Master's Thesis Internship- Master Water Science and Management (30 ECTS)

Managed Aquifer Recharge: Opportunities and barriers

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Abstract

This multi-disciplinary study analyzed the barriers and opportunities of managed aquifer recharge (MAR) in the world. Managed aquifer recharge (MAR) is a collective name for techniques that infiltrate and store water in an aquifer. Increasing water scarcity and high net groundwater abstraction rates are challenging issues now and in the future. Currently two-third of the global population experiences water scarcity at least once a month. In a world with increasing water issues, adequate water management becomes more vital. Groundwater users and ecosystems suffer from the consequences of inadequate groundwater management. Global population growth will increase the pressure on groundwater sources and in combination with climate change, water supply and demand will show increasing fluctuations. MAR could bring solutions to regions with water scarcity and groundwater management issues worldwide. The focus of this study is on identifying hydrogeological, climate, socioeconomic and institutional boundary conditions for MAR. These conditions are compared with a database of existing MAR projects. This specific comparison leads to new data in this area of research. It creates new insights of the barriers and opportunities for MAR worldwide.

The study shows an inventory of the 14 available MAR techniques and the (boundary) conditions for each technique. Other products are a set of 12 different hydrogeological boundary conditions, 23 relevant cost factors and 17 objectives for using MAR. There are 22 opportunities and 22 barriers to the implementation of MAR, for hydrogeological, climate, socioeconomic and institutional settings. The greatest opportunity can be found in arid and semi-arid regions because 1) they have the highest need for MAR and because 2) current practices are more seen in humid regions.

The scientific insights provided by this study can add clarity to science, as much of the knowledge on MAR was more fragmented up till now. In addition, the study clearly shows that there are still several knowledge gaps in the field of MAR and that further MAR potential studies are recommended. This study could help education programs on water storage and retention worldwide, in showing the importance of the adequate management of aquifers, including the barriers that might have to be overcome. This study clarifies the importance of adequate implementation of MAR techniques worldwide. Found insights can form a new direction in groundwater policy worldwide.

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1 Introduction

1.1 Background

In the following paragraphs the importance of groundwater, the threats to groundwater and the current situation on groundwater management will be discussed.

Groundwater is the largest source of freshwater on Earth (Aeschbach-Hertig & Gleeson, 2012). It is stored in layers in the subsurface known as aquifers. Groundwater abstraction represents 26% of global freshwater withdrawal and supplies half of the drinking water in the world (Connor, 2015; United Nations, 2012). Groundwater is also the largest (unfrozen) freshwater reservoir in the world (Bouwer, 2002). Therefore, the importance of groundwater for humankind is evident.

There are several challenges related to groundwater. Due to global climate change, water supply and demand show increasing fluctuations (Gale, 2005; Pachauri et al., 2014). Also, storms and heavy rainfall events have higher intensity and frequency. Besides these challenges, land subsidence resulting from excessive groundwater abstraction is an issue in several places in the world (Gale, 2005).

Aquifers are over-exploited in parts of the world because of increased abstraction (Gleeson et al., 2012; Konikow, 2011; Wada et al., 2010). A new study by NASA showed that one-third of the big groundwater basins in the world is over-exploited (Richey et al., 2015). This stress on aquifers is caused by human activities. Another recent study found that currently 4 billion people, which is about 66% of the world’s population, experience water shortages for at least one month a year (Mekonnen & Hoekstra, 2016). Worldwide population growth and climate change will increase these shortages and water stress on aquifers in the future (Veldkamp et al., 2015).

The current situation and the threats to groundwater show the importance for adequate management of aquifers. Storing water in rainy periods, or periods with high river discharge, can alleviate periodic water shortage (Maliva & Missimer, 2012). The stored water can then be used in dry periods. This is required for example in sub-tropical climates with a monsoon. These regions have excessive rainfall during a few months and almost no rainfall during the rest of the year. Water shortages during the dry season could be alleviated, at least partially, by properly storing water during the wet season (Chinnasamy et al., 2015). This multi-disciplinary study will explore the opportunities and barriers of deliberate storage of groundwater known as ‘managed aquifer recharge’.

1.2 Managed aquifer recharge

According to Topper et al. (2004), managed aquifer recharge (MAR) is “any system created to infiltrate and store water in an aquifer”. There have been several names for managed aquifer recharge, such as artificial recharge, enhanced recharge and water banking (Dillon, 2005). Tuinhof & Heederik (2003) use the broader term, managed aquifer recharge and subsurface storage (MAR-SSS). Previously the term artificial recharge was most common but due to the negative association with the word ‘artificial’ the term ‘managed aquifer recharge’ has become prevalent (Dillon, 2005; IGRAC, 2007)**.** In this study managed aquifer recharge will be referred to as MAR.

There are three general methods of MAR: 1) interception in the river bed, 2) direct infiltration through wells, 3) indirect infiltration from the land surface (Dillon et al., 2009a; Tuinhof et al., 2012)**.** Some of the most important types of MAR are: aquifer storage and recovery (ASR), aquifer storage, transfer and recovery (ASTR), spreading methods and induced bank infiltration. An example of several MAR techniques in their physical environment is given in Figure 1.

