space; *withdrawal* represents the right to harvest the benefits of recharge water, aquifer storage space, or recovery of recharge; *exclude* represents the right to determine who will have access; *manage* represents the right to regulate use patterns and arrangements; and *alienate* represents the right to lease, sell or transfer the set of rights (Schlager and Ostrom, 1992). An attribute of entitlements may include a specified level of security, for example a high or low level of security.

Entitlements relate to an enduring share of the resource held by an individual as a fraction of the total number of shares, whereas *allocations* relate to the time-varying volume of water represented by that entitlement in any given year or season. Allocations are ideally managed through a separate process from entitlements and determined each year or season, to account for the temporal variability in the volume of the water resource available to entitlement holders. The process for setting allocations is based on measurements of the volume of water in storage and flows on specified dates. Hence in a dry year, allocations are reduced in equal proportion for all entitlement holders at the same level of security.

To further differentiate entitlements and allocations, consider that if the volume of water available for allocation declines, say due to aquifer depletion or due to low flows in a river during drought, then each user retains their same percentage share (entitlement) but of a reduced allocatable volume. For example, if the annual volume of water for allocation declines to 60 percent of the volume on which entitlements are based, all users would receive an allocation of 60 percent of the volume of their specified entitlement. This is a way of equitably and transparently sharing water in a time of water stress and avoiding disputes. When establishing a MAR project under such a water plan, the operator would need the following from the water resources management authority:

1. an entitlement or an allocation to take water from a surface water source (including stormwater or recycled water) to recharge an aquifer – which may occur by using an existing entitlement or periodic allocation, or purchasing such a right by trade with an accredited user or from the owner of the recycled water;
2. an entitlement to recharge water to an aquifer – such as specifying volumes, or an acceptable range of heads at specified wells at which recharge would stop, to ensure adverse impacts did not occur to the aquifer or other groundwater users and property owners; and
3. an entitlement to recover water from an aquifer – such as specifying volumes in relation to volume of recharge, or the acceptable range of heads at specified wells at which recovery would stop, to ensure adverse impacts did not occur to the aquifer or other groundwater users.

Further considerations in relation to water quality and any risks to human health and the environment would also need to be made (as indicated in Table 3). Generally this is undertaken as the next stage in project development, as discussed in Section 3 - *Considerations forConsiderations for Water* Quality Management.

In many systems where streams are hydraulically connected to groundwater (e.g., where groundwater pumping causes streamflow depletion), catchment and basin water allocation plans need to be integrated to avoid over-allocation of the available groundwater and surface water. More on conjunctive management of surface water and groundwater can be found in Evans and Dillon (2019) with implications for MAR in Ward and Dillon (2012), such as accounting for loss of stored water to streams (unintentionally or intentionally).

When considering MAR projects, the sovereignty of Indigenous (First Nations) people, along with the status of Indigenous' entitlements or rights to water, must be acknowledged and respected. The governmental entity responsible for establishing MAR regulations and implementation for non-Indigenous communities, in many cases, may have no jurisdictional authority related to Indigenous people. Identifying opportunities for collaboration on MAR efforts can benefit both Indigenous and non-Indigenous communities. An example of a voluntary agreement to adhere to state regulations is the Gila River Indian Community's MAR program in the State of Arizona, USA, where the agreement has led to water management, cultural, and financial benefits to the Gila River Indian Community and water management benefits to non-tribal entities (Bernat et al., 2020). Another Arizona example is the Arizona Water Banking Authority's use of MAR to meet state requirements for reliability of water supplies and assist in settling water rights claims (Megdal et al., 2014).

The water needs of nature (environmental allocations) are often underestimated or unaccounted for in water management plans. In over-allocated river and groundwater systems, MAR generally comes late in water development, but not too late to play a constructive role. MAR projects can be designed to incorporate environmental considerations, including directing a portion of high security water entitlements earned though MAR to benefit the environment.

Standard instruments may be used for entitlement and allocation processes of each MAR system for each of the three basic components: rights to access a volume of surface water for recharge, rights to recharge the aquifer with a volume of water, and rights to recover a volume of water that is related under the plan to the volume recharged (Table 4). Obligations and conditions of use are applied to ensure third parties using the source water, aquifer or recovered water are not adversely impacted by MAR operations. Consider this example: if an ASR (aquifer storage and recovery) operation in a confined aquifer, causes a neighbor's water supply well, that was previously not artesian, to overflow, the MAR operator is responsible for resolving this problem in agreement with the neighbor.

Table 4 - Natural resources management governance instruments for MAR based on the robust separation of rights (from Ward and Dillon 2011).

MAR governance instrument	Source water harvesting	Recharge	Recovery	End-use
Entitlement (tradeable)	Unit share in the consumptive pool of surface water (or recycled water) (i.e., available water in excess of environmental flows)	Unit share of aquifer's finite additional storage capacity	Extraction or recovery share (function of managed aquifer recharge volume)	N/A
Periodic allocation (tradeable)	Periodic allocation (usually annual or seasonal) rules; potential for additional storm water or recycled water with high flows or development offsets	Annual right to raise the piezometric surface (subject to ambient storage and abstraction)	Extraction volume contingent on ambient conditions, natural recharge, and spatial constraints	N/A
Obligations and conditions of use	Third party rights of access to infrastructure for surface water, urban stormwater and suitably treated recycled water	Requirement not to interfere with entitlements of other water users including MAR operators	Requirement not to interfere with entitlements of other water users including MAR operators	Water-use license subject to regional obligations and conditions, for use and disposal

Source Water Entitlements, Allocations and Obligations

Source water entitlements, allocations, and obligations can occur in numerous forms. When developing a MAR operation, determining the statutory limits of the source water is critical. In some regions, this can be constrained by inter-jurisdictional agreements, or prior appropriations that have become entrenched; in other regions, entitlements and allocations could be flexible depending on existing sharing arrangements and how much source water is available. An example of the allocations of surface water from a catchment to environmental flows, basic human needs, and consumptive uses is shown for a wet year and a dry year in Figure 6. In the dry year, the consumptive use pool reduces the volume available for irrigation and basic human needs, but each user retains their independently-determined entitled proportional share of the consumptive use pool. For simplicity, environmental allocations are shown as a constant proportion of flow in Figure . However, schemes normally would account for variable ecosystem needs, and the allocation for basic human needs, such as drinking water, is prioritized so that the allocations in the consumptive use pool are only adjusted for economic development uses, such as irrigation.

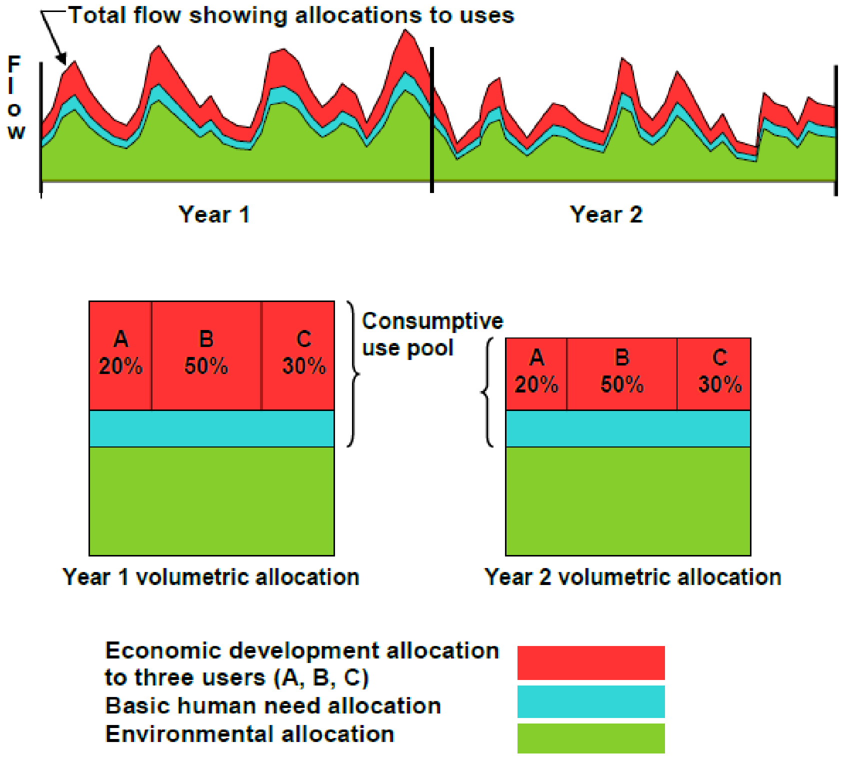

Figure 6 - Example of distribution of allocations for environmental flow, basic human needs and consumptive uses by three users (that may include MAR operators) in a wet year (year 1) then a dry year (year 2) (from Ward and Dillon 2011). In year 2 the consumptive use pool is reduced so volumetric allocations to all users are reduced accordingly. Their entitlement, which is their percentage share of the consumptive use pool, remains unchanged.

Urban Source Waters

A growth area for MAR is in harnessing urban stormwater and recycled water to substitute for urban non-potable or potable water supplies. If some of this water already contributes incidental recharge to the aquifer the actual benefit of MAR is the net increase in recharge as well as ensuring the quality of recharge water for groundwater quality protection. Few urban stormwater catchments are subject to a regime of entitlements, allocations and end-use obligations described by a water plan. This presents problems for traditional approaches and opportunities for innovation in MAR governance. The high imperviousness of urban landscapes substantially increases runoff coefficients. Hence, considerable harvesting could occur without impinging on natural environmental flows. However, a potential issue in some areas is that large-scale harvesting of urban stormwater may be considered as capturing water that would otherwise go to a downstream user who has a "senior" right to that water. Runoff in urban catchments is usually intermittent with short duration. Consequently, environmental flows, the consumptive pool, and flow-sharing arrangements are more problematic than in systems where flows have a stronger base flow component and are more predictable, such as in rural catchments. Urban stormwater is typically managed by a local government entity, in which case awareness of MAR opportunities would facilitate uptake.

Governance innovations could include the local government (the stormwater infrastructure owner) issuing volumetric licenses to each stormwater MAR harvesting operation within the same catchment. To increase cost effectiveness through economies of scale and ensure operator cooperation, license holders could rely on a single licensed harvesting operator, either public or private, subject to competitive tendering for the operating license for a fixed period of time. By default, in the absence of a sharing plan, MAR located upstream has priority access to stormwater over downstream locations. However, such adhocracy removes the incentive to invest in MAR due to lack of certainty of access to water for recharge to accumulate redeemable water credits.

In the future, entitlements to a volumetric share may rely on emerging technology for real-time automated control of diversions, based on forecast rainfall and runoff prediction models and more comprehensive water quality monitoring and control systems. As cities invest in water-sensitive urban design, increased stormwater detention and subsequent entitlements for harvesting enable subsurface storage to become increasingly feasible.

A system can be conceived whereby landholders within the urban catchment are awarded stormwater entitlements - for example related to their impervious area - together with accompanying obligations to manage stormwater on-site or alternatively to contribute to local government costs to manage off-site. This would be a means of funding appropriate investment in MAR and other stormwater harvesting and water supply infrastructure to meet urban water planning objectives, so long as nuisance to others is prevented and water quality is demonstrably managed.

Sewage is a highly reliable water resource and following appropriate treatment can be recycled for irrigation or drinking water supplies with aquifers used to buffer imbalances between supply and demand. As one caveat, conservation during droughts may decrease the amount of treated effluent available. It is suggested that the appropriately credentialed organization responsible for sewage collection and treatment be responsible for setting entitlements to treated water for MAR by itself or by contracted MAR operators, in order to meet all of its obligations, including those for the discharge of treated sewage effluent and all associated health and environmental regulations. The requirements of MAR operators to manage health and environmental risks are discussed in Section 3 - *Considerations for Considerations for Water* Quality Management.

Recharge Entitlements, Allocations, and Obligations

Just as excessive drawdown can be a problem in aquifers, so too can excessive recharge where recharge is enhanced by MAR systems. In general, MAR recharge entitlements will not be an issue in over-exploited aquifers, as adequate aquifer storage capacity is available for multiple MAR operations, and MAR would help to restore hydrological equilibrium. However, localized exceptions exist, such as where clay units hinder infiltration or divert the water back to a surface water body.

In aquifers in existing long-term balance or with piezometric levels that are trending upwards over a number of years, recharge capacity is finite and depends on changes in groundwater extraction. In unconfined aquifers, excessive recharge could cause the water table to rise, potentially causing waterlogging, soil salinization, flooding of basements, differential expansion of clays, damage to building structures, or unintended discharge of groundwater.

In confined aquifers, excessive recharge via wells can cause other wells to become artesian, and in exceptional cases with deep wells under high pressure in some formations, can potentially trigger earthquakes. These risks need to be assessed, such as by following the Australian MAR guidelines (NRMMC-EPHC-NHMRC 2009), which had been applied in six countries by 2010 (Dillon et al., 2010a). Cumulative impacts of multiple recharge operations need to be considered to allocate sustainable recharge capacity among MAR operators in an equitable and transparent way. In brackish aquifers this should account for the hydraulic interference between recharge wells that displaces the centroid of injected freshwater away from each recharge well potentially lowering the proportion of injected volume that could be recovered at acceptable salinity from both wells. In such circumstances having a single recharge operator to manage all recharge operations in an area would internalize such conflicts and avoid litigation. Buffer exclusion zones could be specified around existing MAR operations as a first step to mitigate adverse interference from new MAR operations. Recharge entitlements could be transferable as MAR operations mature and the remaining recharge capacity of an aquifer diminishes.

Recovery Entitlements, Allocations, and Obligations

Recovery entitlements and allocations typically account for the following factors:

- the proportion of recharged volume that may be recovered;
- an annual depletion rate for recoverable accumulated storage;
- recovery efficiency in brackish aquifers;
- the time period over which recharge credits may be recovered;
- the maximum annual recovery; and
- the transfer of entitlements and allocations to recover water to other groundwater users.

An accounting system is required to ensure recovery entitlements are recorded transparently, unambiguously, and consistently, and account for the above factors in a way that is appropriate for the specific situation. A generalized form for recording these entitlements is expressed by Equation 1. This can be applied to MAR projects ranging from those mainly aimed at intra-year storage to water banking projects aimed at securing drought and emergency supplies. The accrued storage credit, S_i at the end of year i, since the start of recharge at the MAR project, is based on measurements:

$$S_i = \alpha\, I_i - R_i + \beta\, S_{i-1} \tag{1}$$

where:

S_i and S_{i-1}	=	accrued storage credit at the end of years i, and $i-1$, respectively
I_i	=	measured MAR recharge volume that occurs in year i, contributing to storage credit
R_i	=	measured MAR recovered volume that occurs in year i against the storage credit
α	=	maximum cumulative proportion of the recharge for which a recovery entitlement may be issued (relating primarily to exogenous impacts on the aquifer)
β	=	annual rate of retention of accrued storage credit (relating primarily to natural capability of aquifers to retain water and the uncertainty with which this is known)

Distinct reasons for the use of α and β and an explanation of why and how their values differ under different conditions are given below.

Maximum Proportion of Recharge Volume that May Be Recovered (α)

Disregarding for a moment issues relating to hydraulic residence time in aquifers, for aquifers in hydrologic equilibrium (that is, no net long-term storage decline) there is no need to prevent the recharging entity from recovering the full volume they recharge. That is, $\alpha = 1$ so long as no other groundwater user or ecosystem is adversely impacted by the rate of injection or recovery (the latter is addressed later). In aquifers with a long-term storage decline, α would normally be set less than one, so a residual contribution to the recovery of the depleted aquifer would benefit all groundwater users and groundwater-dependent ecosystems. Such declines are due to exogenous impacts on the aquifer such as over-exploitation in concert with climate change. The entity recharging the aquifer makes use of the aquifer storage capacity which is regarded as a common-pool resource, so the residual contribution $(1-\alpha)$ could also be seen as a resource rent for the use of this storage.

The allowable proportion recovered, α, should be determined through monitoring and consultation and recorded in the aquifer's groundwater management plan. In 2010, five workshops conducted in Australia for water resources managers of different states and territories converged on a value of $\alpha = 0.9$ for aquifers under stress (Dillon et al., 2010b). This was considered to be large enough so as not to materially reduce incentives for investing in MAR, while still providing a demonstrable contribution towards the sustainability of the groundwater system. However α should be determined locally, based on the local situation and the reliability with which it is known.

