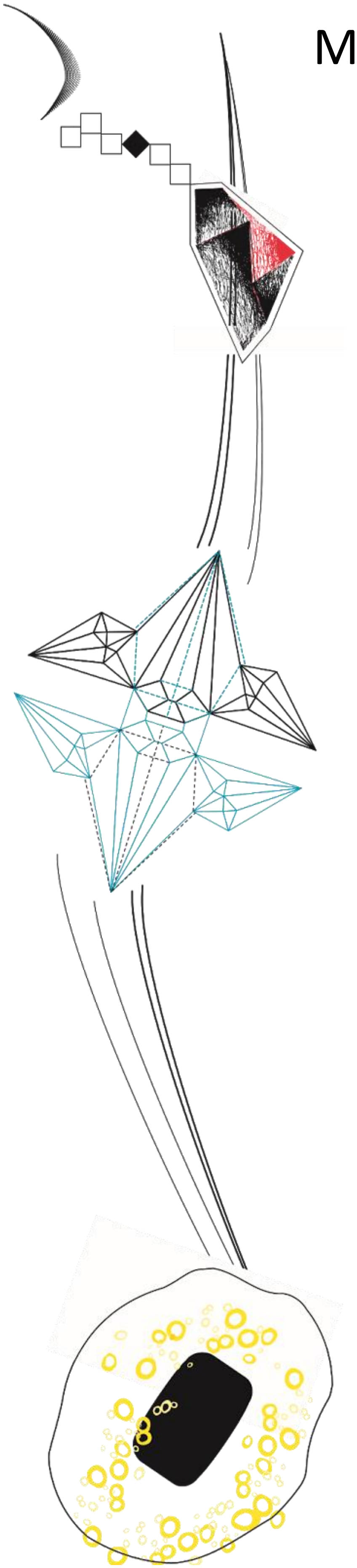

Managed aquifer recharge as a way to mitigate water scarcity explored

A state-of-the-art literature review on managed aquifer recharge and its feasibility in agriculture

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August 31st, 2020

Picture on cover page from Fernández-Escalante and San Sebastián Sauto (2019).

Management Summary

A growing number of people, currently some four billion people, are affected by severe water scarcity for at least one month a year. Half this number lives in areas where groundwater resources are under threat. Many aquifers are being depleted during the last decades, due to rising groundwater demands, groundwater being a common pool resource, and either neglection of or unconsciousness on it being a finite resource, and driven by the rising populational needs. A significant part of all groundwater extraction is unsustainable, where extraction rates are higher than the natural recharge. About one third of the largest aquifer systems are overexploited, of which the Upper Ganges and Upper Arabian aquifer systems have the most severe depletion rates. This has especially adverse effects on agriculture, as that sector is by far the biggest contributor to global groundwater withdrawal. Yet, for many areas in the world, enough water is present year-round, but it simply is not retained during water excesses effectively enough to cover the periods of drought. As such, it is paramount the groundwater resources should be better managed, especially in aquifer dependent regions. One method to do so, is Managed Aquifer Recharge (MAR), where water is injected in times of excesses, to be extracted in times of drought. Previously, MAR was perceived as an emerging technology, innovative, but risky and unreliable for water supply systems. This perception was kept in place due to an absence of well-available, centralised and generalised information on MAR. Although many studies have been conducted to show MAR as a feasible option, most studies only focus on the technical, hydrogeological aspects of MAR feasibility, and largely neglect other important contexts with important roles in MAR's feasibility, such as the (other) environmental, institutional, and economic disciplines. Additionally, there is no common understanding on criteria, weights, and methods for feasibility mapping of MAR is absent. Among others due to the found gaps in literature as a result from this largely monodisciplinary approach to MAR in research and absence of common guidelines to feasibility mapping for MAR, MAR is still often either unknown or neglected by water managers and farmers when trying to improve the water management systems, resulting it often costlier, and potentially less effective solutions. This restrains the uptake by water managers of MAR. The gap was for the biggest part not so much in the (non)existence of knowledge on i.e. the factors influencing feasibility for MAR, but on the *availability* and *accessibility* of the *combined knowledge* from these contexts for people outside of a select group of researchers specialised in the field of integrated groundwater management. As such, the aim of this study was to reduce this gap by exploring MAR in a multidisciplinary manner as a method to improve management of groundwater resources, and better combat the future droughts. This can eventually result in MAR being regarded by both water managers and farmers as a more trustworthy method to counter (ground)water stress.

This was done by using the theories of policy transfer and lesson drawing while conducting an extensive, state-of-the-art literature review, and creating an overview, to the author's knowledge the most comprehensive in a single study to date, of MAR's multidisciplinary merits and barriers. The study combines a lot of different quantitative and qualitative data, enabling a general overview with detailed parts where necessary. To establish this overview, several steps have been undertaken. First, current groundwater use and depletion are explored, to determine why and how much additional storage, potentially using MAR, is required. Second, MAR and its potential merits are explored to create a broader understanding on how MAR can aid in, among others, alleviating groundwater stress. Third, it is assessed how MAR currently already contributes to alleviating water stress. For this research question, the historical development will also be looked at. These results show whether MAR is useful and as such helps create more confidence in the possibilities of MAR. For the fourth step, the factors influencing feasibility of MAR in environmental, socioeconomic, and institutional contexts are sought out. These contexts have been chosen, since they have been identified in previous literature as the most important, underexposed, disciplines influencing the feasibility of MAR. For the environmental context, lacking provision of information on hydrogeological and hydrogeochemical factors and what role they play in the feasibility of MAR, have been identified as restraining MAR's implementation. For the socioeconomic context, this study found that implementation of

MAR is often lacking due to absence of a clear economic case. This was mostly due to neglection or unawareness of contingencies, the absence of an all-encompassing overview of the costs involved in a MAR project, difficulties with monetizing the benefits of MAR. Moreover, reaching sufficient funding for a MAR project proves difficult, as the main beneficiaries of a MAR project are often not the financers of said project. For the institutional context, elements in the field of stakeholder management, legislation on groundwater withdrawal and use, and legislation on groundwater quality have been identified as restraining the implementation of MAR. The cobweb of stakeholder incentives in a MAR project, is a large barrier in a MAR project and should be properly managed. The legislation on groundwater governance differs largely in different parts of the world, and even between neighbouring countries, and is effectively a patchwork of local customs, national legislation, regional agreements, and global treaties. To improve the groundwater governance, lessons should be drawn from countries that have an effective legal system in place. In the fifth and last step of the study, it is looked at how the found factors are implemented in current feasibility studies to find whether there is a hiatus in these current feasibility studies. This is also as a start towards a more generalised implementation of feasibility studies.

Results from this report, which can be used by water managers and farmers, are an overview of the broader merits of MAR (sixteen were found), an extensive overview of (the fifteen) identified MAR techniques, and charts on the current usage of MAR. Here it was found that, according to the most-comprehensible inventory of MAR-sites available, Aquifer Storage (Transfer) and Recovery (ASR/ASTR) is the most popular MAR technique in agriculture. Additionally, in the study a multidisciplinary insight is created into the, for the feasibility of MAR, most important elements of the environmental, socioeconomic, and institutional contexts of MAR. Attention should always go to these elements when thinking about implementing MAR. For the environmental context, a list with eleven hydrogeological parameters that heavily influence the feasibility of MAR techniques is given, including how they influence this feasibility. Additionally, it was found that hydrogeochemical reactions can have adverse results on groundwater quality, even when the source water of MAR is of high quality. For the socioeconomic context and to improve the chances on reaching a clear economic case for a MAR project, several contingencies are identified that are typically neglected in economical MAR studies, the benefits are divided into direct and in-situ benefits and some guidance is given how these might be monetized, and an overview is given with the types of costs that should be incorporated in a standard economical MAR study. Lastly, several funding constructions are explained. For the institutional context, a method to smoothen the difficulties resulting from the cobweb of stakeholder contingencies is discussed. Additionally, a comparative study of the legal groundwater governance systems of Australia, the EU, and the USA resulting in an overview of strengths and weaknesses to draw lessons from is given. Additionally, (issues concerning) lacking transboundary groundwater governance systems are discussed. Lastly, when compared with implementation of parameters and elements in current feasibility studies for MAR around the world, it is found that hydrogeological factors are highly incorporated, but economic and environmental factors are (highly) under-represented. The institutional factors discussed in this report are not at all incorporated in current feasibility studies.

This report adds clarity to science, as information on MAR was up till now more fragmented. Additionally, the study has shown several, more specific knowledge gaps in the field of MAR, especially of quantitative origin on the use, output, and costs of MAR. The found insights in this report can aid in steering the global groundwater policy into a more sustainable direction, by improving the possibilities for a well-founded decision process.

Preface

In recent years (2018 onwards), the Netherlands, a country widely regarded as extremely water-rich, has begun experiencing more severe periodic droughts. When I started writing this report, the precipitation deficit in the Netherlands was higher than at that date in the driest year in (measured) Dutch history, and the KNMI (the Royal Dutch Meteorological Institute(and Rijkswaterstaat were anxious for the effects of the drought in the then upcoming period. In the end, also this most recent drought was survived, but these droughts have had big effects on many different aspects of Dutch political, financial, and environmental contexts. By investigating (a part of) the topic of droughts, I hoped to gain valuable knowledge from parts of the world where the water scarcity situation is currently more severe than in the Netherlands. This to potentially aid in my own understanding of how to alleviate the Dutch droughts in the future, assuming such events will become more and more frequent here as well, due to climate change.

With this report, which is my Bachelor thesis report, I conclude the bachelor phase of my study in Civil Engineering (CE) at the University of Twente, the Netherlands. The bachelor thesis is a research that commonly includes a somewhat practice-oriented or -based approach and is meant as a possibility for bachelor students to have a small taste of what it is like in the working field. Normally then as well, CE students conduct their bachelor thesis at an external organisation, typically a company or research institute in the civil engineering field. However, due to the interesting times the year 2020 has brought, I have conducted my thesis internally at the University of Twente, in the Multidisciplinary Water Management research group of the Civil Engineering Department. Together with my internal supervisors, I had opted for a research with as few dependencies from external parties as possible, to ensure the smoothest path possible towards finishing my bachelor programme. As a consequence, this study was fully based on literature review, which could have been rather monotonous. However, I was also given the opportunity to entirely create my own research, covering topics of my own interest and using a method of my own choosing. This ensured that my interest was fully captured from start to end, and thus did not fade throughout the quartile that I had to conduct it. Now, while writing this preface on the last day before sending in this final version, I can say that I have indeed learned a lot regarding integrated groundwater management, groundwater usage, water stress, and the possibilities and barriers of MAR in countering droughts. Moreover, I have noticed that I have experienced a substantial growth in my understanding of how one should conduct research.

As the (almost) final lines I write in this report, I would like to thank my supervisors, Rick Hogeboom and Fatemeh Karendish, for thinking along on how to tackle strange situation that followed the COVID-19 outbreak and guiding me through the research with valuable feedback, as well as Bas Krewinkel for his support on defining potential lines of research I could conduct from a work-from-home situation in the fields of my interest and his help when I was stuck and doubting on the best route to take to continue my research.

I am curious what the knowledge gained while conducting this research, might bring me in the future. I hope you enjoy reading this report as much as I enjoyed writing it, and that you find it equally valuable as well.

All the best,

Ype Willemsen

Enschede, the Netherlands

31 August 2020

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List of Abbreviations

ASR Aquifer Storage and Recharge

ASTR Aquifer Storage, Transfer, and recharge

CBA Cost-benefit analysis

CRF Capital recovery factor

DEMEAU Demonstration of promising technologies to address emerging pollutants in water and wastewater – An EU FP7 project

EC European Commission

EGD European Groundwater Directive

ENB Expected net benefits

EU European Union

EWP Economic water productivity

HDI Human Development Index

IC Capital investment costs of a MAR system

ILC United Nations International Law Commission

Inowas Innovative web-based decision support system for water sustainability under a changing climate

IGRAC International Groundwater Resources Assessment Centre

MAR Managed Aquifer Recharge

MARSOL Demonstrating MAR as a SOLution to water scarcity and drought – An EU FP7 project

NWI National Water Initiative

OC Operational costs of a MAR system

ORE Operational recovery efficiency

SABS South African Bureau of Standards

SAT Soil Aquifer Treatment

SES Socioeconomic status

SRE System recovery efficiency

TWW Treated wastewater

WTP Willingness to pay

WFD Water Framework Directive

Glossary of Terms

Aquifers or **aquifer systems** are three-dimensional continuous subsurface domains that serve as both a reservoir for groundwater and a preferential natural conduit for groundwater flow ('subsurface highway') (Margat & van der Gun, 2013: 41).

Aquifer (confined) is an aquifer below the land surface that is saturate with water. Layers of impermeable material are both above and below the aquifer (USGS, 2020a).

Aquifer (unconfined) is an aquifer whose upper water surface (water table) is at atmospheric pressures and have no impermeable layers above them. Also known as a *water-table aquifer.* (USGS, 2020a)

Barriers of MAR are situations that negatively influence the uptake of MAR. Barriers can potentially be alleviated by improving the provision of information surrounding and/or conducting additional research on said barrier.

Capital recovery factor is the ratio used to determine the present value of a series of equal annual cash payments. The ratio translates the present value of successive payments over a fixed amount of time.

Constraints of MAR are restrictions or limitations that play a constraining role in the uptake of MAR. Constraints are as they are, and can only be acknowledged by improving the provision of information on them, not adapted.

Economic value of water is the monetary amount that a rational user of a publicly or privately supplied water resource is willing to pay for it (Ward & Michelsen, 2002).

Economic water productivity is the value of monetary output obtained with one unit of monetary input (Economics Web Institute, 2001).

Factors are elements that influence the feasibility of a MAR project and can either be positive or negative. Examples are barriers and constraints.

Groundwater depletion or **groundwater overexploitation** is the prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes. The opposite is *Sustainable groundwater use.* (Bierkens & Wada, 2019)

Groundwater governance can be defined as the system of formal and informal rules, rule-making systems and actor networks at all levels of society that are set up to steer societies towards the control, protection and socially acceptable utilization of groundwater resources and aquifer systems.

Groundwater potentiality is the total amount of permanent storage that exists in an aquifer. It is the function of the porosities of the rocks and amount of open space in rocks that could store water (Kebede, 2013).

Groundwater recharge is the inflow of water to a groundwater reservoir such as an aquifer from the surface. Precipitation moving to the water table is one form of natural recharge.

Groundwater scarcity refers to the volumetric abundance, or lack thereof, of groundwater supply for human needs. Groundwater scarcity is one of four elements contributing to *groundwater stress*. (Schulte, 2014)

Groundwater stress refers to the ability, or lack thereof, to meet both human and ecological demand for groundwater. Groundwater stress considers several aspects related to water resources, including water scarcity, but also the demands regarding water quality, environmental flows, and the accessibility of water. (Schulte, 2014) When there is a sufficient volume of water, but of insufficient quality, there is no water scarcity, but there can be water stress.

Hydraulic conductivity of an aquifer is the rate of flow under a unit hydraulic gradient through a unit cross-sectional area of the aquifer (Duffield, 2019).

In-situ benefits of MAR are objectives of MAR systems that involve aquifer recharge of which the recovered water itself is no part.

Lateral hydraulic gradient in an aquifer is the horizontal (lateral) gradient of the groundwater. A high lateral hydraulic gradient means a steep, high velocity groundwater flow.

Managed Aquifer Recharge (MAR) is the purposeful (artificial) recharge of water to aquifers.

MAR method or **MAR technique** is a method used to facilitate managed aquifer recharge, such as aquifer storage and recovery or an infiltration pond.

Storativity of an aquifer is the volume of water released from storage per unit surface area of the aquifer per unit decline in hydraulic head. Also known as *storage coefficient* (Duffield, 2019).

Sustainable groundwater use is the prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities not exceeding average annual replenishment, nor causing unacceptable environmental or socioeconomic consequences. The opposite is *Groundwater depletion.* (Bierkens & Wada, 2019)

Vadose zone is the zone in the ground between the soil's surface and the groundwater table (Holden & Fierer, 2005).

Water Sensitive Design (WSD) is the design of sustainable water infrastructure, and can consequently be considered as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Water consumption is the portion of the withdrawn water lost from its source. The water is removed from available supplies without return to the water resource system (e.g., water used in manufacturing, agriculture and food preparation that is not returned to a stream, river, or water treatment plant).

Water withdrawal describes the total amount of water withdrawn from a surface water or groundwater source.

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1. Introduction

Some four billion people worldwide are affected by severe water scarcity for at least one month a year, while half a billion people even face severe water scarcity for the full year (Mekonnen & Hoekstra, 2016). Simultaneously, year-round water demand has increased almost six times between 1960 and 2010, with intensification of hydrological droughts as a result (Wada et al., 2013). In 2010, the total water demand was in the order of 3300 km^3 (Wada et al., 2014). The main reason for this increased water demand varies per region, but fit in two categories: i) population growth and/or higher demand for agricultural irrigation (e.g. Africa, western and central USA, the Mediterranean, Asia), and ii) higher per capita water demand based on changing life styles (e.g. north-western Europe, eastern USA) (Wada et al., 2013, 2014). Yet, Mekonnen and Hoekstra (2016) state that at the global level and on annual basis, enough freshwater is available to reach the demand, also when taking climate change and changing lifestyles into account. However, the large spatial and temporal differences present and with water availability becoming more variable throughout the year (Carden et al., 2018; Kuzma & Luo, 2020; Mekonnen & Hoekstra, 2016), Mekonnen and Hoekstra (2016) also reason that more frequent and severe periodic droughts will become reality, and the number of people affected by periodic water scarcity will only grow.

Due to surface waters being already exploited, since 2000, a flattening growth in surface water (e.g. lakes, rivers) withdrawal is visible, while the growth in demand for groundwater (from aquifers) has increased (Siebert et al., 2010). The third main fresh water source, desalinated water (e.g. from oceans), plays a neglectable role (Siebert et al., 2010).

Aquifers are naturally recharged. 30.1% of the Earth's fresh water is groundwater (USGS, 2016). To compare, surface water has a share of 1.3%. According to combined information by Margat (2008) and Margat and Van der Gun (2013), annual groundwater withdrawal (1000 km^3 yr^{-1}) is less than 8% of the global mean recharge (exceeding 12.000 km^3 yr^{-1}). However, singular aquifers can get depleted when their extraction is higher than their (natural) recharge (Gleeson et al., 2012). In the past decades, many aquifers are being depleted, due to it being a common pool resource and either neglection of or unconsciousness on groundwater being a finite resource and driven by the rising populational needs. (Gleeson et al., 2012; Mazzoni et al., 2018; Ross, 2016). In the period 1979 to 2010, the demand for groundwater has experienced a 70% growth (Wada et al., 2014). In Gleeson et al. (2012) it was estimated that the global groundwater footprint is currently 3.5 times the actual area of aquifers. Aeschbach-Hertig and Gleeson (2012) stated that the effects of groundwater depletion are complex and dependent on the aquifer, and include i) lowering of water tables leading to increased cost of pumping or drying up of wells; ii) reduced groundwater baseflow to streams, springs, and wetlands affecting ecosystems; and iii) land subsidence potentially damaging buildings and infrastructure. Moreover, lowered water tables can lead to salinization by saltwater intrusion in coastal regions. Similarly, groundwater depletion can promote the spread of other types of pollution. With 70.1% of the extracted groundwater being meant for agricultural irrigation, the expected rise in hydrogeological droughts will especially affect agriculture and hence the global food security (Siebert et al., 2010; Wada et al., 2014).

For many water stressed areas, water security and reliability do not necessarily depend on the absolute amount of precipitation, but on the fraction of water that is efficiently retained as storage for future use (Shiklomanov, 2000). As such, periodic water scarcity can be alleviated by storing water available during wetter periods for later use during dry periods (Maliva & Missimer, 2012). Coupling this with many aquifers being depleted and with the information given by Mekonnen and Hoekstra (2016), it is illustrated that management of the extraction and recharge of aquifers, or Managed Aquifer Recharge (MAR), is crucial for aquifer-dependent regions. MAR can be described as it being the purposeful artificial recharge of water to aquifers, e.g. for subsequent recovery or environmental benefit (Dillon et al., 2019). An interesting abstract by Sprenger et al. (2017: 1909) on the potential of MAR:

'In the face of numerous stresses on the availability of water such as climate change, increased weather variability, salinization, as well as increased urbanization of coastal zones and emerging substances, MAR has the potential to facilitate optimal (re)use and storage of available water resources and to take advantage of the natural purification and low energy requirements during MAR operations. (…) As globally, the pressure on freshwater supplies increases by growing water demand, intensified by continued urbanization, increased agricultural needs for food production and the desire to preserve ecosystem integrity, MAR is expected to be increasingly relied on.'

There are many different MAR techniques, from an underground dam to a pumping station that simply pumps water into the ground, and from infiltration ponds to rainwater harvesting and storage. These fit in five main groups: i) spreading methods, ii) in-channel modifications, iii) well, shaft and borehole recharge, iv) Induced bank infiltration, and v) rainwater and run-off harvesting (Stefan & Ansems, 2018). Each technique comes with its own set of risks, constraints and opportunities (Page et al., 2018).

Research on MAR has seen a huge increase in the past decades and currently several hundreds of scientific journal articles on MAR have been published (Dillon et al., 2019). These include among others suitability mapping studies, cost-benefit studies, effectiveness studies and risk assessment studies (Dillon et al., 2019). Throughout the years, MAR has proven itself to be a feasible option from an engineering point of view (IGRAC, 2020a). When properly executed, MAR has clear economic and ecological benefits, Dillon et al. (2019) argue. Due to the increase in research, many hydrogeologists are aware of the advantages of MAR (IGRAC, 2020a). However, it has proven to be difficult to create this awareness on MAR (i.e. what it is and how it can aid in water management schemes) among the majority of the organisations involved in decision making on the division of water supplies, such as water utility managers, water management agency officials, and political leaders (the 'water managers') (Dillon et al., 2019; IGRAC, 2020a). Consequently, often much costlier, but considered to be 'safe' solutions are preferred over MAR by the water managers (Sheehan, 2009).

An important reason for this is a lack of access to centralised and generalised, broad information on MAR (e.g. corresponding demonstration projects). Additionally, most studies are monodisciplinary. They typically only focus on the technical, hydrogeological aspects of MAR feasibility and largely neglect governance factors. This while factors such as culture, economics, authoritarian competency, environmental context and water rights can be as decisive for MAR's potential success as these hydrogeological factors, since groundwater schemes are entrenched in a web of interdependencies (Dillon et al., 2019; Van der Gun, 2012). In this, especially the frequent absence of a clear economic case seems to be important (Maliva, 2014). A report by IGRAC and Acacia Water (2007: 5) stated that '*MAR techniques are usually not stand-alone interventions but are part of a broader hydrological and water management system'* and it therefore is necessary to take the (integrated) risks of these broader factors into account, and that water managers are aware of their role. Another aspect due to which uncertainties and thus barriers grow for water managers, is the absence of common guidelines on setting up a feasibility assessment for potential MAR sites. As an example, when information that potentially has a high influence on MAR's feasibility, is missing, it currently is simply excluded from the feasibility study (Sallwey, Bonilla Valverde, et al., 2019). Consequently, a high variability in the inclusion and weighting of key aspects in the multicriteria decision analysis (MCDA) is present (Sallwey, Bonilla Valverde, et al., 2019).

The absence of well-available multidisciplinary information creates and/or maintains barriers restraining the implementation of MAR. By providing clear, combined information for farmers and water managers on what MAR and MAR's merits are, as well as showcasing where MAR has already been successfully implemented, and creating better insight in the broader factors of MAR playing a role the feasibility of its implementation and adapting the feasibility studies accordingly, a more well-founded decision process can be undertaken to come to a better, more cost-effective and sustainable decision.

2. Research Approach

2.1. Research goal

The following research goal has been formulated:

"The goal of this research is to inform farmers and water managers on MAR and MAR's potential merits, and provide insight in what influential factors they may encounter while conducting feasibility studies for MAR, by reviewing state-of-the-art literature on MAR theory and practical MAR cases."

2.2. Research questions

The main research question for the proposed research is as follows:

"How can Managed Aquifer Recharge aid in alleviating groundwater stress and is there a hiatus in the current inclusion of multidisciplinary factors influencing the uptake of MAR in feasibility studies?"

To solve this main question, several sub-questions have been established. These build from broad understanding on groundwater and the concept of MAR, to specific information regarding feasibility studies on MAR and what multidisciplinary factors influence this feasibility. First, current groundwater use and depletion are explored, to determine why and how much additional storage, potentially using MAR, is required. Second, MAR and its potential merits are explored to create a broader understanding on how MAR can aid in, among others, alleviating groundwater stress. Third, it is assessed how MAR currently already contributes to alleviating water stress. For this research question, the historical development will also be looked at. These results show whether MAR is useful and as such helps create more confidence in the possibilities of MAR. For the fourth research question, the factors influencing feasibility of MAR in different contexts are sought out. In the fifth and last research question, these factors are compared with the current implementation of these factors in feasibility studies to find whether there is a hiatus. The research questions are presented in Figure 1.

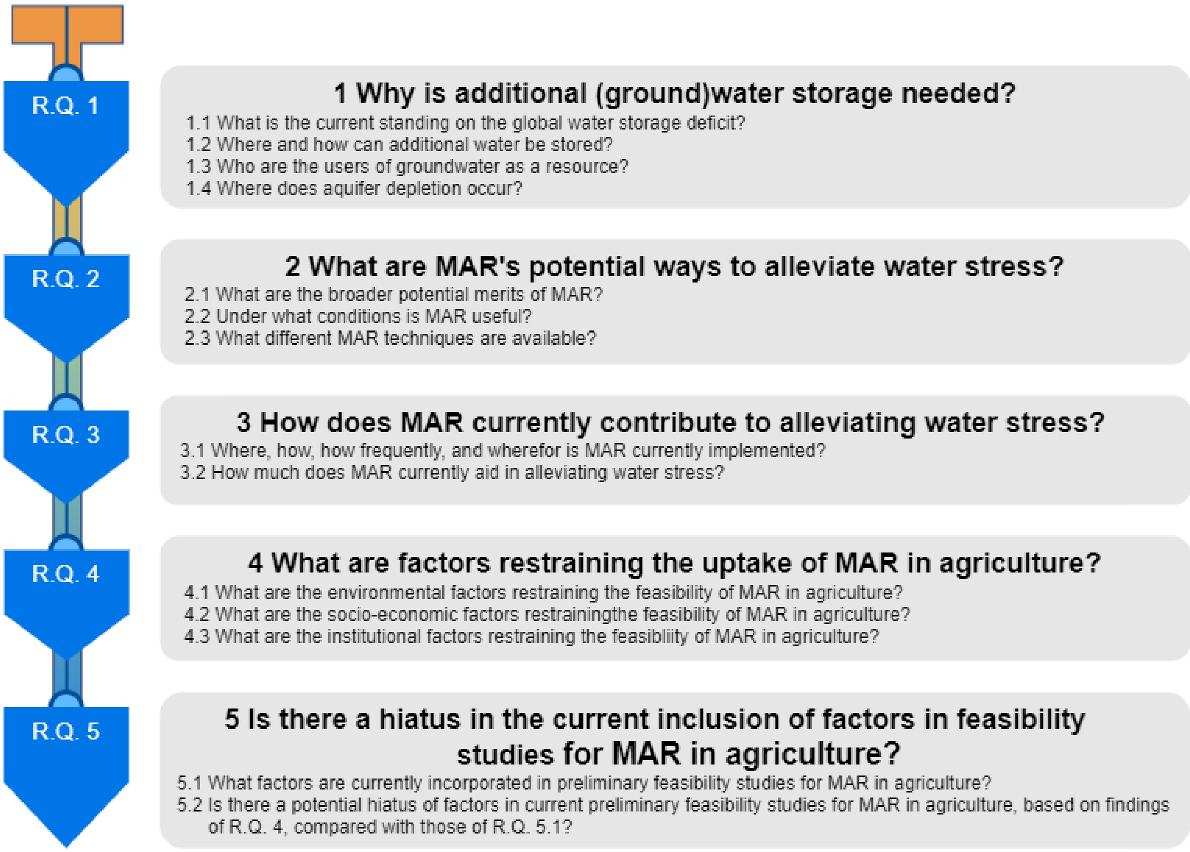

Figure 1 A schematic overview of research questions (R.Q.'s) in the study.

2.3. Research scope

MAR techniques are being discussed in a global context, bringing together field-focused research on (mostly) case-specific Managed Aquifer Recharge sites.

Because of the growing impact of agricultural irrigation on the global (ground)water systems, this research is focussed on MAR for agricultural end-use purposes.

Additionally, the physical aspects of MAR have been thoroughly assessed in other studies already. This research will touch on these physical aspects to be able to determine and understand the key-aspects within the physical risks but will not focus on it. The main focus will be on the influences of the socioeconomic, environmental and governance situations on MAR. The laws of nature will apply no matter what, hence acknowledging (instead of thoroughly understanding) the physical risks is deemed enough for this research.

In this research, 'factors' are elements that influence the feasibility of a MAR project and can either be positive or negative. 'Constraints' are physical limitations constraining the feasibility of a MAR project (e.g. that there should be water available) and cannot be changed by improved provision of information, but should be known. Barriers are situations that negatively influence the feasibility of a MAR project, but can potentially be alleviated by improving the provision of information surrounding and/or conducting additional research on said barrier. Both constraints and barriers are examples of a factor.

2.4. Research method

The method describes all methods that will be used to find the answers to the five research questions. First, a general narrative on the overall methodology is given. Hereafter, the research question-specific methodology is elaborated on, including a flowchart with the full research methodology.

2.4.1. Lesson drawing and policy transfer

Based on literature research, knowledge gaps have been identified. From these gaps, a research goal and several research questions have been set up. An important aspect in this goal and these questions are the interdisciplinary and integrated nature of the barriers in (highly) varying conditions and contexts. However, no existing framework has been found for systematically assessing the combined barriers from the different contexts. Therefore, in this research two known theories have been used to find these and use and compare data found in different contexts, to sufficiently answer the posed research (sub-)questions. These are the theories of i) policy transfer and ii) of lesson drawing. These theories are briefly described in Dolowitz and Marsh (1996: 344):

> *'Policy transfer, emulation and lesson drawing all refer to a process in which knowledge about policies, administrative arrangements, institutions etc. in one time and/or place is used in the development of policies, administrative arrangements and institutions in another time and/or place'*

According to Dolowitz and Marsh (2000), the theory of policy transfer assumes certain policy that's working in certain places, usually cannot be directly implemented in another place. Instead, the policy will have to be adapted to the new environment and contexts. This can be either voluntarily or forced (e.g. to receive funds from the International Monetary Fund, a country can be obliged to make certain policy changes). James and Lodge (2003) state that the theory of lessons drawing, where a 'lesson' is identified as 'a detailed cause-and-effect description of a set of actions that governments can consider in the light of experience elsewhere, including a prospective evaluation of whether what is done elsewhere could someday become effective here', assumes that policy makers try to learn from previous works' strengths and pitfalls on an certain issue or case, by rationally implementing the strengths and omitting the pitfalls. Therefore, in lesson drawing, a policy does not necessarily have to be transferred. This study will passively make use of the theory on policy transfer, by acknowledging MAR is not a solution to any and all water scarcity, water excess and water variability issues, but is bound to the environment's specific conditions and contexts (IGRAC, 2020b). No specific lesson drawing framework applying to MAR has been found in literature. Still, by comparing case studies and their differences, supported by literature research, it is possible to learn ('draw lessons') and determine general risks and constraints for MAR, as well as opportunities. Therefore, despite the absence of a framework, this study still will actively make use of the theory on lesson drawing.

2.4.2. Literature studies

Literature data collection has been the main type of data collection for this report. For this, a search for relevant studies was carried out collecting scientific papers, conference proceedings, freely available written reports and (educational) books on groundwater and MAR, either in English or in Dutch. For this, several search engines were used, as well as through reference lists of already found literature, and recommendations from the supervisors involved in this report and others working in the field of water management. The most-used search engines and databases of scientific literature were Google Scholar, the Mendeley-database, ResearchGate, ScienceDirect, Scopus, SpringerLink, and the online library of the University of Twente. Research terms included: aquifers (hydrogeology), artificial aquifer recharge, AS(T)R/aquifer storage(, transfer) and recharge, cost-benefit studies MAR, economics of MAR, groundwater (availability/depletion/scarcity/use), MAR/managed aquifer recharge, and MAR feasibility studies, and specifications of these into agriculture and irrigation.