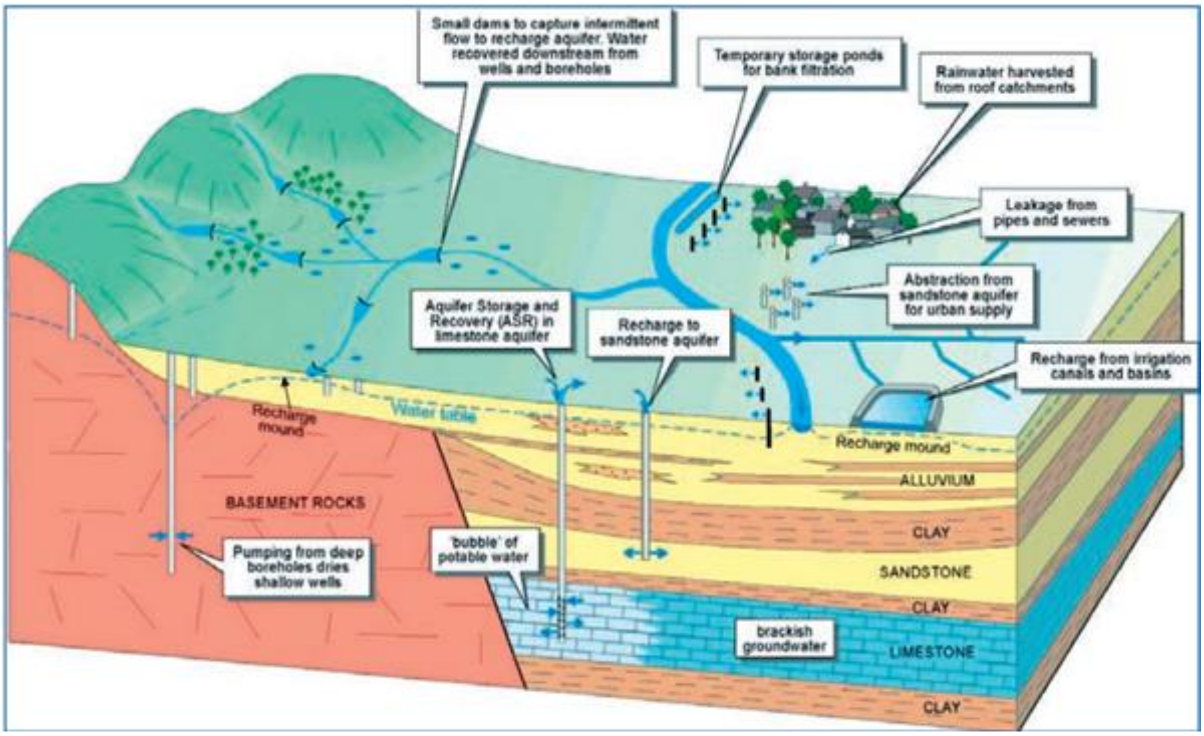
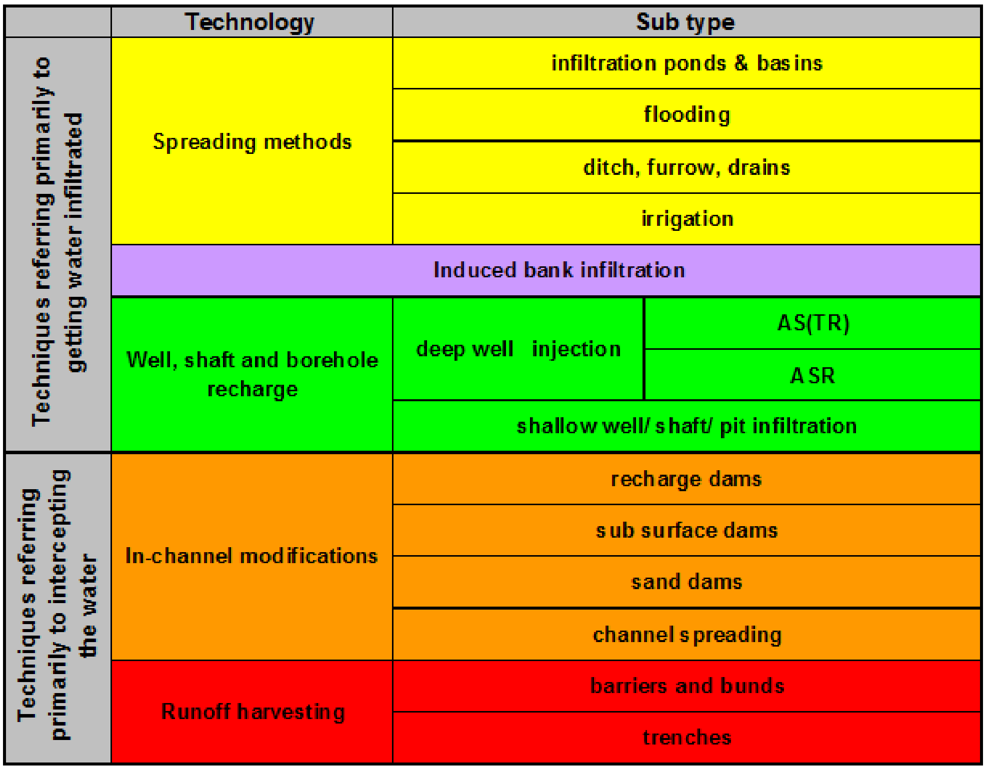