It is important to understand that the value of measured recharge, I_i, used in Equation 1 is the actual recharge volume. With infiltration basins, the volume measured is the water diverted into the basin. Typically, 2 to 8 percent of the volume entering an infiltration basin may be lost through evaporation and not reach the aquifer as recharge. Hence, the *loss fraction*, ε ($\varepsilon \sim 0.02$ to 0.08) must be deducted from the measured inflow to derive the volume of recharge (so in this case with $\alpha = 0.9$, the recharge credit would be 0.88 to 0.82 of basin inflow). For injection wells, up to ~ 4 percent of source water may typically be lost in treatment processes and as purge water to manage well clogging ($\varepsilon \sim 0.00$ to 0.04). The regulator is expected to specify the most likely value of ε for each recharge operation, and this value could be revised if the operator provides adequate evidence from monitoring.

A Retention Rate for Accumulated Storage (β)

It is important that accrued recovery credits are actually available to be recovered, otherwise the legitimate groundwater entitlements cannot be realized and would become worthless and undermine the credibility of groundwater management and entitlement markets. This is particularly important for ensuring that water banking operations produce the drought supplies for which they were established.

Putting aside, for a moment, issues relating to aquifer hydraulic equilibrium, aquifers experience recharge and discharge, and each aquifer has a natural capability to retain water, that is affected by its scale, slope, storage and transmissivity characteristics, inter-connections with other aquifers, perimeter topography and distance to, or absence of, hydraulically connected streams or points of groundwater discharge. Zones within an aquifer can have different hydraulic residence times (Modica et al., 1998) depending on these factors. Methods to allow determination of residence times are well established (Cook, 2020).

The hydraulic retention time, T_R, is a broad-brush term defined by the initial storage in the aquifer divided by the annual rate of natural recharge. Hence, each year some proportion, β, of water from a MAR scheme that has accrued as storage in the aquifer, can be thought of as retained in the aquifer and accessible for recovery. With each passing year, and in the absence of further recharge or recovery, Equation 1 would simplify to Equation 2, which represents an exponential decline (or depreciation in economic terms) in recoverable storage, i.e.,

$$S_{i+n} = \beta^n S_i \tag{2}$$

where:

S_{i+n} and S_i = the accrued storage credit at the end of years $i + n$ and i respectively

One postulation for setting an annual retention rate for accrued recovery entitlements is to relate it to the local hydraulic retention time T_R (in years) by assuming that 10 percent of the initial storage remains after T_R years as in Equation 3:

$$\beta = 10^{-1/T_R} \tag{3}$$

where:

T_R = Local hydraulic retention time (in years)

Hence, for a T_R of 30, 50, or 100 years, β would be 0.926, 0.955, or 0.977, respectively; after the T_R has elapsed, the residual recovery credit in each case is 10 percent of its initial value.

A MAR scheme will also increase local hydraulic gradients (Hantush, 1967; Bouwer, 1978) and potentially increase the rate of groundwater flow in the aquifer to discharge zones or beyond accessible recovery. The volume of natural recharge will generally dominate over the volume of MAR (with the possible exception of arid zone relic aquifers), so the reduction in natural hydraulic retention time would be small, particularly in extensive aquifers. However, if discharge zones are in close proximity to MAR sites, such as shown in Figure , β may decline noticeably. This decline can be taken into account, for example through flow and solute transport modeling, and validated by techniques described by Cook (2020) and references therein. Such MAR operations may have the primary objective of maintaining baseflow in streams, so the delayed discharge is more important than preserving entitlements to recover.

A value of $\beta < 1$ is suggested, with allowance made for uncertainty in hydraulic retention time, to ensure that the depreciated recovery credit is indeed capable of being recovered without adverse impacts on other groundwater users or ecosystems. During drought periods when the accrued storage credit is almost depleted, more frequent monitoring of groundwater levels and recovered water quality is warranted to assess whether the calculated residual credit is recoverable.

Regulators may have valid alternative approaches for large aquifers with deep water tables, long hydraulic retention times, and a long history of recharge and use. These may involve setting $\beta = 1$. In such cases it would be wise to also have a policy in place to extinguish recharge credits earned ~30 or so years before to accommodate changes to aquifer behavior, such as streams that were previously hydraulically disconnected becoming hydraulically connected and hence retention time being abruptly reduced.

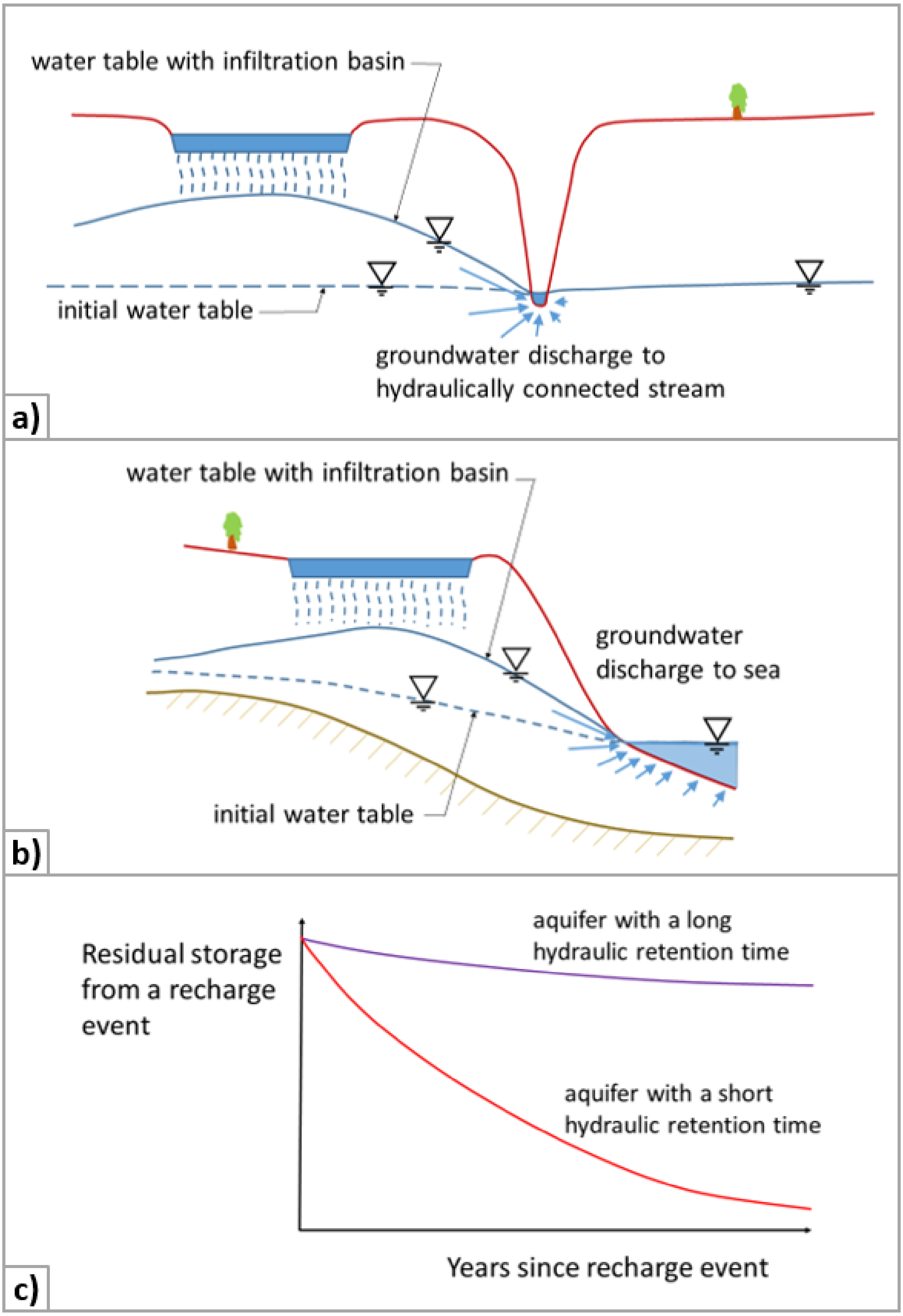

Figure 7 - a) An aquifer that discharges to a hydraulically connected stream and b) a steep coastal aquifer are examples of systems where the hydraulic retention time of water recharged by MAR is limited. Hence, as shown in c), in these cases water cannot be stored for many years before use because it will have discharged from the aquifer beforehand (extended from Ward and Dillon, 2011).

Recovery Efficiency in Brackish Aquifers (γ)

In an increasing number of innovative cases, an aquifer initially containing brackish groundwater is used as a MAR storage zone, with recovered water meeting the water quality requirements of its intended use (e.g., Ros and Zuurbier, 2017; and case studies in Zheng et al., 2021). The term, *recovery efficiency*, γ, defines the proportion of the volume of recharge at which the recovered water reaches the acceptable salinity threshold for its intended use. The mixing processes that occur within the aquifer that influence γ have been analyzed by Ward et al., (2009).

Recovery would cease when water reaches this salinity threshold (at γ) or the percentage of recharge constraint, α, whichever occurs first. Where stormwater is recharged to a brackish limestone aquifer in South Australia, as reported by Clark et al., (2015), the recovered water typically reaches the salinity threshold for irrigation when about 80 percent of the volume recharged in the preceding winter has been recovered (i.e., $\gamma < \alpha$). This amounted to an annual retention rate of stored freshwater of 0.844 for a particular ASR operation over an 11-year period. In Israel, the recovery efficiency was considerably lower in karstic aquifers (Harpaz, 1971). Pyne (2005) found that creating a fresh water "*target storage zone*" around an ASR well before routine recovery, could increase recovery to 100 percent of the recharge that had occurred in the preceding year.

These experiences, together with analysis by Ward et al., (2009) show that the way a site is operated determines γ. Responsibility for managing this salinity constraint should rest with the MAR operator, as they are the most affected by this and they have the means to manage it. Other groundwater users should be adequately protected by the application of α as the maximum cumulative proportion of the recharge that may be recovered and specifications of maximum rates of recharge and recovery. The regulator may instead require the operator to monitor the electrical conductivity of the recovered water and shut down recovery when it reaches an unacceptable level. In this way, the operator carries the risk of when that shutdown would occur, and can take steps, such as setting up and monitoring a buffer storage zone, to avoid this problem.

Salinity is used as a constraint here, as this is a natural geogenic conservative contaminant. Adoption of this approach is not recommended for anthropogenic or non-conservative contaminants (e.g., nitrate, arsenic), which instead should be addressed through the water quality management methods described in Section 3 -*Considerations for Considerations for Water Quality Management*.

Time Period Over Which Recharge Credits May Be Recovered (T_{max})

Allowing recharge credits to persist beyond the *aquifer hydraulic residence time*, T_R, would be illogical because on average the water would no longer be retained in the aquifer. In general, recharge credits should be as enduring as possible to encourage water banking and building up of groundwater storage to buffer against droughts. However, even in aquifers with very long residence times, there is a good reason to constrain the period, T_{max}, over which recovery credits can be redeemed.

The water resources management authority needs flexibility to deal with unforeseen changes to climate, land use, water use requirements, scale of MAR, and technology. A sunset clause on rights generated, gives a margin for uncertainty about the aquifer's response to future climate, water use and residence time changes. Granting rights in perpetuity would create a burden for future managers, and is not required by MAR operators who need only have a tenure on entitlements for the economic life of a project, say about 30 years, in order for a project to proceed. Ongoing recharge will keep moving forward the time window for recovery.

A sunset clause as a condition of issue, is the fairest possible way of making any future changes across all MAR operations, should this become necessary. Any recovery entitlements so extinguished should be re-assigned to the agency responsible for sustaining the aquifer (nominally the state as the sovereign right entity) and not transferred to a new, entitlement holder for additional recovery. This would apply unless the aquifer has transitioned from being in long-term storage decline to achieving a status of hydraulic equilibrium. The groundwater management plan would need a transparent and agreed-upon procedure to make the determination of hydraulic equilibrium. In the latter case, MAR operators would benefit from an increase in the maximum proportion of their recharge credits (α) from that date.

Administrative convenience for water accounting systems would also be helped by a sunset clause on recovery entitlements, so that recharge and recovery records need not be retained longer than say 30 years, or as determined within the local groundwater management plan.

Maximum Recovery in Any Year (R_{max})

In some situations, it may be necessary to restrict recovery in any year to a defined limit, R_{max}, that is less than the allocation specification derived from Equation 1. This is to avoid excessive recovery rates causing adverse impacts on groundwater yield or salinity of the wells of nearby groundwater users, or to retain a buffer against multi-year drought. While this may be addressed by invoking the "obligations and conditions of use" (see Table 4), the onus of proof of impacts in multi-user aquifer systems is difficult and subject to dispute.

The recoverable volume in any year is any amount up to the storage credit (assuming the recharge season occurs before recovery). Rearranging Equation 1, and noting that there is no diminution of antecedent storage credit until the end of the year in which recharge and recovery may take place (Equation 4):

$$R_i \leq min\, [(S_{i-1} + \alpha\, I_i) , R_{max}] \tag{4}$$

A simple rule of thumb, to restrict annual recovery to the peak annual recharge (Equation 5), may be useful for specifying R_{max} in the absence of other information. This is particularly appropriate for ASR systems where upconing in the aquifer during injection and drawdown during recovery have spatial symmetry. This approach may also give incentive for operators to maximize their recharge operations to relax this recovery constraint.

$$R_{max} = \max\ [I_{1,}I_{2,}I_{3,} \dots \dots I_i\ ] \tag{5}$$

In some circumstances, particularly when recovery is relatively rare (such as where water banking is undertaken for drought resilience and emergency supplies) more pragmatic alternatives that demonstrably protect other groundwater users and ecosystems may need to be developed. In some cases, instantaneous rates of recovery may need to be constrained to avoid excessive drawdown and loss of yield of neighboring wells and hence satisfy obligations and conditions of use (as per Table 5).

Table 5 summarizes generic recovery entitlement management factors that are proposed to come into play for various aquifer characteristics. Note that in all cases it is proposed that there is at least one parameter applied by the regulator to constrain recovery entitlements, in order to ensure there is a mechanism available to protect the value of recovery entitlements, in the absence of confident information on the retention of water in the aquifer under likely future scenarios. In brackish aquifers, the recovery efficiency constraint (γ) would generally be applied by the operator rather than the regulator. Recall that α is the maximum cumulative proportion of the recharge for which a recovery entitlement may be issued, β is the annual rate of retention of accrued storage credit, and γ is the recovery efficiency in brackish aquifers.

Table 5 - Influence of aquifer hydraulic characteristics and groundwater salinity on suggested application of α , β and γ.

Aquifer hydraulic characteristics	**Short hydraulic residence time**		**Long hydraulic residence time**	
	Brackish	Fresh	Brackish	Fresh
Storage depletion	α, β, γ	α, β	$\alpha\ , \gamma$	α
Hydraulic equilibrium	β, γ	β	β, γ	β

Note: Recommended values of T_{max} and R_{max} to be specified for all situations and default values are suggested in the text. The value of γ that applies to brackish aquifers is an advisory matter for MAR operators, as this may be a tighter constraint on recovery than those specified by the water management authority for the purposes of aquifer protection and prevention of harm to neighboring groundwater users and ecosystems.

Transfer of Recovery Entitlements

Allowing transfer of recovery entitlements enables water to be used for its highest value uses (Bernat et al., 2020). That is, MAR creates an entitlement to recover water from the aquifer and the owner of that right would normally be allowed to sell part or all of that right to other groundwater users or to environmental water license holders, such as government agencies. Recovery allocations based on storage credits can be traded on the water market, and rules for recovery allocations would be best developed in consultation with groundwater users and incorporated into the groundwater management plan.