The literature research conducted in the first research question is quantitative. If applicable, qualitative information is given, for example on potential locations for additional water storage. The second research question's literature research is however mostly quantitative, i.e. mainly descriptive notes on the different potential merits of and techniques for MAR. Although qualitative data, especially regarding costs and capacities of the different MAR techniques was looked for, limited literature on it was found. The third research question contains a combination of qualitative and quantitative information, as is the fourth research question. Where available in the found literature, the quantitative information is presented, i.e. the output of MAR, the values for the transmissivity of an aquifer and what that means for an aquifer's potentiality, and the (threshold) values of chemical substances in the groundwater. However, and especially for the fourth research question, the qualitative information serves as the thread running through the given information.

Key references in this report are presented in Table 1.

Table 1 Key-references used in this report.

Research question	Heading	Key reference(s)
1.1	3.1	(Maliva & Missimer, 2012; Richey et al., 2015)
1.2	3.2	(Margat & van der Gun, 2013; Tuinhof & Heederik, 2003)
1.3	3.3	(Bierkens & Wada, 2019; Siebert et al., 2010; Wada et al., 2014)
1.4	3.4	(Bierkens & Wada, 2019; Gleeson et al., 2012; Richey et al., 2015)
2.1	4.1	(Maliva & Missimer, 2012; Van Lidth de Jeude & Bierkens, 2016)
2.2	4.2	(Van Lidth de Jeude & Bierkens, 2016)
2.3	4.3	(Gale, 2005; IGRAC & Acacia Institute, 2007; INOWAS, 2018; Maliva & Missimer, 2012)
3.1	5.1	(Hannappel et al., 2014; IGRAC, 2020a; Sprenger et al., 2017; Stefan & Ansems, 2018)
3.2	5.2	(IGRAC, 2020a)
3.3	5.3	(Dillon et al., 2019)
4.1 (Environ-mental)	6.1.1	(Gale, 2005; Grützmacher & Sajil Kumar, 2012; Jimenez & Asano, 2015; Maliva & Missimer, 2012; Margat & van der Gun, 2013; Murray, 2009; Şen, 2015; Vanderzalm et al., 2020; Wolf et al., 2007)
4.1 (Eco-nomical)	6.1.2	(Damigos et al., 2017; Maliva, 2014; Maréchal et al., 2020; F. A. Ward & Michelsen, 2002)
4.1 (Insti-tutional)	6.1.3	(Brunner et al., 2014; Capone & Bonfanti, 2015; European Commission, 2010, 2014; Gale et al., 2006; Garduño et al., 2010; Ross, 2016)
5.1	6.2	(Sallwey, Bonilla Valverde, et al., 2019)
5.2	6.3	(Sallwey, Bonilla Valverde, et al., 2019)

2.4.3. Research question-specific methods

See Figure 2 for a full overview of the steps within research questions and the paired method to conduct this step. In this flowchart, the line of reasoning and structure of the steps within the research question is shown. Hereafter, the five research steps are explained in more detail.

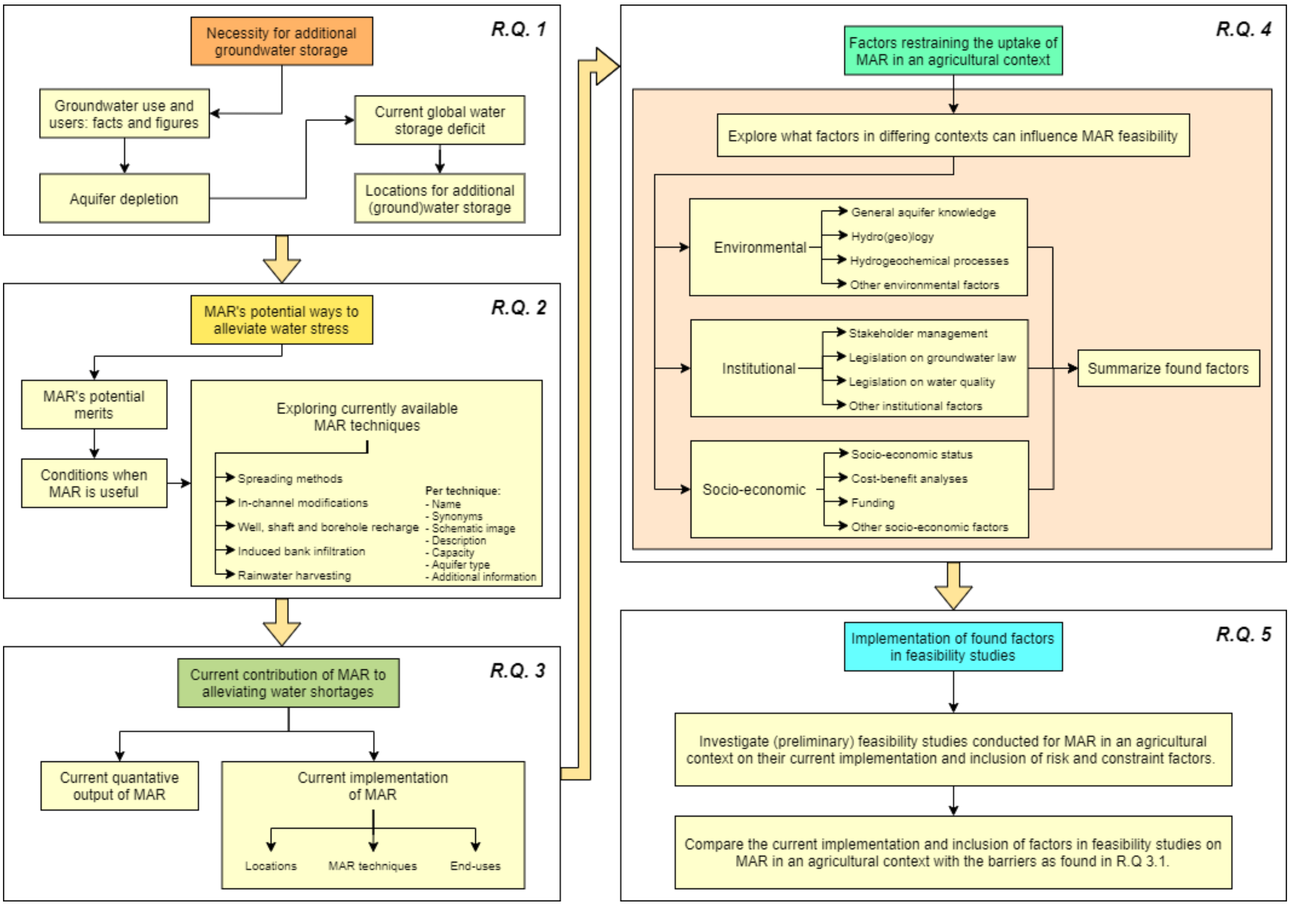

Figure 2 A flowchart of the complete research method.

R.Q. 1; Why is additional (ground)water storage needed?

For the first research question literature review has been conducted on the background of groundwater use. Firstly, the current quantitative worldwide use of groundwater, specifically in agriculture, is explored and coupled with the (severity of the) global groundwater depletion. Next, the water storage deficit to overcome the droughts, among others related to the groundwater depletion, is assessed, and coupled with possible ways and locations for additional (ground)water storage.

This resulted in a rather straight-forward inventory of information on water storage and groundwater use and depletion, as well as showing, on a global scale, where additional groundwater storage is possible.

The results serve as setting of the background of this report.

R.Q. 2; What are MAR's potential ways to alleviate water stress?

For the second research question, different potential merits of MAR are looked for, as it can aid in more than only replenishing the depleted aquifers. Furthermore, a literature study is performed on the currently available MAR techniques. For this, the framework proposed by Van Lidth de Jeude and Bierkens (2016), the first of its kind, is utilized. In this framework, for each MAR technique the elements as stated in **Error! Reference source not found.**, such as their costs and capacity, are presented, if available.

This research question resulted in a substantive inventory of MAR-techniques and an enhanced knowledge on wherefor, how and where these techniques can be used.

This information can serve as foundation for a better understanding of MAR and MAR's merits.

R.Q. 3; How does MAR currently contribute to alleviating water stress?

In this research question, the current contribution of MAR to alleviating water stress was explored. For this, there was looked at where MAR is already being implemented, and what techniques are used for what end-uses. This is a numerical study only looking at the number of MAR sites. Additionally, the current quantitative output of MAR is examined, to determine MAR's contribution in the global (ground)water scheme.

This inquiry has resulted in a quantified inventory of information on MAR's implementation and output.

This information may serve as foundation for trust in MAR for future projects. For this, lesson drawing has an important function. Using the information gathered in this research question, it becomes clear in what regions and in what conditions a certain MAR-technique seems to work (otherwise it wouldn't exist), which then, using the theory on lesson drawing (James & Lodge, 2003), can be translated to the MAR-technique potentially also working in the water manager's region.

R.Q. 4; What are factors restraining the uptake of MAR in agriculture?

For the fourth research question, a desk study has been performed on the underexposed factors influencing the feasibility of MAR in agriculture. According to Jakeman et al. (2016), the most prominent and influential on the feasibility of MAR of these are oftentimes in the environmental (including the aquifer's hydrogeology), socioeconomic, and institutional contexts. Therefore, this report has further focussed on the factors in these three contexts to explore what influences and restrains the uptake of MAR. To do so, MAR in general and, if applicable and possible, specifically aquifer storage (transfer) and recharge (AS(T)R) as the most-used MAR technique in agriculture (based on the output of R.Q. 3.1), have been investigated. This one MAR technique is seen as exemplifier for other MAR techniques and represents MAR in agriculture in general. For this, general MAR literature has been extensively used, as well as specific case studies to get a better grasp on e.g. the water quality-related risks of MAR.

This investigation has resulted in a broad overview of quantitative as well as qualitative information on factors influencing feasibility of MAR in agriculture, and of ASR/ASTR specifically.

With this information, one of the main issues with knowledge on MAR, namely the fact that it is not centralised and literature is almost always monodisciplinary, is somewhat lessened. As such, water managers as well as farmers can have an improved understanding of what they should keep in mind about MAR, both positive and negative, when thinking about implementing MAR and what should be incorporated in feasibility studies for MAR.

R.Q. 5; Is there a hiatus in the current uptake of factors in feasibility studies for MAR in agriculture?

Current feasibility studies on MAR are highly variable in the factors they incorporate, resulting in, overall, lower quality feasibility maps and consequential lower trust in MAR by water managers (Sallwey, Bonilla Valverde, et al., 2019). By reviewing literature on the implementation of the GIS-MCDA in MAR, such as Sallwey et al. (2019), key-criteria and their weights for a feasibility assessment can be extracted and a generalized framework might be set up. The found criteria currently incorporated in feasibility studies have been coupled with the factors found in the three contexts investigated in R.Q. 4. This since factors that are currently not included in feasibility studies, but potentially should be, are otherwise overlooked. As such, possible hiatus were looked for in the incorporated criteria in current preliminary feasibility studies.

This research question has resulted in improved insight on what factors are incorporated most often in current feasibility studies, as well as on potential hiatus of factors from underexposed contexts, as a start towards a more standardized GIS-MCDA set-up for MAR feasibility studies.

This information can initiate further analyses into which factors should be included in preliminary feasibility studies, including their weighting. This can eventually result in MAR being regarded by both water managers and farmers as a more trustworthy method to counter water stress in agriculture. It should also be noted that this research aimed at providing a basis on which factors need to be considered for a more standardized framework on the incorporation of different criteria in feasibility studies for MAR. It has not aimed to develop that framework itself.

3. The need for additional groundwater storage

3.1. Groundwater use

Most of the quantified assessments of global water resources had a focus on surface water (Alcamo et al., 2003; Oki & Kanae, 2006; Postel et al., 1996; Vörösmarty et al., 2000). More recently, focus has shifted towards quantifying the groundwater withdrawal as well (Döll et al., 2012; Hanasaki et al., 2018; Konikow, 2011; MacDonald et al., 2012; Richey et al., 2015; Rodell et al., 2009; Wada et al., 2010, 2012; Wada & Bierkens, 2014) The quantified results of these authors have a variability, as they have looked into differing years and timespans, used differing sources and were either data driven or model based. These show that it remains difficult to accurately assess the groundwater withdrawal (Bierkens & Wada, 2019). In recent studies, the water withdrawal for the year 2000 gave results in the order of 700 to 900 km^3 yr^{-1}, whereas for 2010 a withdrawal of 950 - 1100 km^3 yr^{-1} holds (Bierkens & Wada, 2019). Compared to 1% annual increase in surface water extraction in the period 1990 to 2010, groundwater extraction has annually increased by 3% (Wada et al., 2014). Wada et al. (2014) mention that this higher percentage is most likely because surface water sources are already largely exploited. Wada et al. (2014) estimated that in 2010, groundwater was the source of 34% of the water withdrawal and 44% of the water consumption. In this, it is important to differentiate between regions, as there are large regional deviations in groundwater use, and as such, improved groundwater management is not in each region equally urgent. In general, regions with high groundwater use are more urgently in need of groundwater management (Dillon et al., 2019). The groundwater use is relatively high in (semi) arid regions, such as northern Africa, the Middle-East, north-western India and central USA (Siebert et al., 2010; Wada et al., 2014). In some countries it constitutes the principal source of supply (Margat & van der Gun, 2013; Wada et al., 2014). An extensive, regionalised overview of data on water withdrawal and groundwater's share therein is presented in Appendix A.

The sectors using groundwater can be divided in four sectors: domestic, agriculture, industry and ecosystems (Margat & van der Gun, 2013). The importance of groundwater in each of these sectors as well as the sector's relative importance in the global groundwater scheme, differ. Based on data presented in various literature, a short overview has been created and presented in Table 2. From this, the importance and influence of agriculture in the global groundwater withdrawal is evident, with a share of over 70%.

Table 2 Overview of key-data per sector of groundwater users.

Sector of usage	Groundwater's share in sector's global usage		Sector's share in global groundwater withdrawal	
Domestic	36%	(Margat & van der Gun, 2013)	21.2%	(Margat & van der Gun, 2013)
Agriculture	42%	(Döll et al., 2012; Siebert et al., 2010)	70.1%	(Siebert et al., 2010; Wada et al., 2014)
Industrial	22%	(Margat & van der Gun, 2013)	8.7%	(Margat & van der Gun, 2013)
Ecosystems	No data		No data	

Groundwater is so popular as source for agriculture, because it often is the '*most easily and individually accessible'* source of irrigation water for farmers (Margat & van der Gun, 2013). Additionally, it often has the lowest exploitation costs and is in many cases the '*most flexible source in daily practice'* for farmers (Margat & van der Gun, 2013). In total, some 545 km^3 groundwater is annually consumed in agriculture, mostly as a result of the evapotranspiration of the crops (Siebert et al., 2010).

As with water withdrawal in general, the contribution of groundwater in agricultural water withdrawal and consumption varies largely per region (see Table 3). Especially in arid regions or where surface water is difficult to control, groundwater is the main source for irrigation (Margat & van der Gun, 2013).

Table 3 Regional data on Irrigational Consumptive Water Use (ICWU) and groundwater's (GW) share therein. Source: Siebert et al., 2010

Region	ICWU ($km^3\ yr^{-1}$)	ICWU_GW ($km^3\ yr^{-1}$)	GW share
South Asia	463	262	57%
Middle East	131	71	54%
Northern America	186	100	54%
Central America	224	107	48%
World	**1277**	**545**	**43%**
Western and central Europe	43	17	40%
East Asia	167	57	34%
Northern Africa	65	16	25%
Eastern Europe	5	1	20%
Oceania	16	3	19%
Southern America	34	6	18%
Central Asia	68	5	7%
Sub-Saharan Africa	33	2	6%
South-East Asia	60	3	5%

Table 4 gives an overview of the most important data.

Table 4 Quantified key-data on water withdrawal

Key-data type		Value ($km^3\ yr^{-1}$)	Source
Global	Total water withdrawal	3277	Wada et al. (2014)
	Total water consumption	1650	Wada et al. (2014)
Groundwater	Groundwater withdrawal	1113	Siebert et al. (2010)
	Groundwater consumption	712	Wada et al. (2014)
Agriculture	Water withdrawal for agriculture	2294	Siebert et al. (2010)
	Groundwater withdrawal for agriculture	964	Döll et al. (2012), Siebert et al. (2010)
	Groundwater consumption for agriculture	545	Siebert et al. (2010)

Based on a wide variety of sources, Siebert et al. (2010) has estimated how much surface area equipped for irrigation was irrigated with groundwater. From this a map followed, as presented in Figure 3, with that data on country-level and smaller. The regions in red (groundwater dependency of >55%) can be classified as currently aquifer dependent regions, and will typically have an additional need for good groundwater management (Dillon et al., 2019; Gale, 2005; Siebert et al., 2010). Notably these are: Northern Africa, the Middle East, the Republic of Iran, western India, China, and the USA and Mexico.

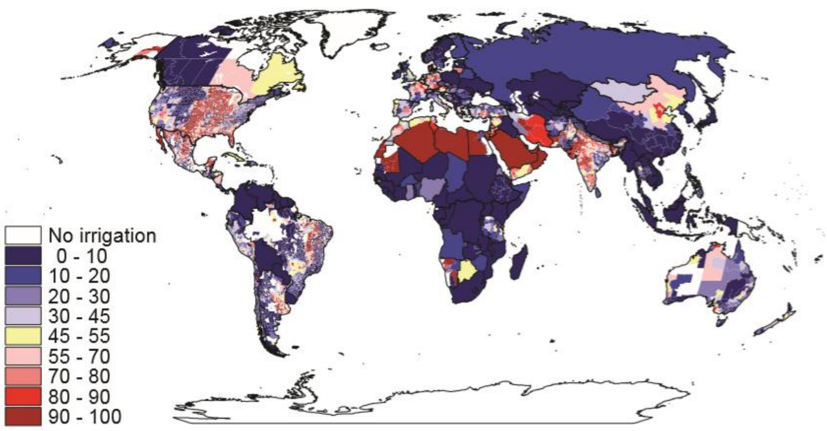

Figure 3 Percentage of area equipped for irrigation that is irrigated with groundwater. Source: Siebert et al., 2010: 1871

3.2. Groundwater depletion

With a grow in quantified research into groundwater withdrawal, also unhealthy groundwater depletion rates came to light. In this research, the definition of groundwater depletion as defined by Bierkens and Wada (2019: 3) is used: '*the prolonged (multi-annual) withdrawal of groundwater from an aquifer in quantities exceeding average annual replenishment, leading to a persistent decline in groundwater levels and reduction of groundwater volumes*'. As with groundwater withdrawals, significant variations in the results on groundwater depletion are visible in recent literature. For the year 2000, estimated depletion ranged from 113 $km^3\ yr^{-1}$ to 510 $km^3\ yr^{-1}$. However, if this is looked at, all researches show a growing trend in groundwater depletion in time. Bierkens and Wada (2019: 14) have summarized the outcomes in these researches as given in Table 5.

Table 5 Global estimates of groundwater depletion.

Reference	Groundwater depletion ($km^3\ yr^{-1}$)	Year
Wada et al. (2010)	126 (±32)	1960
	283 (±40)	2000
Konikow (2011)	145 (±39)	2000-2008
Wada et al. (2012)	64 (±16)	1960
	204 (±30)	2000
	295 (±47)	2050
Döll et al. (2014)	113	2000-2009
Wada and Bierkens (2014)	90	1960
	304	2010
	597 (±85)	2099
Yoshikawa et al. (2014)	510	2000
	1150	2050
Hanasaki et al. (2018)	182 (±26)	2000

The improved awareness on the importance of groundwater in the global cycle has led to (unrelated) inventories of unsustainably managed aquifers from Gleeson et al. (2012) and Richey et al. (2015). The prior introduces the groundwater footprint for aquifers, which is then used to assess the impact of groundwater consumption on the natural stocks and flows. The latter compares found data on the ratio between groundwater use and availability with satellite data. Gleeson et al. (2012) mentions that the increased groundwater demand has resulted in 20% of world's aquifers being (heavily) overexploited and under direct stress, most prominently in south-western Asia, the Middle East and northern America. The 'highest scoring' main aquifers are the Upper Ganges (overexploited 54.2 times), Upper Arabian (overexploited 48.3 times and the South Arabian (overexploited 38.5 times) aquifers (Gleeson et al., 2012). Richey et al. (2015) even states that ⅓ of the world's 37 largest aquifers are overexploited. See also Figure 4 from Gleeson et al. (2012). The depleted aquifers largely correspond with the aquifer-dependent regions for agriculture, that was discussed in section 3.1. Dillon et al. (2019) state that, in general, 15% of all groundwater extraction is unsustainable, and that this often happens in areas with already large water scarcity issues. According to Gleeson et al. (2012), 1.7 billion people live in areas under threat of groundwater resources being depleted and/or where groundwater-dependent ecosystems are under threat. This shows that, if groundwater is to be used even more, it will be key to implement groundwater management methods, and that all water available should be used effectively and efficiently. This especially holds for arid regions. Managed Aquifer Recharge (MAR) is one of these methods.

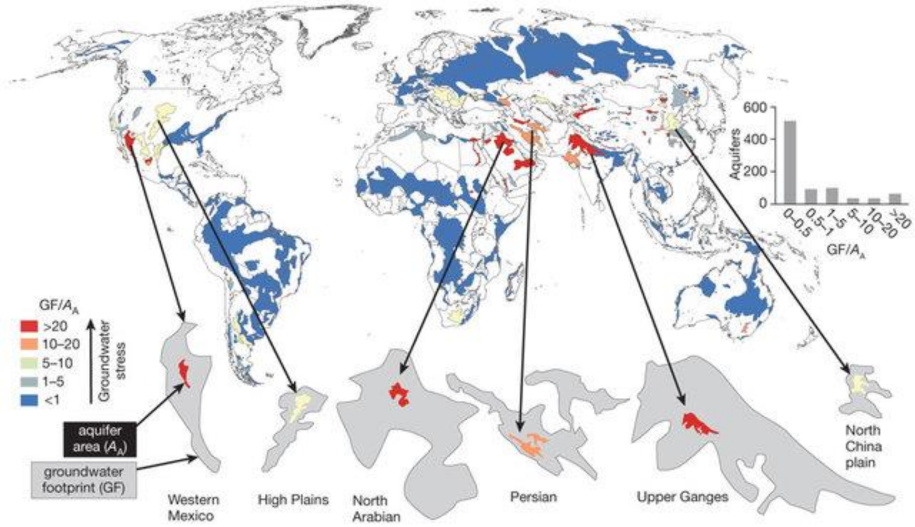

Figure 4 Groundwater footprint of aquifers; a first estimation. Source: Gleeson et al., 2012: 198

3.3. Water storage deficits

The effects of droughts can be lowered by creating a larger buffer of additionally stored water, in such a way that the (locally) present water in the 'wet' season, can be used in the 'dry' season (Maliva & Missimer, 2012). In general, it can be stated that the required additional storage volume should be similar to the water storage deficit (Maliva & Missimer, 2012). No quantified information on the global deficit was found in literature, but some regional data, i.e. for several droughts in the Amazon and in south western China, is available in Richey et al. (2015) and Chao et al. (2016). To achieve a quantified, global overview of the global deficit, additional water scarcity assessments of sufficiently detailed level (keeping in mind that the droughts' occurrence is highly spatial) should be undertaken (Richey et al., 2015). As such, no clear answer can be given to *how much* the local and/or regional water storage capacities should be enlarged on a global scale to be able to mitigate the increasing (number of) droughts, but it is clear *that* it should be enlarged.

3.4. Additional (ground)water storage

Enlarging the water storage capacity is possible in a variety of ways. Tuinhof and Heederik (2003) mention that, in general, five ways of storing water can be distinguished:

- Closed tank storage (e.g. rainwater storage in tanks for potable water);
- Water conservation in the soil profile or surface storage in depressions (e.g. a wet soil);
- Subsurface storage on different scales (e.g. by managed aquifer recharge);
- Storage in small dams and reservoirs;
- Storage in large dams and reservoirs.

In these, the first two are mainly for short-term water storage and only store relatively small amounts of water, whereas the other three storage options often cover longer periods (weeks, months, years) and concern relatively large quantities (Tuinhof & Heederik, 2003). Surface water storage, with dams, has always been the most popular way of storing water, but due to among others population growth and higher competence of land, good sites for dams have become more scarce (Bouwer, 2002). When there is a wish to store large quantities of water, only subsurface (aquifer) storage and above-surface storage in large dams and reservoirs are feasible options (Keller et al., 2000). In Appendix B, a comparison of these are given, based on Keller et al. (2000) and Tuinhof and Heederik (2003). Notable points of data from this comparison are:

- Development costs for additional aquifer recharge are generally lower than surface water reservoirs;
- Development risks for additional aquifer recharge are often less than perceived, while those of surface water reservoirs are often higher than assumed;

- Evaporation losses for additional aquifer recharge is much lower than of surface water reservoirs, but, dependent on the soil type, hydrogeological losses can be higher.

In many cases additional water storage in aquifers should be the preferred option (Dillon et al., 2019). How much water can be stored in aquifers, is dependent on the subsurface type. With regards to water storage potential, Struckmeier and Margat (1995) identified three different classes, based on the dominant type of the aquifer medium combined with the degree of structural complexity.

- Class A (blue): Major groundwater basins. The aquifers they include may range from shallow unconfined aquifers to deep confined aquifers. The major groundwater basins have significant volumes of groundwater in storage, they contain highly productive aquifers and may include artesian zones (flowing wells).
- Class B (green): (green): Areas of complex hydrogeological structure. They include rather productive local aquifers, in particular karst or volcanic aquifers, shallow or deep, and with significant storage.
- Class C (brown): Areas with only local and shallow aquifers. This class includes alluvial aquifers and aquifers in weathered or fissured rock. Stored groundwater volumes are small.

Based on findings by Margat and Van der Gun (2013), 35% of the continental land area is highly suitable for groundwater storage and fits in Class A of the classification of Struckmeier and Margat. 18% fits in Class B and is moderately suitable. 47% of the world's surface is only marginally suitable for groundwater storage and fits in Class C.

Richts et al. (2011) have visualized the information of Struckmeier and Margat (1995) in a map and combined the intensity of the estimated mean annual groundwater recharges with it. The map is shown in Figure 5. In the map, a lighter colour tone means a lower estimated groundwater recharge rate. This is for the most part influenced by the local and regional precipitation rates.

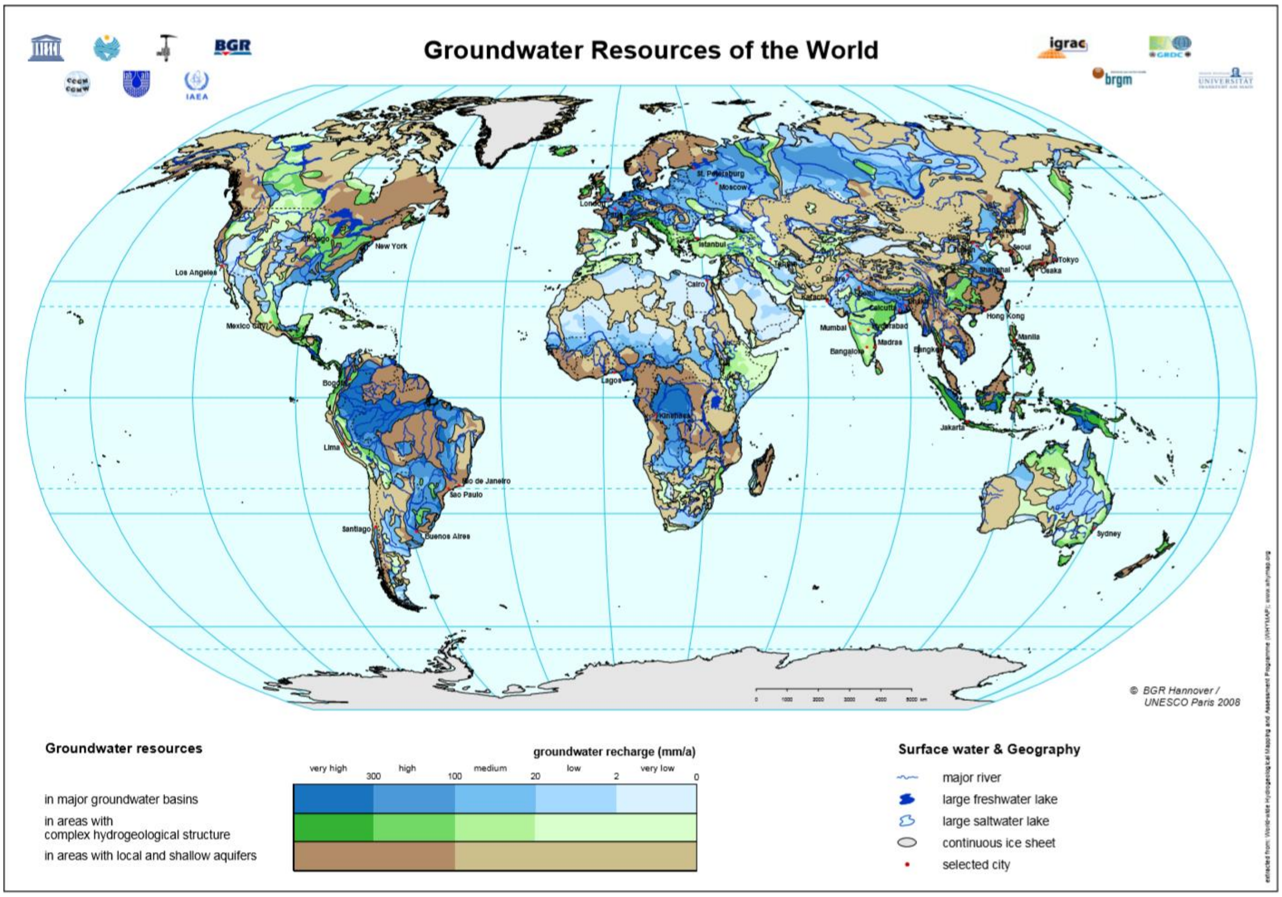

Figure 5 The groundwater resources around the world. Source: Richts et al., 2011: 164

4. Ways in which MAR can aid in alleviating water stress

4.1. Potential merits of MAR

MAR can aid in alleviating water scarcity issues, as it helps storing additional water in the ground. (Maliva & Missimer, 2012). There are also several other potential objectives for using MAR. In a literature review into opportunities of MAR by Van Lidth de Jeude and Bierkens (2016), sixteen objectives have been extracted. These can be divided into three groups: i) climatic threat to counter droughts, ii) climatic threat to counter water excesses, and iii) general objectives for using MAR. In Figure 6, a flowchart with a schematic overview of these potential objectives is given, based on Van Lidth de Jeude and Bierkens (2016). It should be noted that several objectives have overlap and can be applicable simultaneously. This is also what makes it interesting to investigate the broader potential merits of MAR, instead of focussing solely on the water storing and extraction capabilities of MAR. Most found objectives apply for regions where droughts occur. Moreover, four potential objectives of MAR have been found that can be applicable in all situations and are not necessarily influenced by (secondary) climate threats: store water for long term storage, smooth out demand/supply fluctuations, improvement of water quality, and providing water for multiple uses. In light of this report, the two most interesting merits are smoothing out demand/supply fluctuations and creating a buffer capacity for droughts.