Figure 1: Conceptual image of a number of MAR techniques in a physical environment (NRWM, 2015)

A full classification of types and sub-types has been made as shown in Figure 2 (Gale, 2005). MAR can have several purposes. It can be used to store water in aquifers for later use (increasing long-term availability of groundwater for abstraction); to create a buffer capacity for droughts (this smooths out supply and demand fluctuations); to reduce storage loss through evaporation; improve water quality; store excess stormwater and to manage saline intrusion or land subsidence (Gale, 2005; Tuinhof et al., 2012).



	Technology	Sub type	
Techniques referring primarily to getting water infiltrated	Spreading methods	infiltration ponds & basins	
		flooding	
		ditch, furrow, drains	
		irrigation	
	Induced bank infiltration		
	Well, shaft and borehole recharge	deep well injection	AS(TR)
			ASR
		shallow well/ shaft/ pit infiltration	
Techniques referring primarily to intercepting the water	In-channel modifications	recharge dams	
		sub surface dams	
		sand dams	
		channel spreading	
	Runoff harvesting	barriers and bunds	
		trenches	

Figure 2: Classification of MAR techniques (Gale, 2005)

From these uses it follows already that different types of source water may be used for MAR such as perennial rivers and streams, intermittent streams, (urban) storm runoff, hortonian overland flow, storage dams, aqueducts and other similar structures, drinking water treatment plants, desalinization plants and sewage water treatment plants (Bouwer, 2002; Gale, 2005; Maliva & Missimer, 2012).

A typical process of MAR, using an infiltration pond, is shown in Figure 3.

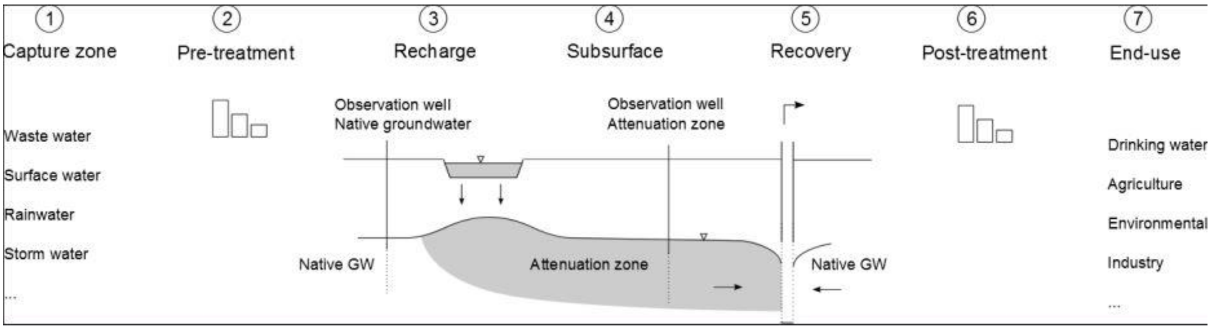


Figure 3: The typical process of MAR, here an infiltration pond system (Scheibler et al., 2015).

History and current extent

The enhanced recharge of groundwater has a long history. In China, already in the Qin Dynasty (221–206 B.C.) artificial recharge was performed by digging wells up to 200 meters depth to raise groundwater levels for agriculture (Wang et al., 2010). Later in the Yuan and Ming Dynasties (1271-1644), structures were made to store excess river flood water in aquifers. These were in fact recharge projects. Although a worldwide history of MAR was not found in literature, examples will be given in this study in a historical overview of MAR techniques.

The full extent of MAR projects worldwide is unknown. There are probably thousands of MAR projects, as the first global MAR inventory in 2016 contained already more than 1200 MAR projects (IGRAC, 2016a).

1.3 Comparison of the different methods of water storage

Water retention and storage can be done in four different ways, which are described by Tuinhof et al. (2012). First, open surface water storage can be done in lakes, behind dams and in open storage tanks. The main advantage of surface water storage is that large volumes can be directly available. Disadvantages are that open surface water storage is vulnerable to contamination and has a high potential for water loss through evaporation. Second, closed or cistern tanks are another relatively simple way of water storage but usually have small storage volumes. Third, storing water in the vadose zone is a good way of water storage as it is readily available for the plants and excess soil water percolates to the groundwater below. Finally, the medium in which groundwater is stored is a reservoir which holds more than 90% of the unfrozen global freshwater and has more space available for water storage in the future (Bouwer, 2002; Tuinhof et al., 2012). Underground storage of excess water has numerous benefits: high recharge rates utilizing relatively small surface areas; the transformation of often polluted surface water into groundwater of good quality; and protection against evaporation and atmospheric sources of pollution (Maliva & Missimer, 2012; Stuyfzand, 2015). Some disadvantages can be clogging of wells, undesirable natural reactions with the soil or unforeseen changes in the water balance (Maliva & Missimer, 2012).