Transfers of allocations enable MAR operators to benefit from the sale of their unused recovery entitlements to other water users or for environmental water, for example to sustain aquatic and riparian refuge habitats. This can benefit the broader community by moderating the market price of such water allocations. Importantly, market exchange of either recovered water or recovery entitlements could reduce public expenditure on aquifer restoration. If a regulator were to impose a volumetric excise on traded water entitlements to benefit an over-exploited aquifer, it is recommended this not be applied to MAR recovery entitlements, as the MAR operator at their own expense has already made a net contribution to the aquifer of $(1 - \alpha)$ times their recharge volume. However, any subsequent trading of any part of that traded entitlement originating from MAR should be treated as a normal groundwater entitlement transfer, with no further privileges accorded because of its MAR origin. Transfers of recovery entitlements or allocations provide a means for groundwater user cooperatives to invest in recharge as an alternative to, or in combination with, reducing consumption (demand management). Figure illustrates how MAR schemes can combine recharge and recovery measures to restore equilibrium in previously over-exploited aquifers.

In principle, transfer of recovery rights should be allowed in all aquifers to maximize the value of the water resource. Demonstrating the water recovered contains the recharged water, or that the hydrostatic pressure at the point of recovery has been directly affected by recharge, is not necessary. However, rules must be placed on transfers to ensure all existing groundwater users and the environment are protected from harm. This requires knowledge of the hydrogeology to be able to determine whether the impact of such transfers would be acceptable.

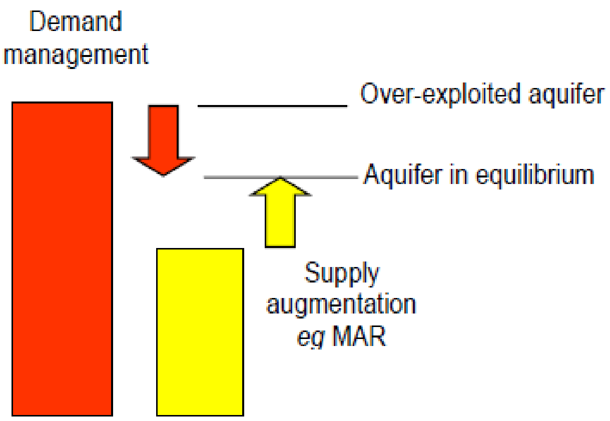

Figure 8 - Integrated use of managed aquifer recharge and demand management to reduce the amount of demand reduction required to restore hydrologic equilibrium in over-exploited aquifers (Ward and Dillon, 2011).

As an example, MAR recovery entitlements should not be traded down-gradient from a MAR operation in a stressed groundwater system. This simple rule stops transfers of entitlements and allocations into existing cones of depression where groundwater is already locally over-exploited. Hence, it prevents the deepening of an existing cone of depression and avoids increased energy use for pumping. This aspect is illustrated in Figure . As an alternative, if necessary, water could be recovered at the MAR site with water piped into the drawdown area to substitute for existing groundwater allocations.

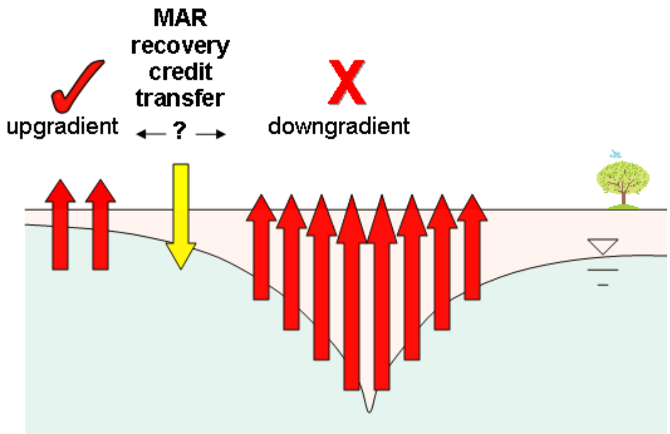

Figure 9 - Down-gradient restriction placed on transfer of MAR recovery entitlements in an overdrawn aquifer (Ward and Dillon 2011). Recovery credit can be transferred upgradient of the MAR recharge site (yellow arrow) as this prevents further stress on the aquifer in a downgradient cone of depression, shown as having multiple extraction wells (red arrows).

Variation in groundwater salinity (a highly conservative natural contaminant) across an aquifer should also be considered in trading MAR recovery entitlements. At the location of the MAR site, health and environmental approval would normally require the salinity of recharge water to be no greater than that of native groundwater at the recharge site. Hence, in an aquifer that has a lateral salinity gradient, water being recharged could have a higher salinity than water in other parts of the same aquifer. Transferring the recovery entitlement to a zone with a similar or higher salinity within an aquifer is desirable to achieve a net freshening effect or no effect on the aquifer salt balance. On occasion, transferring recovery entitlements to lower salinity zones in the same aquifer may also be attractive. To reduce the risk of diminished water quality over time in such aquifers, recovery entitlements or allocations traded to lower salinity wells could be reduced in volume, say in proportion to the ratio of salinity of ambient groundwater at the recovery well to the salinity of recharged water (see Figure). This gives incentives for MAR operators to trade into areas with no reduction in traded entitlement, or where possible to reduce the salinity of recharged water by selective harvesting, blending source waters, or desalination.

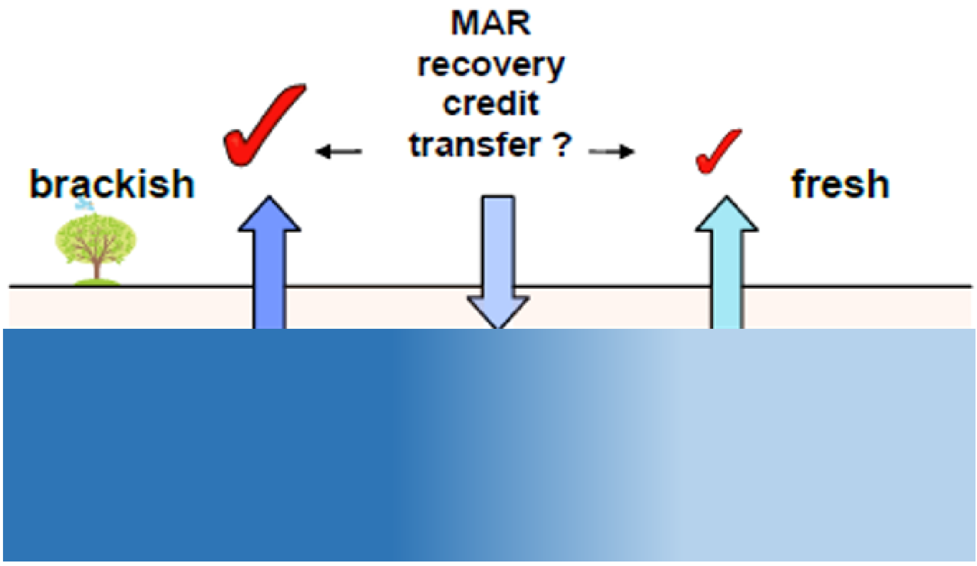

Figure 10 - Illustration of reduction of transferred recovery entitlements and allocations (shown by reduced size of check mark / tick) in an aquifer with a salinity gradient between the recharge site and the location of the proposed recovery well.

Inter-aquifer transfers of recovery entitlements are possible under conditions where no groundwater user or aquifer is compromised by such a transfer. For example, a coastal municipality in South Australia recharges stormwater in a previously over-allocated aquifer used for irrigation and recovers water from a separate brackish-saline aquifer to top-up an urban lake with considerable amenity value (SA NRMC, 2007), creating a net benefit for the aquifer and its users. As a general principle, the environmental, social, and economic benefits and costs for all stakeholders should be considered when determining conditions of inter-aquifer transfer of MAR recovery entitlements.

Water quantity and quality monitoring is needed to record annual recharge and recovery volumes and verify the protection of the environment and human health at MAR sites. A summary of conditions for transfer of recovery entitlements is shown in Table 6.

Table 6 - Considerations for transfer of recovery entitlements or allocations.

Aquifer Characteristics	Transfer prevented or constrained	Transfer unimpeded, subject to an impact assessment
Aquifer has zone of head drawdown (cone of depression) that is not permitted to deepen or extend	Transfer prevented into a cone of depression	Elsewhere in the aquifer
Aquifer has a lateral salinity gradient	Transfer constrained into a fresher part of the aquifer than at the recharge site	Elsewhere in the aquifer (noting that native groundwater salinity may constrain recovery)
Transferring allocations into a different aquifer	Above constraints apply	The aquifer from which recovery is granted and the recharged aquifer are not adversely impacted

Monitoring

The monitoring requirements for each MAR site will depend on the needs of the operator for effective operation of the project as well as the information requirements specified by the water resources manager and the health and environmental regulator. Monitoring is essential to assure the MAR system is operating as intended to produce the benefits sought by the operator without impinging on the rights of other water users including environmental water requirements.

The purpose of the recharge scheme and its potential impacts, together with the nature of the aquifer, will determine what needs to be measured and where, and at what frequency, and over what time duration. A monitoring plan would cover how the data are checked, stored, and reported. Careful thought about a monitoring plan that identifies, monitors, and reports on the various aspects of a scheme will assist in its success and longevity.

Among the basic monitoring requirements, which are further discussed in Section 3 - *Considerations for Considerations for Water* Quality Management for the purposes of human health and environmental protection, monitoring of MAR operations for water planning and management should generally seek to determine accurate measures of the annual mass balances of recharge and recovery for:

1. water volume;
2. salt mass (using average electrical conductivity for incremental volumes); and
3. heat flux (using average temperature for incremental volumes).

Water balance is essential and salt and heat balance are highly desirable with respect to providing evidence of the sustainability of the system. Salt may be inconsequential in some temperate areas but important in arid and semi-arid areas over the long-term for restoring aquifers to higher valued uses. Thermal balance is likely to be more important at higher latitudes and elevations where aquifer biogeochemical processes and ecosystem responses may be influenced over the short- and long-term.

Web-based reporting systems can aggregate to daily, monthly, and annual figures for retention and use in annual reporting of operations, but resources and staffing are required to establish and maintain the web page and the database that supports it. In general, the 'Internet of Things' is making data acquisition and real-time process control more powerful and cost-effective in water supply and treatment, and hence also in MAR. This can simplify the extraction of components of operational data useful for MAR operators into automated reports that are periodically required for water resources and environmental compliance reporting (e.g., Barry et al., 2010 and Zheng et al., 2021).

When water is diverted from one or more sources, the amounts diverted and their proportion of the available flow for each source should be recorded. This information is necessary to determine future prospects for MAR in the same catchment.

All locations where hydraulic head in the aquifer may be used for control of the MAR operations warrant automated monitoring and uploading to web, as well as annual reporting for operational refinement and for reporting of when and where any threshold has been triggered that would start or stop recharge or recovery operations. Monitoring for a period, notionally at least 12 months before a MAR system becomes operational, is important to establish baseline conditions.

If environmental protection or ecosystem sustenance are motivations for a MAR system, appropriate indicators should be identified for assessing success, and these require monitoring, annual reporting, and reporting of any significant exceptions as they occur.

End-User Obligations

End-users of recovered MAR recharge entitlements and allocations (as per Table 4) must demonstrate that the use and disposal of water complies with existing groundwater and catchment water management plans, and with planning, environmental impact, and health policies. Examples include minimum standards for water use efficiency that apply to all uses, and requirements to prevent nuisance runoff or seepage from the area where recovered water is used. The price paid by end users for recovered water should fully account for the pro-rata costs of the MAR system including monitoring, reporting, and any identified reparations for externalities. Managing a large number of small MAR systems may be most efficient via regulations applied over the entire aquifer rather than assessments performed for every individual system.

2.7 Institutional Arrangements and Incentives for MAR

In the Absence of Defined Groundwater Entitlements

MAR can progress in the absence of water resources management plans and regulatory foundations for assigning formal entitlements. However, it would be more likely based on actions devised in response to identified water challenges relevant to the specific basin.

India provides an outstanding example, where the Government of India over many years has encouraged investment in the construction of streambed structures to increase groundwater recharge aimed at enabling farmers to remain productive on their own land where water tables have been falling. About US$5.6 billion of this investment has been through programs of the National Rural Employment Guarantee Act (Dillon et al., 2013). National and state watershed development programs have also supported water and soil conservation activities at the farm level and at the level of catchments of low-order streams, which have enhanced recharge and maintained existing streambed recharge structures. Most projects were undertaken under government design and supervision, but many were implemented by non-government and community development organizations. The combination of these measures has seen the annual volume of recharge augmentation reach greater levels in India than in any other country (Dillon et al., 2019).

Furthermore, in urban areas of some states experiencing groundwater level declines - such as Tamil Nadu, Gujarat and Rajasthan - planning requirements now mandate that all new houses discharge roof runoff to soakage pits to increase groundwater recharge with water of suitable quality.

The rural MAR investments and urban planning examples reflect aquifer risk management strategies and proxies in lieu of more formal, systematic aquifer planning, and are pragmatic approaches to avoid the prohibitive transaction costs of assigning entitlements and allocations to individual farmers and households. Hence, these act as operational examples of an alternative to sequenced instrument approaches (shown in Figure) but these are not devoid of planning.

The investment in India was instigated as a result of many years of groundwater monitoring and the development of a Master Plan for Artificial Recharge by the Central Ground Water Board (CGWB) in 2005 and updated in 2013 (CGWB 2013). The CGWB produced a manual on artificial recharge (CGWB 2007) to help facilitate effective MAR, focused in areas with declining groundwater storage. With the relatively recent advent of the National Water Resources Management Act, which is in the process of devolving to the State level, it would be timely to consider the framework for investment in the context of catchment–wide and aquifer–wide water management plans, and to build on the recent innovation of community-crafted Village Groundwater Cooperatives (Jadeja et al., 2018; Maheshwari et al., 2014) where groundwater is managed as a common pool resource.

With Defined Groundwater Entitlements

Where planning instruments are established that specify water entitlements, a range of measures are at the disposal of innovative water resources authorities to encourage MAR. Several examples are discussed here from the United States of America and Australia.

First, conjunctive management of water resources (Evans and Dillon 2019; Foster et al., 2019) encourages water users to draw on both surface water and groundwater depending on the instantaneous level of abundance and cost as a climate change adaption strategy. This reduces the size of the conceptual step to MAR particularly for water banking during wet seasons and years, to augment a groundwater reserve that can be drawn on during drought. Diverting surface water to MAR is a valid use of surface water entitlements, and the price of additional allocations in wet periods is very much less than during drought. For example, Gonzalez et al. (2020) found the difference in unit price of surface water allocations in Australia's Murray Darling Basin between wet and dry years was sufficient to cover more than twice the estimated costs of MAR. The process of MAR creates a groundwater entitlement that is expected to have greater durability than if the water was left in surface water storages and exposed to evaporation over a long period. Hence there is macro-scale water use efficiency as well as micro-scale economic benefit. Intelligent arrangements for transfer of entitlements could lead to broad-scale economic benefits as well as environmental flow benefits.

In the Orange County Water District in California, USA, water utilities have funded their own recharge schemes since the 1950s (Mills 2002) through a groundwater replenishment assessment (a water use related charge). The assessment is used to repressurize aquifers to prevent saline intrusion and augment supplies through basin spreading. The utilities have invested in research and innovation in water treatments, recharge systems, and monitoring and control systems. These demonstrably improved the security and size of their water supplies in an economic and sustainable way. This approach continues today and has supported expansions of groundwater replenishment and treatment improvements over the years with a transparent approach to water accounting and setting of the replenishment assessment, which includes consultation with users (OCWD website↗). The cost of water is about one-third of that of the southern part of Orange County, which relies primarily on imported surface water.

In California's Central Valley, eight local institutions known as Water Storage Districts commenced constructing dams and canals in the 1940s to alleviate drought. In the 1960s, projects evolved into water banking and conjunctive use projects to supply water to US Bureau of Reclamation water supply projects. Public funds enabled the Water Storage Districts to increase the resilience of urban and agricultural water supplies using unconfined aquifers. These water banks have reversed groundwater declines and sustained agricultural productivity (Scanlon et al., 2016). One example is the Arvin-Edison water bank, which recharges up to 0.16 km^3 per year in wet years and recovers similar volumes in dry years. About 0.4 km^3 was recovered during a five-year continuous drought, representing half of the cumulative banked volume and demonstrating the resilience provided by water banking.