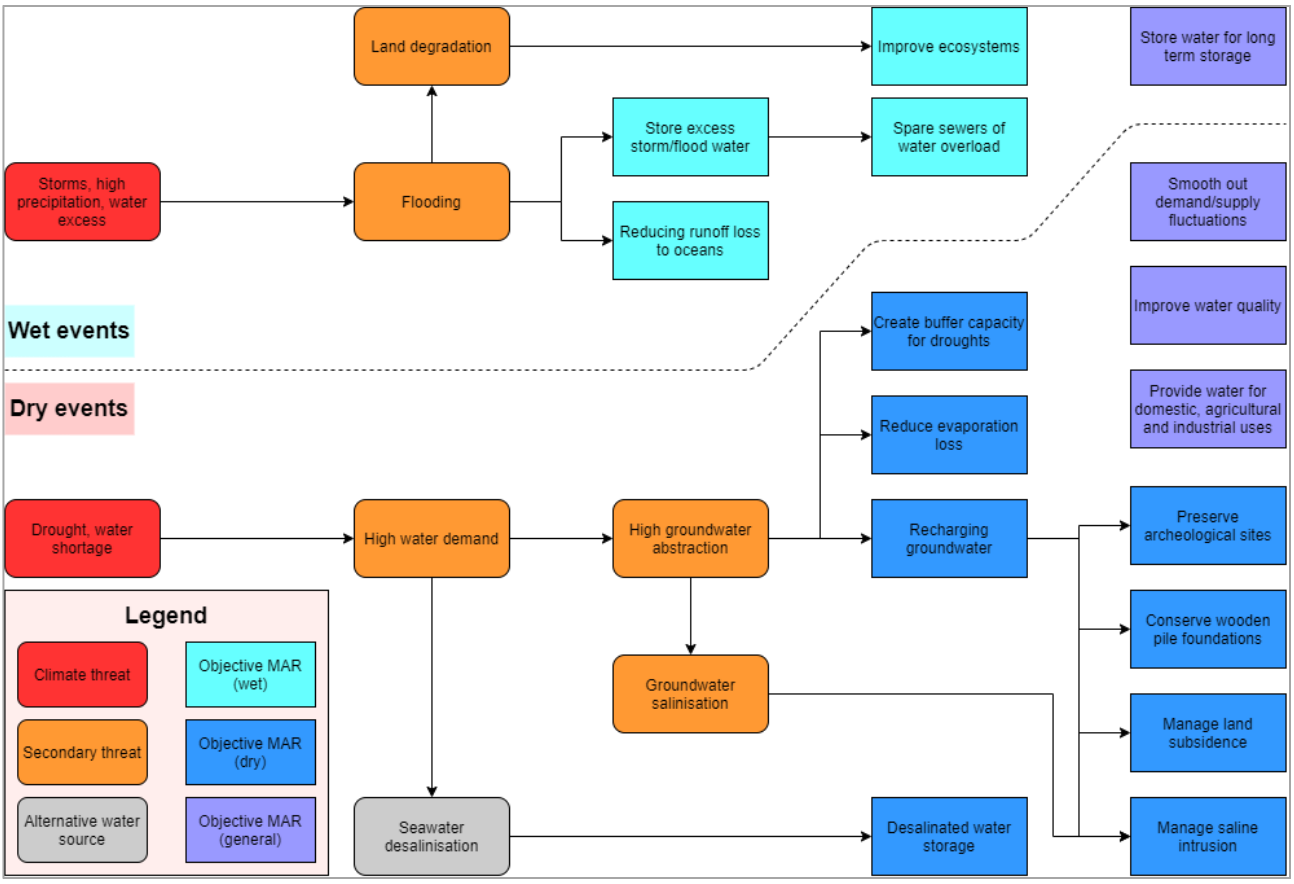

Figure 6 Flowchart with the potential objectives of MAR, divided per event-type the objective is applicable to.

Most of the found potential objectives are for medium to long term time spans, while only three of the sixteen potential objectives ('store excess storm/flood water', 'reducing runoff loss to oceans', and 'spare sewers of water overload') are meant for short-term, rapid storage. Additionally, most objectives are meant for water quantity management, while only three of the sixteen found potential objectives ('Improve water quality', 'manage land subsidence', and 'improve and sustain ecosystems') are related to water quality management.

4.2. Regions where MAR is useful

Van Lidth de Jeude and Bierkens (2016) argue that, based on the list of potential objectives as given in section 4.1, MAR might be especially desired in regions with the following conditions:

- High seasonal rainfall peaks
- Flooding
- High evaporation
- Drought vulnerable
- Over-exploited aquifers
- Land subsidence
- Salinization of groundwater
- Desalinization plants

In the remainder of this report, there will be focussed on regions that are vulnerable for droughts and/or are dependent on (currently over-exploited) aquifers, since these are the most pressing issues on a global scale (Döll et al., 2012; Kuzma & Luo, 2020; Mekonnen & Hoekstra, 2016; Siebert et al., 2010; Van Lidth de Jeude & Bierkens, 2016; Wada et al., 2013).

4.3. Techniques for MAR

There are five main types of MAR techniques (Stefan & Ansems, 2018). These were also classified by Gale (2005). These main types are further categorized in fifteen sub types of MAR techniques. The (sub) techniques are presented in Table 6. Many techniques require low levels of technology and can be implemented with little engineering knowledge, such as water harvesting and water bunds (Gale, 2005). Well digging skills have been in use for millennia, with the oldest wells found on Cyprus dating back to 7500 BC (Ashkenazi, 2012), but the techniques have been increasingly developed over past generations (Gale, 2005). More engineering design and knowledge is required for sand storage dams, spillways to river banks and perennial dams, increasing further when drilled wells and boreholes for injection or for aquifer storage and recovery are to be used (Gale, 2005). Gale (2005) further states that, although the principles are relatively simple, for efficient operation of spreading basins and infiltration techniques, sound understanding of physical, hydraulic, microbiological and geochemical processes in operation are crucial. Additionally, roof top rainwater harvesting has similar issues, mentions Gale (2005). For all five the main types, water is recharged into the aquifer either by gravity, or using machinal pumping. The five main types are addressed in the subsections below. An inventory of available MAR techniques giving a systematic, more detailed look on them individually is given in Appendix B. There, if available in literature, information is given on the technique's description, capacity, aquifer requirements and additional information on e.g. the costs, and will also include a schematic image. In Figure 7, a hypothetical example of a water system in which several of these MAR techniques are combined, is shown as visualisation.

Table 6 MAR (sub) techniques, based on Gale (2005).

Spreading methods	In-channel modifications	Well, shaft and borehole recharge	Induced bank infiltration	Rainwater harvesting
Infiltration ponds	Percolation ponds	Shallow wells and shafts	Bank filtration	Field bunds
Soil Aquifer Treatment (SAT)	Sand storage dams	Aquifer Storage and Recovery (ASR)	Inter-dune filtration	Rooftop rainwater harvesting
Controlled flooding	Subsurface dams	Aquifer Storage Transfer and recovery (ASTR)		
Incidental recharge from irrigation	Leaky dams and recharge releases			

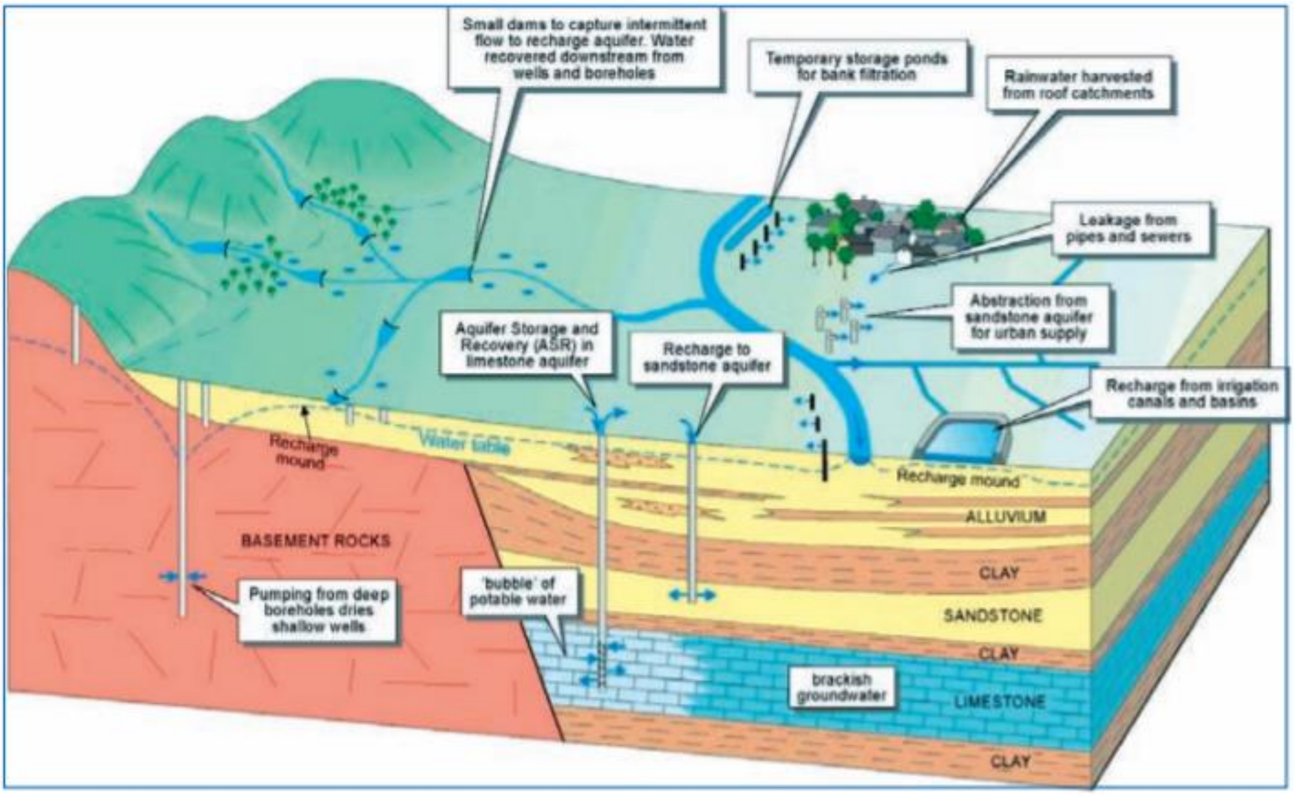

Figure 7 MAR techniques in a water system. Source: Gale, 2005: 10

4.3.1. Spreading methods

Water spreading methods are MAR techniques where water is directly infiltrated from the surface into the groundwater system. These are the most simple and oldest techniques to apply (Maliva & Missimer, 2012) and have the aim to increase contact area and residence time of surface water over the soil to enhance the infiltration (Indian Central Ground Water Board, 2007). For water spreading to be effective, several hydrogeological conditions are required (Gale, 2005; Indian Central Ground Water Board, 2007). For example, the aquifer needs to be unconfined and sufficiently thick to provide storage space. Furthermore, the surface soil, the vadose zone, and the aquifer itself should be permeable. Additionally, the aquifer should be at or near the ground surface, since a thicker vadose zone lowers the infiltration rate. Lastly, the aquifer material should have moderate hydraulic conductivity, to ensure the recharged water is retained for sufficiently long periods in the aquifer and can be used when needed. An important benefit of spreading methods is the filtering function the surface and soil have for the recharged water. Additionally, evaporation rates are minimized and only play a minor role in the water balance, Gale (2005) mentions.

The most prominent potential issue with spreading methods is clogging (Gale, 2005). When clogging occurs, filter skin is created at the bottom and/or sides of a spreading basin, lowering the permeability of the surface. In Gale (2005), several options to counter clogging are given as well, depending on the specific technique that is used. For example, mechanical treatment of the recharge water by primary sedimentation is advised to remove suspended solids. Also, mechanical treatment of the soil by ploughing is given as an option to increase permeability. Furthermore, chlorination of the recharge water might be feasible to inhibit the microbial activity, and by using a rotational system of water spreading and drying and subsequent scraping of the basin, the infiltration rates can be restored.

4.3.2. In-channel modifications

In-channel modifications intercept water where it runs off in order to have water retention and storage. They include various modifications to the stream channel in order to increase the infiltration capacity (Maliva & Missimer, 2012). This is done by e.g. retaining run off water (percolation ponds), adding additional storage volume (sand dams), detaining aquifers in alluvial aquifers (subsurface dams) or mitigating the flow (leaky dams and recharge releases) (Gale, 2005).

Since these modifications differ largely in their prerequisites and potential yield (Maliva & Missimer, 2012), no further general consensus on in-channel modifications as a main MAR type can be expressed.

4.3.3. Well, shaft and borehole recharge

With well, shaft and/or borehole recharge methods, the recharge water is infiltrated into an aquifer at a deeper level than the (near) surface, opposed to what is the case for spreading methods. According to Gale (2005), deep well infiltration is the most primary used technique, especially if an impermeable layer, such as clay, lies above the aquifer. Well, shaft and borehole recharge techniques are the preferred techniques for MAR in regions with certain hydrogeological conditions. Based on Gale (2005) and Maliva and Missimer (2012), these conditions are: i) low permeability strata are present above the aquifer, ii) for confined aquifers, iii) where high evaporation losses go hand in hand with surface infiltration, and iv) where the water table lays deep below the surface. Additionally, in regions with limited land available and where spreading methods consequentially are unfeasible, well, shaft and borehole recharge techniques are preferred (Maliva & Missimer, 2012).

An important issue with well, shaft and borehole recharge techniques is potential groundwater contamination, due to a lack of filter for the recharged water. Additional modifications to the MAR system should be put in place to counter this (Gale, 2005). However, in turn these modifications often lead to clogging, making the system less efficient (Gale, 2005). Also without the additional modifications in place, clogging is an issue due to among others chemical precipitation, microbial growth, and suspended sediment from the recharge water itself (Gale, 2005).

4.3.4. Induced bank infiltration

Induced bank (in)filtration describes the natural process where surface water infiltration through spreading methods is induced through nearby groundwater extraction (Dillon et al., 2019). In this, an extraction technique is placed close to a (potentially artificial) surface water body, which lowers groundwater pressure and consequentially induces the surface water to infiltrate into the underlying aquifer (Gale, 2005). The main aim of induced bank infiltration is filtering the induced water to increase its quality (Gale, 2005) and not increasing the total amount of groundwater in the aquifer. As such, induced bank infiltration techniques cannot aid in lowering an aquifer's depletion. However, using these techniques, the potential uses of the extracted water has increased (e.g. water that first was not of sufficient quality for potable water, now is). This results in having more flexibility in choosing a source for water uses with higher water quality demands and lowering dependency on otherwise unsustainably extracted sources.

Induced bank infiltration has comparable constraints and issues as spreading methods (Gale, 2005).

4.3.5. Rainwater harvesting

With rainwater harvesting, rainfall from a larger area is collected for productive use. This is often done to use the concentrated rainwater as potable water, in a smaller area as soil moisture or for recharging groundwater (Gale, 2005), each with a specific technique. The main aim of rainwater harvesting in areas with (temporal) water scarcity, is to reduce the surface runoff and evaporation, such that a larger share of the precipitation can be used e.g. in agriculture or within households (Gale, 2005). As such, it is comparable with relatively small scale in-channel modifications. An additional benefit of rainwater harvesting is that it reduces stormwater runoff and consequential flooding in times of water excesses (Gale, 2005).

Dependent on the desired use and the chosen technique, rainwater harvesting can be nothing more than a systematically rain-fed spreading method. Consequentially, largely the same issues and constraints apply to rainwater harvesting as do for spreading methods. An additional and/or more prominent issue with rainwater harvesting is contamination of the water, e.g. from air pollution, bird and animal droppings, insects, and microbial growth in the collection area.

4.3.6. Combined overview on capacity and costs of MAR techniques

In Table 7, an overview of the fifteen MAR techniques is given, including information as found in literature on the technique's capacity, cost and main objectives. In the inventory presented in Appendix B, these techniques are discussed more elaborately. The sources are given at their respective sub-appendices.

Table 7 Overview of quantitative and qualitative information found for the fifteen MAR techniques.

<table>
<tr><th colspan="2" rowspan="2">MAR technique</th><th colspan="2">Capacity*</th><th colspan="2">Cost</th><th rowspan="2">Main objective(s)</th></tr>
<tr><th>Quantitative (10^6 m^3 yr^-1)</th><th>Qualitative</th><th>Quantitative (US$ m^-3)</th><th>Qualitative</th></tr>
<tr><td rowspan="4">Spreading</td><td>Infiltration ponds</td><td>Up to 45</td><td>Large</td><td>0.23</td><td>Low-medium</td><td>Agriculture, domestic, industrial</td></tr>
<tr><td>SAT</td><td>Up to 130</td><td>Large</td><td>1</td><td>Medium</td><td>Water quality improvement</td></tr>
<tr><td>Controlled flooding</td><td>-</td><td>Large</td><td>-</td><td>Lowest</td><td>Agriculture, flood risk management</td></tr>
<tr><td>Incidental recharge from irrigation</td><td>-</td><td>Large</td><td>-</td><td>Low</td><td>Agriculture</td></tr>
<tr><td rowspan="4">In-channel</td><td>Percolation ponds</td><td>Up to 9.3</td><td>Large</td><td>-</td><td>Low-medium</td><td>Strategic water storage</td></tr>
<tr><td>Sand storage dams</td><td>0.0002-0.03</td><td>Medium-small on average</td><td>0.4</td><td>Low</td><td>Water storage</td></tr>
<tr><td>Leaky dams</td><td>-</td><td>> Percolation ponds</td><td>-</td><td>> Percolation pond</td><td>Peak flow mitigation, water table recovery</td></tr>
<tr><td>Subsurface dams</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Wells, boreholes</td><td>Shallow wells and shafts</td><td>-</td><td>Large</td><td>0.1-0.3</td><td>Low</td><td>Stormwater disposal, water table recovery</td></tr>
<tr><td>ASR</td><td>-</td><td>Very large</td><td>0.26-0.65</td><td>Low-medium</td><td>Agriculture, desalinization, potable water</td></tr>
<tr><td>ASTR</td><td>-</td><td>Very large</td><td>> ASR</td><td>Medium-high (> ASR)</td><td>Agriculture, desalinization, potable water, water treatment</td></tr>
<tr><td rowspan="2">Induced filtration</td><td>Bank filtration</td><td>Up to 146</td><td>Very large</td><td>-</td><td>Medium-high</td><td>Water treatment</td></tr>
<tr><td>Inter-dune filtration</td><td>Up to 90</td><td>Very large</td><td>-</td><td>Medium</td><td>Water treatment</td></tr>
<tr><td rowspan="2">Rainwater harvesting</td><td>Field bunds</td><td>-</td><td>Medium-small</td><td>0.1-0.3</td><td>Low</td><td>Water storage, erosion reduction</td></tr>
<tr><td>Rooftop rainwater harvesting</td><td>-</td><td>Small</td><td>-</td><td>Low</td><td>Water storage, prevent</td></tr>
</table>

* For almost all MAR techniques, it holds that the potential capacity is heavily influenced by the scaling of the MAR system. The capacities given here are based on the high-end of data found in literature.

The quantitative output and costs are highly variable and influenced by, most importantly, the size of the MAR sites (Gale, 2005; INOWAS, 2018; Maliva, 2014). Additionally, the costs are influenced by many other factors as well, such as the end-use of the to-be-recharged water (thus its necessary quality), local water prizes, and local labour costs for construction and maintenance. This high variability is also represented in the lack of quantitative data found in literature. The qualitative data can however serve as a valuable indicator for the potential of the specific MAR technique. For example, it can be said that almost all MAR techniques can have large capacities, except for rainwater harvesting techniques. Furthermore, generally speaking, MAR techniques have relatively low costs over their lifespans, but, dependent can have high initial investments costs.

5. Contribution of MAR to alleviating water stress

5.1. Current implementation of MAR

The total contribution of MAR to the water cycle is still unknown, as there is no comprehensive global inventory. In recent years however, two projects have started to create inventories and databases of MAR-sites. The first extensive (yet incomprehensive) catalogue has been created by the (EU-funded) DEMEAU-project in 2014 (Hannappel et al., 2014), of which an article was published in the *Hydrogeology Journal* by Sprenger et al. (2017). With this MAR catalogue, the DEMEAU-project put a first step into structuring the existing information on European MAR sites into a homogeneous overview. In this database, several standardized terms, e.g. with regards to the influent source water, used MAR-technique, the site's end-use and the main objective of the MAR site, have been formulated and implemented. Based hereupon and adopting the now standardized terms, the International Association of Hydrogeologists Commission on Managing Aquifer Recharge (IAH-MAR commission), started with the fashioning of a global MAR-site database. This resulted in the International Groundwater Resources Assessment Centre global MAR inventory (IGRAC inventory), created by the IAH-MAR commission and a team of researchers from several European institutions such as the INOWAS-consortium, Acacia Institute and members of the DEMEAU-project (Stefan & Ansems, 2018). This, contrary to the DEMEAU-project's catalogue, contains open-source data. The sites considered for the inventory are all from scientific literature review. New/better data can be submitted to the IGRAC inventory and, after data-review, the inventory is updated and/or extended. There are currently 1119 MAR-sites divided over 62 countries included in the IGRAC inventory, but it's likely there are thousands of MAR sites not yet inventoried (IGRAC, 2020a). Despite a clear lack of data, the IGRAC inventory is the most comprehensive inventory of MAR sites yet (IGRAC, 2020a). Therefore, to determine where, how and how often MAR is currently implemented, this inventory will be used.

5.1.1. Locations where MAR techniques are currently used

The 1119 MAR-sites incorporated in the IGRAC inventory are divided over the different continents as presented in Figure 8 (extracted from IGRAC (2020a)). Most documented sites can be found in North America (308, or 27.5%), Asia and Europe (both 281, or 25.1% each). Africa, Oceania, and South America have relatively little MAR sites incorporated in the IGRAC inventory.

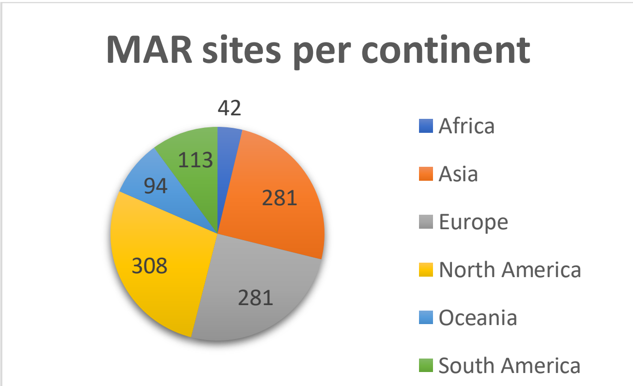

Figure 8 Division of MAR sites incorporated in the IGRAC inventory.

In Figure 9 a complete overview is presented on the country-specific locations of MAR sites that are incorporated in the IGRAC inventory, grouped per continent. For this, countries with less than five MAR sites incorporated, are put together under 'others'. From this overview it becomes apparent that there is a small group of seven countries with a high number (>50) of MAR sites incorporated in the IGRAC inventory, while numbers dwindle fast thereafter. Despite the IGRAC inventory being incomprehensive, this does give an indication which countries are implementing MAR already.

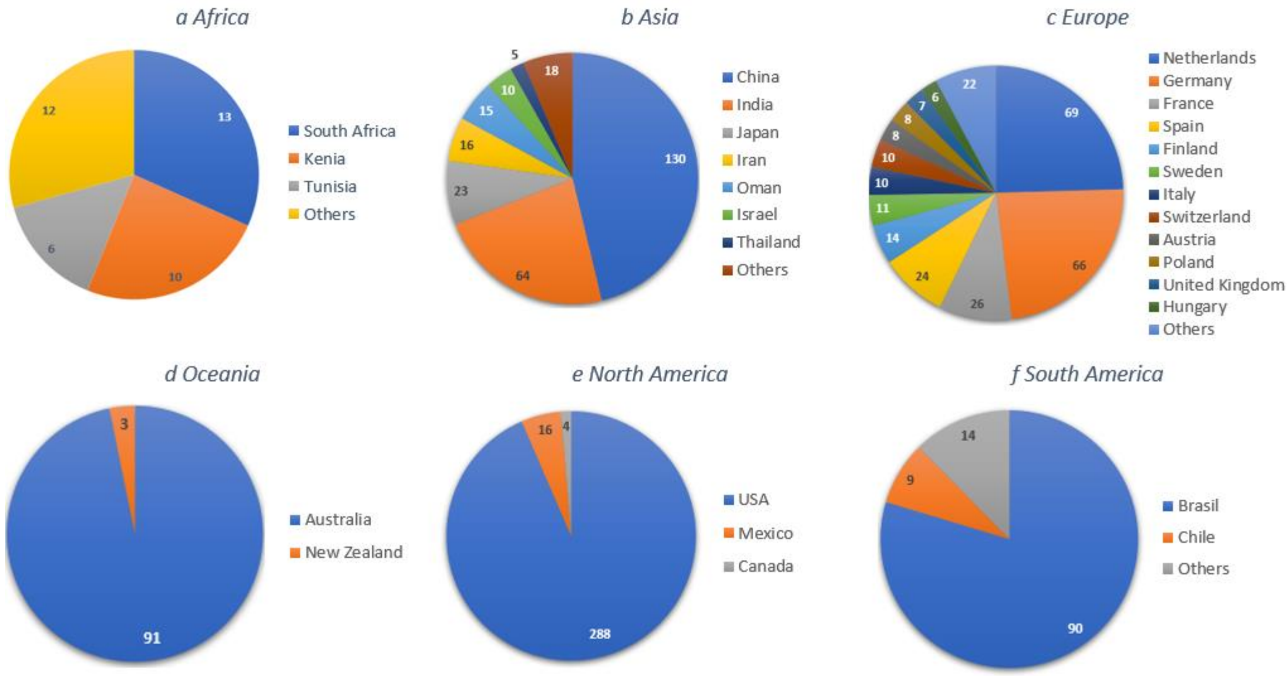

Figure 9 Division of MAR sites per continent.

The eight countries with the highest number of MAR sites incorporated in the IGRAC inventory are presented in Figure 10.

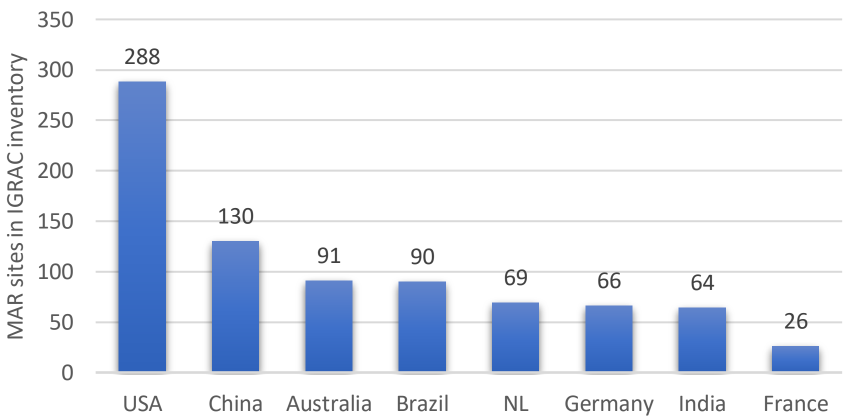

Figure 10 The eight countries with the most MAR sites incorporated in the IGRAC inventory. NL is the Netherlands.

5.1.2. The current goals of the usage of MAR techniques

Not only do the numbers of total incorporated MAR sites vary largely between continents, the end-uses for these sites do so as well. See Figure 11. The major locational differences mentioned in section 3.1 are also visible in these figures.

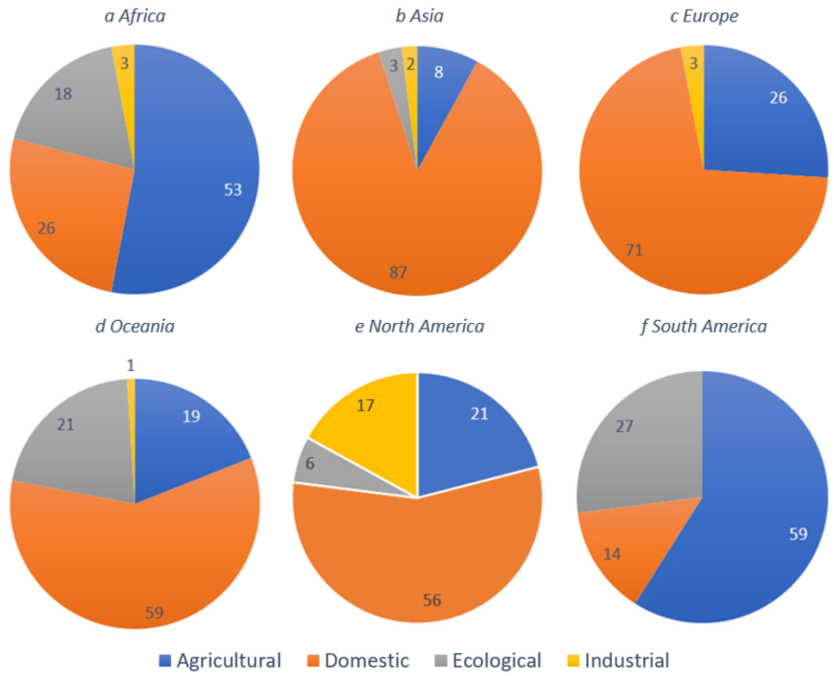

Figure 11 Division per continent of end-uses of MAR sites as incorporated in the IGRAC inventory.

The 1119 MAR-sites incorporated in the IGRAC inventory are divided over the different methods and end-uses as is presented in Table 8 (adapted from IGRAC (2020a)). Based on this information, the biggest share of documented MAR sites is for domestic uses (40.4%), with agriculture (21.3%) as second-most implemented end-use. This seemingly contradicts the data presented by among others Siebert et al. (2010) and Wada et al. (2014) stating that agriculture is the end-use of over 70% of the total water withdrawal, but does not. The data given is only a numerical summation of MAR sites, and not data on the output (volume) of these. Moreover, the dataset is incomprehensive (IGRAC, 2020a). It is expected that the MAR sites meant for domestic uses are better-mapped than those with agricultural end-use. This since the ownership of MAR sites for domestic use is expected to more often lie with the larger water distribution companies with higher importance of scientific soundness for their investment plans and as such will have more literature available for incorporation in the IGRAC inventory, opposed to the more often privately owned sites in agriculture (e.g. by a (group of) farmers) with lower reliance on scientific proofing.

Based on this data, ASR/ASTR is the most popular MAR technique, both in total and specifically for agriculture. However, looking at its relative difficulty of design, and high investment costs (compared to other MAR techniques), it is expected that in reality this is not the case. Instead, it seems more logical to assume that infiltration ponds are the most-used technique, be it undocumented, due to its relative ease of implementation and low costs. For example, the City of Cape Town, South Africa, has already 737 stormwater infiltration ponds, (mostly) for domestic uses, on its own (Rohrer & Armitage, 2015). None of these are currently incorporated in the IGRAC inventory. As such, it remains difficult to give quantified data on the actual implementation of MAR techniques.

Table 8 Division of MAR sites in the IGRAC database over different methods and end-uses.

MAR technique	Agricultural	Domestic	Ecological	Industrial	Research	No Data	Total
ASR/ASTR	61	52	20	7	0	138	**278 (25%)**
Infiltration Ponds and Basins	39	84	13	17	0	108	**261 (24%)**
Induced Bank Filtration	12	114	2	5	0	16	**149 (13%)**
Subsurface Dam	58	58	5	0	0	0	**121 (11%)**
Recharge Dam	26	49	15	0	0	6	**96 (8.6%)**
Dug Well/ Shaft/ Pit Injection	7	34	11	2	2	19	**75 (6.7%)**
Rooftop Rainwater Harvesting	3	31	7	0	0	0	**41 (3.7%)**
Ditch and Furrow	11	8	3	0	0	1	**23 (2.1%)**
Trenches	11	4	6	0	0	2	**23 (2.1%)**
Flooding	1	7	2	3	0	4	**17 (1.5%)**
Reverse Drainage	4	1	1	1	1	5	**13 (1.2%)**
Excess Irrigation	1	5	0	1	0	2	**9 (0.8%)**
Channel Spreading	3	2	0	0	1	1	**7 0.6%)**
Barriers and Bunds	1	2	1	0	1	0	**5 (0.4%)**
Sand Storage Dams	0	1	0	0	0	0	**1 (0.1%)**
Total	**238 (21.3%)**	**452 (40.4%)**	**86 (7.7%)**	**36 (3.2%)**	**5 (0.4%)**	**302 (27%)**	**1119**

5.2. Quantified output of MAR

A comprehensive overview of all MAR sites worldwide is non-existent. Therefore, a sound investigation of quantified data analysis on the global output of MAR is also near impossible. Nevertheless, a first attempt to do just that has been conducted by Dillon et al. (2019). The authors have created an historical overview of the worldwide development of MAR in the past six decades (since 1965). This overview contains nationally aggregated estimates of annual recharge volumes and groundwater use. Additionally, it includes among others global estimates of natural groundwater recharge, annual groundwater exploitation, and accumulated groundwater depletion. The authors state that 'none of these quantities is subject to simple direct measurement, but the estimates rather are derived as the sum of a mix of data acquired in very different ways (including correlations and guesses) and finding different versions of the same statistic reported is not uncommon' (Dillon et al., 2019: 3). Albeit them being 'best estimates', it therefore should be emphasized that the data given in their overview, are subject to considerable uncertainty. This is also stretched by the authors themselves. Nevertheless, the overview does give a good indication and helps put the quantities of water involved in MAR in proper perspective.