Type of Storage	Advantages	Disadvantages
Open surface water	-large volumes	-vulnerable -high evaporation loss
Closed tank (or cistern)	-relatively simple	-small volumes
Soil moisture	-percolation of excess infiltration to the aquifer	-water not available after (only for plants)
Groundwater	-large volumes -improved quality -no evaporation loss -protection from air pollution	-more difficult -no direct access -well clogging

Table 1: Some advantages and disadvantages of different types of water storage (Maliva & Missimer, 2012; Tuinhof et al., 2012).

1.4 Social Relevance: impact on society

As became clear in paragraph 1.1, groundwater, especially as reservoir, is an essential part of the hydrological cycle. The possible consequences of declining groundwater storage are the deterioration of groundwater dependent ecosystems, higher pumping cost including higher energy use, saline groundwater intrusion, land subsidence, agricultural issues with irrigation water and overall an unhealthy competition for water resources (Gale et al., 2006). Therefore, more use of effective, more knowledge-based, and site-specific designed aquifer recharge projects (MAR) might have the potential to sustain freshwater availability and therefore prevent the mentioned future problems. Besides preventing problems, aquifer recharge projects can provide benefits. According to the EU action group (FP 7 INNO-DEMO MARSOL) on MAR, transferability studies in this area could "allow a major social advance (in Europe and worldwide) and can clearly contribute to improving living standards and job creation, as it increases the water availability to important economic sectors, improves human health and well-being, and sustains ecosystem functions and biodiversity" (EIP Water, 2016). An integrated water resources management approach can improve the economic and social welfare and will support ecosystems and the environment in a sustainable way (Kalbus et al., 2012).

1.5 Relevance for the internship organization

This study was initiated as part of an internship with Deltares, in order to gain more knowledge in the field of water storage and retention worldwide. Deltares is an independent institute for applied research in the field of water and subsurface technology. As told in paragraph 1.3, MAR techniques are "among the most significant adaptation opportunities for developing countries seeking to reduce vulnerability to climate change and hydrological variability" (IGRAC, 2016b; Shah, 2009; Sukhija, 2008). Finding sustainable solutions for water scarcity and mitigating adverse climate change effects is at the core of Deltares' research activities. Therefore, more knowledge on using MAR techniques might be useful for Deltares. On top of the added value for Deltares this study has the potential to also fill a scholarly knowledge gap.

1.6 Scientific relevance and knowledge gaps

Short literature review

Numerous studies have been carried out in the study area of MAR. These include hundreds of scientific journal articles, management reports and hydrological assessments. These are effectiveness studies, suitability mapping studies, hazard and risk assessment studies, cost-benefit studies and so on. Several studies have been done on finding the hydrological conditions required for MAR which are named in Ghayoumian et al. (2007), and Gale et al. (2006). For example, the importance of the source of water that will be infiltrated has been reviewed by Rahman et al.(2012). Focusing on the more non-technical aspects of MAR, some policy papers describe the water management conditions to be looked at when implementing MAR, such as a report of UNESCO-IHP (Gale, 2005). Cost-benefit analysis of MAR has been done among others by Tuinhof et al.(2012). Hazard and risk assessment studies are also done by many (Assmuth et al., 2016; Zhang et al., 2016). The collection of the existing MAR techniques is described, among others, by Gale (2005) and Bouwer (2002). Essential as a knowledge base for this study is an inventory on what kind of MAR techniques do exist. Two of the most updated overviews of the MAR techniques are described by Maliva & Missimer (2012) and by Escalante et al.(2014). The international groundwater resources institute IGRAC has also done extensive work on the subject of MAR. They recently published a worldwide GIS map of locations where MAR projects are being performed or have been performed and this map is updated continuously (IGRAC, 2016a). Also, an overview of the main advantages and disadvantages per technique, although not scientifically backed, has been made by IGRAC (IGRAC, 2007). Overall, a lot of aspects of MAR are covered by scientific literature or policy reports. Besides, global (scientific) networks in the field of MAR such as the International Association of Hydrologists (IAH recharge) and bebuffered (3R initiative) contribute to literature. Scientists and international organizations participate in conferences such as the recently held 9th international symposium on managed aquifer recharge which was held in conjunction with the 14th biennial symposium on managed aquifer recharge (UNAM, 2016).

Knowledge gaps

Although numerous studies have been done, still several studies indicate the knowledge gaps that currently exist and recommend further research. For example, there are few scientific site selection studies done for MAR (Rahman et al., 2012). Moreover, most studies focus only on the technical aspects of MAR feasibility and do not touch on governance factors. Often technological factors are leading but essential institutional factors such as water rights, competent authorities, finance and culture may be as decisive for MAR being successful. MAR techniques are usually not stand-alone interventions but are part of a broader hydrological and water management system (IGRAC, 2007). Therefore, it is necessary to assess the hydrological and water management components of the site where MAR is considered. An overview of all kind of these components can show the MAR potential, as MAR will not be the solution for water scarcity in all areas (IGRAC, 2016b). Furthermore, an evaluation of the MAR potential in different climatic, socioeconomic and hydrogeological regions is never done based on a sound scientific analysis (Gale et al., 2006). The need for further studies on integrated water management in these different type of conditions, i.e. site specific, is also supported by Kalbus et al. (2012). This scholarly gap needs to be overcome in order to sufficiently answer the multiple question sentence of when, where, why and how to use MAR.