More recently, the 2014 California Sustainable Groundwater Management Act (California Department of Water Resources, 2014) committed to bring depleted aquifers into balanced levels of pumping and recharge, and the Department of Water Resources was tasked with providing assistance to local communities to achieve that goal. These entities behave as a public-private partnership and are funded primarily by their constituent water users supplemented where needed by the state government. They have local management boards and operate under state law to enter into contracts, including those to construct and maintain MAR facilities. This provides a vehicle for implementing well-planned and coordinated projects with strong local ownership.

Long-term monitoring of piezometric levels gives evidence of the contribution of MAR to reversing the decline in groundwater storage in part of the Central Valley of California (Wendt et al., 2021). Similarly, long-term piezometric records of a confined aquifer in Colorado enabled calibration of a model that revealed reduced drawdown during recovery where 20 percent of annual average extraction was recharged in ASR wells (Alqahtani et al., 2021). Such evidence gives regulators, operators, and proponents of MAR confidence in the magnitude of beneficial impacts of MAR.

Arizona, a semi-arid state located in the southwestern part of the USA, has been considered a leader in groundwater management since the passage of its 1980 Groundwater Management Act and has long relied on MAR to assist with meeting water management objectives. Pursuant to state statutory language added in the mid-1980s and strengthened in 1994, a robust system of permitting recharge facilities, water storage, and recovery has been implemented by the Arizona Department of Water Resources, the agency in charge of groundwater management. Primarily, MAR is used by water and wastewater utilities for treating surface water and effluent through soil aquifer treatment and storing water for future use or offsetting groundwater pumping (e.g., Tucson Water as discussed in Megdal and Forrest 2015). MAR has been an integral part of Arizona's water management approach since the early 1990s, but took on even greater significance with the 1996 statutory creation of the Arizona Water Banking Authority (AWBA). This small but dynamic entity was created to store water in aquifers for drought relief for Arizona as well as Nevada and California, to sustain active groundwater management areas and to meet Native American water needs (Megdal, 2007; Megdal et al., 2014). AWBA storage has been funded by multiple sources, including groundwater withdrawal fees, property taxes, and some general funds. The importance of storing Colorado River water for times of delivery cutbacks has become ever more evident given over 20 years of poor runoff conditions in the Colorado River Basin. Arizona has been reliant on deliveries of Colorado River water for close to 40 percent of state water demands.

The AWBA and others who store water have used aquifer capacity available in central Arizona's basin and range aquifers. Water is stored through direct storage, where water enters the aquifer through deep spreading basins, stream-bed recharge, or injection wells. Water can also be stored through indirect storage or groundwater savings facilities, where surface water or effluent is used in lieu of pumping groundwater. The regulatory system allows for annual storage and recovery, whereby the recovery occurs in the same calendar year as the storage. Water remaining in the aquifer at the end of the year is eligible to accrue a long-term storage credit, after a 5 percent cut-to-the-aquifer is assessed against the amount stored. Credited amounts account for transpiration and evaporation. Permit terms, which consider water quality and impacts due to rise in the water table (known as *mounding*), include monitoring and quantity limitations that mounding may trigger. Recovery can occur outside the area of hydrologic impact of the storage, but only if the recovery wells are located in areas not experiencing annual drawdown greater than about one meter per year.

Though Colorado River drought conditions have to a large extent curtailed the water available for AWBA storage, much MAR activity remains. As of the end of 2018, over 10.5 km^3 in long-term storage credits had been accrued through the storage of Colorado River water delivered through the Central Arizona Project, with 40 percent of that accrued by the AWBA. The remainder has been accrued by other entities, many of whom have contracts for water that will continue to be delivered under "mild" shortage conditions. Similar to Colorado River water management, which spans seven American states and the Republic of Mexico, Arizona water management is complex. Differential delivery priorities and regulatory schemes apply based on geography and type of water contract and/or use. What is unambiguous is that MAR plays an important role in enabling Arizona to meet its water policy objectives.

Idaho, in the northwestern USA, has had to deal with declining water levels in the state's largest aquifer since the 1950s. The Eastern Snake Plain Aquifer (ESPA) extends over 26,000 km^2 in the south of the state and supports a major part of the state's economy. The ESPA is a "leaky" aquifer that significantly contributes to surface water flows in the region; therefore, the decline of the ESPA impacts both groundwater and surface water users. The Idaho Water Resource Board (IWRB) is the state agency responsible for developing Idaho's State Water Plan and developing initiatives to address the state's water- related issues. As a first step to address the problem, the IWRB developed a Comprehensive Aquifer Management Plan (CAMP) that was adopted in 2009. This was created through a stakeholder process to develop a range of tools, including the development of a MAR program, to address the decline by replenishment of the aquifer. Funding was a key consideration and hurdle in the development of this long-term program. Various funding methods were considered, including joint funding by a variety of stakeholder groups such as farmers, municipalities, electrical power generation and other industries, and the state. Ultimately, the state chose to fully fund the program in 2014 after further droughts and various court litigations among water users. The IWRB was allocated approximately US$5 million for the development of a sustainable MAR program capable of recharging on average 0.31 km^3 (250,000 acre-feet) per year. To achieve this goal the IWRB invested over US$20 million in MAR infrastructure. Over this time period, the IWRB added over 62 m^3/s (2,200 cfs) of recharge capacity and has averaged annually over 0.35 km^3 (280,000 acre-feet) of MAR including over 0.56 km^3 (450,000 acre-feet) between the fall of 2019 and spring of 2020. Opportunities are large when there are large and interconnected aquifer systems throughout the basin. The ESPA in Idaho provides a nearly perfect opportunity to implement MAR. The recent average annual recharge rate via MAR in Idaho now appears to exceed that of Arizona as a consequence of these initiatives.

The work on the ESPA CAMP and the partnerships that have been developed with the stakeholders have played a major part in the success of the program. Idaho's MAR program has proven to be relatively economical by using existing infrastructure (irrigation canals) to conduct recharge and for conveyance to dedicated MAR sites. A conveyance fee is paid for the use of the existing infrastructure, and this has proven to be more economical and efficient than constructing new infrastructure to recharge the required volumes.

From an administrative perspective, the recharge accomplished by the IWRB is solely for the benefit of the aquifer, and no "credits" are generated for this recharge. Van Kirk et al. (2020) reported that conservation groups are unable to engage directly in water transactions, hampering MAR for fisheries protection, even where this has been shown to be beneficial. Provisions are made for using MAR as part of a mitigation plan for groundwater pumping. In the ESPA, MAR is also used as part of private settlement agreements between surface water and groundwater users as mitigation for groundwater pumping, which currently occurs on an annual basis.

In recent years, a new instrumentality – the Recharge Development Corporation (RDC™), a commercial entity founded in Idaho in 2013, has fostered public-private partnerships to manage investment in MAR and the water entitlements it develops. Its founding principle parallels an established practice of cost-sharing among water-using organizations investing in surface water storages, whereby they develop an entitlement to a share in the reservoir capacity. However, their volumetric allocation depends on the actual volume of water in the reservoir. In the case of RDC, water users are encouraged to invest in MAR by buying an entitlement to a share of the aquifer capacity for MAR, called "Aquifer Recharge Units" (ARUs™), conceived of as initially dry but fillable aquifer storage capacity (Tuthill and Carlson, 2019). The actual volume of MAR is measured and credited to a class of ARUs, where it is available for allocation. A depreciation rate equivalent to evaporative storage losses in dams is applied for administrative convenience so there is no differentiation between accounting for surface and subsurface storage. Water credits earned through recharge are subject to state regulations on groundwater use. Recharge and extractions from all wells are monitored through meters with many having real-time data acquisition to the web for transparent and up-to-date reporting to inform decisions. A water delivery company was established to convey the water. Ownership of ARUs also gives a right to shareholding in the local private water company. The earlier ownership is taken up the higher the priority when any surplus recharge is offered for sale. The value of shareholdings is expected to increase with time as has occurred for surface water storage space. Ninety percent of the income from ARU sales is used to cover project development. The amount of private recharge conducted in the past year by Eastern Snake Plain Aquifer Recharge Inc., (the private local delivery company organized under the precepts of RDC) was 0.018 km^3 (14,815 acre-feet).

A recent example of a jurisdiction giving intended operators clarity on the pathway for establishing potential new MAR projects is provided by the Government of Western Australia (2021). The Western Australia Department of Water and Environmental Regulation (DWER) has issued an easy-to-read policy on MAR that links all of the relevant legislation, and explains activities that are considered to be MAR, or are excluded from consideration as MAR. It also explains how MAR operations will work, how MAR is regulated, and applicants' rights to review the department's decisions. This policy document, together with a brief guideline on water and environmental considerations for MAR (based on the Australian MAR Guidelines, NRMMC-EPHC-NHMRC, 2009) and a 24-page brochure on MAR, provide a "one-stop shop" for industry and developers and are intended to encourage soundly based MAR to provide alternative, fit-for-purpose and climate-resilient water supplies.

While these case studies exhibit differences in the way incentives are applied for establishing MAR to increase volumes and security of water supplies, they all firmly rely on the concept of a water resources management plan (or at least water management goals, such as in Arizona) to ensure sustainability of the resource and to protect the value of entitlements that are earned through investment in MAR. Some government-run programs use MAR as part of a mitigation plan for groundwater pumping without granting recovery entitlements, likely as a first step towards eventual transitioning to fully specified recovery entitlements.

This concludes the discussion of water resources planning and management. As shown in the water policy matrix (Table 3), water quality aspects of MAR, relating to human health and environmental protection, need to be addressed and these are outlined in Section 3. Hence, Sections 2 and 3 need to be considered collectively when evaluating proposed MAR projects prior to approval.

2.8 Opportunities to Exercise Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 4 through 15. Links are provided to each exercise below.

Exercise 4↴

Exercise 5↴

Exercise 6↴

Exercise 7↴

Exercise 8↴

Exercise 9↴

Exercise 10↴

Exercise 11↴

Exercise 12↴

Exercise 13↴

Exercise 14↴

Exercise 15↴

3 Considerations for Water Quality Management

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3.1 Introduction

Managed aquifer recharge (MAR) requires management of both water quantity and quality to meet the following key water quality objectives:

1. health protection on recovery and for third parties drawing on the aquifer;
2. environmental protection of ecosystems in the aquifer and where groundwater discharges;
3. prevention of clogging of recharge facilities and recovery wells; and
4. management of mixing in the aquifer and ensuring adequate recovery of water fit for its intended use.

Water quality management encompasses the water quality of the recharge source, groundwater and recovered water, and includes assessment of the potential for water quality improvement or degradation during MAR. Many processes can alter water quality prior to recovery, including mixing, inactivation, biodegradation, cation exchange, sorption, redox or acid-base reactions, precipitation, or dissolution (Appelo and Postma, 1996; Maliva, 2020; Pyne, 2005). These processes occur in the unsaturated zone during infiltration (where relevant) and in the aquifer storage zone. Water quality can be both improved (e.g., attenuation of pathogens) or degraded (e.g., mobilization of arsenic) by the combination of these processes. Therefore, pre-treatment alone may not be sufficient to ensure acceptable quality of recovered water and in some instances treatment of recovered water may be required prior to use.

3.2 MAR Scheme Components

While many methods can be used for MAR, seven components are common (American Society of Civil Engineers, 2020; NRMMC-EPHC-NHMRC, 2009) where water quality and quantity can be managed in MAR schemes. Figure provides examples of the seven components for well-injection and infiltration types of MAR, while Table 7 describes the key water quality considerations for each component. Pre- or post- treatment may not always be required and in some cases, such as for streambed recharge structures and bank filtration, pre-treatment may not be possible.

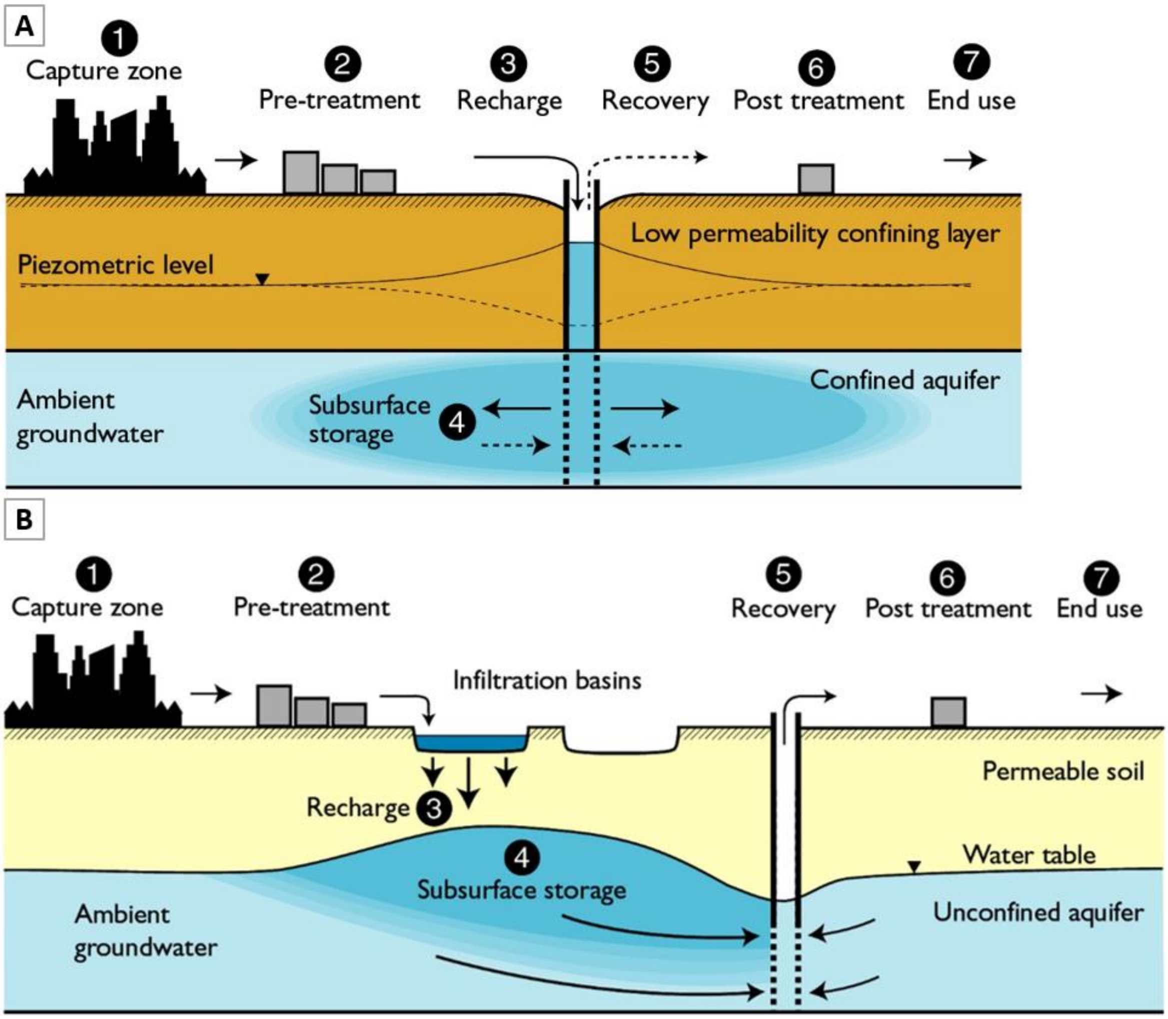


Figure 11 - Schematic diagram of a) aquifer storage and recovery (ASR) and b) infiltration basin type MAR schemes (NRMMC-EPHC-NHMRC, 2009).

Table 7 - Management involves consideration of water quality in each component of MAR schemes (after NRMMC-EPHC-NHMRC, 2009).

Component	Examples	Water quality considerations
1. Capture zone (or source of recharge water)	• Rooftop • Harvesting using weirs and wetlands • Connection to a recycled water pipeline/reclamation plant	Source water quality
2. Pre-treatment	• Passive systems such as wetlands • Engineered treatment	Treatment may be required to protect the target aquifer (water quality or permeability) or minimize negative water quality changes
3. Recharge	• Infiltration basin • Infiltration gallery • Recharge weir • Injection well	Water quality changes (treatment or degradation), soil or aquifer clogging
4. Subsurface storage	• Target aquifer for storage	Water quality changes (treatment or degradation), aquifer clogging, impact on existing groundwater users or groundwater dependent ecosystems
5. Recovery	• Recovery well • Intentional discharge to a groundwater-dependent ecosystem	Recovered water quality
6. Post treatment	• Engineered treatment • Passive systems such as wetlands	Post treatment may be required for end use
7. End use	• Drinking water • Agriculture • Industry • Aquatic ecosystems	Suitability of recovered water

These seven components can integrate natural treatment (e.g., attenuation of pathogens in aquifers) and engineered treatment (e.g., use of filtration such as membrane systems). This is termed a treatment train (Figure), where each barrier is part of the overall system to manage water quality risks. Generally, multi-barrier approaches are used to ensure health is resiliently protected.