From the overview of Dillon et al. (2019), it can be extracted that since 1965, worldwide MAR-implementation has accelerated by 5% per year. Simultaneously, the global groundwater withdrawal in total rose by 1.8% per year (Wada et al., 2014). The yield from MAR currently accounts for approximately 1% of the total global groundwater withdrawal and about 2.4% of the global groundwater use. MAR is likely to exceed towards entailing 10% of the global groundwater withdrawal in the coming decades, if research and the establishing of awareness on it is continued (Dillon et al., 2019).

In Table 9, a short overview is presented on the data gathered by Dillon et al. (2019). It includes the specifics for the eight countries that had the most documented MAR sites in the IGRAC inventory (see **Error! Reference source not found.**), with the exception of Brazil and inclusion of Spain. This since no data on Brazil was given by Dillon et al. (2019). In Appendix D, a more extensive and detailed table is presented.

Table 9 Global growth in use of MAR since 1965. Source: Dillon et al., 2019

Country/region	Average annual MAR output (Mm^3yr^{-1})		Annual gw* use (Mm^3yr^{-1})	MAR as % of gw* use	MAR volume growth (%yr^{-1})
	1965	2015			
Australia	79	410	4960	8.3%	3.6%
China	20	106	112.000	0.1%	3.6%
France	20	32	5710	0.6%	1.0%
Germany	No data (867 in 1975)	870	3080	28.2%	0.0%
India (5 states only)	154	3070	39.800	30.9%	6.6%
Netherlands	181	263	1600	16.4%	0.8%
Spain	3	380	5700	6.7%	10.9%
USA	302	2569	112.000	2.3%	4.7%
Global total	**1029**	**9945**	**414.110**	**2.4%**	**4.9%**

*gw = groundwater

6. Multidisciplinary factors in restraining the uptake of MAR

6.1. Environmental factors

Each MAR technique has its own prerequisites for the hydrogeology and the aquifer's hydrogeology determines whether MAR is possible altogether. It is the decisive factor for selecting the best location and suitable technique (Grützmacher & Sajil Kumar, 2012). According to Margat and Van der Gun (2013), the composition of the subsoil determines for example porosity, permeability and solubility, which are all properties that define the water storage capacity of the aquifer. Additionally, the groundwater quality can be heavily influenced when using MAR, with potentially far-reaching consequential environmental effects. Although improving the groundwater quality can be one of the goals and is one of the potential merits of MAR, it can also be negatively influenced by injecting water, due to various hydro- and geochemical processes. As such, the environmental factors are divided into hydrogeological constraints and hydrogeochemical factors.

6.1.1. Hydrogeological constraints

In general, it is wished for to find aquifers with large storage capacity, which do not release the (recharged) water too quickly (Indian Central Ground Water Board, 2007). Aquifers can be differentiated into several standard classifications. An aquifer can be unconfined (with a (somewhat) permeable layer above the aquifer) or confined (with an impermeable layer above the aquifer). See **Error! Reference source not found.**. T he size of an aquifer can vary from small to large, with surface areas ranging from only a few to more than a million square kilometres (Margat & van der Gun, 2013). Moreover, Margat and Van der Gun (2013) mention that the thickness of an aquifer varies, from a few meters to several kilometres. Gale (2005) states that, next to these classifications, there are four types of aquifers for MAR, all with their own performances. These are alluvium, fractured hard rock, consolidated sandstone, and carbonate rock aquifers. In this, it is relevant to note that the consolidated sandstone aquifers normally achieve the highest storage capacity and have the most favourable transmissive properties, while carbonate rock aquifers typically result in high hardness rates of the groundwater, due to its high reactivity in terms of hydrogeochemistry (Gale, 2005; Margat & van der Gun, 2013). The four types are further explained in Appendix E, including an overview of what aquifer type suits which MAR techniques.

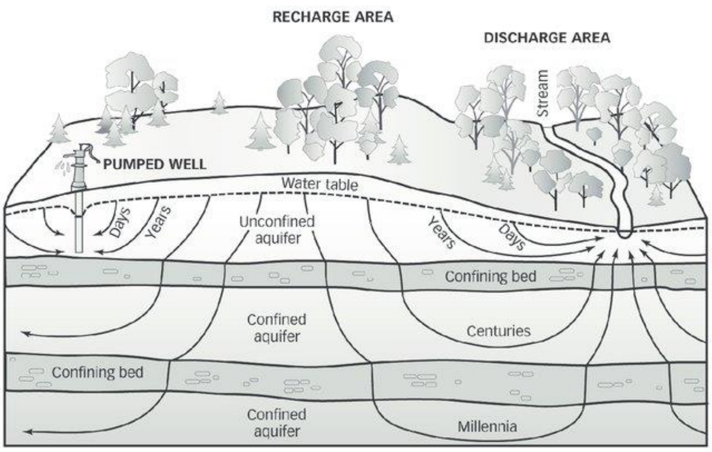

Figure 12 Schematic image of confined and unconfined aquifers. Source: Eckstein and Hardberger, 2010

According to Maliva and Missimer (2012), the relevance of certain hydrogeological factors strongly differs per MAR technique. ASR and ASTR are deep well infiltration techniques mostly used for confined aquifers, where an injection and extraction pump is drilled through the impermeable layer(s) into the aquifer. With ASR, one pump serves as both, while for ASTR, there is a pump for both injection and extraction of water, at differing locations. For a more elaborate description of ASR and ASTR, see **Error! Reference source not found.** a nd Appendix A. When looking at these techniques, the hydrogeological constraints of the layers above the aquifer, such as the vadose zone, are only marginally relevant, as they are bypassed using the MAR system. It is more important to know the hydrogeological conditions of the aquifer and its direct environment.

For water storage in confined aquifers, several parameters are important to consider. In general, next to hydrological parameters regarding the volume of potentially available water and the distance to this source, the lithology type (or the hydrogeological parameters of the aquifer) is a boundary condition for potential recharge (Sanford, 2002). From Gale (2005) and Şen (2015), the four parameters below are identified as key-parameters and essential parts of information to assess the feasibility of ASR/ASTR. These are in turn dependent on other hydrogeological parameters, which are discussed later.

- **Groundwater potentiality** implies extraction possibilities of groundwater from the aquifers and is the most interesting parameter when assessing feasibility of ASR/ASTR (Şen, 2015);
- **Aquifer thickness** is the thickness of the saturated zone of the aquifer;
- **Hydraulic conductivity** of the material can be defined as the ability of the fluid to pass through the pores and fractures rocks and is dependent on the type of soil (Saravanan et al., 2019). Also called the coefficient of permeability (Shaw et al., 2011);
- **Transmissivity** is the product of the saturated thickness of the aquifer and the average value of the hydraulic conductivity (Freeze & Cherry, 1979).

Thick aquifers have a higher storage capacity than thin aquifers. Hydraulic conductivity is dependent on the lithology (the geochemical, mineralogical, and physical properties of the soil) (Hartmann & Moosdorf, 2012; Saravanan et al., 2019). The transmissivity of the aquifer is directly linked to the aquifer's potentiality, where a higher transmissivity results in a higher potentiality of the aquifer (Şen, 2015). Based on Şen (2015), values for transmissivity and potentiality can be linked to each other as presented in Table 10.

Table 10 Aquifer transmissivity and potentiality values Source: Şen, 2015

Transmissivity (m^2/day)	Potentiality description
T < 5	Negligible
5 ≤ T < 50	Weak
50 ≤ T < 500	Moderate
500 ≤ T	High

Next to these four parameters, the quality of the groundwater needs to be known, as this determines for what uses the water can be extracted (Wolf et al., 2007). Once the water is infiltrated, the storativity, lateral hydraulic gradient and the hydraulic conductivity play the most important roles with regards to the movement of the water (Indian Central Ground Water Board, 2007; Jimenez & Asano, 2015). When the lateral hydraulic gradient is near-absent or gentle, the water stays closer to the point of infiltration, which is desired for ASR/ASTR (INOWAS, 2018). If the aquifer is consolidated, well construction is easier and clogging issues are lower (Wolf et al., 2007). Wolf et al. (2007) state that for recovery of water, the groundwater quality, i.e. its salinity, and minerology are relevant, as the recharged water can react with the these minerals. Lastly, the redox state, or the aerobic/anaerobic conditions, of the groundwater are important to incorporate in the feasibility study. In aerobic conditions, the groundwater can have high rates of inactivation of pathogens and endocrine disrupting chemicals, while in anaerobic conditions the groundwater can have high rates of biodegradation of trihalomethanes (Jimenez & Asano, 2015). The redox state of an aquifer does not influence the feasibility for MAR per se, but can be a strong indicator of contaminants that might be present at elevated concentrations and as such the pollution present in the aquifer (USGS, 2020b). Of the hydrological parameters, the volume of the potential source water in time and the distance of this source to the ASR/ASTR site must be known. With regards to agriculture, this source can very well be recharged wastewater, under condition that it is treated accordingly (Thebo, 2016). An overview of relevant hydrogeological and hydrological parameters and their qualitative characteristics is given in Table 11, based on Jimenez and Asano (2015: 262) and Wolf et al. (2007: 42).

Table 11 Relevant properties for deep well injection techniques. Source: Jimenez and Asano, 2015, and Wolf et al., 2007

	Factor	Qualitative characteristics	ASR/ASTR potential positively influenced if factor is
Hydrogeological	*Confinement*	- *Confined* - *Unconfined*	*Unrelated*
	Aquifer permeability	- Low - Moderate - High	High
	Aquifer thickness	- Thick - Thin	Thick
	(Un)conformity of hydraulic properties	- Heterogeneous - Homogeneous	Homogeneous
	Lateral hydraulic gradient	- None - Gentle - Steep	None
	Consolidation	- Unconsolidated - Consolidated	Consolidated
	Groundwater quality; salinity	- Fresh - Brackish - Saline	Fresh, but groundwater quality can be altered after injection of source water
	Groundwater quality; redox state	- Aerobic - Anaerobic	n.a.
	Mineralogy	- Reactive with infiltrated water - Unreactive with infiltrated water	Unreactive
Hydrological	Source water availability	- Low - Moderate - High	High
	Distance to source water	- Low - Moderate - High	Low

6.1.2. Hydrogeochemical processes

With the injection of source water into an aquifer using ASR/ASTR, hydro- and geochemical processes between injected water, native groundwater, and the subsoil start. Where this can have a 'cleaning' effect on the native groundwater in case the source water is of higher quality than the native groundwater, it can also have adverse effects for the water quality if the source water is of lower quality (Maliva & Missimer, 2012). Moreover, case studies such as Murray (2009) show that, even if the source water is of high quality, the injection process itself and the ASR/ASTR system being in place can have negative influences on the groundwater quality.

The case study performed by Vanderzalm et al. (2020) shows an example of how chemical processes within ASR/ASTR can be benefitted from. In this study, an ASR system is used to inject and recover treated wastewater (TWW) in Australia in a brackish, anoxic carbonate aquifer. The TWW is of appropriate quality to use for irrigation as is. The TWW is injected and added to the native, high salinity groundwater and later on only the earlier added TWW (and thus not extract the brackish native groundwater) is recovered for irrigational use when needed and/or discharged into the marine system (which has higher water quality demands than irrigation). This water should have a higher quality after recovery, due to the filtrating effects of the soil on the injected water. The aim of the case study was to assess the capabilities of the ASR system in increasing the source water's quality, as a potential alternative to already proven further nutrient removal techniques (e.g. a membrane bioreactor process). For this, nutrient values (nitrogen, N, and phosphorus, P, specifically) and salinity of the source water pre- and post-ASR were compared. It followed that ASR in an anoxic carbonate aquifer removed 50% of the total nitrogen (TN) and of nitrate (which is the dominant nitrogen species) that was left in the TWW, and 95% of ammonia. From the total phosphorus (TP) about 90% was removed. However, salinity of the TWW increased by 50%. The authors reasons that this was due to dilution with the native groundwater (which was accounted for while calculating N- and P-removal) and that it can be considerably reduced by leaving residual of source water in the aquifer to create a buffer zone between the native groundwater and the injectant. The results of the case study are shown in Table 12.

Table 12 TWW quality before and after MAR using ASR in an Australian carbonate aquifer. Source: Vanderzalm et al., 2020

Substance	Local threshold value for irrigation (mg L^{-1})	Native groundwater (mg L^{-1})	TWW pre-ASR (mg L^{-1})	TWW post-ASR (mg L^{-1})	Removal from TWW with ASR
TN	5 LTV*, 25-125 STV*	1.60	15	7	53%
Nitrates (NOx)	-	1.56	13	6.55	50%
Ammonia (NH_3)	-	<0.005	0.62	0.028	95%
TP	0.05 LTV*, 0.8-12 STV*	0.013	8.6	1.2	86%
Salinity	-	2200	705	1050	-49%

*LTV = Long term (100 years) trigger value; STV = Short term (20 years) trigger value.

Murray (2009) shows how chemical processes within ASR/ASTR can also negatively influence the water quality. The author looked at the changes in key-water quality values before and after recharge of a South African breccia aquifer using an ASTR system with high quality source water. For this, first 35%-50% of the total volume of low-quality native groundwater was extracted and then replaced. The results are shown in Table 13, including the local threshold values according to the SABS 241. From this study it follows that the pH value and fluoride and ammonium levels decreased. However, the electrical conductivity (EC), sulphate and arsenic concentrations increased over the short time that the water was stored. The author mentions this provided a warning that sulphide minerals are being converted to sulphate, dissolving and releasing arsenic and other potentially toxic substances. Murray (2009) reasons that this effect is partly caused by atmospheric oxygen entering the breccia, which is difficult to prevent. Oxygen enters the subsurface when the water table drops each time the breccia pipe is pumped out. Sulphate concentrations have risen since the drilling and test pumping first allowed oxygen into the subsurface and the effect escalated after the injection trials further disturbed the geochemical system. Arsenic is released simultaneously with the sulphate, since it comes from the same sulphide minerals. This shows that, even if source water is treated sufficiently and is of high enough quality, purely due to the injection process, the groundwater quality can be negatively influenced in some aspects.

Table 13 Groundwater quality before and after MAR using ASTR in a South-African breccia aquifer. Source: Murray, 2009

Element/ substance	Breccia (pre-ASR) (mg L^{-1})	Source water (mg L^{-1})	Recovery (post-ASR) (mg L^{-1})	Local norms for drinking water (mg L^{-1})
pH	*9.8*	7.1	9.1	5-9.5
EC (mS m^{-1})	8.9	19	95	<150
Ammonium (NH_4)	*1.3*	<0.1	0.7	<1.0
Fluoride (F^-)	*10.6*	0.1	*7.0*	<1.0
Arsenic (As)	*0.26*	<0.001	*0.40*	<0.05
Sulphate (SO^{2-}_4)	64	20	157	<400

As such, a thorough understanding of the (consequences of) hydrogeochemical processes is important when looking at implementing MAR and ASR/ASTR specifically. Even high-quality source water can negatively influence native groundwater quality. Values for i.e. nitrogen or phosphorus that are too high, have adverse effects on the ecosystems using the aquifer and negatively influences crop yield (Bundy et al., 2001; Camargo & Alonso, 2006; Hart et al., 2004). To prevent these effects, toxicological threshold levels should be set up and adhered to.

6.2. Socioeconomic factors

From a social perspective, MAR projects can improve the quality of people's lives in several ways, resulting in a higher socioeconomic status (SES). Yet, Maliva (2014) states that implementation of MAR is often hindered by the absence of a clear economic case for the investment. In general, to justify investments in infrastructure, the benefits of the project should equal or, preferably, exceed the construction and operational costs. Additionally, the costs should be lower than that of an alternative project that could give the same benefits. For MAR, such a justification is normally done with use of a Cost-Benefit Analysis (CBA) and can be represented by the economic water productivity (EWP). The EWP is the value of monetary output obtained with one unit of monetary input (Economics Web Institute, 2001). The unit of EWP is $€_{output}/€_{invest}$. This parameter gives the return-rate of a project and creates a business case for potential MAR project developers. A higher economic water productivity results in a higher return-rate for the investments. The input unit is presented in the levelized total cost (LTC, € m^{-3}) of the project, which evaluates the total cost per m^3 of recharged water. The output unit of ASR/ASTR is the expected net benefit (ENB, € m^{-3}). If the EWP is lower than 1, the project is not feasible. The formula for the EWP is given by Equation 1.

$$EWP = 1 + \frac{ENB}{LTC} \tag{1}$$

Ward and Michelsen (2002) have observed a knowledge gap in giving monetary value to (the output benefits of) MAR. Eighteen years later, Maréchal et al. (2020) came to a similar conclusion: although information on what types of costs MAR projects generally have is lacking as well, especially the benefits are difficult to monetarize. This is, first of all, since water only has a relevant economic value when its supply is scarce relative to its demand (Maliva, 2014). In such a scenario, water takes on value because many users compete for it (Ward & Michelsen, 2002). Moreover, the benefits of MAR '*should not be based only on market revenues or costs'* (Damigos et al., 2017). Instead, Maliva (2014) notes that, for economic feasibility assessments, '*consideration must be given to the importance of water to the total economy, to the value of water for various uses, as well as to the direct and intangible benefits that may accrue'.* This section aims at giving relevant information to be able to give this required consideration. For this, based on Damigos et al. (2017), Maliva (2014), Maréchal et al. (2020) and Ward and Michelsen (2002), five main factors have been identified playing a role in the socioeconomic context. These are the influences of MAR on the socioeconomic status, unfolding typical contingencies, discovering the costs, monetizing the benefits, and funding of the project. Of these, the contingencies, benefits, and costs are what the EWP is constituted of and as such are especially relevant.

6.2.1. Socioeconomic status

The socioeconomic status (SES) is an indicator of a person's economic and social status, and is quantified by education, income, and occupation (Baker, 2014). To this end, the United Nations have introduced the Human Development Index (HDI), which is equally based on income, health, and educational factors. The HDI can be aligned with the sustainable development goals (SDG's) as set up by the United Nations in 2015 (UNDP, 2016). They are mutually strengthening. MAR can be linked to SDG#6, which is to ensure availability and sustainable management of water and sanitation for all. This includes aquifer protection and restoration. As such, when MAR is implemented, SDG#6 comes nearer, which then improves the region's HDI and SES. The SES in turn defines the socioeconomic context of a region. This process is visualised in Figure 13.

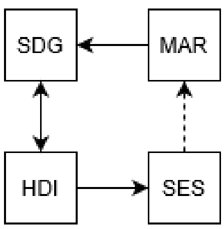

Figure 13 Relationships between MAR and the SES.

In principle, one can relate MAR techniques to the HDI. In this, it is to be expected that a relatively low SES negatively influences the possibilities surrounding MAR. Moreover, it can be expected that a region with higher SES can more easily implement additional and more expensive MAR methods. As such, the SES can give a first indication on the feasibility of certain MAR techniques. Until now, no studies have been found that looked for this connection. As ASR/ASTR are relatively expensive techniques (INOWAS, 2018), it is expected that this technique is only feasible from a certain HDI-value or higher.

6.2.2. Contingencies

Maliva (2014) states that the most neglected aspect in economical MAR studies, is adequately addressing the risks and uncertainties, or contingencies, in CBAs. Not considering the contingencies biases CBAs by increasing expected benefits. According to Maliva (2014), the principle contingency associated with MAR systems is that they may fail to meet performance objectives.

Maliva (2014) mentions that contingencies with adverse results include:

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

Such risks and uncertainties can be incorporated into CBA through an expected value analysis (Boardman et al., 2018). For this, the future is characterized in terms of a number of distinct contingencies. Maliva (2014: 1271) says that the modelling of risk and uncertainty of a MAR project '*begins with a set of contingencies that are mutually exclusive and capture the full range of likely variations in the costs and benefits of a project or policy'.* To evaluate the risks, one assigns a probability to the occurrence of each possible contingency. The sum of all contingencies is equal to one. Probability of each contingency can be based on historic experience (such as rainfall data), or subjective opinions of experts (Maliva, 2014). The then expected net benefits (ENB, € m^{-3}) are calculated as is given in Equation 2.

$$ENB = \sum P_i \, (B_i - C_i) = \sum P_i \, (B_{Ti} - LTC_i) \tag{2}$$

In this, P_i is the probability of contingency 'i', and B_{Ti} and LTC_i are the monetarized total benefits and levelized total costs under contingency 'i' respectively.

6.2.3. Monetizing benefits

The monetarized total benefit of a MAR system (B_T, € m^{-3}) is a summation of the direct financial yield on recharged water (B_d, € m^{-3}) and the in-situ benefits of MAR (B_{is}, € m^{-3}) derived from the groundwater being in place (Maliva, 2014). The in-situ benefits are objectives of systems that involve aquifer recharge without recovery. Reduction of pumping costs due to the higher groundwater table can be an example of this. The value of the water and the in-situ values can be assessed independently Maliva (2014). The formula for the B_T is given by Equation 3 below.

$$B_T = B_d + B_{is} \tag{3}$$

To determine B_d, it is key to determine its economic value. The economic value of water is defined as '*the amount that a rational user of a publicly or privately supplied water resource is, theoretically, willing to pay for it'* (F. A. Ward & Michelsen, 2002). The willingness to pay (WTP) for water reflects the water user's willingness to pay a certain amount rather than do without it, and is measured by a demand schedule relating the quantity of water used at each of a series of different prices (Ward & Michelsen, 2002). In principle, the WTP can be assumed equal to the B_d. The economic value to society of the recharged water is the aggregate of the WTP of all individuals using (and paying for) it. The economic value of water is not a fixed, inherent attribute of a good or service, but largely depends on the time, circumstances, and individual preferences (Maliva, 2014). Very little is known in literature on the quantitative values of the WTP, but Damigos et al. (2016) have looked at the WTP of eight (prospective) MAR sites in the Mediterranean. These are given in Table 14. Maliva (2014) mentions that the WTP is constrained by a person's income in that someone with a higher economic status can afford and may thus be willing to pay more for the same unit water than someone of a lower economic status. Moreover, the WTP is unrelated to the chosen MAR technique and instead dependent on the quality of the recharged water and the potential end-uses (Damigos et al. 2016). Based on the findings of Damigos et al. (2016) and the note by Maliva (2014), the WTP of Spain, Israel and similar countries seems to be 0.40 € m^{-3} to 0.50 € m^{-3}, which might be higher or lower depending on whether the SES is higher or lower than that of Israel and Spain (HDI indicators of 0.89 and 0.91 respectively). Moreover, in agriculture the WTP is highly dependent on the value of the crop, where higher value crops result in a higher WTP (Arshad et al., 2014).

Table 14 TWP of eight (prospective) MAR sites in the Mediterranean. Source: Damigos et al., 2016

Location	WTP*	Uses
Lavrion, Greece	50 € yr^{-1} household $^{-1}$	Domestic
Algarve, Portugal	20 € yr^{-1} household $^{-1}$	Agriculture, Environmental
Arenales, Spain	0.41 € m^{-3}	Agriculture
Llobregat, Spain	0.40 € m^{-1}	Domestic
Brenta, Italy	40 € yr^{-1} household $^{-1}$	Agriculture , Domestic
Serchio, Italy	40 € yr^{-1} household $^{-1}$	Domestic
Menashe, Israel	0.50 € m^{-3}	Agriculture, Domestic
Malta south, Malta	*Not applicable*	Environmental

*Damigos et al. (2016) did not quantify the annual water needs of a unit 'household'. Comparing these data is therefore difficult.

As the B_d is highly determined on the amount of water that is extracted using a MAR system, the systems recovery efficiency (RE) plays an important role. As the recharged water can migrate in the ground and, e.g. due to fluid-rock interactions such as metals leaching, deterioration of the recovered water's quality can happen, not all the injected water can be extracted and used. The RE is defined as the percentage of the volume of the recovered water (V_{rec}) at a quality suitable for its intended use (Maliva & Missimer, 2012) over the total volume of injected water (V_{inj}). The RE is given by Equation 4:

$$RE(\%) = 100(\frac{V_{rec}}{V_{inj}}) \qquad (4)$$

According to Maliva and Missimer (2012), the RE can be calculated over the entire operational history of a system (system recovery efficiency; SRE) or over an individual operational cycle (operational recovery efficiency; ORE). As often the injected water of an ASR-system is of better quality than that of the native groundwater, ORE tends to improve over time following repeated operational cycles. A reasonable long-term ORE-target for an ASR system in a brackish-water aquifer as a storage zone is 70-80% (Maliva & Missimer, 2012).

To monetize the in-situ benefits of MAR, several methods can be used (Maliva, 2014). The most popular is calculating and/or estimating the damage costs. This means that the damage costs that are avoided are estimated, such as flood damage, health impacts due to water stress and the avoided depreciation of crops during droughts. Maliva (2014) has discussed each of the different methods in his works.

6.2.4. Costs

The LTC of the implementation of ASR/ASTR is defined as the constant level of cost each year to cover all the initial capital investments (IC) and the annual operating and maintenance expenses (OC) over the life of the project, divided by the annual volume of recharge (Q), taking into account the capital recovery factor (CRF) (Maréchal et al., 2020). The IC include amongst others the preliminary studies and all construction costs. The OC include among others the costs for water and its (pre-)treatment, energy, and maintenance of the constructions. The CRF is the ratio used to determine the present value of a series of equal annual cash payments and translates the present value of successive payments over a fixed amount of time. The CRF uses the discount factor, which is the rate at which the value of an asset is reduced each year (Maréchal et al., 2020).

No literature has been found on the costs of ASR/ASTR specifically, but Maréchal et al. (2020) have inventoried the different costs for a typical MAR site, based on French researches, and created a cost function. Maréchal et al. (2020) were the first to publish such a comprehensive yet general overview of the costs of MAR. According to Maréchal et al. (2020), a typical MAR system is divided into seven components: surface water source monitoring, water abstraction system from the water source, water transfer pipe towards the MAR site, a pre-treatment system, the infiltration and extraction system, and groundwater monitoring. To this end, first key-characteristics per step in the process were identified (Maréchal et al., 2020). Based on these characteristics, the costs can be identified. The findings of Maréchal et al. (2020) are given in Table 15 below, including their respective process step. The findings are divided into the initial IC and yearly OC. Based on the chosen technique and the situational circumstances, some costs presented here might not be applicable. In Appendix F, the found key-characteristics as found by Maréchal et al. (2020) for a feasibility study for a MAR project are presented, as well as a more elaborate version of Table 15 including the formula for and/or the value of the cost, and, if needed, an additional comment. A brief explanation of the different costs themselves can also be found in Appendix F. The final formula of Maréchal et al. (2020) for the LTC, which determines the cost per m^3 recharged water, is given by Equation 5.

$$LTC = \frac{CRF * IC + OC}{Q} \tag{5}$$

Table 15 Summary of costs for a MAR scheme. Source: Maréchal et al., 2020

Process step	Cost description	Unit
Other	IC_1: Engineering studies	€
	OC_7: other yearly costs	€ yr^{-1}
Water abstraction	IC_2: Pump installation	€
	OC_1: water cost	€ yr^{-1}
	OC_2: pump maintenance	€ yr^{-1}
Water transfer	IC_3: pipe building	€
	OC_3: lifting energy	€ yr^{-1}
Water treatment	IC_4: system building	€
	OC_4: System maintenance	€ yr^{-1}
Water infiltration and extraction	IC_5: land purchase	€
	IC_6: infiltration and extraction system building	€
	OC_5: infiltration and extraction system maintenance	€ yr^{-1}
Water monitoring	IC_7: monitoring equipment	€
	OC_6: yearly monitoring	€ yr^{-1}
Total	IC: (Summation of) capital investment costs	€
	OC: (Summation of) operational costs	€ yr^{-1}
	T: Operating life	yr
	r: Discount rate	Decimal
	CRF: Capital recovery factor	Decimal
	LTC: Levelized total cost	**€ m^{-3}**

6.2.5. Funding

Maréchal et al. (2020) have mentioned that, even though funding should logically be a vital part of economic studies on MAR, literature related to the funding parties seems lacking in attention. Tuinhof et al. (2012) mention that the financing of MAR is, in general, dependent on the size of the system, the financial benefits, the socioeconomic conditions and the beneficiary. Financial constraints are often most severe in poor areas of developing countries (Maliva, 2014). Maliva (2014) also states that funding of MAR projects by governments takes place through i) revenues from sale of water, ii) general tax revenues, iii) property tax (ad valorem tax), and iv) direct assessment. According to Maliva (2014), MAR projects can also be funded by external parties, such as international agencies and non-governmental organizations (NGOs) (Maliva, 2014).

6.3. Institutional factors

Even if hydrological and hydrogeological factors are favourably to the success of implementation of MAR, its success cannot be assured unless it is managed and operated effectively and institutional factors are favourably as well (Gale, 2005). The main institutional factors influencing feasibility of MAR projects are either in the field of stakeholder management and participation, or of legislative origin (Brunner et al., 2014). The legislative origins relate to either groundwater's use or abstraction, or to pollution of the groundwater quality. These will be discussed below.

6.3.1. Stakeholder management

Stakeholder participation in MAR projects is an essential part of MAR projects (Garduño et al., 2010). The management of their participation has proven to be difficult, due to the high number of stakeholders and their differing aims, possibilities, and ambitions.

Garduño et al. (2010) have formulated a standardized list of seven stakeholder-groups that are involved in a typical MAR project and how these groups desirably would interact with each other. These are Village Water Supply Councils, Groundwater-user groups, Non-Governmental Organisations, Local authorities, Water user association, Aquifer management organisation, and the River basin/national authority. The authors mentioned that participation approaches will vary according to both the specific interests of the stakeholders and the nature of customary rules and rights for water and land in the area concerned. As such, many variations are possible depending on amongst others the geographic scale of the aquifer and territorial level of local government agencies. A desired way of interaction of stakeholder groups is presented in Figure 14.

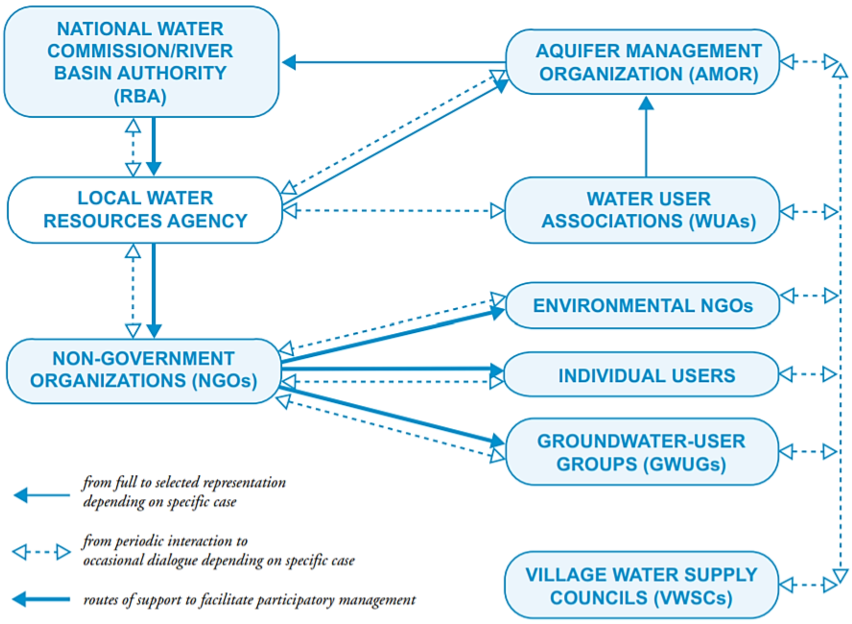

Figure 14 Desirable institutional interaction in participatory groundwater resource management projects. Source: Garduño et al., 2010

To look at stakeholder management and participation issues on a slightly more detailed level, their role in the implementation of a MAR system is divided into pre- and during construction, and post-construction during operation of the MAR system.

6.3.1.1. Stakeholder management before and during construction

While conducting an extensive study on groundwater management for Chennai City, India, Brunner et al. (2014) demonstrated a key-difficulty when looking for a solution to groundwater overexploitation: highly differing stakeholder interests. Even though policies at each different governmental level support the use of MAR, the differing interests made it highly difficult for MAR to take off (Brunner et al., 2014). The authors have performed a stakeholder analysis for MAR and identified a total of 25 MAR stakeholders at national, regional, and local levels. These ranged from government agencies, companies and Chennai City residents to organisations and action groups such as National Green Tribunal and the Hindu Religious and Charitable Endowment Board (Bruner et al., 2014). Moreover, the case study showed that interests of users of groundwater, such as industry, water companies and residents, are not directly aligned with groundwater recharge. In the study of Brenner et al. (2014), a problem with the coordination of the MAR projects was found due to this conflict of interests. As a solution, a new governmental authority was created on behalf of all stakeholders, to guide the project and, in general, oversee MAR (Brunner et al., 2014). An overview of all stakeholders, including their main interests (either groundwater quality, use, or recharge, or other issues), and their level of operation (national, state, or municipal government, or local non-governmental) is presented in Appendix G.