1.7 Objectives

Given the existing knowledge gaps in literature research and the added value for the internship organization, the research aims of this study are:

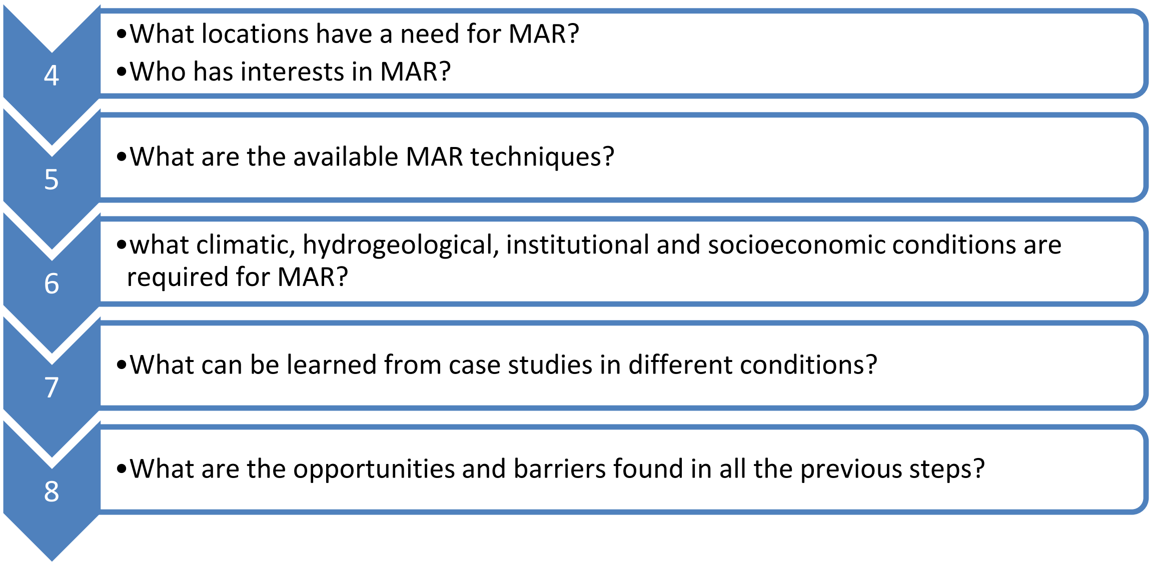
1. To assess under which conditions MAR is helpful and necessary as a key to mapping global need for MAR
2. To provide an inventory of which MAR techniques are available and under what conditions they are applicable
3. To identify the global opportunities for MAR and the possible climatological, hydrogeological, institutional and socio-economic barriers for its application.

1.8 Research Question

The research question, following from the knowledge gaps in literature, is:

What are the barriers and opportunities for managed aquifer recharge in different climatic, hydrogeological, institutional and socioeconomic settings that exist around the world?

To answer the main research question and to achieve the research objectives, the steps described below are taken.



4
- What locations have a need for MAR?
- Who has interests in MAR?

5
- What are the available MAR techniques?

6
- what climatic, hydrogeological, institutional and socioeconomic conditions are required for MAR?

7
- What can be learned from case studies in different conditions?

8
- What are the opportunities and barriers found in all the previous steps?

Figure 4: Schematic of research steps taken in the study. The numbers refer to the chapters in this study.

In order to find the opportunities and barriers for MAR worldwide, an assessment has to be made why and where MAR is desired. Also, when implementing MAR a set of conditions is required. What are these different conditions? For a complete overview, a state of the art assessment should be made on what MAR techniques currently exist. How and where are they performed? In order to learn from practices throughout the world, case studies under different conditions should be looked at. This combination should lead to opportunities and barriers for MAR worldwide.

2 Theory

From literature research, a knowledge gap was identified from which the research question followed. However, no existing framework or model has been found to systematically investigate the potential of MAR in different climatic, hydrogeological, institutional and socioeconomic conditions. Therefore, two known theories are used in this study to find the MAR potential for answering the sub-questions. These are the theory of policy transferring and the theory of lesson drawing. The first one will only be used passively and the one on lesson drawing actively. The theory of policy transferring assumes that if certain policy works in a certain place, it can usually not be copy pasted to another place (Dolowitz & Marsh, 2000). Certain policy changes will have to be made. This study will make passively use of policy transferring, as a basis for saying that MAR is not a solution to all water scarcity or water excess issues but is bound to environment specific conditions (IGRAC, 2016b). With lesson drawing one tries to learn from previous cases done on a specific subject, from its strengths and pitfalls, in order to achieve greater success elsewhere (Krajcik & Blumenfeld, 2006). However, no specific lesson drawing framework was found which applies to MAR. Still, with comparing differences in different case studies, supported by literature research, one can learn what conditions determine barriers and opportunities for MAR. Therefore, the theory of lesson drawing will be applied actively.