Water treatment can be used prior to recharge to ensure the recharge source is suitable for recharge and/or after recovery to ensure the recovered water is suitable for its intended use/s. The type of treatment required is influenced by the quality of the source of water for recharge, the intended use, the recharge method, and existing use/s of the target aquifer. For recycled or reclaimed water, treatment before recharge typically differs between infiltration and injection MAR schemes, with a higher level of treatment (e.g., reverse osmosis, RO) sometimes required to manage the risk of injection well clogging (described later). Some example combinations of treatment trains are given in Figure .

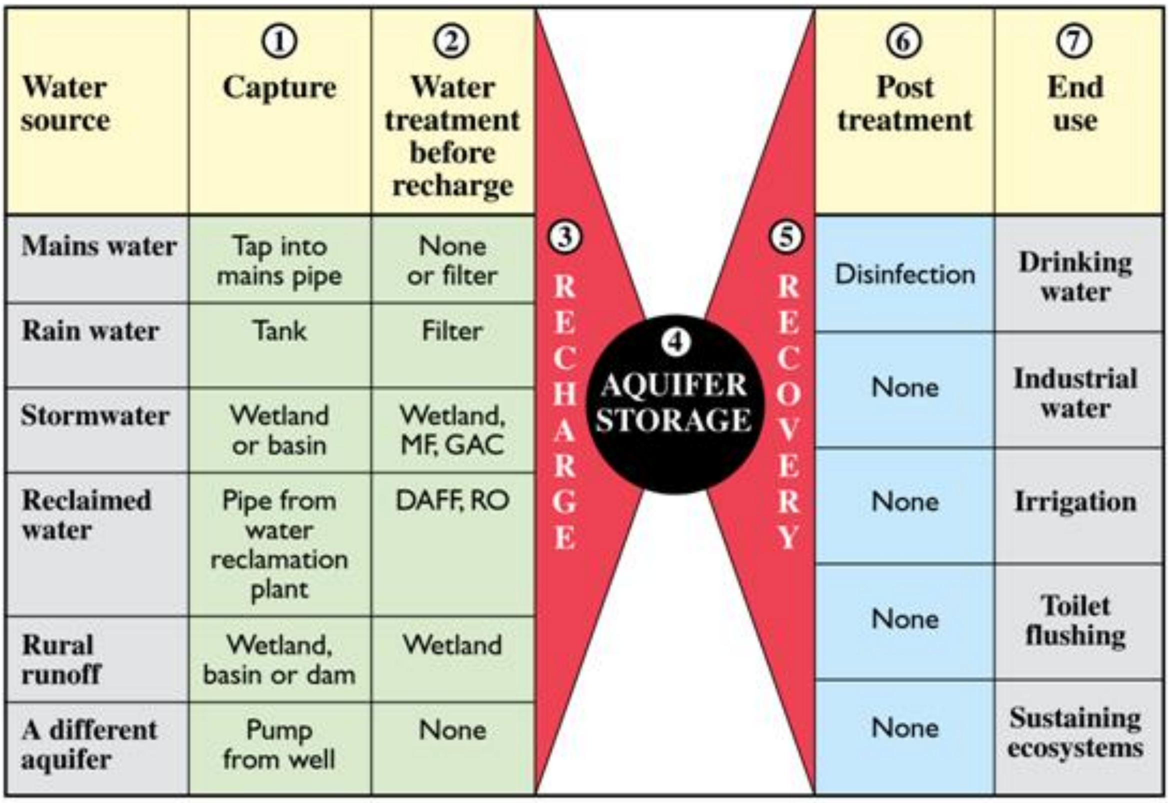


Figure 12 - All sources of water with appropriate treatment can be used for MAR. Water treatment requirements in MAR depend on the recharge source, aquifer, recharge method, intended water use, and other preventive measures to manage risks (from Dillon et al., 2009).

Warning: The pre- and post- treatments shown here are somewhat "typical" examples only and actual treatments would depend on a project-specific risk assessment and may involve other treatments not shown. "None" should not be taken to mean that treatment is not required. Common pre- or post-treatments include: MF=microfiltration; GAC=granular activated carbon filtration; DAFF=dissolved air flotation and filtration; RO=reverse osmosis; membrane bioreactor; ultrafiltration; chlorination; ozonation; aeration, rapid sand filtration (e.g., for Fe/Mn removal).

3.3 Main Methods for Water Quality Management in MAR

Currently the approaches applied to water quality management in MAR can range from: (1) qualitative management where input data are limited; to (2) prescriptive management based on policy or legislation; to (3) risk-based management adapted on a scheme-by-scheme basis. These approaches are differentiated by the level of effort and hence assurance of water safety. They reflect the way in which water quality management is practiced in that country or jurisdiction and are generally commensurate with the stage of economic development.

Qualitative Management

This approach is based on the principles of a sanitary survey type approach and identifies hazards and hazardous events that may impact the quality of water recharged or recovered from a MAR scheme. It assesses health risks from "catchment to consumer" within a water safety plan approach (World Health Organization, 2005). A qualitative approach is applied in the absence of expertise and equipment to measure, monitor and analyze water quality, and is based on visual observations. For example, in a sanitary survey, the presence of human or animal feces or sewage is considered indicative of a pathogen hazard, whereas land uses such as crops with pesticide use or the presence of anthropogenic activities such as industry, roads and mining, are used to indicate the potential for chemical hazards.

This approach has been applied to water quality management in India (Dillon et al., 2014; Bartak et al., 2015) and Chile (Page et al., 2020) to protect aquifers from contamination arising from MAR and subsequently to protect the health of those drinking water from those aquifers. In India, this guidance incorporated the sanitary survey approach and the first stage (entry-level assessment) of the Australian risk-based framework for MAR (described later) and relied solely on visual observations for input. Actions taken in response to observations can prevent recharge of obviously contaminated water by excluding it or shutting down the recharge system. While this sanitary survey approach would increase the safety of MAR schemes, the water recharged cannot be validated as safe in the absence of water quality measurements. This approach is better suited to low-risk MAR projects recharging natural waters in unconfined aquifers for use in irrigated agriculture (Page et al., 2020). In India, aquifers are often also the only drinking water source for villages, so guidance avoids direct recharge to such aquifers and requires infiltration through the unsaturated zone to mimic the natural recharge during monsoons. Higher risk projects, such as those for public drinking water supply, require additional capacity for water quality monitoring and rigorous risk assessment and management (see sub-section below on *Risk-based Management*).

Prescriptive Management

Prescriptive management usually stipulates a suite of specific parameters for which water quality standards (e.g., maximum contaminant levels; MCLs) must be met prior to recharge and/or on recovery and stipulates the frequency of sampling. This is intended to be a receptor based approach and MCLs commonly address public health protection (e.g., in drinking water supply) but can also accommodate environmental protection targets where relevant (e.g., in irrigation water supply). Usually, these water quality specifications are generic requirements for all MAR within the country or jurisdiction and refer to existing water quality regulations. This prescriptive approach is applied in many countries, e.g., USA (American Society of Civil Engineers, 2020; United States Environmental Protection Agency, 2018), Mexico (Cruz-Ayala and Megdal, 2020; Palma Nava et al., 2018), Belgium, Israel, Italy, South Africa, Spain and the Netherlands (Fernández Escalante et al., 2020).

Source water is often required to be of high quality (even to meeting drinking water standards) as a way of minimizing risks. For example, in the European Union, the Water Framework Directive precludes the entry of contaminants to the saturated zone. This one-size-fits-all approach can mean that low-risk projects are over-managed and high-risk projects are under-managed. Typically, this approach does not acknowledge the role of the aquifer in improving water quality, and sometimes not even for deteriorating the quality of recharged water, such as by arsenic mobilization (as discussed later in Water Quality Hazards).

While water quality standards (e.g., maximum contaminant levels) used in this prescriptive approach are underpinned by broad risk-assessment concepts, they are often constrained to a reduced set of variables that can influence water quality (e.g., geographic area/aquifer, MAR type, recharge source water). For example, two regulations in Mexico specify source water quality requirements for MAR: one for MAR using reclaimed water (NOM-014-CONAGUA-2003); and another for infiltration of runoff (NOM-015-CONAGUA-2007). These regulations are described in Cruz-Ayala and Megdal, 2020; and Palma Nava et al., 2018). Similarly, Florida has four standards for water quality in MAR to allow for the recharge method (injection wells or infiltration basins) and aquifer type (Fernández Escalante et al., 2020). While these prescriptive approaches provide clear guidance on water quality requirements and reduce uncertainty for proponents, they are limited by the lack of flexibility to account for the various forms a MAR scheme can take (type, source water, aquifer characteristics) or to address emerging water quality hazards (e.g., pharmaceuticals and personal care products) and the potential to result in onerous management requirements regardless of risk. For example, monitoring a prescribed set of water quality parameters regardless of scheme risk can result in unnecessary and expensive monitoring or energy consumption for treatments thereby limiting adoption of MAR schemes. Furthermore, it may be possible that the prescribed monitoring requirements may not address all potential water quality risks.

Risk-based Management

Risk-based quantitative approaches allow for the development of human health and environmental protection targets based on the environmental values (or 'beneficial uses') of the aquifer at the MAR site. Environmental values apply to all existing and potential uses (including ecosystem protection) of the groundwater at its ambient quality. This results in more stringent recharge water quality targets for aquifers that are used for drinking water supply than for those containing groundwater that is unsuitable for drinking. Importantly, efforts and resources are targeted toward monitoring and managing the hazards that constitute potential risks, rather than on analytes just because they are in a national register.

Risk-based management is achieved through four stages of risk assessment (Figure 13):

- entry-level assessment; followed by

- maximal (inherent) risk assessment in the absence of preventative measures or operational procedures; then
- residual risk assessment to ensure adequate measures are in place to reduce risks to an acceptable level prior to construction and commissioning of a MAR scheme; and finally
- operational risk assessment and a risk management plan to ensure ongoing operation of the scheme has acceptably low residual risks. The risk assessment process is iterative and requires periodic review to ensure ongoing safe operation.

Entry-level assessment	**Maximal risk assessment**	**Pre-commissioning residual risk assessment**	**Operational residual risk assessment & Risk management plan**
• Assess MAR scheme viability • Use existing information and regulations	• Assess maximal (inherent) risks in the absence of preventative measures and operational procedures • Investigations required	• Assess preventative measures and operational procedures required to ensure acceptably low residual risks • Investigations required	• Assess whether ongoing operation has acceptably low residual risks • Use information from commissioning phase

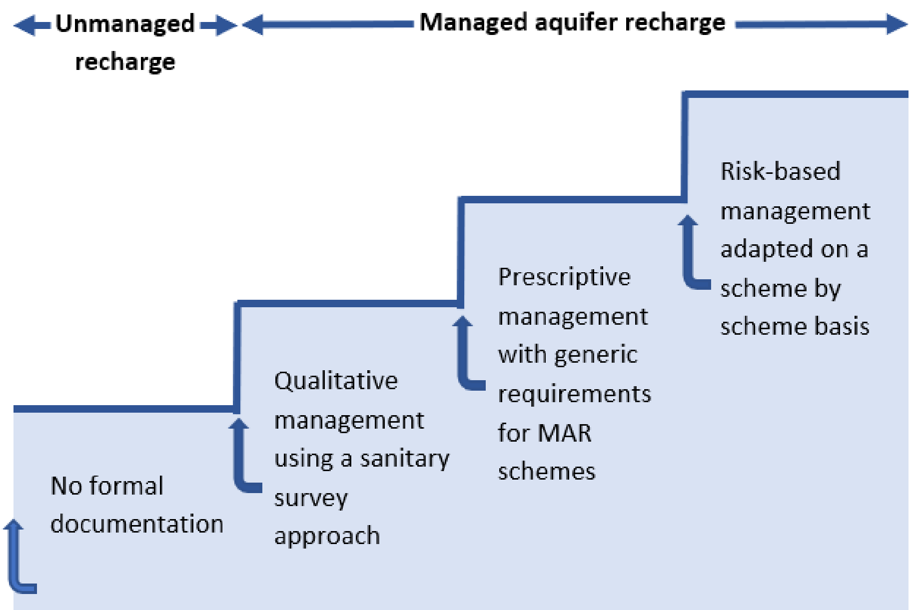
Figure 13 - Stages of risk assessment used to achieve risk-based water quality management in MAR (after NRMMC-EPHC-NHMRC, 2009).

Risk-based management does not usually set generic water quality standards (e.g., *E. coli* numbers in recharge water not to be exceeded), but instead refers to standards that are relevant to the protection targets at the point of exposure. For example Disability Adjusted Life Years (DALYs) for protection of human health from water-borne disease (World Health Organization, 2005) can be achieved by disinfecting water during recharge or on recovery, or by validated inactivation in the aquifer, or by exposure controls, such as timing or method of irrigation, and for resilience usually involves a combination of several methods.

This approach promotes integrated risk-management from catchment to consumer and recognizes the role of the aquifer and unsaturated zone in providing water quality improvements, where appropriate. Combining natural and engineered treatment processes can improve the economic viability of MAR schemes (e.g., Wintgens et al., 2016) by reducing the requirements to treat the source water prior to recharge. For example, chlorination to manage pathogen risks prior to recharge may not be necessary if pathogen inactivation in the aquifer is accounted for, consequently reducing the pre-treatment requirement (e.g., Donn et al., 2020; Page et al., 2010) and reducing the risk of water quality degradation due to the formation of disinfection by-products (Pavelic et al., 2005; 2006a).

To address public health, California has adopted a risk-based water quality framework (California Code of Regulations, Title 22, Division 4, Chapter 3) for groundwater replenishment with recycled water for drinking water (State Water Resources Control Board, 2014). An example of a risk-based water quality management framework for MAR that addresses both public health and environmental protection is in Australia (NRMMC-EPHC-NHMRC, 2009). The Australian MAR guidelines consider comprehensive categories of water quality hazards as well as the attenuation or formation of these hazards between recharge of water and its recovery or discharge to where it must meet relevant environmental values. This is in contrast to setting absolute water quality standards (maximum concentration limits; MCLs) for specific parameters at the point of recharge. This approach acknowledges that risk is very often site-specific and requires detailed investigations and pilot schemes to quantify and assess scheme risks and management strategies (Nandha et al., 2015). It also provides the flexibility required to address emerging water quality concerns, that may not be addressed by generic water quality standards. The risk assessment is then used to determine the monitoring requirements to manage those risks as well as to support the ongoing operation of a MAR scheme (e.g., to manage clogging). However, the key limitations of this quantitative risk-based approach are the reliance on input data and the need for considerable capability for water quality monitoring, analysis and control (Dillon et al., 2010, 2020). This has limited its adoption in countries within the low- to mid-range of economic development and is also a challenge with respect to the capacity of operators and regulators of small-scale MAR schemes in more economically advanced countries.

These differing approaches to management of water quality for health and environmental protection will vary depending on the local regulations and the capability for monitoring and assessment. Regardless of management approach, MAR intended for water supply will ultimately be subject to water quality standards for the intended use/s with the aim to improve the safety of the MAR operation. Figure represents the stepwise progression toward sustainable and safe MAR schemes from unmanaged to risk-based management.



Water quality focus:	Not explicit	Public health	Public health & environment	Public health & environment
Risk assessment:	None	Qualitative	Assumed generic	Quantitative
Sampling and analysis required:	None	Visual observations only	Generic analyte list	Analytes based on locally assessed risk
Level of safety:	Unknown	Safer	Safer	Safest

Figure 14 - Approaches for management of water quality in MAR progressing toward risk-based management of public health and the environment (modified from Dillon et al., 2014).