6.3.1.2. Stakeholder management during operation

Especially when there is a role for rural communities in the operational phase of a MAR system, as is often the case, common problems regarding the upkeep and maintenance of recharge structures have come to light in past project experiences (Gale et al., 2006). The duties and obligations of different stakeholders, from communities and committees to implementing agencies, often remain grey area. The result is that the maintenance is often lacking, lowering the system's efficiency and reliability. According to Gale et al. (2006), there are several contributing factors to this:

- The long- instead of short-term value of MAR makes that the community stake in recharge may be lessened after initial enthusiasm.
- Uncertainty by communities about the availability of water recharged by them for their own use. This is mainly due to a lack of understanding by these communities on groundwater hydraulics that is acting as an impediment to MAR.
- Community members may be reluctant to contribute to operation and maintenance activities that they feel will, or might, benefit others. This since recharge systems tend to be viewed as community assets, but distribution of costs and benefits can be very uneven.
- Whole-community financing of projects with a broad community demand (such as MAR) is difficult, as costs and benefits are unevenly distributed or, on the benefit-side, difficult to see.
- The long legacy of government driven programmes and projects is such that rural people expect the government to take responsibility for the upkeep of structures that are predominantly government funded.

To counter this, two actions should be undertaken (Gale et al., 2006):

- Project promotion and planning phases that communicate the basic approach, rules and procedures under which communities are eligible to receive support before construction begins. This should include responsibilities for the maintenance and upkeep of the recharge structures.
- Give a highly detailed overview of distributional issues at the outset, paying particular attention to which areas and households are likely to benefit in particular physical and social settings.

6.3.2. Legislation on groundwater usage and abstraction

The stakeholder participation must be managed using legislation (Capone & Bonfanti, 2015). The legislation should describe where participation will take place, how representatives are chosen and what roles they play, and make sure all stakeholders are accurately represented. This might proof especially challenging with regards to disadvantaged groups and non-articulate, small scale users (Capone & Bonfanti, 2015).

The importance of examining in depth the establishment and functioning of MAR from a legal perspective is, according to Capone and Bonfanti (2015: 7) in their legislative overview and analysis for the European Union's MARSOL demonstrative project *"intimately entwined with the relevance of the right that such mechanism contributes to enhance, i.e. the right to water".* This right to water was already acknowledged in 1977 by the United Nations (UN), and in later years it was defined more specifically what was meant by it (e.g. what 'sufficient, safe, acceptable, physically accessible and affordable water' is) (Capone & Bonfanti, 2015). Traditionally, in western and western-influenced systems the framework disciplining the use of groundwater conferred specific rights on the owner of the overlying land. Four doctrines have been widely applied. These are 'absolute ownership', 'reasonable use', 'correlative rights', and 'prior appropriation' (Mechlem, 2012). However, in other contexts there has never been a right of ownership on groundwater, as it was always seen as public good. According to Capone and Bonfanti (2015), this approach is followed by the Islamic law, and several customary regimes in many parts of the world consider groundwater resources as belonging to the community and reject the concept of individual rights over water. Burchi and Nanni (2003) found a predominant trend to recognize the State's superior right to the management of resources instead of individual ownership. Following this shift towards groundwater being globally seen as a public good, it became possible for governments to put in place a system of formal water rights that allow the states to manage and protect groundwater resources in the interest of the public (Capone & Bonfanti, 2015).

Where India's MAR planning commission concluded in 2007 that, and despite clear indications from the field as illustrated by Brunner et al. (2014), no change in basic legal regime relating to groundwater seemed necessary ('since the problem of groundwater overexploitation does not arise from inadequate legislation and therefore cannot be solved through legislative remedies') (World Bank, 2010), several countries have adopted their own legislation. In a comparative study, Ross (2016) has looked into the groundwater governance of Australia, the EU and the USA. The comparison was performed based on five main classes: architecture of the governance system, access and use, accountability, adaptation, and agency. These are further explained in Appendix H.1. Using the comparative classes, Ross (2016) found several key-elements with regards to the groundwater governance and legislation. These are presented in Table 16.

Table 16 Key elements of groundwater governance in Australia, the EU, and the USA. Source: Ross, 2020

Class	Australia	EU	USA
Architecture	National Water Initiative (NWI) Tradable property rights Water plans Drinking water standards	EU water framework directive (WFD) Groundwater quantity standards River basin management plans	State or regional strategy, instead of a national strategy Tradable property rights Augmentation/mitigation plans Drinking water standards
Access and use	Return overallocated basins to sustainable use	Maintain good groundwater quantity	Maintain property rights of senior (surface water) users – prior appropriation system
Accountability	NWI consultation principle National monitoring of NWI, State monitoring of water plans	WFD consultation principle Report on river basin plans	No national accountability except for drinking water standards
Adaptation	Variable 'share' allocations Water markets	EU/National drought-management plans Flexible implementation of WFD	Water 'rationing' by means of prior appropriation system Flexible implementation of prior appropriation
Agency	Centralised governance	Subsidiarity principle Wide range of national settings	Emphasis on local governance by courts and water users monitored by States.

The set up of the groundwater governance systems contain interesting fragments, both strengths and weaknesses, to draw lessons from. Ross (2016) states that the EU WFD has gone furthest towards an integrated framework to manage groundwater quantity and quality objectives, but there are many implementation challenges. Australia's system of annually adjustable water entitlements and related water markets provides security, efficiency, and flexibility but it is not yet clear how successfully environmental water allocations can be integrated within this framework (Ross, 2016). The system of prior appropriation in the USA provides clearly defined priorities for water allocation, but lacks flexibility during extreme droughts (Ross, 2016). An especially interesting element of the regulation mechanism in the USA is that farmers can 'buy' rights to extract additional groundwater, by first recharging water into the aquifer. A strength of the WFD is that groundwater allocation is included in river basin plans. The state level strategy of the USA results in local legitimacy, but also lacks in its potential to counter impacts of larger scale aquifer systems and contingencies. Although the central coordination and planning of Australia and the EU result in improved strategic planning, both are also reliant upon local delegation and implementation. This results among others in variability in the monitoring and reporting quality. An extensive comparative overview of the strengths and weaknesses of the groundwater governance systems of Australia, the EU and the USA, based on the findings of Ross (2016), is given in Appendix H.2.

Legislative complexity for MAR increases largely when the aquifer is transboundary, what most of the larger aquifer systems are. To take these transboundary issues into account, the UN Convention on the Law of Non-Navigational Uses of International Watercourses, or the UN Watercourse Convention (1997), which pertains the uses and conservation of all waters that cross international boundaries, including both surface and groundwater, was created (United Nations, 1997). This convention is however limited in two ways:

- The number of states that ratified it is low (currently 37), excluding relevant countries with regards to MAR such as China, India, Iran, and the USA. It took 17 years for the convention to enter into force in 2014 with the participation of a 35th state (United Nations, 2014).
- The scope of groundwater in the convention appears narrow and limited (Stephan, 2009). It only considers groundwater when it is related to surface water, flowing to a common terminus, thus excluding groundwater resources that are either unrelated to surface water, or do not share a common terminus with it.

As a result, transboundary aquifers receive limited coverage in international (water) law. To improve this coverage, the UN International Law Commission (ILC) has developed a set of 19 draft articles on the law of transboundary aquifers (McCaffrey, 2009). These articles deal with protection, preservation and management, and procedural issues, as well as sovereignty and ownership (Capone & Bonfanti, 2015). Capone and Bonfanti (2015) state that, despite the non-binding nature, these draft articles are the most authoritative statement on the law of transboundary shared groundwater resources.

Even though there are no general, legally binding, rules in place to regulate the issue in a uniform and coherent way, in a very few cases (in 2011 only five in total) involved states in a transboundary aquifer management system have concluded binding agreements (Capone & Bonfanti, 2015). According to Capone and Bonfanti (2015), the most famous example is the French-Swiss Convention for the Protection, Use, and Recharge of the Genevese Aquifer System of 1997, for which France and Switzerland split the costs and co-managed a MAR system situated in Switzerland. The most recent example of a signed transboundary agreement is one for the Guaraní Aquifer System, one of the world's largest aquifer systems crossing Argentina, Brazil, Uruguay, and Paraguay. This agreement focusses mainly on the sovereignty of the involved states over their respective portions of the aquifer, whereas sustainable and rational use of, the obligation not to cause significant harm to, and protection and conservation of the aquifer as a resource are of lower importance. Moreover, the agreement contains several clauses on notification and exchange of technical information, cooperation, the identification of critical areas and dispute resolution (Capone and Bonfanti, 2015).

To conclude, using the words of Tvedt et al. (2014: 17) '*(ground)water law as found around in the world today is a patchwork of local customs and regulations, national legislation, regional agreements, and global treaties, reflecting that water law developed in a highly contextual manner, mirroring political systems, religious traditions and economic activities and relations.'* It appears that the right to water is recognized at an international level, but its implementation is not (yet) performed in an effective way, which is especially true for groundwater. Yet, several countries have adopted interesting legislative groundwater governance systems, that can be learned from. On the other hand, crucial issues such as the management of shared, transboundary aquifer resources, are for from soundly and widely regulated.

6.3.3. Legislation on groundwater quality

To ensure the groundwater remains of high enough quality, toxicological threshold values are established worldwide. The specific values are often country- or region specific, and where the USA's values are determined by the USA Environmental Protection Agency (EPA), Australia has the Australian EPA and South Africa follows the guidelines as set by the South African Bureau of Standards (SABS). These however seem lacking with regards to MAR in that they focus on the water quality of the source water, and as such do not include the potentially adverse effects of the injection process. For the EU, the European Groundwater Directive (EGD) is set up by the European Commission (EC), as part of the broader Water Framework Directive (WFD) (European Commission, 2010), and will be looked at in some more detail.

The EGD establishes a regime which sets groundwater quality standards and introduces measures to prevent or limit inputs of pollutants into groundwater (European Commission, 2019). With the aim to have had the EGD implemented in 2015 at the latest, the EGD requires members states[1] to:

- Create groundwater quality standards;
- Conduct pollution trend studies to be carried out by using existing data and data which is mandatory by the WFD to create a baseline level;
- Reverse pollution trends so that environmental objectives are achieved in time. This should be done by establishing a programme of measures for achieving WFD environmental objectives, such as groundwater extraction control and MAR, regulation of point source discharges and diffuse sources liable to cause pollution, and prohibition of direct discharges of pollutants into groundwater.
- Ensure measures to prevent or limit inputs of pollutants into groundwater to be operational so that WFD environmental objectives can be achieved;
- Perform reviews of technical provisions of the directive in 2013 and every six year thereafter;
- Comply with good chemical status criteria, based on EU standards of nitrates and pesticides and on threshold values established by member states.

As the review of 2019 has not yet been approved and published by the EC, the 2013 review (European Commission, 2014) it the most recent available. As the EC aimed for the EGD to be implemented in 2015, the 2013 review did not incorporate the final outcomes of all requirements listed above. The 2013 review gives first insights in results of and proposes changes to the report by the EC on determining toxicological threshold values from 2010 (European Commission, 2010).

The regime and threshold values that follow are country specific, as each member state has to create its own, since the threshold value should be based on the natural presence of the pollutants. In total, the member states established a list of 158 different pollutants/indicators, ranging from 0 (Portugal), to 58 (United Kingdom) per member state. These include pesticides, nutrients, metals, synthetic substances, other

[1] Still including the United Kingdom as former member state.

substances (e.g. calcium, bromate, cyanide), and indicators (e.g. acid capacity, hardness, pH). A list with the most common and important substances and indicators is presented in Appendix H, including the threshold values (European Commission, 2010, 2014). The threshold values show a wide range, following the different requirements and varying approaches individual member states may have used, and as each threshold value is potentially adapted to an individual groundwater body. E.g. ammonium ranges from 0.084 to 52 μg L^{-1}, copper from 10.1 to 2000 mg L^{-1}, and sulphate from 130 to 4200 mg $L^{=1}$. Although the threshold values themselves may thus not be fully comparable within Europe (let alone globally) and are up for debate, these substances and indicators are the most important to keep in mind for groundwater quality assessments. The EGD is legally binding for the member states.

6.4. Summary of multidisciplinary factors influencing feasibility of MAR

Regarding environmental factors, hydrogeological and hydrogeochemical factors are found. For the hydrogeological factors, the aquifer type is a constraint for ASR/ASTR. The final parameter of interest for ASR/ASTR feasibility, is the groundwater potentiality, or the potential water volume for extraction. Many parameters play a role in the potentiality. Of these, the most prominent is the transmissivity. Other important parameters are among others the (un)conformity of hydraulic properties in the aquifer, the lateral hydraulic gradient, the groundwater's quality, and the availability of source water. When looking at hydrogeochemical factors, the hydrogeochemical processes when injecting source water into the aquifer are found to be most important. Injecting source water can have a positive, cleaning effect on the native groundwater('s quality), but since the water is directly injected into the aquifer using ASR/ASTR, pre-treatment is essential. However, case studies have showed that even if the source water is of (very) high quality, purely the injection process itself can have adverse effects on the groundwater quality. This shows that understanding of these hydro-geochemical processes is of high importance.

Regarding the socioeconomic factors, five main factors were found: the effects of MAR on the socioeconomic status (SES) of a region, unfolding typical contingencies in the operation of a MAR site, discovering the costs, monetizing the benefits, and the funding of a typical MAR project. In this, it is assumed that the SES can tell something on whether the region can financially bear the investment for an expensive MAR technique such as ASR/ASTR. Simultaneously, the implementation of MAR will have a positive feedback on the SES. Often, MAR projects are not even started, due to the absence of a clear economic case. To have an economic case, the economic water productivity (EWP) of the MAR project should be known and be 1 or higher. The contingencies, the costs, and the benefits play a role in determining the EWP. However, contingencies surrounding MAR and the operation of a MAR site are often neglected or simply unknown, it is unclear what different types of costs there are, and it has been found that monetizing the benefits is (extremely) difficult. Additionally, even if there is an economic case for a MAR project, achieving sufficient funding for the project proves an obstacle. This results in low trust in the economic feasibility of a MAR project, which is a barrier to the uptake of MAR. To counter this, several contingencies are identified that are standardly neglected in economical MAR studies, the benefits are divided into direct and in-situ benefits and some guidance is given how these might be monetized, and an overview is given with the types of costs that should be incorporated in a standard economical MAR study. Lastly, several funding constructions are explained.

For institutional factors, stakeholder management and the legislation on groundwater use and withdrawal, and on water quality, have been identified as important factors influencing feasibility of MAR and ASR/ASTR. MAR projects are often entrenched in a cobweb of disagreeing incentives for different stakeholders, impeding implementation and operation of MAR systems. Brunner et al. (2014) found that for a project in India, adding an additional governmental authority, comprising representatives of the different stakeholder groups and solely tasked with overseeing and guiding MAR projects in the region, smoothened the planning and construction process largely. Moreover, from Gale (2006) it follows that the operational process, especially when there is a role in it for rural communities, might be smoothened by paying particular attention to and giving a highly detailed overview of the beneficiaries of efficient operation of the MAR system. For legislation on groundwater use and withdrawal, it is mostly the absence of a clear and legally binding (ground)water law, especially when aquifers are transboundary. Current groundwater law is a patchwork of local customs and regulations, national legislation, regional agreements, and global treaties, making its implementation ineffective. However, several countries have set up a national system where interesting lessons can be drawn from, most notably Australia, the EU, and the USA, which groundwater governance systems have been looked at in a comparative study by Ross (2016). The EU WFD has gone furthest towards an integrated framework to manage groundwater quantity and quality objectives, but there are many implementation challenges. Australia's system of annually adjustable water entitlements and related water markets provides security, efficiency, and flexibility but it is not yet clear how successfully environmental water allocations can be integrated within this framework. The system of prior appropriation in the Western US provides clearly defined priorities for water allocation but lacks flexibility during extreme droughts. As for the legislation on groundwater quality, many regions and/or countries have set up toxicological threshold levels to ensure the groundwater remains of high enough quality. As an example, the groundwater quality legislation as put into operation by the EU has identified fifteen substances that should always be monitored to stay below a certain threshold level when working with groundwater.

7. Hiatus in preliminary feasibility studies

7.1. Current preliminary feasibility studies

When MAR is actively considered as an option for mitigating water stress, preliminary assessments of the potential of MAR and potential MAR-sites can start. The selection of a suitable recharge site is, according to the extensive literature review on MAR feasibility mapping by Sallwey, Bonilla Valverde, et al. (2019: 138), '*a critical step in the design stage of a MAR project, as the site influences the selection of an appropriate recharge technique, the operation strategy, and the maintenance of the MAR system*'. A comprehensive feasibility assessment should encompass a wide variety of factors, as shown in Figure 15. A preliminary feasibility study is currently mostly used to evaluate whether MAR would be possible from an engineering point of view, and whether is has economic feasibility (Sallwey, Bonilla Valverde, et al., 2019).

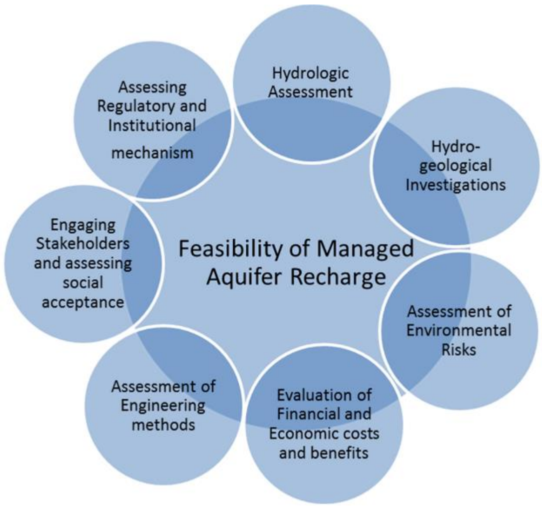

Figure 15 A framework for the feasibility of MAR. Source: Arshad et al., 2014: 2751

7.1.1. Lacking guidelines on feasibility studies

A preliminary feasibility study for MAR is often achieved combining multicriteria decision analyses (MCDA) with geographical information systems (GIS) into an GIS-MCDA, and with use of a prioritization method (most commonly a pairwise comparison) (Sallwey, Bonilla Valverde, et al., 2019). As such, it combines the spatial analysis capacity of GIS with MCDA methodology which guides decision processes in a structured way (Malczewski & Rinner, 2015). Sallwey, Bonilla Valverde, et al. (2019) state that the site selection for MAR is undertaken by combining and weighting the geospatial data characterizing the study area based on the study's objectives. Despite many feasibility studies have been conducted using GIS-MCDA for MAR site selection, common understanding on criteria, weights, and methods to be used, is absent (Sallwey, Bonilla Valverde, et al., 2019). According to Sallwey, Bonilla Valverde, et al. (2019), there are no guidelines or a common understanding on how suitability mapping for MAR should be conducted, and there is considerable variability as to what factors are assessed and how they are weighted. Where some suitability assessments put the focus on the landscape characteristics, others put a high load on the volume of excess water to determine the suitability (Stefan & Ansems, 2018). As such, the theoretical framework as given by (Arshad et al., 2014) is not found in practice. An important shortcoming with regards to the selection of criteria, is (the effect of) data availability. When data is either of poor quality or entirely unavailable, the criteria is simply excluded from the list. In studies where e.g. subsurface information was present, it was regarded as one of the most important criteria. Yet, when this information was missing, the study often didn't even mention this knowledge gap (Sallwey, Bonilla Valverde, et al., 2019). As a result, the quality of the feasibility maps strongly depends on the input data quality as well as the expertise of the decision maker (Sallwey, Schlick, et al., 2019).

7.1.2. Standardizing guidelines on feasibility studies

A first step to standardize GIS-MCDA methodology for MAR site selection was taken by Rahman et al. (2012), by creating a GIS-based tool for MCDA site selection analyses. Russo et al. (2015) compared the weights assigned to different criteria by a variety of GIS-MCDA studies. For his dissertation, Bonilla Valverde (2018) performed an analysis of 25 GIS-MCDA studies for MAR. Based thereupon, Sallwey, Bonilla Valverde, et al. (2019) reviewed a total of 63 MAR feasibility studies using GIS-MCDA on the applied MAR methods and location characteristics, as well as the criteria, weights, and decision rules used. 90% of these were from 2010 or more recent. With the resulting overview for the most used criteria and assigned weights, the authors hoped to guide decision-makers in their own GIS-MCDA process. The authors also stated that analysing the most commonly used practices and methodologies in GIS-MCDA for MAR suitability mapping can constitute as a starting point for the discussion of standardizing the mapping procedure. To this end, Sallwey, Schlick, et al. (2019) have created two web-based tools, based on the data presented by Sallwey, Bonilla Valverde, et al. (2019). The first is a query tool making the MAR- and MCDA-relevant information easily accessible. The second tool comprises a simplified web GIS as well as supporting tools for weight assignment and standardization of the criteria, based on the most commonly used MCDA practices in the assessed studies.

7.1.3. Review of current feasibility studies

Sallwey, Bonilla Valverde et al. (2019) found a total of 467 criteria across the 63 reviewed studies. The authors grouped these into five main fields: aquifer, surface, water quality, hydrometeorology, and management. Based hereupon, fifteen sub-fields are established, with amongst others the economic feasibility as part of the management field of criteria. These are presented in Figure 16.

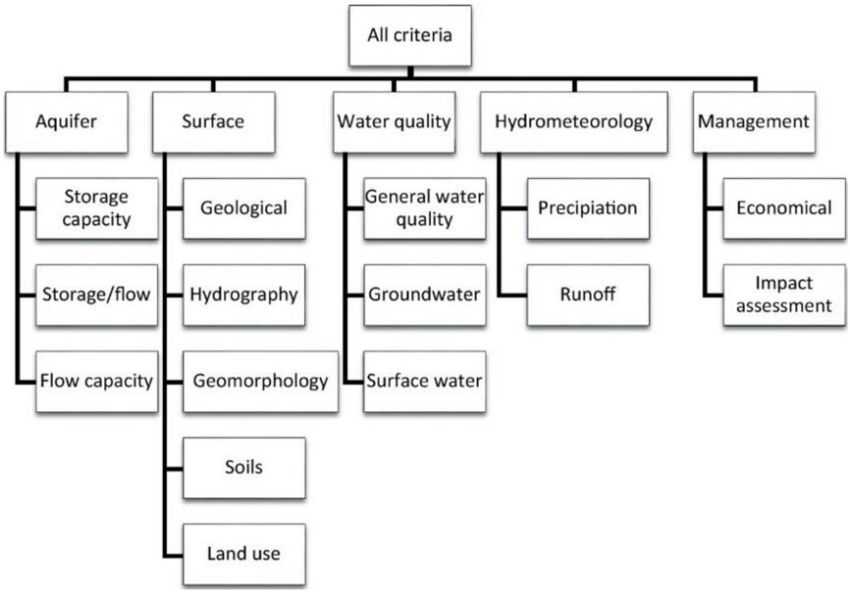

Figure 16 Grouping of criteria used in GIS-MCDA studies. Source: Sallwey, Bonilla Valverde et al., 2019

Sallwey, Bonilla Valverde, et al. (2019) distinguished their findings among four main MAR-types, based on Gale (2005) but excluding induced bank infiltration. These are spreading methods (SM), in-channel modifications (IM), well, shaft and borehole recharge (WSB), rainwater harvesting (RWH), and unspecified. As ASR and ASTR fall under WSB, this report will further only look at the data given by Sallwey, Bonilla Valverde, et al. (2019) regarding WSB. Shallow wells and shafts recharge is the only other MAR technique in WSB.

Relatively little is known on WSB, as Sallwey, Bonilla Valverde, et al. (2019) only found nine GIS-MCDA studies for WSB. These studies deviated between 77 different criteria. Within these, sixteen criteria concerning the aquifer were found, and 35 criteria related to the surface. For both water quality and for hydrometeorology, five criteria were mentioned. Lastly, sixteen different management criteria came forth from the review.

Figure 17 shows the further division of criteria per sub-field. On average, the nine reviewed studies had 7.8 criteria incorporated in the feasibility analysis.

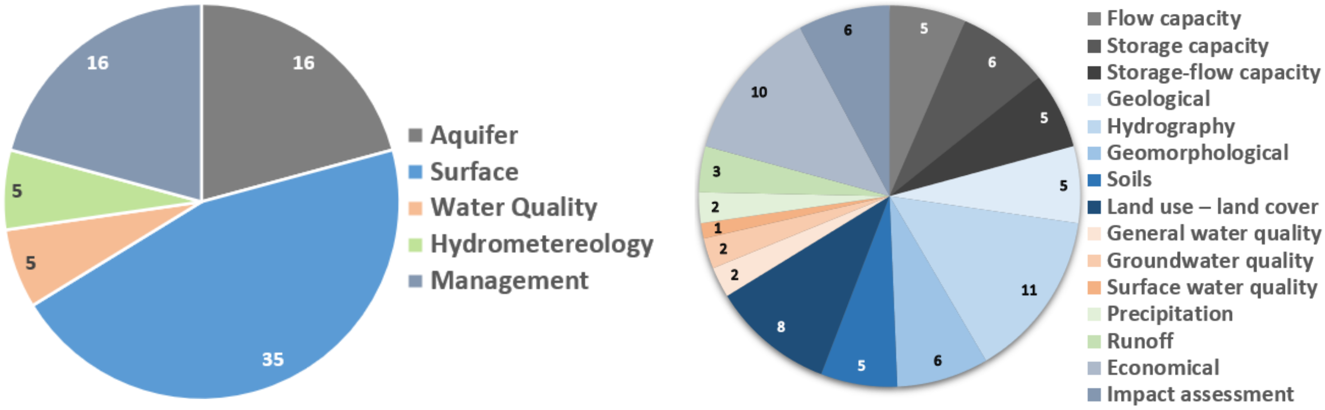

Figure 17 Division of found criteria per sub-field in GIS-MCDA for WSB methods. Left: main criteria. Right: sub-criteria.

When looking at the assigned weights, Sallwey, Bonilla Valverde, et al. (2019) presented a list with the seven most-used criteria for WSB-methods. These are consequentially assumed to be the most prominent. The authors also gave the range of and median weights assigned to it. From this it follows that the slope of the surface is the most used criterion for GIS-MCDA feasibility studies for WSB, with seven of the nine studies reviewed reporting its use, and a median weight of 13.8%. The criterium with the highest influence is, by far, geomorphology, with a median weight of 20%. However, only four studies reported to have used this criterium. Land use, soil type, and lineament density are assigned weights around 10% and show little variation. The highest variations for assigned weights are visible for geology and geomorphology. The ranges and average values of weights are presented in boxplots in Figure 18, adapted from Sallwey, Bonilla Valverde, et al. (2019). It is noteworthy that of the seven most-used criteria, six are surface-criteria, while one fits in the aquifer-criteria. No further specification is given by Sallwey, Bonilla Valverde, et al. (2019) on what the other used criteria are, e.g. what water quality criteria were mentioned in those studies that included them.

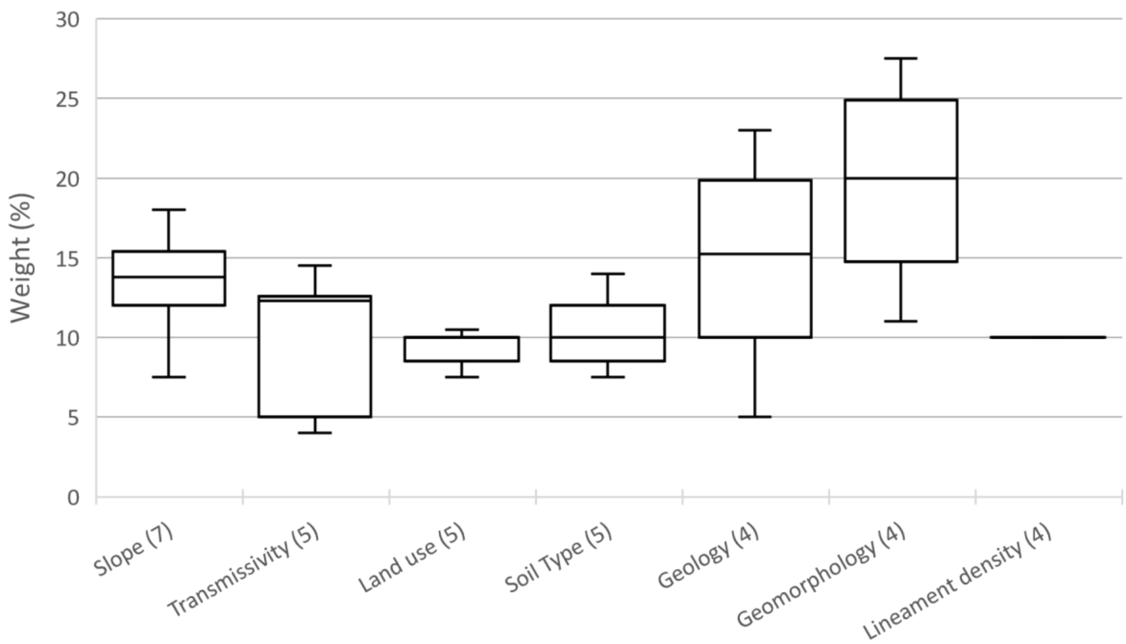

Figure 18 Ranges and median values of weights assigned to most used criteria for WSB studies. Between brackets the number of studies that have reported the criterium. Source: Sallwey, Bonilla Valverde, et al., 2019

Following **Error! Reference source not found.** and Figure 18, it can be stated that most attention in current preliminary feasibility studies for WSB-methods, goes to surface-related criteria, while water quality criteria are only sparsely considered.

7.2. Comparison of found barrier's implementation in current feasibility studies

In this report, barriers and influential factors are deviated into the groups 'hydro-geological', 'economic', 'institutional', and 'environmental'. In the review of Sallwey, Bonilla Valverde, et al. (2019), the criteria are grouped differently. The environmental factors are divided into the hydrogeology-related factors 'aquifer', 'surface' and 'hydrometeorological', and the hydrogeochemical factor 'water quality'. Other, non-water quality related environmental factors (such as environmental benefits of the in-situ groundwater), are not mentioned. Economic factors are part of 'management'. The institutional factors, i.e. stakeholder management and legislation, seems to be no part of the criteria for current feasibility studies at all, as it does not fit the description of any of the groups given by Sallwey, Bonilla Valverde, et al. (2019). See Figure 19.

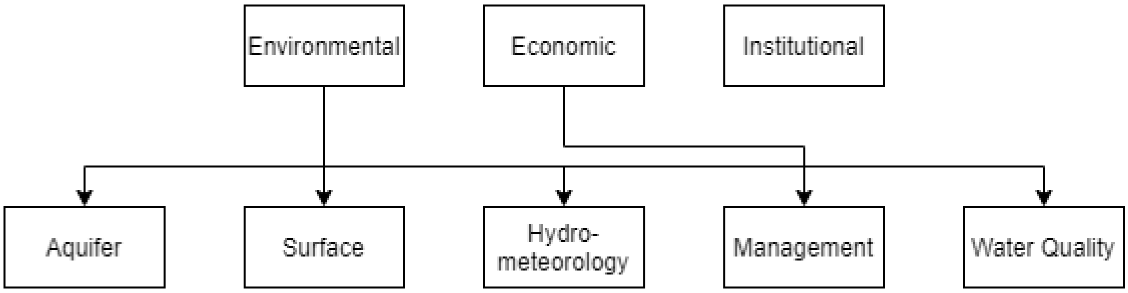

Figure 19 Conversion of this report's barriers to criteria for feasibility studies as grouped by Sallwey, Bonilla Valverde, et al. (2019).

Effectively comparing the found barriers and influential factors from **Error! Reference source not found.** with t he exact criteria used in feasibility studies from 7.1, is difficult. Sallwey, Bonilla Valverde, et al. (2019) did not differentiate between ASR and ASTR (which are only scarcely influenced by surface-characteristics) and other WSB-methods (which are largely influenced by these characteristics).Where the authors showed a high attention to surface-related criteria in current feasibility studies for WSB (35 of the 77 total criteria for WSB), it can be expected that many of these are of little relevance to ASR and ASTR, as the layers above the aquifer are simply bypassed by the pumping installation. Additionally, only the seven most-used criteria in feasibility studies for WSB-methods are specified by Sallwey, Bonilla Valverde, et al. (2019), and Sallwey, Bonilla Valverde, et al. (2019) had limited literature on ASR/ASTR feasibility studies to include in their review (only nine GIS-MCDA studies for WSB).