3 Methodology

The approach in finding the opportunities and barriers to MAR worldwide had four steps. To execute these steps literature research was performed (step 1-3) as well as data analysis (step 4). The four steps are shown in Figure 5 and Figure 6. They show the line of reasoning and structure. In addition, the text frames are the headings in this research paper.

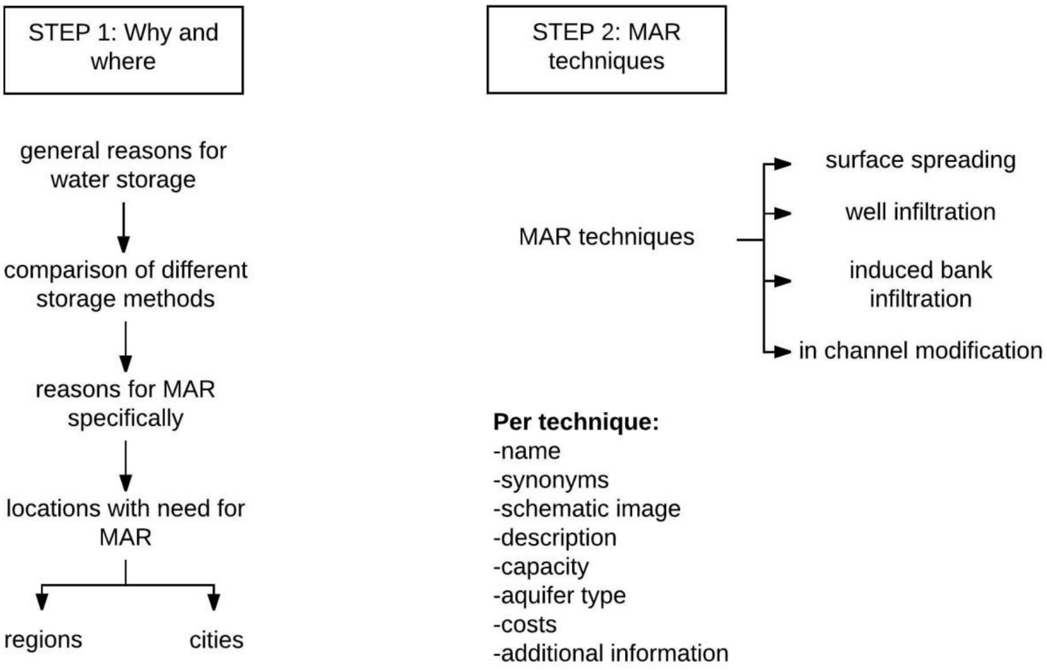


Figure 5: Methodology step 1 and 2

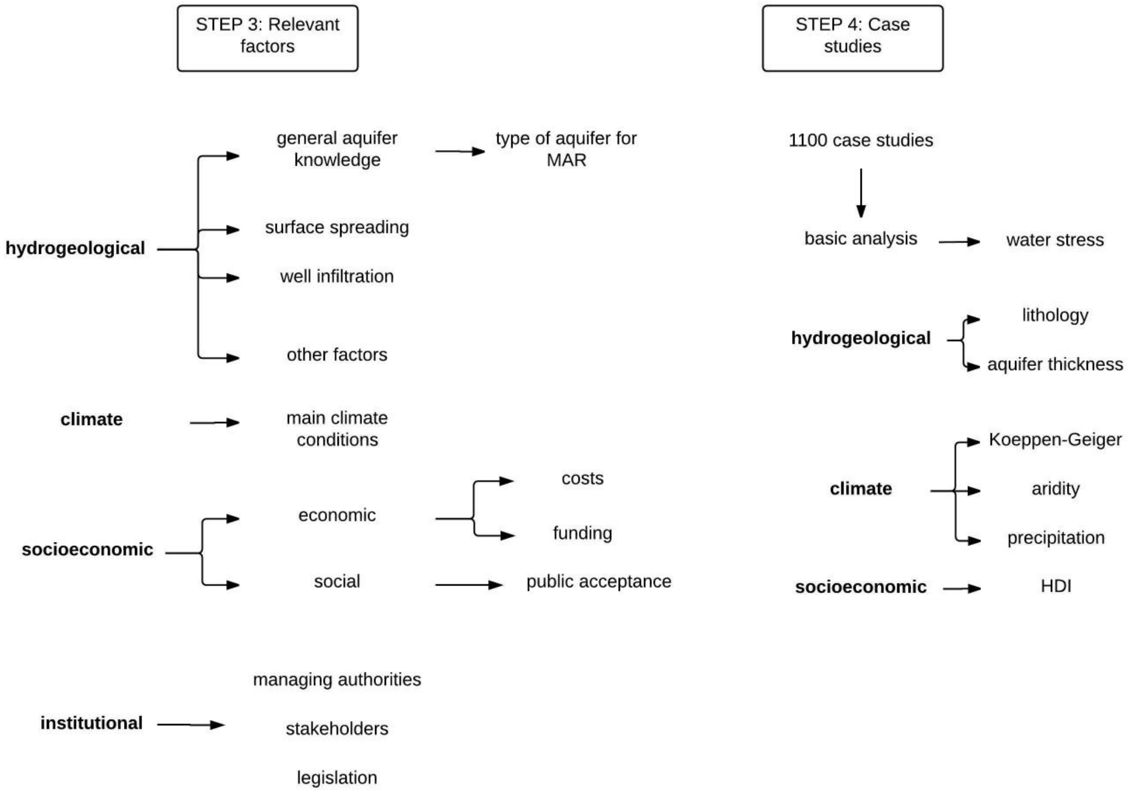


Figure 6: Methodology step 3 and 4

The literature research performed in the first three research steps was mostly qualitative. If applicable, quantitative information on for example costs was given. The fourth research step, where a large number of case studies were analyzed, involved quantitative analyses, i.e. mainly descriptive statistics. Hereafter, the four research steps will be explained in detail.