3.4 Guidance on Water Quality Monitoring

Specific water quality monitoring requirements will differ based on the management approach taken. This can vary from none for unmanaged systems, visual observations for qualitative approaches, predetermined requirements for prescriptive approaches including types of analytes and frequency, to being entirely risk-based and so tailored to the situation. While specific requirements of differing approaches may vary, MAR monitoring programs should always:

- be commensurate with the complexity and risk of the proposed MAR recharge scheme;
- be integrated with the risk assessment and management approach adopted;
- have clear objectives, in terms of the types of monitoring being undertaken and the information content that is obtained;
- aim to maximize information content and the value of measurements in relation to risk management objectives; and
- dovetail with monitoring requirements for water quantity management (see Section 2.6, sub-section on *Recovery Entitlements, Allocations, and Obligations*).

The four principal reasons for water quality monitoring include:

- *baseline monitoring*: baseline monitoring provides information for the maximal risk assessment (Figure) and it is used to define the state of the system before commissioning a MAR scheme;
- *validation monitoring*: validation is essential when there is a reliance on the treatment capacity of the aquifer. It quantifies the treatment efficacy of any new or uncharacterized treatment steps, such as subsurface treatment at a new locality. It may also include pre- and post-treatment technologies, and exploration of water quality deterioration (e.g., arsenic release, formation of disinfection byproducts);
- *operational monitoring*: operational monitoring is fundamental to the risk management of all operational MAR schemes. The bulk of the monitoring effort for most MAR schemes should occur in the day-to-day operation for operators to manage risks. Operational monitoring provides timely information for use as critical control points in the risk management plan. It often includes supervisory control and data acquisition (SCADA) and web-based reporting systems that provide near real-time data. Operational monitoring is fundamental to setting appropriate critical limits and management responses, e.g., shutting down recharge due to poor quality source water, shutting down recovery due to salinity limits being exceeded, backflushing ASR wells at the onset of clogging and changing treatment processes; and
- *verification monitoring*: verification monitoring is not timely enough for operational management, but provides an important check to confirm that the MAR scheme is performing as anticipated. Verification monitoring can be performed on a compliance basis, for prescriptive management approaches and for audit of risk-based management.

These monitoring types each generate useful data and information for risk assessment of a MAR scheme, operation and subsequent risk management. More details on these monitoring approaches are given in EPHC-NRMMC-AHMC (2006).

Proponents of any new MAR scheme must budget for monitoring. This can be small, such as a few percent of establishment and annual operating costs for projects with inherently low risks. However, for some more complex projects with higher risks, the cost of an adequate monitoring program (including drilling costs) may be sufficiently large so as to make the scheme unviable. In that case the project should not proceed. A marginally economic project causes problems because operators cannot afford to maintain their system to ensure it meets its requirements.

3.5 Tools for Managing Water Quality During MAR Scheme Development

Management of water quality during MAR requires an understanding of source water quality, groundwater quality and any processes that can impact water quality or recharge rate. This understanding can be obtained from desktop, laboratory and field investigations and commences with a review of existing information to assess the viability of MAR. The viability assessment identifies potential concerns (or risks) at an early stage and identifies knowledge gaps that require further investigation in subsequent stages of project development. Targeted investigations assess technical feasibility and inform scheme design, including the necessary preventative measures to manage health and environmental risks, prior to scheme construction, commissioning, and operation. Numerous tools are available for use in the targeted investigations and commissioning trials (Table 8) to address scheme-specific knowledge gaps identified in the initial viability assessment. For example, laboratory column studies are typically used to understand clogging mechanisms, test pre-treatment and define source water quality targets to manage clogging (e.g., Rinck-Pfeiffer et al., 2000; Vanderzalm et al., 2020; Zhang et al., 2021). Reactive transport modeling is also useful for a mechanistic understanding of geochemical processes impacting water quality (e.g., Fakhreddine et al., 2015), but relies on sufficient data from laboratory (e.g., aquifer characterization, aquifer reactivity (as noted in Descourvieres et al., 2010)) and field investigations (e.g., spatial and temporal sampling and analysis of groundwater and recharge source water quality).

Table 8 - Overview of tools available to manage water quality in MAR

	Investigations
Desktop	Review available information on hydrogeology, sediment geochemistry, and water quality to assess scheme viability and identify potential water quality or clogging risks (i.e., Entry-level assessment in Figure)
	Review literature on case studies having similar conditions (e.g., Zheng et al., 2021)
	Groundwater flow and transport modeling (e.g., FEFLOW, MODFLOW)
	Hydrogeochemical modeling (e.g., mass balance, WATEQ, MINTEQ, PHREEQC, Easy-Leacher, the Geochemist's Workbench, PHT3D)
	Quantitative microbial risk assessment (QMRA)
	Energy and greenhouse gas accounting of treatment options and effects (e.g., lifecycle analysis)
	Economic analysis of treatment options and their effects (Present value benefit/ cost analysis, lifecycle accounting)
Laboratory	Sediment characterization and reactivity/leaching tests (e.g., for metal & metalloid mobilization)
	Column & batch studies of water quality (i.e., contaminant fate, redox processes, metal & metalloid mobilization), clogging mechanisms, rates and pre-treatment requirements
Field	Sediment (soil and aquifer core) sampling and analysis (hydraulic properties, hydraulic response to injection, hydrogeochemistry
	Source water, recovered water, and groundwater sampling and analysis, preferably along flow paths
	Clogging material (e.g., well backwash water, scrapings from infiltration basins) sampling and analysis to identify clogging mechanisms
	Field monitoring during commissioning and operation of MAR system (see section 3.4)

3.6 Water Quality Hazards

Water quality hazards must be addressed in relation to health and environmental protection (the first two water quality objectives listed in Section 3.1). These hazards may be introduced by the source water for recharge, by the ambient groundwater, or due to reactions that occur during recharge and storage between the recharge water and groundwater or recharge water and soil and aquifer sediments. For simplicity the following broad hazard categories relevant to health and environmental impacts are used in risk-based management:

1. pathogens;
2. inorganic chemicals;
3. salinity and sodicity;
4. nutrients;
5. organic chemicals;

6. turbidity and particulates;
7. radionuclides; and
8. temperature.

The first seven are described in NRMMC-EPHC-NHMRC (2009), with information on their effect on public health and the environment, sources, fate in the subsurface, monitoring and management, and the last is a proposed new addition (Dillon et al., 2020). All are summarized briefly here.

Pathogens

Pathogens are the most important human health hazard due to the prevalence and potential health impacts (mortality) of waterborne disease (World Health Organization, 2005). Waterborne pathogens considered include index pathogens from the bacteria, viruses, protozoa, and helminth categories. Attenuation of pathogens can occur via inactivation and attachment (Schijven, 2001; Page et al., 2015; Sasidharan et al., 2017) in the unsaturated and saturated zones. Pathogen inactivation in the subsurface is highly variable and difficult to validate and is influenced by many factors including pathogen type, recharge water source, temperature, redox state, activity of indigenous groundwater microorganisms, and aquifer geochemistry. The removal rate is typically faster in oxic conditions, such as those found in the unsaturated zone and, in general, protozoa and viruses persist far longer than bacteria (Sidhu and Toze, 2012; Sidhu et al., 2015), as shown in Table 9. Owing to their larger size, helminths (parasitic worms) are typically removed by source water treatment or by filtration in soils and aquifers; helminth survival and transport may require consideration in dual-porosity aquifers (e.g., karst). Attachment is influenced by pore-water velocity, solution chemistry, and aquifer mineralogy, but can be reversed (detachment). Natural treatment of pathogens requires irreversible attachment or inactivation on the solid phase (Sasidharan et al., 2017).

Accurate pathogen numbers in source water and their associated attenuation rates are key limitations to the application of risk-based management approaches but assessment methods are improving rapidly (Dillon et al., 2020).

Preventative measures to manage pathogen hazards include natural treatment in the aquifer (which requires validation), source control, pre-treatment of source water prior to recharge or on recovery (e.g., disinfection), and measures to reduce exposure during use of the recovered water. As an example, California regulations for indirect potable reuse of wastewater require 12-log reductions of enteric viruses. Water recharged through injection wells meets this regulation through pre-treatment using advanced treatment processes. Water recharged through spreading basins must first undergo at least tertiary treatment with disinfection, which is credited with a 6-log reduction. Soil aquifer treatment is relied on to complete the process of pathogen inactivation and removal. A 1-log credit for enteric virus reduction is received per month of aquifer retention time. The retention time must be demonstrated using tracers or modeling. Full credit only applies if an added tracer is used to demonstrate the retention time; lesser credit is given for natural tracers or modeling studies. (California State Water Resources Control Board, 2018).

Table 9 - Pathogen inactivation in the subsurface is highly variable. This example of removal times (in days) for a 90 percent loss (T90) of pathogen or indicator during MAR at four Australian sites illustrates faster removal rates for bacteria than for protozoa and viruses (Sidhu et al., 2015).

Pathogen/indicator	**Removal time for 90% loss (T_{90}) (d)**
Escherichia coli	0.1-1.5
Enterococcus fecalis	1-2.5
Salmonella enterica	0.7-2
Coxsackievirus	17-169
Adenovirus	28-65
Rotavirus	34-185
Cryptosporidium parvum	38-120

Inorganic Chemicals

Inorganic chemicals are a broad hazard category that includes metals, metalloids, major ions and gases. These hazards to human health and/or the environment may arise from the source water, native groundwater, or reactions between them or with the aquifer material. Common inorganic chemical hazards result in recovery of iron, manganese, arsenic, trace metals or metalloids and hydrogen sulfide above the guidelines for intended use or a change in the major ion chemistry of the recovered water. Increases in inorganic chemical concentrations can be caused by redox reactions (e.g., pyrite oxidation, reduction of iron(hydr)oxides), mixing between the native groundwater and the source water, desorption, and mineral dissolution. Arsenic mobilization can be a water quality issue for MAR schemes for drinking water supply. Alteration of the native geochemistry as a result of intentional recharge can induce several mechanisms that can release arsenic from sediments to groundwater including desorption (due to competitive anions such as phosphate or pH changes), dissolution of arsenic-bearing minerals (due to changes in redox conditions), and reduction of arsenate to the more mobile arsenite (due to changes in redox conditions) (Fakhreddine et al., 2015). Summary diagnostics of the potential for the release of arsenic and iron are given in Appendix 7 of NRMMC-EPHC-NHMRC (2009). Soils and aquifers can also provide natural treatment of inorganic chemicals through dilution, filtration, sorption, redox reactions, ion exchange and precipitation. Given the diversity of analytes in this category, it is necessary to undertake a geochemical assessment, i.e., of improvement or degradation of water quality (American Society of Civil Engineers, 2020; Descourvieres et al., 2010; Ginige et al., 2013; Schafer et al., 2018, 2020; Seibert et al., 2016;

Sun et al., 2020). Geochemical reactions can also affect clogging as discussed in Section 3.7 - *Clogging*.

Preventative measures to manage inorganic chemical hazards include pre- or post-treatment, natural treatment in the aquifer (which requires validation), source control, and selective diversion from recharge of continuously monitored source water when it is outside specified water quality criteria (e.g., pH, electrical conductivity).

Salinity and Sodicity

Salinity and sodicity hazards are primary health concerns and can have significant impacts on the environment (e.g., vegetation, soil, or aquifer) and infrastructure (e.g., corrosion). Mixing between the recharge water and brackish groundwater is the primary reason for salinity to increase during recovery. Changes in the major ion chemistry (e.g., inorganic chemical hazards) can also alter the sodicity of the recovered water and its suitability for irrigation use (NRMMC-EPHC-NHMRC, 2009). Salinity and sodicity can also impact clogging (see Section 3.7 - *Clogging*).

Preventative measures to manage salinity and sodicity chemical hazards include source control, aquifer selection, MAR scheme type, duration of recharge and storage, selective recharge/diversion of source water outside continuously monitored water quality criteria (e.g., electrical conductivity), mixing of recovered water with a lower salinity source and pre- or post-treatment.

Nutrients

Nutrient hazards in MAR include nitrogen, phosphorus and organic carbon and can impact human health but are usually of greater concern in relation to the environment. Nitrogen and phosphorus can cause nutrient imbalance in irrigation water, eutrophication, and result in toxic effects on terrestrial biota. Organic matter can stimulate microbial activity in the subsurface which can affect the concentrations of nitrogen and phosphorus along with other water quality hazards (pathogens, inorganic chemicals, organic chemicals) and aquifer permeability (i.e., clogging). The recharge water is usually the main source of nutrient hazards in MAR; however, unconfined aquifers can also be subject to nutrient contamination from land use such as agriculture. Aquifers can provide natural treatment of nutrients through filtration, sorption, redox reactions and precipitation (Vanderzalm et al., 2018).

Preventative measures to manage nutrient hazards include natural treatment in the subsurface (which requires validation), source control, selective recharge/diversion of continuously monitored source water that is outside specified water quality criteria (e.g., color) and pre- or post-treatment.

Organic Chemicals

Organic chemicals are a diverse hazard category that can impact human and environmental health but are the least understood in terms of risks. They include contaminants of emerging concern (e.g., per- and polyfluoroalkyl substances as described in Page et al., 2019) as well as herbicides, pesticides, hydrocarbons, industrial chemicals, algal toxins, pharmaceuticals, personal care products and disinfection byproducts. The recharge water is usually the main source of organic chemical hazards in MAR; however, unconfined aquifers can also be subject to organic contamination from land uses (e.g., pesticide use, firefighting, fuel, or chemical storage). Natural attenuation in the subsurface via volatilization and biodegradation has been reported for organic chemical hazards (Patterson et al., 2012; Maeng et al., 2012; Shareef et al., 2014; Alotaibi et al., 2015), although most studies do not assess the risks posed by biodegradation products. A few chemicals have degradation products with similar or greater toxicity than the parent compound, and this risk needs to be taken into account (see Appendix 5 in NRMMC-EPHC-NHMRC, 2009). Generally, adsorption onto the aquifer matrix is not regarded as a sustainable treatment for MAR due to potential for displacement by competing ions, exhaustion of sorption capacity and delayed breakthrough. However, the extended residence time in the aquifer may be used to estimate potential biodegradation (NRMMC-EPHC-NHMRC 2009).

Preventative measures to manage organic chemical hazards include natural treatment in the aquifer (which requires validation), source control and pre- and post-treatment. Conversely disinfection byproducts form in the aquifer and the potential for formation can be lowered by reducing the concentration of organic matter and residual chlorine (Pavelic et al., 2005, 2006a). Unlike many organic chemical hazards, anoxic conditions in aquifers have been reported to accelerate trihalomethane (THM) attenuation (Pavelic et al., 2006a).

Turbidity and Particulates

Turbidity and particulates can indirectly impact human health (e.g., by interfering with disinfection processes during water treatment or acting as carriers for pathogens, metals and organic pollutants), the environment (e.g., aquifer porosity) and infrastructure (e.g., clogging of recharge wells and infiltration basins). All recharge waters typically contain some particulates that need to be managed. In addition, operations can increase particulate concentrations due to mobilization of soil or aquifer particles (e.g., through changes in sodicity and salinity), or backwashing of injection wells. Turbidity and particulates are the key hazard to be managed in purge or backwash water.

Preventative measures to manage turbidity and particulate hazards include natural attachment in the soil and aquifer (which requires validation), source control, selective recharge/diversion of source water outside continuously monitored water quality criteria (e.g., turbidity) and pre- or post-treatment.

Radionuclides

Radionuclide hazards, which can impact human health, predominantly arise from natural sources of radioactive materials (e.g., uranium, thorium, potassium-40 within the aquifer) and their progenies (e.g., radon). Anthropogenic activities such as medical and industrial use can also result in radionuclide hazards in the source water for recharge. Radionuclide hazards in MAR usually arise due to interaction between the recharge source and natural source of radionuclides in the aquifer storage zone. In general, high radionuclide concentrations are found in granitic, fractured rock aquifers and near organic coal deposits.

Preventative measures to manage radionuclide hazards include aquifer selection, source control and pre- and post-treatment.