Despite this limitedly available literature, it can be concluded that attention for water quality aspects in them is lacking. While the report by IGRAC and Acacia Institute (2007) states water quality as one of the most prominent limitations for ASR and ASTR, and (EU's) current legislations mentions fifteen criteria with high impact on the (aquatic) environment and usability of the (recharged) groundwater that should always be incorporated in feasibility studies (European Commission, 2010, 2014), the nine feasibility studies for WSB had a summed total of only five water quality criteria incorporated (Sallwey, Bonilla Valverde, et al., 2019). Regarding economic feasibility, in Sallwey, Bonilla Valverde, et al. (2019), only topographical elements such as distance to water supply sources are mentioned and not broader construction and operational costs. Moreover, no economic benefit-criteria are mentioned.

8. Discussion

To provide increased insight for farmers and water managers on a global scale on the multidisciplinarity of the issues surrounding water availability variability, groundwater depletion, groundwater management, and on the barriers and merits of Managed Aquifer Recharge (MAR) as such a management method, four research questions were established, aiding the main research question *'How can Managed Aquifer Recharge aid in relieving groundwater stress and what are the inter-disciplinary barriers restraining the uptake of MAR within agriculture?'*. The four research questions all had several sub-questions, totalling to thirteen. The first two research questions, '*Why is additional (ground)water storage needed?*' and *'What are MAR's potential ways to alleviate water stress?*' were mainly introductory, yet necessary, questions to the subject of MAR, and to set the stage of the severity of the groundwater depletion and possibilities MAR offers to counter this. The third, fourth, and fifth research questions, '*How does MAR contribute to alleviation water stress?'*, *'What are factors restraining uptake of MAR in agriculture?'*, and '*Is there a hiatus in the current inclusion of factors in feasibility studies for MAR in agriculture?'* followed from an observed gap in literature on the matter, which was also endorsed by said literature. The gap was for the biggest part not so much in the (non)existence of knowledge on i.e. the factors restraining MAR, but on the *availability* and *accessibility* of the *combined knowledge* for people outside of a select group of researchers specialised in the field of integrated groundwater management.

With use of an extensive literature study, answers for all posed questions were looked for. The study was broad in the topics treated, as it was aimed for to provide an informed overview on the important dimensions on the elements mentioned above. Key in the used methodology in this research, and especially applicable to the results of the fourth research question (as presented in Chapter 6), is that no existing framework was at the base of it. Instead, keeping the exploratory character of the study in mind, the steps taken derived from logic. Also, the exploratory character of the study required a relatively broad scope, to be able to determine the multidisciplinary merits and barriers on a global, unspecific scale. Though necessary, this broad scope is probably simultaneously the largest issue with the methodology. Despite the use of several case studies, it has resulted in a general overview of and background story to MAR, with sometimes limited depth. Although focus was sought in agriculture and with looking at one type of MAR technique specifically (ASR/ASTR), with the exploratory and multidisciplinary approach it has proved to be difficult to keep the same level of detail throughout the whole study. This was further impeded due to limited availability of literature on specific MAR techniques, and thus the required upscale of the level of detail back towards MAR in general. Furthermore, difficulties were found in keeping a clear level of detail on the spatial parameter. This study aimed at discussing MAR on a global context, but the issues in which MAR can aid relieving are highly spatial.

Moreover, it should be pointed out that the same data and literature was used multiple times, and especially Gale (2005), Dillon et al. (2019), and Maliva and Missimer (2012). Also, several research questions were (almost) completely answered with use of only one or two sources (e.g. R.Q. 3.2 on the current implementation of MAR with the IGRAC database (IGRAC, 2020a), and R.Q. 5.1 on current feasibility studies for MAR and ASR/ASTR with Sallwey, Bonilla Valverde, et al. (2019)). All this might lead to a low external validity, as the examples given in the sources are presented generalized. Moreover, data from for example the DEMEAU project has been used. This EU-funded project has the aim to demonstrate and *promote* promising technologies to address emerging pollutants in water and wastewater, with MAR as one of the most promising of these. In this, 'promote' is meaningful, as this might indicate some subjectivity in the findings presented.

Below, more research question-specific points for discussion are presented.

8.1. Additional groundwater storage

Quantification of two elements was important for the first research question: the water storage deficit (to see whether MAR could, potentially, cover this), and the current (ground)water withdrawal and depletion.

In both cases this is due to a high uncertainty of what happens in the ground. Where quantification of the global water storage deficit is absent and only limited regional data was found in literature (and as such, no comparisons could be made), large differences were found in articles discussing estimates for the global groundwater withdrawal and depletion. The estimates were obtained through either country level reporting/inventories, or modelling. For the year 2000, the country level reporting-based estimates ranged from 600 to 800 $km^3\ yr^{-1}$ (Bierkens & Wada, 2019). However, as these estimates are reliant on country level government reports based on local and regional measurements of groundwater withdrawal, the reliability of these reports vary significantly. As Bierkens and Wada (2019) mentioned, they tend to contain many missing data in regions such as Asia, Africa, and South America. Modelling-based estimates often use fractional data on the total water withdrawal per country, which is often much better document that groundwater withdrawal itself. For the year 2000, the modelling-based estimates for global groundwater withdrawal ranged from 700 to 1000 $km^3\ yr^{-1}$ (Bierkens & Wada, 2019). Where model-based estimates have the clear advantage over country level reporting-based estimates of global coverage, they often neglect physical, technological and socioeconomic limitations in water withdrawal that exist in various countries (Wada et al., 2014). The uncertainty of these estimations should be kept in mind, but do give a good indication on the scale of the withdrawal volume.

8.2. The ways in which MAR can aid in alleviating water stress

For the second research question, amongst others an inventory of MAR techniques has been set up. For this inventory, the deviation and classification as given by Gale (2005) has been used, with a further specification of ASR and ASTR into two different techniques. In total, fifteen MAR techniques are described. However, these fifteen techniques can also be further divided into additional sub-techniques. As an example, percolation ponds/recharge dams can be wadi dams, permeable dams, gabions, and check dams. These differ in size and material composition, and as such also in their requirements, capacity, and costs. To create a higher-quality inventory, more sub-techniques should be included, instead of solely those given by Gale (2005).

8.3. The current contribution of MAR in alleviating water stress

As followed from R.Q. 3.1, and similar to groundwater withdrawals, a sound, comprehensive, global inventory of MAR sites and yields, is absent in literature.

The IGRAC database was heavily relied upon for research question 3.2. This database is however still a sample of all MAR projects worldwide. Although it is unclear *how* incomplete this database currently is, it is clear *that* it is incomplete. The database currently has some 1100 MAR sites inventories, but it is likely that there are thousands of MAR sites not (yet) incorporated (IGRAC, 2020a). To be filled further, the database depends on scientific articles discussing the MAR sites. It is assumed that the mapping of MAR sites meant for domestic uses is better than those meant for agriculture, as more stringent legislation applies and thus the need for scientific reviews will be higher. Moreover, it is expected that costlier MAR sites (such as ASR/ASTR) are better represented in the IGRAC inventory than less costly sites (such as percolation ponds), as a higher investment costs naturally calls for more intensive investigation of the site. As an example, over 700 stormwater runoff ponds are located in the City of Cape Town, yet none of these is incorporated in the IGRAC database. Moreover, it is unclear when a MAR project is counted as one or as multiple sites in the database. As an example, in Asjdod, Israel, four infiltration pond sites are included, directly next to each other. If the 700 ponds of the City of Cape Town would be included, it is unknown whether they would indeed be included as 700 separate sites, or as one large project. This creates uncertainty in using the IGRAC database for quantitative findings. The database however remains the best available.

Similarly, the information from Dillon et al. (2019) on the quantitative output of MAR is reliant on data with a considerable uncertainty. As it is unknown how many MAR sites are present worldwide, it cannot be known what their summed qualitative output is. As such, this information is based on best estimates.

8.4. Multidisciplinary factors influencing MAR's uptake

For the fourth research question, barriers and factors influencing the feasibility of the implementation of a MAR site, and more specifically of ASR/ASTR, have been looked into. Three different disciplines were used for this, namely environmental (including geohydrology), economical, institutional. It was aimed for to give a broad overview of what farmers and water managers should think about when looking into the potential implementation of MAR. To do so, the most influential topics have been discussed per discipline. These topics derived from literature as stated in their specific sections, but in general were defined by literature as important and influential. General information was combined with information from several case studies to exemplify it. Yet, there might very well be other elements more important or influential for the feasibility of MAR, that are considered by literature unbeknownst to the author of this report.

Furthermore, this report provides a combined source of information on the effects of elements in each different discipline, and as such making it more accessible and available. However, this report does not give a true multidisciplinary overview of the cross-disciplinary influences of the different elements. As an example, the type of bedrock plays a role in geohydrology (where does the recharged water go once injected?), water quality (how does the injected water react with the rocks?), and economics (how expensive will the drilling be?). This study might be further improved by not only pinpointing the influential factors in a *multi*disciplinary manner, but try and grasp these into an overall overview with also *inter*disciplinary linkages between the different disciplines, indeed combining the bedrock with these three disciplines as well.

8.5. Hiatus in preliminary feasibility studies for MAR

With regards to the feasibility studies, from **Error! Reference source not found.** and Figure 18 it followed that feasibility studies for well, shaft and borehole recharge (WSB) sites, under which ASR and ASTR fall, had a high focus on surface-related criteria. For ASR and ASTR this focus seems odd, but it should be kept in mind that under WSB, shallow wells and shafts recharge (SWSR) are also included. Where for ASR and ASTR the surface is of little relevance, for SWSR it is. It is assumed this has had influence on the data as presented by Sallwey, Bonilla Valverde, et al. (2019) and that, were ASR and ASTR separated from SWSR, less attention in the feasibility studies would go towards surface-criteria. It is unknown how many of the nine reviewed WSB studies in Sallwey, Bonilla Valverde, et al. (2019), where relating to ASR and ASTR or to SWSR. To improve the findings of this study, the sources of the literature review by Sallwey, Bonilla Valverde, et al. (2019) could be investigated, instead of solely the literature review itself. By effectively redoing that literature review, it would become clear which of the nine studies were related to ASR/ASTR and which not. This would also aid in finding the exact criteria used, instead of the more generally grouped criteria as presented by Sallwey, Bonilla Valverde, et al. (2019).

9. Conclusions and recommendations

9.1. Conclusions

This study explored issues surrounding water availability variability, groundwater depletion, and groundwater management. Moreover, it investigated the merits of Managed Aquifer Recharge (MAR) as such a management method and the multidisciplinarity of factors influencing the feasibility of its implementation. This study adds clarity to science, as the information presented was, up till now, (much) more fragmented.

Due to an increase in groundwater demand, mostly in agriculture, and especially in arid regions or where surface water is difficult to control, aquifers have been depleted. This was possible due to groundwater being a common pool resource and either neglection of or unconsciousness on groundwater being a finite resource. Based on reviewed literature in this report, it is estimated that 15% of all groundwater withdrawal results in aquifer depletion, and that one third of the 37 largest aquifer systems are being depleted. Of these, the Upper Ganges aquifer has the highest depletion rate. This results in more people being affected by the consequences of water stress. As such, improved management of groundwater as a resource is shown as a necessity. Key in this is storing water when available for use when unavailable otherwise. Although literature did not provide information on global water storage deficits, regional deficits have been shown. From literature it followed that groundwater storage should in many cases be the preferred option over surface water storage, among others to prevent evaporation losses of the already scarce resource. Additionally, it was found in literature that 35% of all continental land is highly suitable for (additional) groundwater storage, while 18% is moderately suitable. These include large shares of water stressed regions such as northern Africa, the Arabian Peninsula, India, and Australia.

The study obtained several useful results for the water managers thinking about implementing MAR, such as an overview of the different merits MAR has to substantiate arguments as to why MAR can or should be implemented and an extensive overview of fifteen MAR techniques available to draw from, as well as an overview of where and how MAR is already being implemented, including its quantified output. The output of MAR in 2015 was accountable for about 2.4% of the global groundwater withdrawal. As such, its influence can still be regarded as minor. However, it was found that the worldwide implementation of MAR has accelerated by 5% per year since 1965, compared to an annual 1.8% growth for groundwater withdrawal. As such, MAR is winning terrain compared with the (unsustainable) groundwater depletion. From the most comprehensive inventory of MAR sites, the IGRAC MAR inventory, it followed that Aquifer Storage (Transfer) and Recovery (AS(T)R) is the most-used technique for agricultural end uses.

Additionally, water managers may draw lessons from the compiled overview of multidisciplinary factors in influencing feasibility of MAR. The disciplines discussed were environmental, socio-economic, and institutional, as reviewed literature named these contexts as the most influential in MAR projects, yet until now underexposed.

- For the environmental context, hydrogeological and hydrogeochemical factors have been identified. Regarding the hydrogeological factors, a comprehensive overview of what parameters play the most important roles affecting MAR's feasibility was often absent. In this study, the aquifer potentiality and transmissivity have been identified as final parameters of interest. Moreover, a list of the nine hydrogeological and two hydrological most influential factors has been set up, and their effects on MAR's feasibility explained. Regarding hydrogeochemical factors, it was found that geochemical processes are often underexposed when looking at MAR feasibility. Moreover, it was found that, even when the source water for MAR is of higher quality than the native groundwater, the injection-process itself can result in adverse effects on the groundwater quality.
- For the socioeconomic context, five factors have been identified playing a role in MAR feasibility, namely the influences of MAR on the socioeconomic status, unfolding typical contingencies, discovering the costs, monetizing the benefits, and funding of the project. Of these, the risks and uncertainties, benefits,

and costs are what the economic water productivity (EWP), a final parameter of interest in economical feasibility studies, is constituted of and as such are especially relevant. It is assumed that the SES can say something about the feasibility of certain MAR techniques, following their necessary expenses. Moreover, this study found that implementation of MAR is often lacking due to absence of a clear economic case and high uncertainties on the EWP. This was mostly due to neglection or unawareness of contingencies, the absence of an all-encompassing overview of the costs involved in a MAR project, difficulties with monetizing the benefits of MAR. Moreover, reaching sufficient funding for a MAR project proves difficult, as the main beneficiaries of a MAR project are often not the financers of said project. To improve the chances on reaching a clear economic case for a MAR project, several contingencies are identified that are typically neglected in economical MAR studies, the benefits are divided into direct and in-situ benefits and some guidance is given how these might be monetized, and an overview is given with the types of costs that should be incorporated in a standard economical MAR study. Lastly, several funding constructions are explained.

- For institutional factors, elements in the field of stakeholder management, legislation on groundwater withdrawal and use, and legislation on groundwater quality have been identified as restraining the implementation of MAR. In literature reviewed in this study (a case study on a MAR project in India), it was found that the cobweb of disagreeing stakeholder incentives of a MAR project can be smoothened by creating an additional governmental authority, that is solely tasked with overseeing and guiding MAR projects in the region. The new authority discussed in the reviewed literature comprised of representatives of the different stakeholder groups. Regarding legislation on groundwater use and abstraction, a predominant trend to recognize the State's superior right to management of groundwater resources (opposed to individual ownership) was found. This enabled governments to put in place a system of formal water rights that allow for management and protection of groundwater resources. Three systems with interesting elements, both strengths and weaknesses, to draw lessons from are those of Australia, the EU, and the USA. The EU WFD has gone furthest towards an integrated framework to manage groundwater quantity and quality objectives, but there are many implementation challenges. Australia's system of annually adjustable water entitlements and related water markets provides security, efficiency, and flexibility but it is not yet clear how successfully environmental water allocations can be integrated within this framework (Ross, 2016). The system of prior appropriation in the USA provides clearly defined priorities for water allocation, but lacks flexibility during extreme droughts. Where on country- and region-level several groundwater governance systems are in place, crucial issues such as management of shared, transboundary aquifer resources are far from soundly regulated in current international legislation. As for the legislation on groundwater quality, many regions and/or countries have set up toxicological threshold levels to ensure the groundwater remains of high enough quality. As an example, the groundwater quality legislation as put into operation by the EU has identified fifteen substances that should always be monitored to stay below a certain threshold level when working with groundwater. However, there seems to be a focus on the water quality of the source of MAR, while the effects of the process of MAR are not incorporated.

When looking at current feasibility studies for ASR/ASTR, it was found that hydrogeological environmental factors are heavily incorporated, yet economic assessment and, especially, water quality elements are under-represented. The institutional factors are not incorporated at all in current feasibility studies. That however does make sense, as those would (or should) follow in later stages of the ASR/ASTR project.

9.2. Recommendations

From a scientific point of view, it is recommended that the knowledge gaps found by this study, should be investigated further. Quantitative information on groundwater storage deficits, as well as on groundwater withdrawal and use could be further improved. Also, quantitative information on the costs and capacities of the fifteen identified MAR techniques is near-absent in literature. Additionally, attention should go to further filling the IGRAC database with representative MAR sites. Furthermore, further research should look into combining the multidisciplinary barriers and factors discussed in this report, into a cross-disciplinary overview to fully create an overview of merits and barriers in an integrated groundwater management system. Furthermore, the influences of and need for MAR are strongly bound to local and regional conditions. As such, and although MAR can offer solutions to groundwater management issues and water scarcity around the world, local and regional conditions should always be considered.

Additionally, a recommendation resulting from this research study is that MAR should be considered more frequently wherever in the world. Water managers should incorporate MAR in their programs. It has shown to be a feasibility option in a multitude of circumstances, and, if properly managed, the advantages clearly out-weigh the disadvantages. Moreover, MAR has the ability to solve many different kinds of issues related to (ground)water management, as well as aid in fulfilling the growing needs for safe and clean water around the globe.

It is further advised to bring the topic of groundwater storage and MAR's potential role therein to the attention of water managers, e.g. by showing the importance and the (economic) opportunities. For this, the positive, historical backstory on already implemented MAR sites, as presented in this report, is paramount, as MAR still is either unknown altogether or perceived as risky. The role and importance of groundwater and MAR could also be brought more to attention in (higher) education, as this will make people more aware of its benefits for people and ecosystems. Moreover, further development of (online) knowledge networks, such as the IGRAC database, that exchange knowledge and experiences on MAR, would be valuable.

It is paramount to bring the topic of groundwater storage to the attention of water managers by showing the importance and urgency, and the (economic) opportunities that lie within. In educational programmes attention to the role of groundwater and its reservoir will make people more aware of its benefits for people and ecosystems. Moreover, an (online) knowledge network or community, exchanging knowledge and experiences on MAR, would be valuable.

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Appendix A Development regionalised water withdrawal and consumption

Table App. 1 Regionalised data on water withdrawal and consumption 1979 --> 2010, adapted from Wada et al. (2014).

Region[1]	GW[2] withd[3] (km^3yr^{-1})		Growth 1979-->2010 GW[2] withd[3]	Total water withd[3] 2010	GW[2]% withd[3] of total withd[3] 2010	GW[2] cons[4] (km^3yr^{-1})		Growth 1979 --> 2010 GW[2] cons[4]	Total water cons[4] 2010	GW[2]% cons[4] of total cons[4] 2010
	1979	2010				1979	2010			
N. America	105	160	52%	280	57%	70	100	43%	160	63%
C. America	45	55	22%	95	58%	25	35	40%	50	70%
S. America	15	25	67%	130	19%	7	15	114%	60	25%
W. Europe	45	55	22%	200	28%	25	40	60%	110	36%
E. Europe	25	40	60%	140	29%	15	25	67%	95	26%
N. Africa	10	20	100%	90	22%	5	15	200%	70	21%
S. Africa	5	10	100%	72	14%	2	5	150%	40	13%
W. Asia	60	140	133%	220	64%	40	90	125%	150	60%
C. Asia	10	15	50%	95	16%	5	10	100%	65	15%
E. Asia	105	190	81%	580	33%	70	125	79%	220	57%
S. Asia	215	380	77%	1050	36%	145	240	66%	512	47%
S.E. Asia	10	20	100%	295	7%	5	10	100%	70	14%
Oceania	2	3	50%	30	10%	1	2	100%	12	17%
World	**652**	**1113**	**71%**	**3277**	**34%**	**415**	**712**	**72%**	**1650**	**44%**

[1] Region: N=Northern, W=Western, S=Southern, W=Western, S.E.=South-Eastern ; [2] GW = Groundwater ; [3] Withd = Withdrawn; [4] Cons = Consumption

Appendix B Comparison of subsurface and surface water storage

Table App. 2 Comparison of characteristics (additional) subsurface and surface water storage. Source: Keller et al,. 2000 and Tuinhof and Heederik, 2003

Type	Characteristic	Aquifers	Surface water reservoirs
Hydrogeological / technical	Resource areas	Relatively unrestricted	Restricted to water courses and canals
	Required land surface for additional storage	Low to medium negatively, dependent on used technique	High
	Natural recharge rate	Very low	Moderate to high
	Residence times	Generally decades/centuries, can be induced	Mainly weeks/months
	Drought propensity	Generally low	Generally high
	Evaporation losses	Low and localised	High for reservoirs
	Hydrogeological losses	Potentially high, soil type dependent	Low
	Abstraction impacts	Delayed and dispersed	Immediate
	Natural quality	Generally high, with local exceptions	Very variable
	Pollution vulnerability	Variable natural protection	Largely unprotected
	Pollution persistence	Often extreme	Mainly transitory
Others / non-technical	Public perception	Mythical, unpredictable	Aesthetic, predictable
	Development cost	Generally modest	Often high
	Development risk	Less than often perceived	More than often assumed
	Style of development	Mixed public and private	Largely public
	Potential for multifunctionality	Low	High (hydropower, tourism)
Key issues		Management of access and use	Social impacts
		Groundwater pollution	Above-surface environmental impacts
		Clogging of installations	Effects downstream of reservoir
			Sedimentation

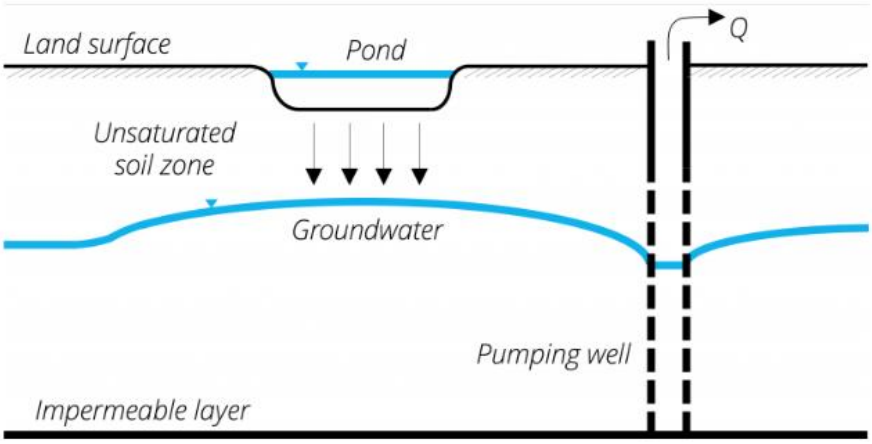
Appendix C The specific MAR techniques

In this appendix, the fifteen MAR techniques as stated in section 4.3 are elaborated on.

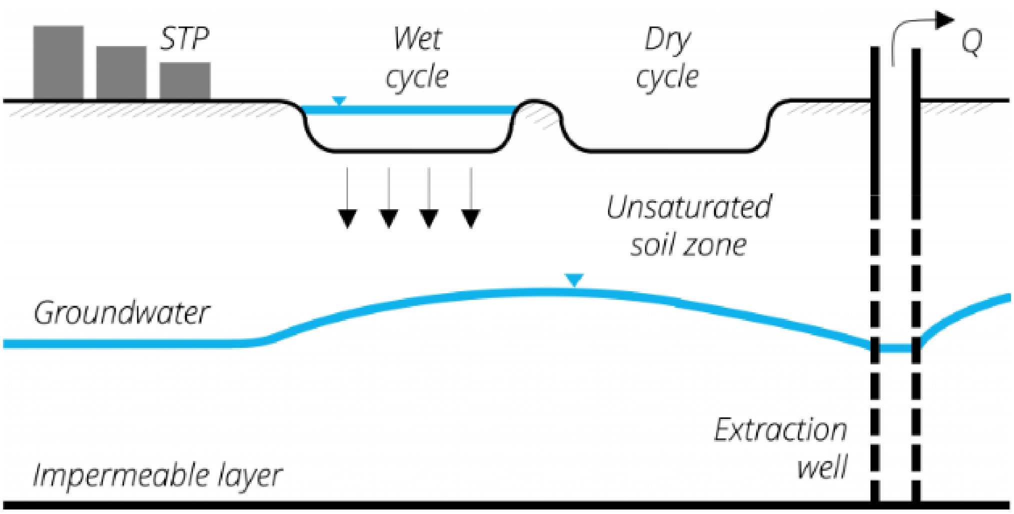
Appendix C.1 Spreading method MAR techniques

See the subsections below for a detailed overview of the four spreading method MAR techniques.

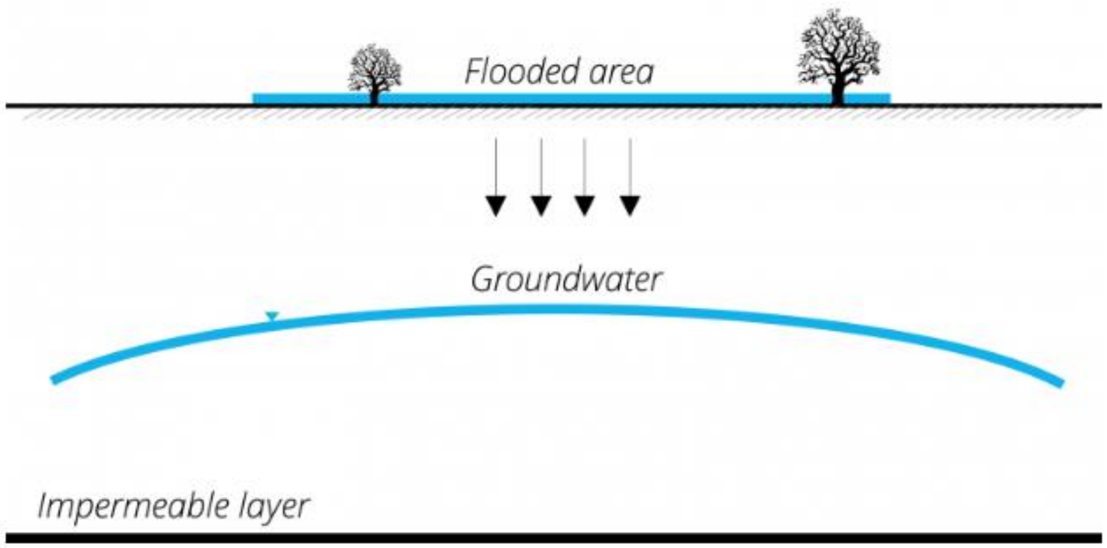
Appendix C.1.1 Infiltration basin

Synonyms	Infiltration pond, retention ponds, wet pond, spreading basin
Description	An infiltration basin is either excavated in the ground, or it comprises an area of land surrounded by a bank, which retains the recharge water (e.g. storm water), until it has infiltrated through the floor of the basin (Gale, 2005). If placed in an ephemeral stream in monsoon regions, the monsoon flow is captured by the basin (Maliva & Missimer, 2012).
Schematic image	 *Figure App. 1 Schematic image of an infiltration basin. Source: INOWAS, 2018*
Infiltration capacity	- Highly variable. Ranging from small (household, $10^2 m^3 yr^{-1}$) to large (town, $10^6 m^3 yr^{-1}$) (INOWAS, 2018); - Dillon et al. (2009) mention capacities up to 45 $10^6 m^3 yr^{-1}$. - Bouwer (2002) mentions that in situations where a reliable source of good-quality input water is present, hydraulic loadings of typically 30 m yr^{-1} can be reached for fine texture soils, 100 m yr^{-1} for loamy soils, 300 m yr^{-1} for medium clean sands, and 500 m yr^{-1} for coarse clean sands.
Costs	- Relative cost is low-medium (INOWAS, 2018); - 0.23 US$$m^{-3}$ (Escalante et al., 2014)
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018); - Flat or gently sloped terrains to enhance infiltration and reduce clogging (INOWAS, 2018).
Advantages	- Low infrastructure demand (IGRAC & Acacia Institute, 2007); - Infiltration of large quantities of water at relatively low cost and maintenance (IGRAC & Acacia Institute, 2007); - Relatively simple anti-clogging procedures (IGRAC & Acacia Institute, 2007); - Pollutants contained in source water may be removed by the soil (IGRAC & Acacia Institute, 2007).
Limitations	- Requires large flat permeable areas (IGRAC & Acacia Institute, 2007); - Potential for surface water related diseases (IGRAC & Acacia Institute, 2007); - Potential water pollution (IGRAC & Acacia Institute, 2007); - Potential evaporation (water losses) (IGRAC & Acacia Institute, 2007).
MAR main objective	- Agriculture, domestic, industrial (INOWAS, 2018).
Additional information	- Depending on water source quality, pre-treatment is necessary to prevent clogging. (Gale, 2005). - Design (e.g. shape, surface) of the infiltration basin can largely affect the hydrologic response of the aquifer (Gale, 2005).

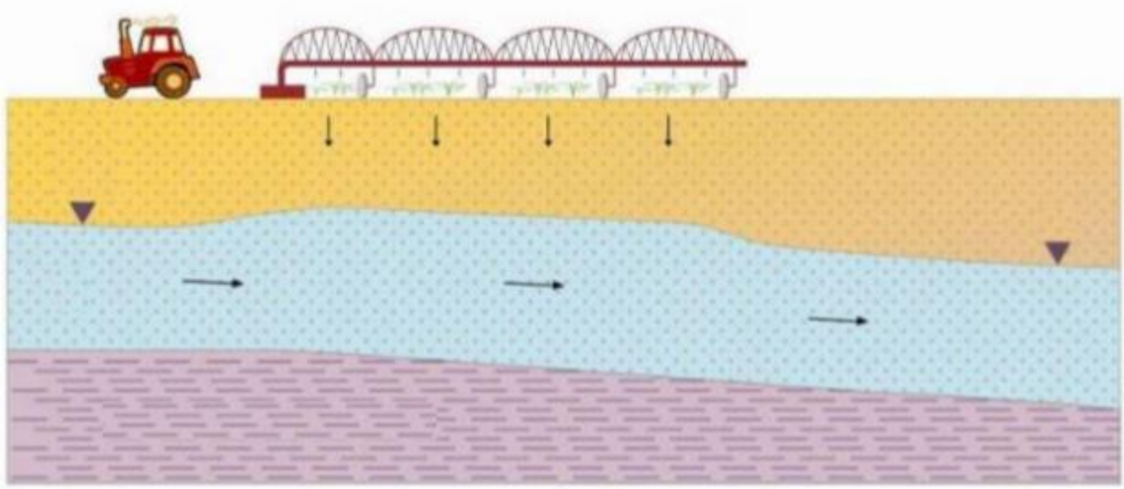
Appendix C.1.2 Soil Aquifer Treatment (SAT)

Synonyms	SAT is a type of infiltration basin, Water reclamation
Description	SAT is a technology to enable reuse of wastewater (e.g. treated sewage water) using infiltration basins (Dillon, 2005). The wastewater is intermittently infiltrated through the infiltration basins and nutrient and pathogen removal is facilitated by passing through the unsaturated zone. After residence in the aquifer, the water is recovered using wells (Dillon, 2005).
Schematic image	 *Figure App. 2 Schematic image of a Soil Aquifer Treatment technique. Source: INOWAS, 2018* STP = Sewage Treatment Plant
Infiltration capacity	- Medium (village, 10^4 $m^3 yr^{-1}$) to large (village, $10^6 m^3 yr^{-1}$) (INOWAS, 2018). - An SAT plant in Israel, one of the largest worldwide, has an infiltration capacity of 110-130 10^6 $m^3 yr^{-1}$ (Wolf et al., 2007).
Costs	- Relatively low construction cost (Gale, 2005); - Medium-high maintenance costs (INOWAS, 2018); - 1-2 US$ m^{-3} (Dillon et al., 2009).
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018); - Soil needs to be unsaturated (INOWAS, 2018); - Flat or gently sloped terrains to enhance infiltration and reduce clogging (INOWAS, 2018).
Advantages	- Reclaimed water treatment through the soil (IGRAC & Acacia Institute, 2007).
Limitations	- Unsaturated soil conditions need to be guaranteed (IGRAC & Acacia Institute, 2007); - Processes need to be controlled to monitor quality improvement (IGRAC & Acacia Institute, 2007); - High maintenance costs (IGRAC & Acacia Institute, 2007); - Risk of clogging (IGRAC & Acacia Institute, 2007).
MAR main objective	- Water quality improvement (INOWAS, 2018).
Additional information	- Pre-treatment is required (INOWAS, 2018). - Design (e.g. shape, surface) of the infiltration basin can largely affect the hydrologic response of the aquifer (Gale, 2005).