3.1 Literature data collection

Literature research was the main type of data collection. Literature was found on Google Scholar. For citing references properly, in Refworks an adapted Utrecht Geo Style version 3 was used.

The key references for each research step are shown in Table 2.

Research step	Heading	Key references
1	4.2	(Margat & Van der Gun, 2013)
	4.3	(Taylor et al., 2013)
	4.4	(Bouwer, 2002; Tuinhof & Heederik, 2003)
	4.5	(Gale, 2005; Gale et al., 2006; Margat & Van der Gun, 2013; Tuinhof et al., 2012; Zekri et al., 2014; Zuurbier et al., 2012)
	4.6	(de Graaf et al., no date ; Gleeson et al., 2012; Konikow, 2011; Tuinhof et al., 2012)
	4.7	(Dillon et al., 2012; McDonald et al., 2014)
2	5.2	(IGRAC, 2016a)
	5.3, 5.4, 5.5	(Gale, 2005; Maliva & Missimer, 2012)
3	6.1	(Margat & Van der Gun, 2013)
	6.2	(Central Ground Water Board, 2007)
	6.3	(Neumayer, 2001)
	6.4	(Brunner et al., 2014)
4	7	(IGRAC, 2016a)

Table 2: Key references for each research step. If no key references, the step is left out.

Persons and organizations contacted for this study are shown in Table 3.

Table 3: persons and organizations contacted

Name	Organization	Information	e-mail
Roelof Stuurman	Deltares	Research topic	Roelof.Stuurman@deltares.nl
Cheryl van Kempen	Deltares	-FWOO study -GIS layers to use	Cheryl.Vankempen@deltares.nl
Henk Kooi	Deltares	Global land subsidence map	Henk.kooi@deltares.nl
Robert McDonald	The Nature Conservancy	Mistakes in database	Rob_mcdonald@tnc.org
M.Arshad & A. Ross	Australian National University and National Center for groundwater Research and Training	Online availability of a study	muhammad.arshad@anu.edu.au, a.ross@unesco.org
Enrique Fernandez Escalante & Jon San Sebastian Sauto	Grupo Tragsa	Images of MAR techniques	Website Tragsa Spain
Tom Gleeson	McGill University	No reply	tom.gleeson@mcgill.ca
IGRAC, Andreas Antoniou	IGRAC	-Possible research questions -GIS map of aquifers not available	info@un-igrac.org, andreas.antoniou@un-igrac.org

3.2 First Step: Why and where

In the first step, the flow of steps shown Figure 5 was elaborated. As it is crucial for decision makers to know the objectives of a (MAR) project, an overview of the objectives and the possible underlying threats was created. The list of conditions was concluded from the list of objectives of MAR in a manner that can be found in Appendix A. The objectives both from the literature and the data were put in a coordinate system showing qualitative versus quantitative management and short term versus long term storage as objectives.

Stressed cities database

A database of stressed groundwater and stressed surface water cities was summarized from a study by McDonald et al. (2014). In this thesis, first, the cities with groundwater stress were selected by applying a filter (stressed). Second, the cities with surface water stress according to both models (WBM and WaterGap) were filtered out. Population growth and income in large cities are seen as basics for a city analyses. Therefore, population estimates for 2015, 2020, 2025 and 2030 were added for the specific cities from the World Urbanization Prospects (United Nations, Department of Economic and Social Affairs, Population Division, 2014). Also, income class from the World Bank was added (World bank, 2016). HDI was added, an indicator which is explained paragraph 3.2.4.

From the research of McDonald et al. (2014) cities over 750.000 inhabitants are accounted for. Both cities with groundwater and surface water stress were studied further. While it seems logical for cities with groundwater stress to use aquifer recharge techniques, for cities with surface water stress it is not directly clear. However, cities suffering under surface water stress might find managed aquifer recharge techniques, if possible, a good mitigation measure for their surface water problems. The cities with groundwater stress are defined by the groundwater footprint as designed by Gleeson et al. (2012). The groundwater supply of a city was defined as ‘stressed’ if abstraction/recharge >1. Abstraction was calculated from country statistics of the year 2000. Recharge was calculated using PCR-GLOBWB, a hydrological model on a global scale which includes return flows from irrigation. In the hydrological cycle, PCR-GLOBWB represents the terrestrial part (McDonald et al., 2014).