Temperature

The temperature of source water for recharge is usually different than the ambient temperature in the aquifer being recharged; if this difference is large, it can impact the sustainability of a MAR operation. For example, if recharge water reaching the aquifer is cooler than ambient groundwater, dissolved gases may be released and potentially cause gas binding (clogging by trapped air) in pores of porous media on the perimeter of recharge wells. Importantly the rates of inactivation of microbial pathogens or rates of biodegradation of organic chemicals may be diminished if groundwater is cooled in the vicinity of the recharge zone. Sidhu et al. (2015) deduced that temperature reduction from 22 to 17 °C was one of the factors reducing the rate of viral and protozoan inactivation in an aquifer.

Temperature is an important attribute of thermal groundwater used for energy or recreation (such as spas). If these aquifers are to be recharged, then predicting temperature changes over the long-term at any proximal geothermal supplies (e.g., at aquifer thermal energy systems) and protecting such supplies are important considerations (Dillon et al., 2020). If recharge water is warmer than the native groundwater, mineral solubility may change, organic carbon could be released and biogeochemical reaction processes could be accelerated (e.g., pyrite oxidation), leading to deterioration of the quality of groundwater. These considerations would generally be more important in well recharge systems than in infiltration type systems where thermal effects will be buffered to some extent during the passage of water through the unsaturated zone. Monitoring of thermal effects of MAR is relatively simple. For example, temperature changes outside a monitoring well casing can be detected inside the casing by lowering a sensor and recording temperature and depth or pressure (e.g., Pavelic et al., 2006b). Furthermore, temperature effects have been modelled by Miotlinski and Dillon (2015) to demonstrate the relative effects of convection, conduction, and thermal dispersion that influence the fate of injected water of a different temperature in an aquifer.

3.7 Clogging

A key water quality consideration is related to clogging (or plugging) of recharge structures. Clogging reduces soil or aquifer permeability and is the greatest operational challenge to the sustainability of MAR schemes (Martin, 2013; NRMMC-EPHC-NHMRC, 2009; Pyne, 2005). It leads to a reduction in flow rates and the volume of water that can be recharged and, in severe cases, can result in scheme failure and subsequent abandonment.

Clogging affects all MAR schemes to some extent (Martin, 2013; NRMMC-EPHC-NHMRC, 2009; Pyne, 2005) and occurs during recharge due to physical, biological, chemical, or mechanical processes. It is largely attributed to the quality of the recharge water but can also be caused by surface processes or operational practices (e.g., compacting of infiltration basins, air entrainment). Management of clogging involves prevention and remediation, both of which rely on understanding the underlying cause(s) of clogging. Prevention is recommended as the most cost-effective management solution, especially for injection schemes as the hydraulic loading rate on aquifer material at the well circumference area is much higher than through the floor of an infiltration basin and therefore the risk of clogging is potentially greater (Martin, 2013). As a result, a higher level of pre-treatment is typically required for injection wells than for infiltration basins. For example, recycled (reclaimed) water may require tertiary treatment (e.g., dissolved air flotation and filtration) prior to infiltration or advanced treatment (e.g., reverse osmosis) prior to injection (Figure). Several causes of clogging include:

1. *physical clogging*: predominantly caused by filtration of suspended solids present in the recharge water or swelling or mobilization of clays. Accumulated solids can be physically removed from infiltration basins by scraping, but they can also build up in bores to form a filter cake that is more difficult to manage;
2. *biological clogging*: caused by the growth of bacterial cells and production of biofilm, or extracellular polysaccharides. Microbial growth and biological clogging are stimulated by food sources such organic carbon, nitrogen, and phosphorus in the recharge water;
3. *chemical clogging*: caused by geochemical reactions that result in precipitation of minerals (e.g., calcium carbonate, iron or manganese oxides and hydroxides); or ion exchange or adsorption that can lead to mechanical clogging (clay swelling or dispersion). Geochemical reactions may also be microbially mediated which means that both chemical and biological clogging processes can occur simultaneously; and
4. *mechanical clogging*: commonly caused by air entrainment and gas binding but can also be due to formation failure (such as collapse of clay banks of infiltration basins or collapse around injection wells of low permeability layers previously supported by material that has been dissolved by recharged water). Air entrainment can occur if the recharge water cascades into the well or if dissolved gases are released from solution due to biogeochemical processes, temperature changes or pressure changes.

Notably, geochemical reactions can also result in dissolution of the aquifer matrix (e.g., calcite in limestone aquifers), which can act to increase hydraulic conductivity and counteract the other clogging mechanisms.

The aquifer hydraulic response during recharge using well injection techniques can provide an indication of the type of clogging (Figure). Air entrainment is typically characterized by a rapid increase in the resistance to flow, filtration of suspended solids results in a linear increase in resistance, and the impact of biological clogging increases exponentially.

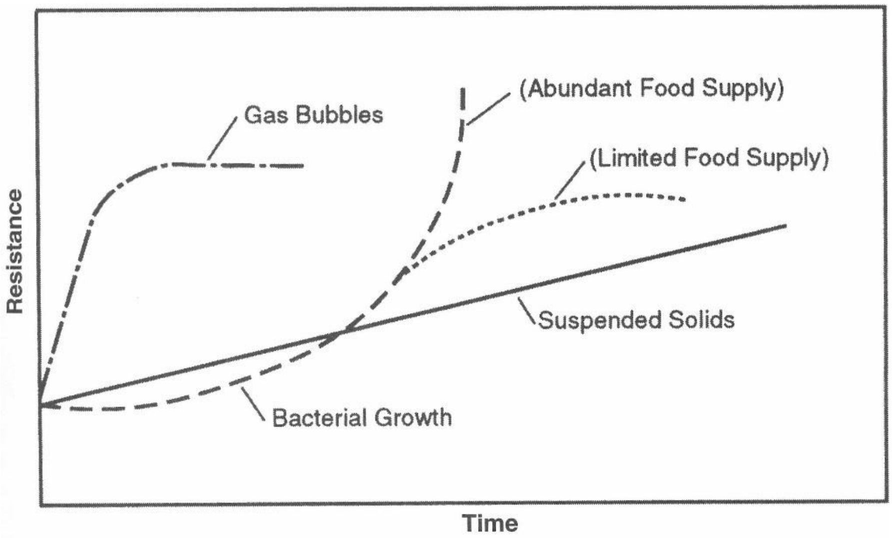


Figure 15 - Typical aquifer hydraulic response for different clogging mechanisms (Pyne, 2005).

Preventative measures to reduce the impact of clogging are often needed and include aquifer selection, scheme design, construction (i.e., drilling methods), source control, selective recharge (e.g., diversion of continuously monitored source water that is outside specified water quality criteria, such as for turbidity), treatment of source water prior to recharge, and operational procedures and controls. Remediation measures that are commonly embedded into scheme operation include drying and scraping the surface of recharge basins and regular, periodic redevelopment of wells (e.g., backwash). Severe clogging may require additional remediation measures such as well acidization, biocide treatment, vacuum pumping, scrubbing, wire brushing or under-reaming to enlarge open hole wells.

A comprehensive coverage of clogging in MAR is provided by Martin (2013), including a description of clogging processes, diagnostic tools, remediation methods and a series of case studies.

3.8 Mixing in the Aquifer and Recovery Efficiency

Salinity is typically the key variable limiting the *recovery efficiency* of a MAR scheme, defined as the proportion of recovered water that is of suitable quality for use as a fraction of the recharge volume (NRMMC-EPHC-NHMRC, 2009; Pyne, 1995). A recovery efficiency of 1 indicates that the entire volume of water recharged can potentially be recovered for use, subject to regulations (see Section 2.6, sub-section on *Recovery Entitlements, Allocations, and Obligations).* However, when the ambient groundwater is too saline for use, mixing between the recharge water and the ambient groundwater may limit the volume of water that can be recovered (recovery efficiency < 1). Continuous monitoring of the electrical conductivity of recovered water allows recovery to continue until a salinity threshold is reached.

Management of mixing and recovery efficiency requires an understanding of flow and solute transport in the aquifer and is influenced by the hydrogeology (i.e., aquifer thickness, permeability, porosity, degree of confinement, heterogeneity, anisotropy (depth-dependent horizontal and vertical hydraulic conductivity), hydraulic gradient, groundwater quality) and MAR scheme design and operation (Pavelic et al., 2002). In addition, the storage zone can be flushed and freshened prior to recharge (Miotlinski et al., 2014) or a buffer zone can be created and maintained to separate the stored water from the surrounding ambient groundwater to improve the recovery efficiency of ASR schemes (Pyne, 2005; Ros and Zuurbier 2017).

3.9 Summary

While many potential complexities affect water quality management in MAR, a careful evaluation during scheme development – from site selection, scheme design and pre-commissioning to commissioning and ongoing monitoring - will enable efficient sustainable operations, with risks well managed for the intended use. As its name imparts, managed aquifer recharge is a managed process. Its reputation is staked on this planned process to give certainty to operators, regulators, and all stakeholders.

3.10 Opportunities to Exercise Knowledge Gained in this Section

To exercise the knowledge gained while reading this section, investigate exercises 16 through 27. Links are provided to each exercise below.

Exercise 16↴

Exercise 17↴

Exercise 18↴

Exercise 19↴

Exercise 20↴

Exercise 21↴

Exercise 22↴

Exercise 23↴

Exercise 24↴

Exercise 25↴

Exercise 26↴

Exercise 27↴

4 Exercises

4.1 Basic concepts

Exercise 1

What are some of the purposes of MAR?

Back to section↑
Click for solution to exercise 1↓

Exercise 2

What are some advantages of MAR over dams?

Back to section↑
Click for solution to exercise 2↓

Exercise 3

What are the five critical elements for a successful MAR project?

Back to section↑
Click for solution to exercise 3↓

4.2 Water Resources Planning and Management

Exercise 4

Is MAR on its own a solution to aquifer depletion?

Back to section↑
Click for solution to exercise 4↓

Exercise 5

MAR has a lot of benefits but can it cause water resources problems?

Back to section↑
Click for solution to exercise 5↓

Exercise 6

What is the first step in introducing a MAR program in the absence of a water resources management plan?

Back to section↑
Click for solution to exercise 6↓

Exercise 7

If you cannot develop a water resources management plan, can MAR still advance?

Back to section↑

Click for solution to exercise 7↓

Exercise 8

How can MAR be used to stimulate acceptance of groundwater demand management?

Back to section↑

Click for solution to exercise 8↓

Exercise 9

What is the difference between a water entitlement and a water allocation?

Back to section↑

Click for solution to exercise 9↓

Exercise 10

What entitlements are needed to operate a MAR project?

Back to section↑

Click for solution to exercise 10↓

Exercise 11

Recovery entitlements for MAR are normally subject to various constraints. Please identify and explain these.

Back to section↑

Click for solution to exercise 11↓

Exercise 12

Where can water recharged in a MAR project be recovered?

Back to section↑

Click for solution to exercise 12↓

Exercise 13

What institutions and policies could be used to assist development of appropriate MAR?

Back to section↑

Click for solution to exercise 13↓

Exercise 14

Why should a monitoring plan be developed for a MAR program?

[Back to section⮥]
[Click for solution to exercise 14⮧]

Exercise 15

What role can the private sector play in MAR development?

[Back to section⮥]
[Click for solution to exercise 15⮧]

4.3 Water Quality Management

Exercise 16

What are the seven components of most MAR schemes?

[Back to section⮥]
[Click for solution to exercise 16⮧]

Exercise 17

What are the different approaches to risk management?

[Back to section⮥]
[Click for solution to exercise 17⮧]

Exercise 18

What are the eight-key water quality hazard categories to be considered in MAR?

[Back to section⮥]
[Click for solution to exercise 18⮧]

Exercise 19

What are the four reasons for water quality monitoring?

[Back to section⮥]
[Click for solution to exercise 19⮧]

Exercise 20

Name three preventative measures that can be used to manage pathogen hazards in MAR?

[Back to section⮥]
[Click for solution to exercise 20⮧]

Exercise 21

Name four types of clogging and a cause for each?

[Back to section↥]
[Click for solution to exercise 21↧]

Exercise 22

What clogging mechanism is likely to result in a delayed exponential increase in the resistance to flow during recharge?

[Back to section↥]
[Click for solution to exercise 22↧]

Exercise 23

How is MAR scheme recovery efficiency defined?

[Back to section↥]
[Click for solution to exercise 23↧]

Exercise 24

What is the key water quality parameter that influences recovery efficiency?

[Back to section↥]
[Click for solution to exercise 24↧]

Exercise 25

What is most important measure for water quality management in a pristine aquifer?

a. avoidance of polluted source water;
b. prevention of contamination by treatment before recharge;
c. attenuation in the subsurface;
d. treating water on recovery; or
e. cleaning up contaminated groundwater.

[Back to section↥]
[Click for solution to exercise 25↧]

Exercise 26

What is the first tool to use in managing water quality during the evaluation and planning stage of MAR scheme development?

a. reactive transport modeling;
b. review existing information;
c. laboratory column study.

Back to section↥

Click for solution to exercise 26↧

Exercise 27

If an operator of infiltration basins wants to start a new project using injection wells (e.g. an aquifer storage and recovery (ASR) project), what are four features in managing water quality they will need to take into account differently?

Back to section↥

Click for solution to exercise 27↧

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6 Exercise Solutions

6.1 Basic concepts

Solution Exercise 1

Managing water supply, meeting legal obligations, restoring or preventing further declines in groundwater levels, controlling saltwater intrusion, halting land subsidence, maintaining minimum flows and levels, water-quality enhancement and protection, managing reuse of treated wastewater, and ecosystem restoration and protection.

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Solution Exercise 2

Lower capital costs, avoidance of evaporation losses, prevention of problems with algae or mosquitoes, and greater flexibility in locating near areas of high water demand. A key advantage is that MAR projects are scalable, allowing for staged implementation. MAR generally results in less loss of prime valley floor land than surface reservoirs, and rarely results in any population displacement.

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Solution Exercise 3

(1) a sufficient demand for recovered water, (2) an adequate source of water for recharge, (3) a suitable aquifer in which to store and recover the water, (4) sufficient land to harvest and treat water, (5) and capability to effectively manage a project.

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6.2 Water Resources Planning and Management

Solution Exercise 4

Aquifer storage levels depend on the water balance in the aquifer and therefore on recharge and discharge. If discharge exceeds the total recharge - that is, the sum of natural recharge and managed aquifer recharge - storage will continue to decline. If recharge enhancement is sufficient to offset the imbalance by which discharge exceeds natural recharge, then MAR can on its own mitigate aquifer depletion. In general however the most economical way of re-establishing hydraulic equilibrium in the aquifer is to first reduce discharge and then augment recharge.

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Solution Exercise 5

Well-planned and designed MAR is highly beneficial. On the other hand, poorly conceived or executed projects can potentially be very harmful to the environment, to the local community and to communities downstream. If a community depends on MAR being effective and the project fails to provide adequate supply, it would be a major problem. Over-estimated source water, poor quality source water, inadequate type or size of facilities, clogging, lack of maintenance, or the aquifer not retaining sufficient water can cause the project to fail to meet its objectives. If too much water is taken for MAR, downstream communities relying on the same water source may become severely deprived and riparian ecosystems may be impacted. If more water is recharged than the aquifer can accept, then water logging and salinization could occur, rising groundwater levels could cause flooding of foundations of buildings or some wells may even become artesian and start flowing. So, while MAR can potentially cause problems, identifying the risks and managing them allows MAR operators to build MAR projects that deliver the benefits and prevent problems anticipated by water resources planners and managers.

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Solution Exercise 6

Developing a water resources management plan is instrumental in the success of each intervention including a MAR program. The plan can be as simple or complicated as needed. Using a stakeholder process to develop the plan (no matter if it is on a village level or over a large region) is a key to fully distinguishing and articulating the problem to be solved. It helps to identify the specific issues and concerns that would be addressed by a MAR program. Establishing a stakeholder group also informs what works and does not work for their situation and could be helpful to adaptively manage the MAR program. Without stakeholder agreement, the likely success of a MAR program is slim considering that MAR is often dealing with a long-term issue/solution.

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Solution Exercise 7

Many examples are available of MAR starting in advance of an agreed-upon water resources management plan. Sometimes establishing demonstration projects is necessary to build an understanding and knowledge of how to design and operate a MAR successfully, so that adoption can proceed. However, it is risky to continue to build more and larger MAR projects without a water resources management plan in place, as these could have insufficient water for economically viable recharge or may deny downstream water users and water environments of flows on which they depend. Such plans also help determine the amount of additional recharge and the amount of demand reduction that need to take place for groundwater to be sustainable, and this effectively gives the surrogate value for a unit volume of recharge.