Appendix C.1.3 Controlled flooding

Synonyms	Flooding, infiltration fields, surface water spreading
Description	Flooding can be used as a MAR technique when excess river water is available during high flow season or when flood events need to be managed. Areas are intentionally flooded, and the water thinly spreads over this surface area. The flooded area than works as a large infiltration basin.(INOWAS, 2018; Maliva & Missimer, 2012)
Schematic image	 *Figure App. 3 Schematic image of controlled flooding technique. Source: INOWAS, 2018*
Infiltration capacity	- Highly variable. Ranging from small (household, $10^2 m^3 yr^{-1}$) to large (town, $10^6 m^3 yr^{-1}$) (INOWAS, 2018).
Costs	- Relative cost is low (INOWAS, 2018); - Flooding is the MAR method with the lowest costs, according to the Indian Central Ground Water Board (2007).
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018); - Preferably flat or gently sloped terrains, close to rivers (INOWAS, 2018).
Advantages	- Flood risk management as a benefit (IGRAC & Acacia Institute, 2007); - Ecosystem enhancement (IGRAC & Acacia Institute, 2007); - Broad areas may be used for aquifer recharge (IGRAC & Acacia Institute, 2007).
Limitations	- Competition with other land uses along rivers (IGRAC & Acacia Institute, 2007); - Large land areas are necessary (Tuinhof et al., 2012); - Potential for surface water diseases (Tuinhof et al., 2012); - Unreliable water source (IGRAC & Acacia Institute, 2007); - Potential of soil and aquifer pollutions with nutrients and salt concentration on the soil profile (IGRAC & Acacia Institute, 2007).
MAR main objective	- Agriculture, flood risk management (INOWAS, 2018).
Additional information	- None.

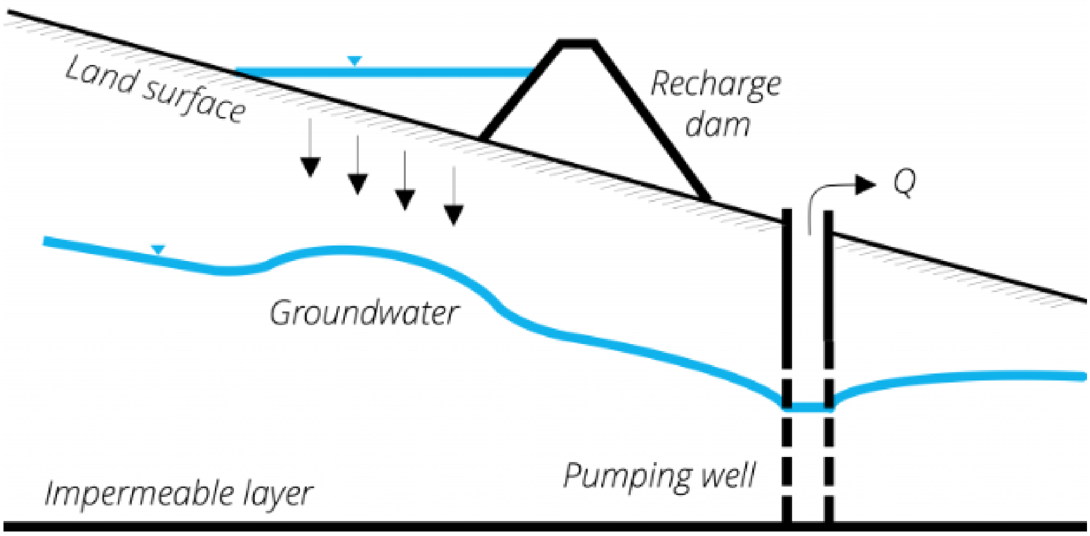
Appendix C.1.4 Incidental recharge from irrigation

Synonyms	Excess irrigation
Description	Excess irrigation as a MAR technique is used on irrigated farmland where excess water is available. Purposefully, more irrigation water than required is distributed during dormant or non-irrigated seasons to allow for aquifer recharge (INOWAS, 2018; Maliva & Missimer, 2012).
Schematic image	 *Figure App. 4 Schematic image of incidental recharge due to excess irrigation. Source: Escalante, 2010: 167*
Infiltration capacity	- Highly variable. Ranging from small (household, $10^2 m^3 yr^{-1}$) to large (town, $10^6 m^3 yr^{-1}$) (INOWAS, 2018).
Costs	- Relatively low costs (INOWAS, 2018).
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018); - Preferably flat or gently sloped terrains, close to rivers (INOWAS, 2018).
Advantages	- No competition with other land uses (IGRAC & Acacia Institute, 2007); - Relative low cost because existing irrigation infrastructure can be used (IGRAC & Acacia Institute, 2007); - Broad areas may be used for aquifer recharge (IGRAC & Acacia Institute, 2007).
Limitations	- Depends on specific site cropping cycles (IGRAC & Acacia Institute, 2007); - Require growers to engage additional coordination issues beyond conventional irrigation for farming (IGRAC & Acacia Institute, 2007); - Potential of soil and aquifer pollution with nutrients and salt concentration on the soil profile (IGRAC & Acacia Institute, 2007).
MAR main objective	- Agriculture (INOWAS, 2018).
Additional information	- Pre-treatment might be necessary depending on the source's water quality (INOWAS, 2018).

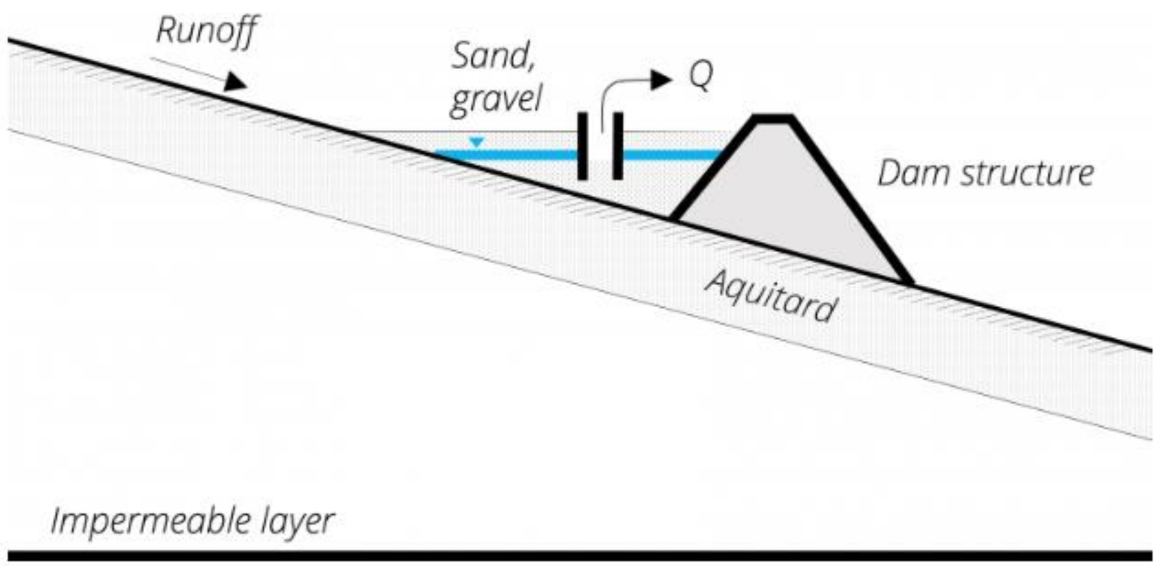
Appendix C.2 In-channel modification MAR techniques

See the subsections below for a detailed overview of the four in-channel modification MAR techniques.

Appendix C.2.1 Percolation ponds

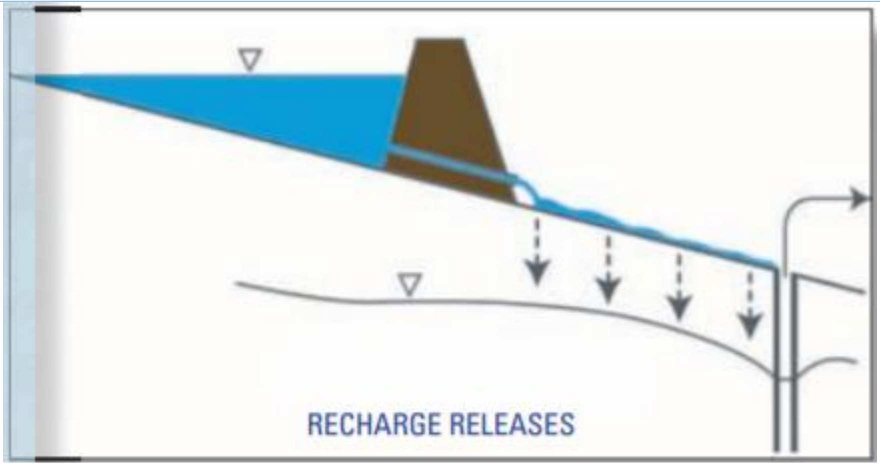
Synonyms	Recharge dams, check dams (if dam is permeable and relatively small (Gale et al., 2006)), wadi dams (if dam's aim is only to retain flood water (Maliva & Missimer, 2012), gabions (if structure is made out of stone baskets (Ramli et al., 2013)
Description	For percolation ponds, small dams are constructed in-stream. These dams serve as way to retain runoff water. This creates an opportunity for the water to infiltrate into the ground as well as reducing soil erosion. The further workings are similar to any other dam. (INOWAS, 2018; Maliva & Missimer, 2012)
Schematic image	 *Figure App. 5 Schematic image of a percolation pond behind a check dam. Source: INOWAS, 2018*
Infiltration capacity	- Medium (village, $10^4 m^3 yr^{-1}$) to large (town, $10^6 m^3 yr^{-1}$) (INOWAS, 2018); - The Siwaqa dam in Jordan, which is classified as a percolation pond, has a maximal infiltration capacity of 9.3 10^6 m^3 yr^{-1} (Wolf et al., 2007).
Costs	- Low to moderate, depending on the size of the dam and chosen material (INOWAS, 2018).
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018); - Flat or gently sloped terrains, close to rivers (INOWAS, 2018).
Advantages	- Little interference with other land use (IGRAC & Acacia Institute, 2007); - Storage of flash floods, decreasing erosion downstream (IGRAC & Acacia Institute, 2007).
Limitations	- Dam failure may cause high damages downstream the dam (IGRAC & Acacia Institute, 2007); - Potential for surface water diseases (IGRAC & Acacia Institute, 2007); - Clogging issues due to sediment transport and settlement, especially when in effect during flooding (Pereira et al., 2002).
MAR main objective	- Strategic water storage.
Additional information	- Mostly implemented on intermittent or ephemeral stream conditions (INOWAS, 2018). - Silt traps may be used to mitigate clogging (INOWAS, 2018).

Appendix C.2.2 Sand storage dams

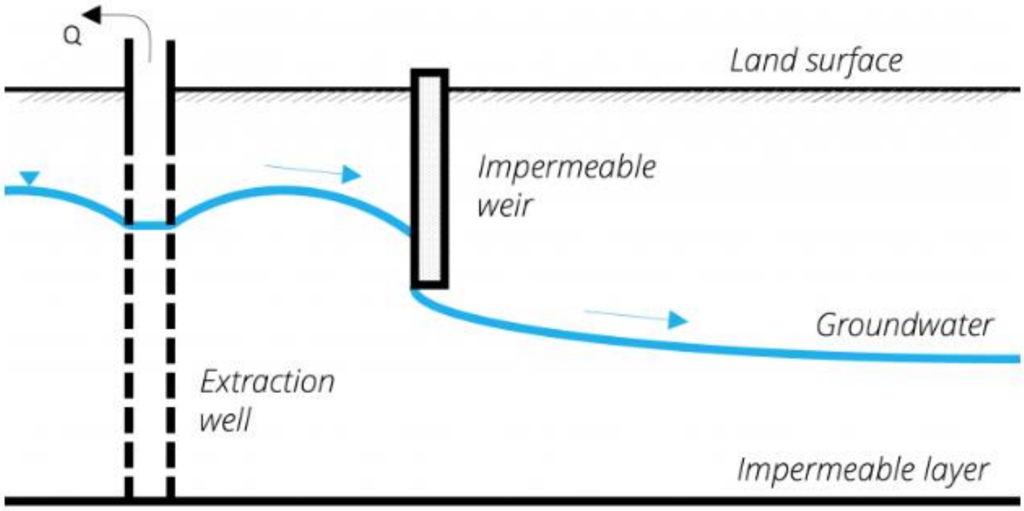
Synonyms	Trap dams
Description	Sand storage dams are structures creating a new water holding formation (Aquifer) (Gale, 2005). They are built above ground within intermittent river channels. Sands and gravels from stormwater runoff will accumulate upstream of the dam, creating the artificial aquifer able to store the runoff water. The reservoirs will fill during rainfall events, and can be abstracted from during dry periods. (INOWAS, 2018)
Schematic image	 *Figure App. 6 Schematic image of a sand dam. Source: INOWAS, 2018*
Infiltration capacity	- Highly variable. Ranging from small (household, $10^2 m^3 yr^{-1}$) to large (town, $10^6 m^3 yr^{-1}$) (INOWAS, 2018); - Infiltration capacities of sand dams in Ethiopia and Kenya range from 200 to 30 10^3 $m^3 yr^{-1}$, with an average in Ethiopia of around 10^3 $m^3 yr^{-1}$ (Lasage & Verburg, 2015; Maddrell, 2016).
Costs	- Relatively low (INOWAS, 2018; Maliva & Missimer, 2012); - 0.4 US$$m^{-3}$ (Lasage & Verburg, 2015).
Aquifer and soil type	- Sandy riverbeds (INOWAS, 2018); - Gently slope terrains (INOWAS, 2018).
Advantages	- Low costs of construction and maintenance (IGRAC & Acacia Institute, 2007); - Due to siting, no interference with other land uses (IGRAC & Acacia Institute, 2007); - Lowers potential for surface water diseases (Clean-water-for-Laymen.com, 2015); - Stimulate high level of community involvement (Clean-water-for-Laymen.com, 2015).
Limitations	- Potential ownership conflicts (IGRAC & Acacia Institute, 2007); - Potential water pollution (IGRAC & Acacia Institute, 2007).
MAR main objective	- Water storage (INOWAS, 2018).

Additional information	- The dam wall can be raised after each successive flooding event, to increase the size of the artificial aquifer (Gale, 2005).
	- If sited above a permeable bedrock, the underlying aquifer can also be replenished, instead of direct abstraction from the artificial aquifer. (Gale, 2005). In that case, the only difference with a percolation pond is that in a sand storage dam, the area upstream of the dam is purposefully filled with sediment, which creates a lower risk to surface water disease.
	- Significant hydrogeological conditions for a sand dam to be feasibility are (Maliva & Missimer, 2012):
	  o River width (≤ 25m);
	  o River slope (preferably 2%-4%);
	  o Relatively high availability of coarse sediments in the river catchment.

Appendix C.2.3 Leaky dams

Synonyms	None known
Description	A leaky dam is a structure that retains high-energy floods. When a flood occurs, it is accumulated upstream of the dam, nihilating the flow velocity. Using pipes through the structure, the retained water can be released in a constant flow. This gives better opportunity to the water to recharge downstream aquifers. That way, less water is lost to catchment or to the sea. (Gale, 2005). A leaky dam has high likeliness with percolation ponds.
Schematic image	 *Figure App. 7 Schematic image of a leaky dam. Source: Gale, 2005*
Infiltration capacity	- No information found in literature; - The structure has a high likeness with percolation ponds. The water flowing downstream is additional to the water in the pond upstream of the dam. The infiltration capacity is expected to be slightly higher than that of a percolation pond.
Costs	- No information found in literature; - The cost is expected to be slightly higher than a percolation pond, since it in practice is a percolation pond including pipes.
Aquifer and soil type	- No information found in literature; - It is expected leaky dams need similar aquifer and soil conditions as percolation ponds.
Advantages	- Creates a more constant flow of water, even during floods (Gale, 2005); - It is expected that a leaky dam has similar other advantages as percolation ponds.
Limitations	- No information found in literature; - A leaky dam is expected to have similar limitations as percolation ponds, with an addition to the necessary maintenance in the pipes.
MAR main objective	- Mitigating peak flows, groundwater table recovery (Gale, 2005).
Additional information	- A leaky dam is largely similar with a percolation pond with regards to the structure. However, with a leaky dam, the aim is to let the water infiltrate downstream the dam, while with a percolation pond, the aim is to let the water infiltrate upstream the dam.

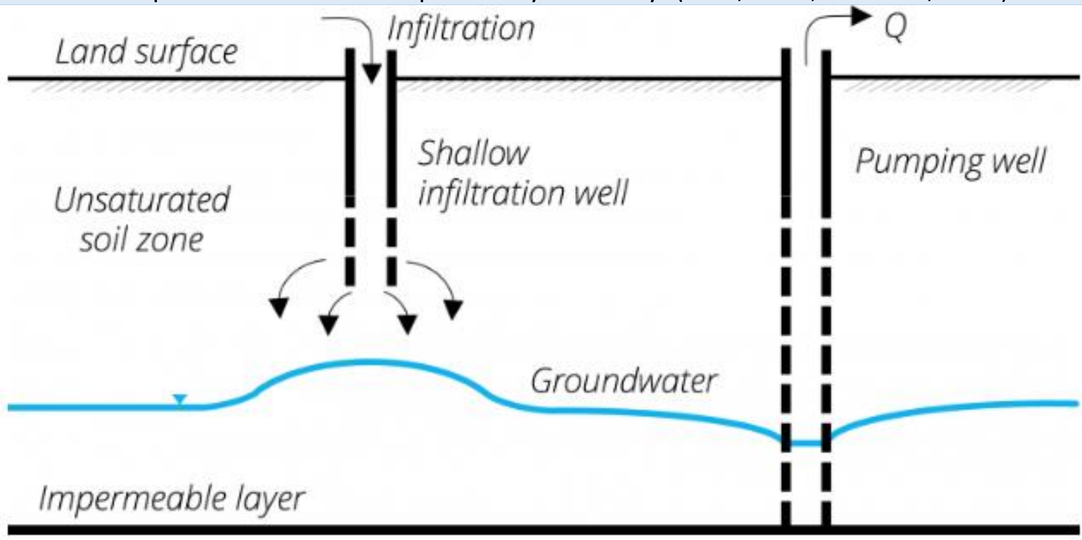
Appendix C.2.4 Subsurface dams

Synonyms	None known.
Description	Subsurface dams are barriers constructed underground. These structures reduce or stop lateral flow of groundwater to elevate the groundwater table upstream of the barrier. (INOWAS, 2018)
Schematic image	 *Figure App. 8 Schematic image of a subsurface dam. Source: INOWAS, 2018*
Additional information	- Although several studies have incorporated subsurface dams in their list of MAR techniques (Gale, 2005; Maliva & Missimer, 2012; Stefan & Ansems, 2018), it will not be taken into account as such in this research. This because the chosen definition of MAR explicitly states that additional water should be infiltrated into an aquifer (Dillon et al., 2019), which is not the case for subsurface dams; there is no additional recharge of water (Gale, 2005), and instead only helps retaining the water already present in an aquifer. Therefore, this technique is not discussed any further in this study.

Appendix C.3 Well, shaft and borehole MAR techniques

See the subsections below for a detailed overview of the three in-channel modification MAR techniques.

Appendix C.3.1 Shallow wells and shafts recharge

Synonyms	Shallow borehole recharge, shallow pit recharge, shallow shaft recharge.
Description	Infiltration through shallow wells, shafts or pits is usually practiced to recharge a shallow, phreatic aquifer where spreading methods cannot be applied because of the existence of low permeability surface layers. Often, abandoned pits are used that had previously fallen dry. (Gale, 2005; INOWAS, 2018)
Schematic image	 *Figure App. 9 Schematic image of a shallow well infiltration system. Source: INOWAS, 2018*
Infiltration capacity	- Medium (village, 10^4 m^3 yr^{-1}) to large (town, 10^6 m^3 $yr^{-1)}$ (INOWAS, 2018).
Costs	- Relative costs are low (use of existing infrastructure) to medium (new infrastructure) (INOWAS, 2018). - 0.1-0.3 US$ m^{-3} and always lower costs than deep wells (Gale, 2005; IGRAC & Acacia Institute, 2007)
Aquifer and soil type	- Unconfined aquifers composed of unconsolidated rocks, impermeable surface (INOWAS, 2018); - Soil types are not relevant for this kind of technology (INOWAS, 2018).
Advantages	- Use of existing facilities (IGRAC & Acacia Institute, 2007); - Recovery from same structure reduces clogging (IGRAC & Acacia Institute, 2007).
Limitations	- High quality requirements of source water (IGRAC & Acacia Institute, 2007); - Chances for clogging are higher than for deep wells and are more difficult to rehabilitate (Maliva & Missimer, 2012)
MAR main objective	- Recover groundwater levels (INOWAS, 2018); - Stormwater disposal (Maliva & Missimer, 2012).
Additional information	- Pre-treatment is needed to prevent clogging and lower chances of groundwater contamination (INOWAS, 2018).

Appendix C.3.2 Aquifer Storage and Recovery

Synonyms

In some studies, aquifer storage and recovery (ASR) is defined as any method to practice aquifer recharge and recovery. However, in this study, following especially the classification of Gale (2005), ASR is defined as (deep) well infiltration.

Description

With ASR, water is injected during periods with water excesses and recovered from the same well when there is a need for water (Gale, 2005). This technique is especially used if a thick and low permeability strata is present above the targeted aquifer (INOWAS, 2018). For this technique, a deep well is connected to the targeted aquifer and is used for both water extraction and injection. The wells can be from 50m to 900m deep (Dillon et al., 2019).

There are three types of ASR systems, that differ in how they achieve the useful storage of water (Maliva & Missimer, 2012):

- Chemically bounded ASR systems achieve useful storage by displacing water of poorer quality. This way, injection results in a new freshwater resource at the time of recovery, that would otherwise not have been available;
- Physical storage ASR systems increase the total volume of water present in an aquifer. This ASR type usually involves injection of freshwater into freshwater aquifers;
- Regulatory ASR systems is mostly physical storage ASR, but of legislative origin. For this, injection of water confers to the right to later pump additional groundwater, which would otherwise not be allowed. It is especially common for agriculture in parts of the USA.

Schematic image

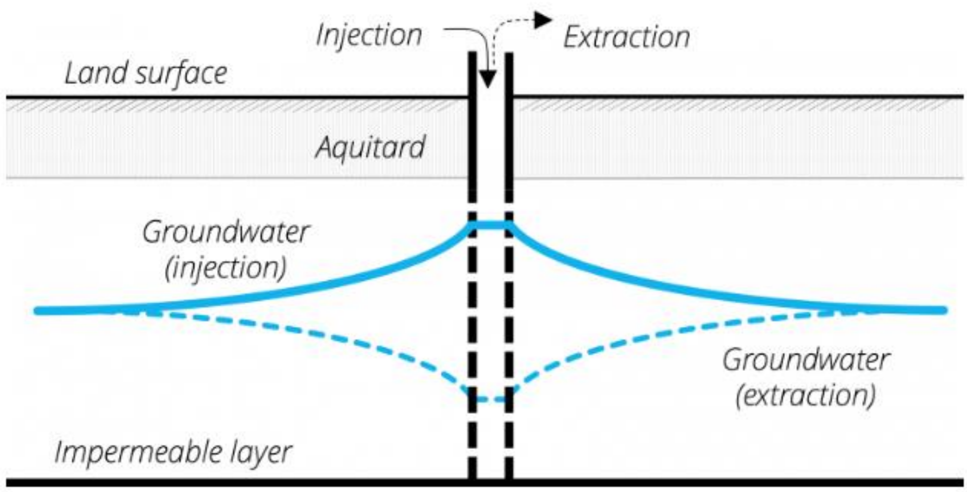


Figure App. 10 Schematic image of an ASR system. Source: INOWAS, 2018

In this, the bold blue line represents the situation during a rain event, while the dotted blue line represents the situation during dry events and water is abstracted.

Infiltration capacity

- Medium (village, 10^4 $m^3 yr^{-1}$) to very large (>town, >10^6 $m^3 yr^{-1}$) (INOWAS, 2018);
- An individual ASR well yields 2.000 to 30.000 $m^3 d^{-1}$ (J. Ward & Dillon, 2011)
- An ASR system in Parafield, Australia with an area of 16 10^6 m^2, with stormwater as its source, has an abstraction up to 2.1 10^6 m^{-3} yr^{-1} and an injection rate of 0.035 m^3 s^{-1} (IGRAC & Acacia Institute, 2007).

Costs

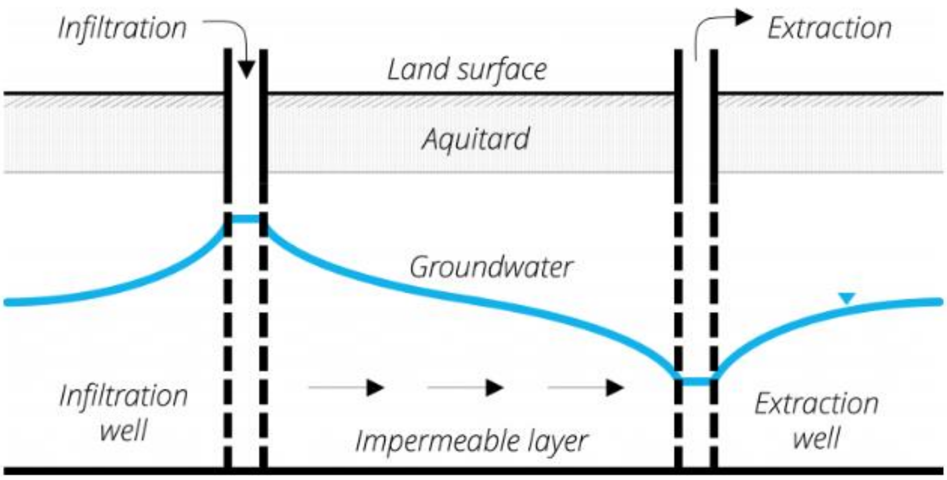
- Cost for ASR is dependent on the required depth of the well.
- Relative costs are low to medium (INOWAS, 2018), but have relatively high initial investment costs (Escalante et al., 2014; Maliva & Missimer, 2012);
- In Spain, costs of ASR are as shown in Table App. 3:

Table App. 3 Costs of shallow and deep ASR wells. Source: Escalante et al., 2014

Well depth	Initial investment cost	Cost over lifetime
50 m	0.19 million US$	0.26 US$ m^3
500 m	0.65 million US$	0.65 US$ m^3

	- The Parafield ASR system (see 'infiltration capacity') had an initial investment of 2.9 million US$ (IGRAC & Acacia Institute, 2007) - The costs are lower than those of ASTR (see Appendix A), since with ASR only one well has to be built (Escalante et al., 2014; Maliva & Missimer, 2012).
Aquifer and soil type	- Confined or unconfined aquifer composed on unconsolidated rocks (INOWAS, 2018); - Soil types are not relevant for this kind of technology (INOWAS, 2018).
Advantages	- Clogging is partially remediated during the recovery cycle (IGRAC & Acacia Institute, 2007); - Infiltration of large quantities of water at relatively low cost (IGRAC & Acacia Institute, 2007); - Non-operative well infrastructure (wells that had fallen dry) can be used to reduce costs (IGRAC & Acacia Institute, 2007); - Groundwater recharge is not determined by surface characteristics (IGRAC & Acacia Institute, 2007); - Compared to surface storage, ASR has less (Maliva & Missimer, 2012): o Land required o Evaporation loss o Water contaminations
Limitations	- Complex design, construction, operation and maintenance (IGRAC & Acacia Institute, 2007); - Intensive monitoring of system performance is required (IGRAC & Acacia Institute, 2007); - High quality source water, as the water is directly injected into the aquifer (IGRAC & Acacia Institute, 2007); - ASR should not be used in aquifers with a strong vertical or lateral gradient if recovery is an important goal, as the water will migrate from the well, becoming unavailable for extraction (Maliva & Missimer, 2012).
MAR main objective	- Agriculture, potable water, counter salinization, groundwater level recovery for environmental benefit (INOWAS, 2018)
Additional information	- Pre-treatment is necessary to prevent clogging and groundwater contamination (INOWAS, 2018). - The performance of ASR is mainly dependent on hydrogeology (Maliva & Missimer, 2012). - In 2016, over 500 ASR systems were knowingly in place in the USA alone. It is unknown how many are present worldwide. (Dillon et al., 2019)

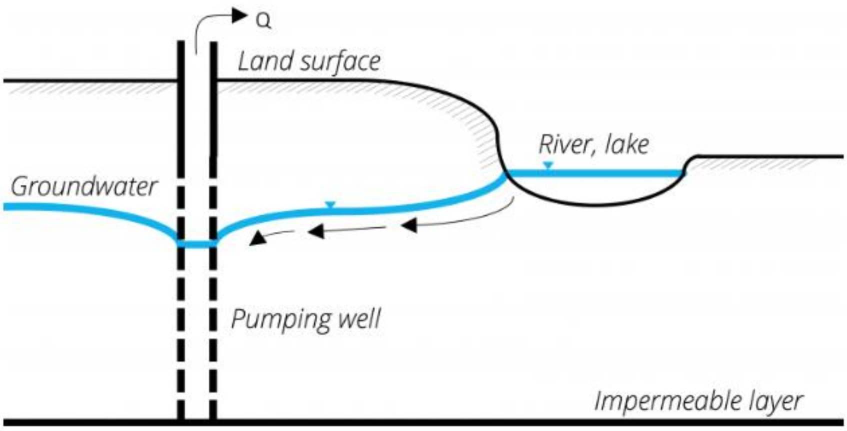
Appendix C.3.3 Aquifer Storage Transfer and Recovery

Synonyms	None known.
Description	For Aquifer Storage, Transfer, and Recovery (ASTR) water is injected into the aquifer through one well and is extracted by another well located some distance away. The underground passage facilitates physical and chemical processes that improve the quality of the injected water. This technique is especially used if a thick and low permeability strata is present above the targeted aquifer (INOWAS, 2018) By extracting the water from another well, a longer travel time and consequential improved water treatment are reached, when compared to ASR (Gale, 2005). ASTR has similar types of systems as ASR (Maliva & Missimer, 2012): - Chemically bounded ASTR systems; - Physical storage ASTR systems; - Regulatory ASTR systems.
Schematic image	 *Figure App. 11 Schematic image of an ASTR system. Source: INOWAS, 2018*
Infiltration capacity	- Medium (village, 10^4 m^3 yr^{-1}) to very large (>town, >10^6 m^3 yr^{-1}) (INOWAS, 2018); - Similar further statistics as ASR (Gale, 2005).
Costs	- Relative costs are medium-high (INOWAS, 2018). - ASTR is more expensive than ASR, since for one system, 2 deep wells need to be constructed (Maliva & Missimer, 2012).
Aquifer and soil type	- Confined or unconfined aquifer composed on unconsolidated rocks (INOWAS, 2018); - Soil types are not relevant for this kind of technology (INOWAS, 2018).
Advantages	- Similar to ASR, with improved water treatment functions (INOWAS, 2018).
Limitations	- Similar to ASR, with higher risk on clogging (INOWAS, 2018).
MAR main objective	- Agriculture, potable water, counter salinization, groundwater level recovery for environmental benefit and improving water quality (INOWAS, 2018).
Additional information	- Pre-treatment is necessary to prevent clogging and groundwater contamination (INOWAS, 2018).

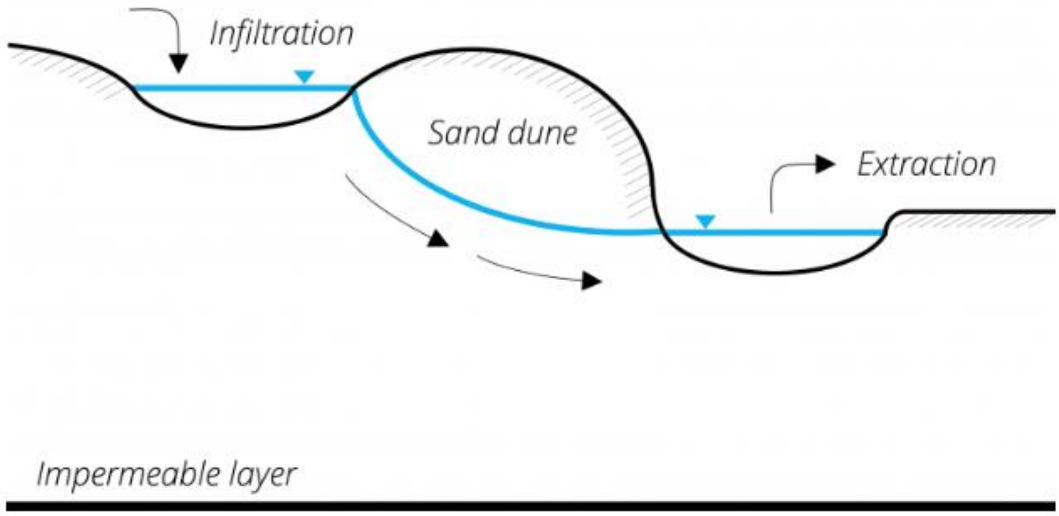
Appendix C.4 Induced bank infiltration MAR techniques

See the subsections below for a detailed overview of the two induced bank infiltration MAR techniques.

Appendix C.4.1 Induced bank infiltration

Synonyms	Riverbank filtration, lake bank filtration
Description	Induced bank filtration is the infiltration of surface water, mostly from a river or lake system, into a groundwater system, induced by water abstraction close to the surface water body. The water abstraction is commonly done by a well gallery or line of wells parallel to the bank of the water source. Pumping at the gallery of wells lowers the water table adjacent to the river or lake, inducing water to infiltrate into the aquifer system. The extracted water is either put back in the surface water body or transported for other uses. The passage of water through the river or lake bed and the aquifer removes dissolved and suspended pollutants and pathogens by chemical, physical and biological processes. (Gale, 2005; INOWAS, 2018; SSWM, 2020)
Schematic image	 *Figure App. 12 Schematic image of induced bank infiltration. Source: INOWAS, 2018*
Infiltration capacity	- Medium (village, 10^4 m^3yr^{-1}) to very large (>town, >10^6 m^3yr^{-1}) (INOWAS, 2018); - The Csepsel Island Bank filtration system at the Danube in Hungary has an infiltration capacity of 146 10^6 m^3yr^{-1} and provides 40% of the potable water of Budapest (IGRAC & Acacia Institute, 2007); - Several studies name the large capacity of induced bank filtration as the main advantage (IGRAC & Acacia Institute, 2007; Schmidt et al., 2003; Tuinhof et al., 2012).
Costs	- Relative costs are medium-high (INOWAS, 2018); - Compared to other MAR techniques, costs are relatively high. However, compared to other drinking water supply methods (in Germany), costs for induced bank filtration can be classified as 'moderate' (Schmidt et al., 2003)
Aquifer and soil type	- Permeable and unconfined sediments (INOWAS, 2018); - Floodplains, lake banks (INOWAS, 2018);
Advantages	- Large quantities of water can be withdrawn (IGRAC & Acacia Institute, 2007); - Pollutants contained in source water may be removed by filtration processes (IGRAC & Acacia Institute, 2007).
Limitations	- Complex design, construction, operation and maintenance (IGRAC & Acacia Institute, 2007); - Intensive monitoring of system performance is required (IGRAC & Acacia Institute, 2007); - High potential for well clogging (IGRAC & Acacia Institute, 2007); - High costs (IGRAC & Acacia Institute, 2007).
MAR main objective	- Improve water quality (INOWAS, 2018).
Additional information	- Commonly induced bank filtration is a pre-treatment technique for other uses.

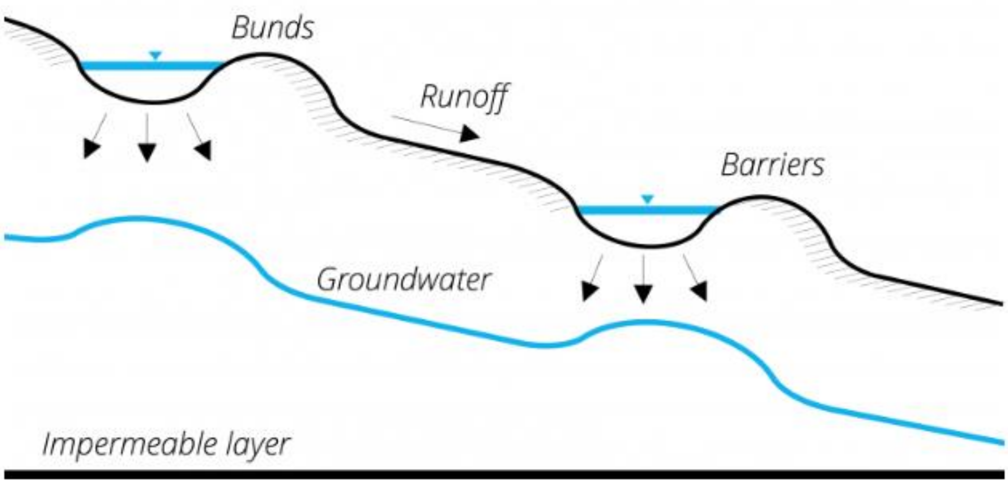
Appendix C.4.2 Inter-dune filtration

Synonyms	Induced dune filtration
Description	Inter-dune filtration is a more specific method of induced bank filtration. Often with inter-dune filtration, the valleys between coastal sand dunes are flooded with water from rivers to infiltrate into the underlying sediments and create a recharge mound. This mound is either a lower lying pond, or a well gallery. This technique is especially popular along the coastline of the Netherlands. (Gale, 2005)
Schematic image	 *Figure App. 13 Schematic image of inter-dune filtration. Source: INOWAS, 2018*
Infiltration capacity	- Medium (village, 10^4 m^3yr^{-1}) to very large (>town, $>10^6$ m^3yr^{-1}) (INOWAS, 2018); - A dune filtration system for Amsterdam of 34 10^6 m^2 filters 90 10^6 m^3yr^{-1}, some 66% of Amsterdam's potable water requirements (AWD.Waternet.nl, 2020; AWD Waternet, 2011) - In Veurne region, Belgium, an inter-dune filtration system of 18 10^6 m^2 has an infiltration capacity of 2.5 10^6 m^3yr^{-1} with wastewater as source (Van Houtte & Verbouwhede, 2006).
Costs	- Relatively medium (INOWAS, 2018).
Aquifer and soil type	- Permeable, unconfined sediments necessary (INOWAS, 2018).
Advantages	- Large quantities of water can be withdrawn (IGRAC & Acacia Institute, 2007); - Pollutants contained in source water may be removed by filtration processes (IGRAC & Acacia Institute, 2007).
Limitations	- Intensive monitoring of system performance required (IGRAC & Acacia Institute, 2007); - High potential for clogging (IGRAC & Acacia Institute, 2007); - The system must ensure a minimal residence time of the water in the soil (Gale, 2005). The length of the required residence time is dependent on the quality of the source water, but e.g. for the water in the filtration dunes for Amsterdam this is three months (Waternet.nl, 2020)
MAR main objective	- Improvement of water quality (INOWAS, 2018).
Additional information	- Commonly induced bank filtration is a pre-treatment technique for other uses.

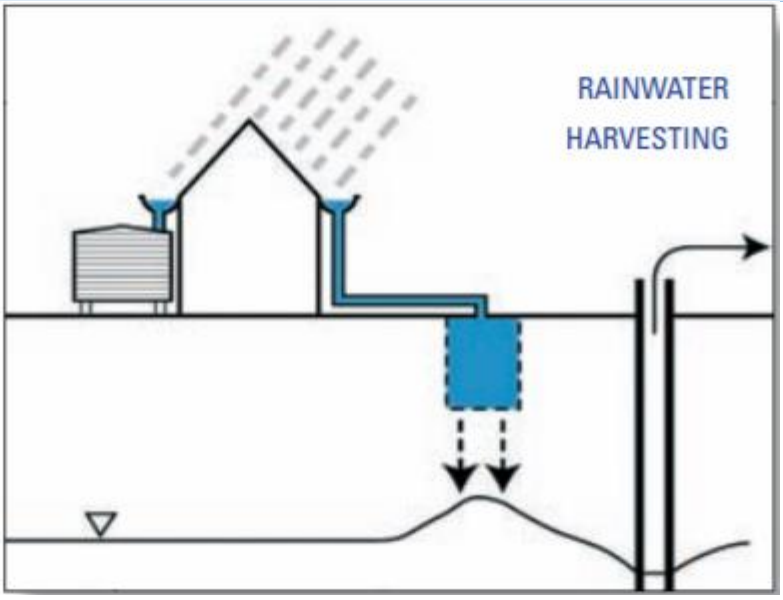
Appendix C.5 Rainwater harvesting MAR techniques

See the subsections below for a detailed overview of the two rainwater harvesting MAR techniques.

Appendix C.5.1 Field bunds

Synonyms	Teras, contour bunds
Description	The ideas of field bunds as barriers is to obstruct surface runoff from catchments and slow downstream flow velocities and aiding the infiltration of water into soil. (Maliva & Missimer, 2012) The collection of rainwater can be achieved by building bunds, barriers or contour ridges. (INOWAS, 2018)
Schematic image	 *Figure App. 14 Schematic image of field bunds. Source: INOWAS, 2018*
Infiltration capacity	- Small (household, $10^2 m^3 yr^{-1}$) to medium-small (small village, $10^3 m^3 yr^{-1}$) (INOWAS, 2018) - Relatively small quantities (IGRAC & Acacia Institute, 2007; Tuinhof et al., 2012)
Costs	- Relatively low costs (INOWAS, 2018) - Costs are 0.1-0.3 US$$m^{-3}$ (IGRAC, 2020b)
Aquifer and soil type	- Unconfined aquifer, permeable soil and surface (INOWAS, 2018) - Rural areas with gentle slopes. (INOWAS, 2018)
Advantages	- Low cost and simple design (IGRAC & Acacia Institute, 2007) - Prevention of soil erosion due to slowing down of runoff water (IGRAC & Acacia Institute, 2007)
Limitations	- Relatively small infiltration quantities (IGRAC & Acacia Institute, 2007) - Water quality might be problematic (IGRAC & Acacia Institute, 2007) - Potential water pollution (IGRAC & Acacia Institute, 2007) - Potential evaporation (IGRAC & Acacia Institute, 2007)
MAR main objective	- Strategic water storage, erosion reduction (INOWAS, 2018)
Additional information	- Rainfall in the region is preferably less than 1000 $mmyr^{-1}$ (Indian Central Ground Water Board, 2007) - The difference between using field bunds and percolation ponds is that with percolation ponds, the water is extracted by a nearby well, while no direct extraction technique is in place for field bunds.

Appendix C.5.2 Roof-top rainwater harvesting

Synonyms	None known.
Description	Roof-top rainwater harvesting can conserve precipitation for either direct consumption or for recharge of groundwater. It is increasingly used in urban areas with often sealed surfaces. It is also implemented to lower chances on urban flooding. (Gale, 2005; INOWAS, 2018)
Schematic image	 *Figure App. 15 Schematic image of a rooftop rainwater harvesting system. Source: Gale, 2005*
Infiltration capacity	- Small (household, 10^2 m^3 yr^{-1}) to medium-small (small village, 10^3 m^3 yr^{-1}) (INOWAS, 2018); - Highly dependent on the size of the system (Gale, 2005); - A project in Delhi, India, had harvested 39.6% of all rainwater in an urban area (rooftops and on the ground), which was some 5 10^4 m^3 yr^{-1} harvested (CSEIndia, 2020). In this project, it was not deviated how much of the rooftop rainwater was harvested, but does give an indication for similar projects.
Costs	- Relatively small costs, but potentially high sums for private owners of the building (INOWAS, 2018); - A project in Delhi, India, had an initial cost of 2300 US$ and a yearly recharge of 5 10^4 m^3 (CSEIndia, 2020). This however was not solely rooftop rainwater, but also from the ground in between.
Aquifer and soil type	- Not relevant if used for direct potable usage; - Unconfined aquifer, permeable soils (INOWAS, 2018).
Advantages	- Only relatively small adaptations to existing infrastructure needed (IGRAC & Acacia Institute, 2007); - Storage of rain events, less flooding (IGRAC & Acacia Institute, 2007); - Relief of waste water treatment plant in case of mixed water collection (IGRAC & Acacia Institute, 2007); - Lowering demand on water supply systems (Gale, 2005).
Limitations	- Susceptible to water pollution, e.g. from the air, due to bird and animal droppings, insects, bacterial contamination or dust pollution if directly used as potable water (Gale, 2005; IGRAC & Acacia Institute, 2007).
MAR main objective	- Strategic water storage, mitigation of effects of urbanization (INOWAS, 2018); - Potable water storage (INOWAS, 2018).
Additional information	- If used to recharge aquifers, additional modifications to the surface to increase its potential for infiltration might be necessary.

Appendix D Worldwide growth in use of MAR since 1965

Table App. 4 Global growth in use of MAR since 1965, adapted from Dillon et al. (2019).[2]

Country/region	Average annual MAR volume in the decade centred on date ($Mm^3\ yr^{-1}$)[3]						Annual gw[4] use ($Mm^3\ yr^{-1}$)	MAR as % gw use	MAR as % of global reported capacity[c]	MAR vol growth (% yr^{-1})	gw use as % global use
	1965	1975	1985	1995	2005	2015	2010	2015	2015	to 2015	2010
Australia	79	144	185	213	257	410	4,960	8.3%	4.1%	3.6%	0.51%
China	20	23	23	24	56	106	112,000	0.1%	1.1%	3.6%	11.41%
Finland	<1	30	35	50	55	65	280	23.2%	0.7%	9.3%	0.03%
France	20	21	26	30	31	32	5,710	0.6%	0.3%	1.0%	0.58%
Germany	–	867	766	875	765	870	3,080	28.2%	8.7%	0.0%	0.31%
India (5 states only)	154	430	706	1,020	1,739	3,070	39,800	7.7%	30.9%	6.6%	4.05%
Israel	87	91	127	132	144	134	1,250	10.7%	1.3%	0.9%	0.13%
Italy	178	294	301	348	391	461	10,400	4.4%	4.6%	2.0%	1.06%
Netherlands	181	240	255	241	275	262	1,600	16.4%	2.6%	0.8%	0.16%
Southern Africa	1	2	6	6	7	10	4,500	0.2%	0.1%	5.1%	0.46%
Spain	3	8	12	60	350	380	5,700	6.7%	3.8%	10.9%	0.58%
UK	0	0	0	5	5	5	2,160	0.2%	0.1%	–	0.22%
USA	302	494	768	1,218	2,026	2,569	112,000	2.3%	25.8%	4.7%	11.41%
Total	1,029	2,656	3,272	4,334	6,296	9,945	414,110	2.4%	100%	4.9%	42.2%
Global gw use	–	–	–	–	–	–	982,000	1.0%	NA[5]	NA	100%
Total (km^3/year)	1.0	2.7	3.3	4.3	6.3	9.9	414.1	2.4%	100%	4.9%	42.2%

[2] Some data (countries) is filtered out, hence the summations do not check out.
[3] It is important to note that the table is not comprehensive. It is known that several countries have additional MAR-facilities, but without quantitative data. Hence, the table is regarded as the best available (conservative) estimate of current national and global MAR, and its publication is intended to stimulate more rigorous reporting of MAR in future.
[4] gw = groundwater
[5] NA = not applicable

Appendix E Aquifer types

The four identified aquifer types by Gale (2005) are explained below (Gale, 2005; Margat & van der Gun, 2013). Each has its own performances.

- *Alluvium aquifers* usually consist of highly permeable, unconsolidated sediments ranging from coarse gravel to impermeable silt and mud. Alluvial aquifers are often found in lower reaches of river basins. In most regions with alluvial aquifers, the water table is observed at shallow depths, except in arid regions. MAR structures such as infiltration basins or trenches may be suitable for this geological setting.
- *Fractured hard rock aquifers* usually consists of fractured bedrock from igneous and volcanic rocks. They are found many parts of the world. In general, they have relatively low storage capacity and transmissivity, but, especially in semi-arid regions, may be the only source of groundwater and as such should be carefully managed. In these rocks, the regolith zone (the upper layer on top of the bedrock) is responsible for absorbing and storing intermittent rainfall, which then can percolate to the underlying aquifer. The regolith zone itself may also be seen as a separate aquifer and can be treated as an alluvium aquifer. Often, due to the slow percolation process, (deep) well injection is the only feasibility option for recharging fractured hard rock aquifers.
- *Consolidated sandstone aquifers* are one of the favourite geological formations for groundwater storage because of their good storage capacity and transmissive properties. However, if the aquifer permeability is too high, the recharged water may dissipate quickly and is thus lost to the base flow in rivers. A thorough knowledge in aquifer hydraulics is necessary for the successful implementation of MAR in this kind of aquifers. In certain locations, annual overdraft was adopted as a measure to create storage during wet season.
- *Carbonate rock aquifers* are highly dynamic formations in terms of hydrogeochemistry. Due to this high reactivity, groundwaters in these formations often exhibit high hardness. Carbonate aquifers can show high dissipation of recharged water and fast pathways for pollutants. Despite of this behaviour, carbonate aquifers are considered as good water bearing formations all over the world. A considerable modification in the flow patterns can be expected in carbonate aquifers within a short period. MAR in these formations demands a good understanding of aquifer hydrogeology.

Based on Tuinhof et al. (2012), an overview is given in Table App. 5 of what MAR techniques can be used for which aquifers.

Table App. 5 MAR techniques per aquifer type. Source: Tuinhof et al., 2012

MAR technique	Aquifer type and classifications
Spreading methods	Unconfined aquifers. Alluvium, sandstone and sometimes carbonate aquifers
Deep well infiltration	Deep and clay covered, confined aquifers
Induced bank infiltration	Dry rivers with dams, or at perennial rivers or streams with adjacent permeable sand layers

Appendix F Explanation of the costs in a CBA for MAR

Appendix F.1 Key characteristics in and overview of costs in MAR projects

Maréchal et al. (2020) have created a cost-function to compute the capital and operational costs of a typical MAR scheme. For this, first several key-characteristics of each step in the process were identified. These are given in Table App. 6.

Table App. 6 Key-characteristics per process-step for the cost-function.

Process	Parameter	Parameter	Unit	Comment
Water monitoring	No specific parameter	-	-	-
Water abstraction	Recharge rate	Q	$m^3\ yr^{-1}$	Annual recharge rate objective for the MAR
	Recharge duration per year	N	$d\ yr^{-1}$	Yearly duration of the period during which water can be abstracted
	Flow rate	$q = \frac{Q}{N}$	$m^3\ d^{-1}$ $m^1\ h^{-1}$	Daily/hourly flow rate for pipe diameter sizing
Water transfer	Distance	D		
	Altitude difference	Z		
	Head losses	$H = -Z + 0.011D$	m	Assumption: linear head losses = 0.01 m per m pipe
	Pipe diameter	$d_i = 22.9\ q^{0.4}$	mm	Hydraulic law
Water pre-treatment	No specific parameter	-	-	-
Water infiltration and extraction	Infiltration surface area	$S = q\ S_\delta$	m^2	S_δ: Required surface area per daily/hourly infiltration volume for δ a chosen MAR technique ($m^2\ m^{-3}\ d$) Assumption: infiltration surface area is dependent on the chosen MAR technique and the required recharge flow rate of the system
	System surface area	$S_S = 1.1\ S$	m^2	Assumption: 10% for land necessary for neighbouring

Based on these key-characteristics, Maréchal et al. (2020) have identified and grouped the main investment and operating costs. These are presented in Table App. 7, including their unit, the formula for and/or the value of the cost and, if needed, an additional comment. The values presented in the research of Maréchal et al. (2020) come from the Observatory of Rhône Mediterranean Corsica Water Agency (AERMC) and as such should be seen in a French context. Hereafter, the different investment and operating costs are explained.

Table App. 7 Summary of costs for a MAR scheme. α and β are fractional parameters in order to define specific costs as a fraction of other costs. δ defines the MAR technique of choice.

Process	Cost description	Unit	Cost/Value	Comment
Other	IC_1: Engineering studies	€	$IC_1 = \propto_1 \sum_{i=2}^{7} IC_i$	$\propto_1$ ratio of engineering studies costs
	OC_7: other yearly costs	€ yr^{-1}	$OC_7 = \propto_7 \sum_{i=1}^{6} OC_i$	$\propto_7$ ratio of yearly costs
Water abstraction	IC_2: Pump installation	€	$IC_1 = 4520\, q + 180800$	q (l/s)
	OC_1: water cost	€ yr^{-1}	$OC_1 = SF + P_w\, PwQ$	SF: Subscription fee (€ yr^{-1}) P_w: Water price (€ m^{-1})
	OC_2: pump maintenance	€ yr^{-1}	$OC_2 = \propto_2 IC_2$	Assumption: portion of the investment costs
Water transfer	IC_3: pipe building	€	$IC_3 = D(0.71\, di + 19.5)$	D: distance from abstraction to infiltration point di: pipe diameter (mm)
	OC_3: lifting energy	€ yr^{-1}	$OC_3 = \frac{24\, N\, P_e\, Q\, H}{367\, \eta}$	N: Recharge duration (d yr^{-1}) P_e: electricity price (€ m^{-3}) H: Head loss (m m^{-1}) from abstraction to infiltration point η : pump efficiency
Water treatment	IC_4: system building	€	$LC_4 = \beta_4\, (€\, m^{-3})$	30% of LC_4
	OC_4: System maintenance	€ yr^{-1}		70% of LC_4
Water infiltration and extraction	IC_5: land purchase	€	$IC_5 = LMV\, S_S$	LMV: Land market value (€ m^{-2}) S_S: System surface area (m^2)
	IC_6: infiltration and extraction system building	€	$IC_6 = P_\delta$	P_δ: Construction costs of δ a chosen MAR technique
	OC_5: infiltration and extraction system maintenance	€ yr^{-1}	$OC_5 = \propto_5 IC_6$	Assumption: portion of the investment costs
Water monitoring	IC_7: monitoring equipment	€	$IC_7 = \beta_7$	Assumption
	OC_6: yearly monitoring	€ yr^{-1}	$OC_6 = \beta_6$	Assumption
Total	IC: Capital investment costs	€	$IC = \sum_{i=1}^{7} IC_i$	Total of IC
	OC: Operational costs	€ yr^{-1}	$OC = \sum_{i=1}^{7} OC_i$	Total of OC
	T: Operating life	yr	T	
	r: Discount rate	Decimal	r	r is based on the investment risks. Lower risks result in a higher discount rate.
	CRF: Capital recovery factor	Decimal	$CRF = \frac{r(1+r)^T}{(1+r)^T - 1}$	
	LTC: Levelized total cost	**€ m^{-3}**	$\boldsymbol{LTC = \frac{CRF * IC + OC}{Q}}$	

Appendix F.2 Explanation investment costs

The investment costs of a typical MAR system cover seven main items (Maréchal et al. 2020):

- Cost of preliminary studies (IC_1): All preliminary characterization studies of the recharge site (e.g., geological and hydrogeological characterization, technical-economic study, impact study, and preparation of the authorization file). In general, in 'water projects', this cost represents between 5% and 20% of the total investment cost depending on the size and complexity of the recharge project.
- Water abstraction cost (IC_2): Cost of civil engineering works for the pumping of water out of the river/canal, as well as pumping equipment (in the case where gravity supply is not possible).
- Water transfer cost (IC_3): In most cases, it will be necessary to transfer the water to the recharge site. This investment item concerns the construction of water transfer infrastructure including the supply pipeline. Depending on distances (up to a few tens of kilometres) and volumes, this investment cost item can be significant in relation to the total investment.
- Cost of recharge water (pre)treatment units (IC_4): The quality of the recharge water must meet regulation standards for recharge authorization. At a minimum, intermediate settling and filtration basins (primary treatment) could be required to limit the clogging of the recharge structures. Additional treatment (secondary or tertiary treatment) may be required (especially in the case of direct recharge).
- Costs related to land acquisition (IC_5): The cost of purchasing land for the construction of infiltration basins, which may be significant depending on the location of the recharge site (rural or urbanized environment). It depends on the number and total surface area of the basins, which in turn will depend on the infiltration rate (i) and instantaneous flow rate (q) of the selected site.
- Cost of infiltration basins (IC_6): In general, this is the main investment item. These costs include the design (civil engineering) and construction of infiltration basins (injection wells in the case of direct recharge), as well as associated equipment.
- Other costs (IC_7): Costs of monitoring equipment (e.g., construction of piezometers), and ancillary works.

Appendix F.3 Explanation operating costs

Operating costs cover the operating and maintenance costs of a MAR system. These are annual and recurring costs, expressed in € yr^{-1}. These expenses can be grouped into seven main items (Maréchal et al., 2020):

- Water purchase cost (OC_1): if applicable, includes the purchase cost in the case of withdrawal from a water canal or network, as well as charges, levies, or other taxes.
- Maintenance cost of the water intake (OC_2): includes the maintenance of the recharge water pumping system in the river.
- Energy cost (OC_3): corresponds with the electricity consumption of the equipment and pumping system used to supply the recharge water to the recharge site (if not gravity-fed). It will depend on the flow rate and the price of energy.
- Pre-treatment operational cost (OC_4): the operational and maintenance costs of the infrastructure for pre-treatment of groundwater (excluding investment). They include, for example, the cost of maintaining and cleaning settling tanks, the cost of chlorination products, etc.
- Cost of maintenance and upkeep of infiltration basins (OC_5): includes the maintenance of the recharge device (e.g., cleaning of infiltration basins) and its surroundings.
- Monitoring cost (OC_6): all the costs related to the control and periodic monitoring of groundwater or recharge water quality (e.g., laboratory analysis cost) or the costs associated with checking the proper functioning of the device (essentially labour costs if an automated control system is not set up).
- Other annual expenses (OC_7): includes all financial expenses not mentioned above: administrative and personnel management expenses, financial expenses on investment and insurance loans, etc.

Appendix G Stakeholders in a MAR project in India

A visualisation of the stakeholders involved in the case study of Brunner et al. (2014), which discussed a MAR project in Chennai City, India, is presented in Figure App. 16, including the main interests of a stakeholder. The used abbreviations are explained in Table App. 8, including their operational level (Brunner et al., 2014: 3743).

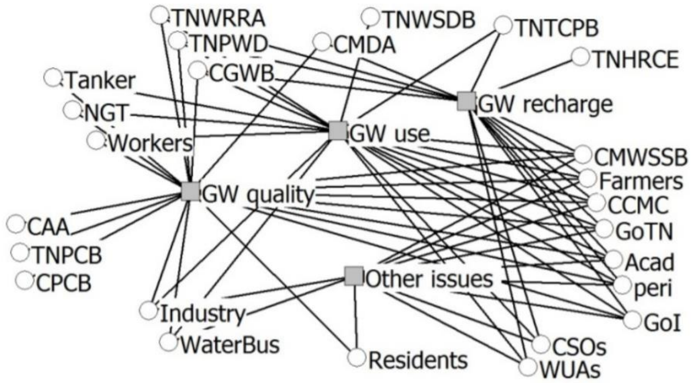


*Figure App. 16 Stakeholders and their groundwater-related interests.**

* The grey squares are groundwater-related interests; "GW quality" = pollution control of groundwater, "GW use" = extraction of groundwater, "GW recharge" = RWH or other MAR infrastructure, "Other issues" = water saving by the use of recycled water or similar questions. White circles represent stakeholders (abbreviations explained in **Error! Reference source not found.**), whereby l ines connect stakeholders to their interests. (Brunner et al., 2014)

Table App. 8 List of stakeholders for a MAR project in Chennai City, India

Stakeholder / Institution	Level	Abbreviation
Government of India, Ministry of Water Resources, Planning Commission	National (Union State)	GoI
Central Pollution Control Board		CPCB
Control Groundwater Board		CGWB
Coastal Aquaculture Tribunal		CAA
National Green Tribunal		NGT
State Government of Tamil Nadu	Tamil Nadu State	GoTN
Public Works Department		TNPWD
Pollution Control Board		TNPCB
Water Supply and Drainage Board		TNWSDB or TWAD
Town and Country Planning Board		TNTCPB
Hindu Religious and Charitable Endowment Board		TNHRCE
Water Resources Regulatory Authority (proposed)		TNWRRA
Chennai City Municipal Corporation	Muni-cipality	CCMC
Chennai Metropolitan Development Authority		CMDA
Chennai Metropolitan Water Supply and Sewerage Board		CMWSSB
Food and mining industry	Local non-governmental	Industry
Private water companies		WaterBus
Tanker truck operators		Tanker
Water users' associations		WUA
Agriculture sector		Farmers
Peri-urban villages		Peri
Peasants without own land		Workers
Residents of the city		Residents
Organisations of civil society		CSOs
Research centres and universities		Acad

Appendix H Comparison of groundwater governance systems

Appendix H.1 Classes used in groundwater governance systems comparative studies

The comparative classes as used in Ross (2016) are explained in Table App. 9.

Table App. 9 Groundwater governance comparison classes as used in Ross (2016).

Class	Class's meaning
Architecture	Central principles, policies and institutions that guide sustainable groundwater use, and interaction between them
Access and use	Institutions and procedures that determine who has access to groundwater, for what purposes and how groundwater is allocated
Accountability	Institutions and procedures that provide accountability for groundwater protection and use
Adaptation	How groundwater users, governments and third parties respond and adapt to changes and uncertainty in groundwater availability, use, and governance
Agency	Private and public responsibilities for groundwater management.

Appendix H.2 Strengths and weaknesses of groundwater governance systems

The strengths and weaknesses of the different groundwater governance systems in Australia, the EU and the USA as found in Ross (2016) are presented in Table App. 10.

Table App. 10 Strengths (+) and weaknesses (-) of groundwater (gw) governance in Australia, the EU, and the USA. Source: Ross, 2016

Class		Australia	EU	USA
Architecture	+	NWI provides for comprehensive gw governance	WFD provides comprehensive gw protection	Prior appropriation system safeguards senior water rights
	-	Weak gw quality regulation	Variable implementation of gw standards	Weak gw quality regulation (except for drinking water)
Access and allocation	+	Water plans set sustainable gw use limits	Gw allocation included in river basin plans	Effective rationing of scarce water
	-	Overallocation of gw use entitlements	Variable implementation of basin plan	Gw overuse in some areas
Accountability	+	Democratic legitimacy	Democratic legitimacy	Local legitimacy
	-	Use monitoring variable, quality monitoring poor	Variable monitoring and reporting	Accountability for impacts at larger scales, variable monitoring
Adaptation	+	Variable annual water allocation	Flexible implementation of EU standards	Local innovation, flexible enforcement of prior appropriation
	-	Centralised system can discourage local innovation	Slow implementation of drought management plans	Rigidity of prior appropriation during droughts
Agency	+	Central coordination and planning	Central coordination and planning	Local empowerment and innovation
	-	Local delegation and implementation	Local delegation (in most countries)	Strategic planning

Appendix I Groundwater quality indicators for the EU

A list with the most common and important substances and indicators is presented in Table App. 11, including the threshold values (European Commission, 2010, 2014).

Table App. 11 Key-substances and indicators in groundwater quality assessments.

Substance/ indicator	Threshold low	Threshold high	Unit
Ammonium	0.084	52	mg L^{-1}
Arsenic	0.75	189	µg L^{-1}
Cadmium	0.08	27	µg L^{-1}
Chloride	24	12,300	mg L^{-1}
Conductivity	4.85	104.8	µS m^{-1}
Copper	10.1	2000	µg L^{-1}
Lead	5	320	µg L^{-1}
Mercury	0.03	1	µg L^{-1}
Nickel	10	60	µg L^{-1}
Nitrites	-	-	mg L^{-1}
Phosphates / total phosphorus	-	-	mg L^{-1}
Sulphate	129.75	4,200	mg L^{-1}
Tetrachloroethylene	1.1	50	µg L^{-1}
Trichloroethylene	1.5	50	µg L^{-1}
Sum of Trichloroethylene and Tetrachloroethylene	5	40	µg L^{-1}