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Solution Exercise 8

In cases where an aquifer is over-allocated, when a community gains an understanding of the benefits of MAR, the water resources manager can declare that MAR is an allowable activity if it is part of a catchment and basin-wide water resources plan, which also includes demand management. Demand management provides pressure for improved water use efficiency, so that the benefits of MAR are maximized. If water users are led to understand the constraints on their future water use with and without MAR, the costs of MAR can be compared to the benefit of additional water availability via MAR. Such calculations should account for the proportion of recharged water that would be available to them. In an over-allocated aquifer this will typically be around 90 percent. The value of water banking should also be taken into account. This increases the reliability of supplies, which in turn may allow higher valued and consistent crops than would otherwise be possible (such as opportunistic field crops grown only in wet years). Hence private investment in MAR could accelerate within the context of a water resources plan that links water supply and demand aimed at sustaining water supplies and the environment.

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Solution Exercise 9

There is a principle of robust separation of rights in association with water entitlements and allocations. Entitlements relate to an enduring share of the resource held by an individual as a fraction of the total number of shares, whereas allocations relate to the time varying volume of water represented by that entitlement in any given year or season.

A water entitlement is a right of a water user to an agreed share of a defined water resource. The share is generally defined at one point in time in relation to a sharing arrangement set by the water resources manager in consultation with all water users, including the appointed representative for environmental water. The resource is generally defined in a cascade of long-term agreements across the whole of a water catchment or groundwater basin. An entitlement applies for each water user for the length of those agreements. Entitlements are usually ascribed by evaluating the average volumetric use of water by all existing users in a given multi-year period, using metered measurements of water use or estimates based on crop area and crop water use estimate.

Allocations are determined each year, or if needed for each irrigation season, to account for the temporal variability in the volume of the water resource that can be allocated to entitlement holders. The process for setting allocations is based on measurements of the volume of water in storage and flows on specified dates. Hence in a dry year, allocations are reduced for all entitlement holders.

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Solution Exercise 10

The proponent of a MAR project needs to have an entitlement (a) to take water from a surface water source to recharge an aquifer, (b) to recharge the aquifer, and (c) to recover water from that aquifer.

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Solution Exercise 11

There are normally four constraints on the recovery of recharged waters:

- Maximum proportion of cumulative recharge recovered: this is intended to ensure that in over-allocated aquifers some residual water will remain in over-allocated aquifers to help defray the deficit, and allow more time for demand reduction or additional recharge enhancement to bring the aquifer back into hydrologic equilibrium.
- Time period over which recovery entitlements are allowed: in part this reflects that hydraulic residence time of water in the aquifer is finite. It may also reflect a pragmatic aspect that keeping accounts of recharge and recovery volumes should have a time after which these are extinguished, so as not to indefinitely accumulate data on which entitlements are based. These also translate to a depreciation rate for storage accumulated by a MAR project.
- Limit the maximum recovery in any year or period to a volume that is similar to the maximum annual volume of recharge, with the aim of not disadvantaging other water users.
- Quality of water recovered is fit for its intended uses: this matter is addressed within Section 3 – concerning health and environmental regulations relating to MAR.

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Solution Exercise 12

Water can be recovered wherever an entitlement is issued. This is not restricted to the area where the same molecules of water that were recharged can be recovered, nor the larger area where hydraulic heads have been influenced by the MAR project. The primary criterion is that extraction of the volume of the recharge entitlement causes no harm to the aquifer, its dependent ecosystems, or other users of the water and that the quality of water is fit for its intended use. Generally this would require groundwater modelling to demonstrate that these conditions are met by any proposal to transfer an entitlement to recover water.

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Solution Exercise 13

A MAR demonstration project that has been designed to meet a need, has been planned in accordance with local water resources management plans (if they exist), is designed and operated to manage water risks in accordance with an accepted MAR guideline, and is monitored to demonstrate its hydraulic and economic performance would be a valuable starting point to give the local community appropriate confidence about the role and value of MAR. This could be implemented by a government agency or a public-private partnership as a prototype, with all information freely disseminated.

A sustainable water resources management plan is developed to enable entitlements to source water, aquifer recharge, and water recovery, and to enable trading of water entitlements and allocations.

A water bank or government program could be established to sustain or enhance water resources and create competition among projects for funding, evaluation of projects prior to approval and after implementation, and mechanisms to recoup costs and recirculate funds through entitlement trading.

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Solution Exercise 14

It is important to have a clear understanding of the current situation, and hence to have the monitoring in place well before a MAR program is established to assess and evaluate its impact. The monitoring plan can be adjusted to fit the size and scope of the problem being addressed. The data from the monitoring plan provide the required information for the stakeholders to assess the effectiveness of the MAR program, adjust the program to meet the objectives, adapt the program to changing conditions, and/or expand the program.

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Solution Exercise 15

While considerable MAR development to date has been sponsored by government, the private sector can have a significant role in advancing MAR, particularly in developed economies. The extent of government funding can wax and wane with the state of the economy, whereas private sector funding can be more sustainable if private ownership can be established. Many surface storage reservoirs and water systems are privately owned and, in the same way, storage in aquifers can be encouraged and enhanced by the private sector, as exemplified by the techniques established by the Recharge Development Corporation in Idaho and by the majority of MAR projects in Arizona.

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6.3 Water Quality Management

Solution Exercise 16

Capture zone, pre-treatment, recharge, storage, recovery, post-treatment, end-use.

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Solution Exercise 17

Qualitative, prescriptive, risk-based.

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Solution Exercise 18

1. pathogens
2. inorganic chemicals
3. salinity and sodicity
4. nutrients
5. organic chemicals
6. turbidity and particulates
7. radionuclides
8. temperature

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Solution Exercise 19

Baseline, operation, validation and verification monitoring.

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Solution Exercise 20

Three of: natural treatment in the aquifer, source control, treatment of source water prior to recharge and measures to reduce exposure during use of the recovered water.

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Solution Exercise 21

1. physical: filtration of suspended solids, clay swelling or mobilization, migration of interstitial fines, migration of drilling fluids.
2. biological: organic carbon, nitrogen or phosphorus in source water.
3. chemical: geochemical reactions and precipitation of minerals, ion exchange or sorption.
4. mechanical: air entrainment due to water cascading into well or gases being released into solution, formation failure.

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Solution Exercise 22

Biological clogging.

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Solution Exercise 23

The proportion of recovered water that is of suitable quality for use as a fraction of the recharge volume.

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Solution Exercise 24

Salinity.

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Solution Exercise 25

They are all important, but the order of importance is as listed starting with avoidance of polluted water as most important. This attacks the problem before groundwater is impacted, and minimizes the level of monitoring and operating costs required to have confidence that water quality is satisfactory. Measures further downstream are more expensive to implement or validate, with contamination demonstrating failure to correctly manage recharge. However, a multiple barrier approach is best where several of these measures are used together to increase resilience, reliability, and confidence that the water quality objectives will be continuously met.

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Solution Exercise 26

All tools play a role in MAR scheme development, but the first tool to use is to review all available information to identify risks and knowledge gaps to be addressed by subsequent investigations.

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Solution Exercise 27

First, the hydraulic loading rate on aquifer material at the well circumference area is much higher than through the floor of an infiltration basin, so water quality will have a more severe effect on clogging and will need to be well managed to avoid remedial measures, which are likely to be more complicated. Second, no unsaturated zone treatment is available for the recharged water, so greater attention will need to be given to managing the risks of polluting the aquifer and impacting other groundwater users. Third, differences in the redox states of recharged water and ambient groundwater are more likely, and hence the potential for geochemical reactions that may result in the mobilization of metals such as iron and arsenic need to be taken into account when recovering water from the aquifer. Finally, biogeochemical processes differ between unconfined and confined aquifers (relating to differences in redox state and temperature), usually resulting in generally lower rates of pathogen inactivation and differing rates of biodegradation of organic chemicals. These need to be understood and pre- or post-treatments identified and implemented to manage risks to the MAR operator and to other aquifer users and ecosystems.

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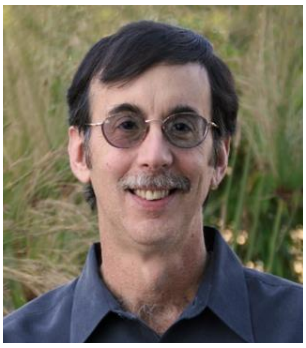
7 About the Authors

Dr. Peter Dillon, following a post-doc at Cornell University, served with CSIRO Land and Water from 1985 to 2014, leading Australian research teams on groundwater quality protection, stormwater harvesting, water recycling and managed aquifer recharge. With Ian Gale (British Geological Survey) he founded the IAH Commission on Managing Aquifer Recharge in 2002 which he co-chaired until 2019, to promote a collaborative scientific basis to advance international MAR research, practice, policy and training. He has edited 10 books, authored 150 journal papers and 200 reports, and led the writing team for the Australian Guidelines for MAR. He, his team and their various MAR projects have been honored by IAH, UNESCO and Australian water industry associations. Currently he is a CSIRO Honorary Research Fellow in Adelaide and adjunct Chair at Flinders University in the National Centre for Groundwater Research and Training.



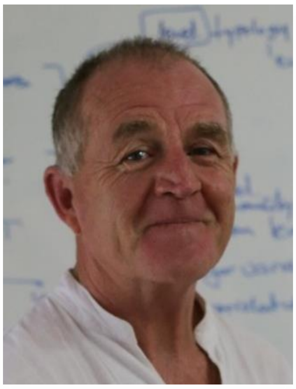
Dr. William Alley is the Director of Science and Technology for the National Ground Water Association. Previously, he served as Chief, Office of Groundwater for the U.S. Geological Survey (USGS) for almost two decades. Dr. Alley has published over 100 scientific publications, along with several general interest books on environmental topics co-authored with his wife, Rosemarie, including *High and Dry: Meeting the Challenges of the World's Growing Dependence on Groundwater*. Among other awards, Dr. Alley received the USGS Shoemaker Award for Lifetime Achievement in Communication and the Meritorious Presidential Rank Award. Dr. Alley was elected a Fellow of the Geological Society of America in 2009. He holds a B.S. in Geological Engineering from the Colorado School of Mines, an M.S. in Hydrogeology from Stanford University, and a Ph.D. from Johns Hopkins University.

Prof. Yan Zheng became a Chair Professor at Southern University of Science and Technology (SUSTech), in Shenzhen, China in 2016. Her cross-disciplinary research contributed to the reduction of exposure to arsenic among private well households in Bangladesh, China, and the USA. She has published extensively in areas including geochemistry, hydrogeology, environmental health, and policy. She obtained her Ph.D. from Columbia University in 1999. Between 1998 and 2020, she held tenured faculty and administrative appointments at the City University of New York and research appointments at Columbia University. She was a water and sanitation specialist with UNICEF Bangladesh between 2009 and 2011. Currently, she serves as the Editor-in-Chief for Environmental Earth Sciences, an Associate Editor for Water Resources Research and as a Co-Chair for the International Association of Hydrogeologists – Managing Aquifer Recharge Commission. Professor Zheng was elected a Fellow of the Geological Society of America in 2010 and a Fellow of the American Geophysical Union in 2021.

Dr. Joanne Vanderzalm is a Senior Research Scientist within CSIRO Land and Water. Joanne joined CSIRO in 2003 after completing her Ph.D. research at Flinders University on 'Hydrogeochemical processes during aquifer storage and recovery (ASR) with reclaimed water in a carbonate aquifer'. Her research interests include water quality, managed aquifer recharge, water reuse, biogeochemical processes, metal and metalloid mobility, natural treatment processes, and application of environmental tracers to assess reaction processes. Her publication record includes 49 journal papers and 8 book chapters and she contributed key sections on inorganic chemical and nutrient hazards to the Australian Guidelines for Managed Aquifer Recharge (2009).

Coauthors of Sections

Dr. Declan Page holds a PhD degree in Chemical Technology from University of South Australia and a Master of Business Administration from Monash University. Currently, Dr. Page is the Principal Scientist in Groundwater Systems research team in the Water Security Program at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia. Dr Page is passionate about urban water management particularly water recycling and stormwater reuse via aquifers and water quality and treatment and water quality risk management.



Dr. John Ward is a director and principal scientist of the Mekong Region Futures Institute (Bangkok) and the Sustainable Futures Institute Australia (Melbourne). He has a PhD in institutional, resource and experimental economics, and more than 20 years experience in research-for-development in Asia, Africa and Australia. John has led trans-disciplinary research teams focused on evidence-based water and natural resource policy design, including for MAR in Australia as leader of CSIRO Institutions Policy and Environmental Governance team. He has been based in Vientiane, Lao PDR since 2010.

Prof. Sharon B. Megdal, Ph.D. is Director of the University of Arizona Water Resources Research Center, Tucson, USA. She aims to bridge the academic, practitioner, and civil society communities through research, education, and engagement. Applied research projects include water management, policy, and governance in water-scarce regions, groundwater recharge, and transboundary aquifer assessment.

Wesley Hipke is the Idaho Water Resource Board Recharge Program Manager for the State of Idaho, USA. For the past thirty years Wesley has been involved with the development and implementation of regional managed aquifer programs and projects first in Arizona and now in Idaho.

Paul Thomas is a former Research Hydrogeologist and Project Manager with the Idaho Water Resource Board Recharge Program, USA, responsible for environmental compliance efforts with Idaho Department of Environmental Quality and the collection and analysis of Program environmental data.

David R. Tuthill Jr., Ph.D., P.E. has worked in the field of water resources throughout his career. He worked for the Idaho Department of Water Resources from 1976 - 2009, concluding as Director of the agency. In 2009 Dave founded Idaho Water Engineering, LLC, and is a co-owner. He serves as Vice-President of Recharge Development Corporation, founded in 2013, and is a Principal in Clean Water Professionals, founded in 2015.

Ronald D. Carlson served as Manager, Eastern Region of Idaho Department of Water Resources for 32 years, and elected Watermaster for Snake River, Idaho, USA where he was responsible for establishing water bank and rental pool structures. He owns an irrigated farm, has a B.S. and M.S. in Agricultural Engineering, and is a founding member and Treasurer of Recharge Development Corporation.

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UNESCO

United Nations
Educational, Scientific and
Cultural Organization

International
Hydrological
Programme

NGWA®
The Groundwater
Association

Organizations that contributed to this book

International Association of Hydrogeologists (IAH)

IAH was established in 1956 and operates in more than 130 countries to further the understanding, wise use and protection of groundwater resources throughout the world. Among its many scientific activities it publishes *Hydrogeology Journal*, runs Congresses, has National Chapters and also Commissions and Networks to focus on particular topics. In 2002, IAH with encouragement from UNESCO, established its **Commission on Managing Aquifer Recharge** to coordinate international effort in this area. IAH-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

UNESCO International 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".* IAH-MAR working groups and the International Groundwater Resources Assessment Centre (IGRAC) have played a key role in developing and applying methods to assess impacts of MAR on water availability and quality, social and economic resilience and local ecosystems. This book follows a recent UNESCO review and synthesis of MAR case studies with IAH and GRIPP, in which governance was determined to be a major gap in advancement of sustainable MAR. More information on UNESCO IHPs activities is given at: http://www.unesco.org/new/en/natural-sciences/environment/water/ihp-viii-water-security/

National Ground Water Association (NGWA)

The National Ground Water Association (NGWA) is a not-for-profit professional society and trade association for the global groundwater industry that was founded in 1948. Its members around the world include leading public and private sector groundwater scientists, engineers, water well system professionals, manufacturers, and suppliers of groundwater-related products and services. The Association advocates for responsible development, management, and use of water. It hosts training courses, conferences, webinars and Groundwater Week, the largest tradeshow in the groundwater industry. It also publishes two peer-reviewed journals, *Groundwater* and *Groundwater Monitoring & Remediation*, as well as a trade publication, *Water Well Journal*. Managed aquifer recharge is a primary area of advocacy for the NGWA. More information about NGWA is available at www.ngwa.org