The cities with surface water stress are defined by two global water stress estimating tools, the Water Balance Model Plus (WBM) and the WaterGap model. Only the cities seen by both tools as ‘stressed’ are used here. The WBM ‘is operating on simulated topological gridded river networks at various resolutions’ (McDonald et al., 2014). For the study in question, a 0.5° spatial resolution was used. The model estimates the availability of global surface water for each grid cell, taking processes such as precipitation, irrigation and infiltration into account. Global population datasets on water use are also used. The WaterGap model consists of two components, a water balance model and a water use model. This model also uses a 0.5° spatial resolution. Input data include time series of climatic data, national country statistics on water use and a global map of irrigated areas. The difference between WBM and WaterGap is that WMB estimates water stress systematically slightly lower than WaterGap. Therefore, WBM is more conservative.

Climatic favourability of cities

A scatter plot of the favourability of stressed cities for MAR, based on climatic factors, was created. This was done in the same manner as in the study by Dillon et al. (2012). This study uses the 'seasonality of rainfall' and the aridity index to show the favourability for MAR.

'Seasonality of rainfall' = driest 6 months of precipitation/total annual rainfall.

In ArcMap, of which the methodology is explained in paragraph 3.2.4, the driest 6 months were calculated. This was performed with data from the precipitation layer and with the raster calculator. The driest 6 months of precipitation layer was added to the map. To the database of stressed groundwater and stressed surface water cities summarized from a study by McDonald et al.(2014), total annual precipitation, driest 6 months of precipitation, and the aridity index were added. This data was downloaded to excel. In excel, the seasonality of rainfall was calculated for all stressed cities. Seasonality of rainfall was plotted against the aridity index in a scatter plot. A high aridity in combination with a high seasonality of rainfall creates the highest favourability.

Water stress combined with rainfall: global map

In ArcMap, of which the methodology is explained in paragraph 3.2.4, a combined map was created to indicate regions where there is 1) a high amount of total annual rainfall and 2) a high water stress. The layers of total annual rainfall and baseline water stress were used, which are explained in paragraph 3.5. In the rainfall layer the attributes with a rainfall higher than 1000 mm were selected and in the water stress layer the attributes (river basins) with a stress higher than 3 were selected. Both layers were 'exported' as new layers for the map. The layers were intersected used the Clip function, as the rainfall layer was raster format and the water stress layer polygon format. The resulting regions were laid on top of the World Countries layer and the stressed cities and the MAR projects (see 3.5) were added.

3.3 Second Step: overview of available MAR techniques

In the second step, a review was made of currently available MAR techniques and a state-of-the-art knowledge base of MAR techniques was created. The structure was vital, as no full and structured overview was found in the existing literature. According to a classification made by Gale (2005), there are 5 typical methods for MAR: spreading methods, 'well, shaft and borehole recharge', induced bank infiltration, in-channel modifications and runoff harvesting (see Figure 2). These types of methods and their sub-types were described. Runoff harvesting was incorporated in spreading methods, as primarily the source water is the only difference.

Before describing the methods, a historical overview of the MAR techniques was made. The history of the techniques is not only interesting but may offer useful lessons for the future.

At first, the main methods of MAR were described in general. Then the sub-types, also called specific MAR techniques, were described in structured tables. The tables list the following information, when available: name, synonyms, schematic image, description, capacity, costs, aquifer type and additional information. Often examples were given due to the lack of complete information. The choice for these factors came 1) from similar tables in literature (e.g. Escalante (2010)) and 2) from requests from the internship organization. In the next paragraph, factors that might need an explanation will be explained briefly.

- Synonyms are meaningful information as other names for the same technique do exist.
- Costs can vary greatly amongst techniques. All costs were converted to US dollars with current conversion rates when found in the literature research in euro's, pounds or Australian dollars.
- Capacity gives an idea of the quantities of water that can be stored or recovered.
- Aquifer type is one of the crucial hydrogeological factors of MAR, as was explained in paragraph 6.1**.**

3.4 Third Step: Relevant hydrogeological, climatic, socioeconomic and institutional conditions

During the third step, literature was searched for climatological, hydrogeological, institutional and socioeconomic conditions required for MAR. The steps shown in flow chart 3, of Figure 6, were elaborated.

Before starting with the fourth step, hypotheses, based on literature research in the first three steps, were formulated and presented in paragraph 6.5. In the discussion (Chapter 8), these hypotheses will be verified or falsified with the use of the data results from step 4 (Chapter 7).

3.5 Fourth Step: Case studies

The fourth step consisted of data analyses on case studies worldwide under different climatic, hydrogeological, institutional and socioeconomic conditions. Data was downloaded from the global MAR Viewer of IGRAC (IGRAC, 2016a), then combined in ArcMap, and finally analyzed in Excel.

In the GGIS MAR viewer

In the Global MAR Viewer of IGRAC (IGRAC, 2016a), in the layer of global managed aquifer recharge (MAR) inventory, data on more than 1100 MAR projects worldwide was selected and downloaded into an Excel file. It contained the following information: ID number, site name country, latitude, longitude, specific MAR type, main objective and references.

In ArcMap

GIS can be used for a variety of purposes (Mahdavi, 2011). In ArcMap 10.2.1 several layers were loaded on the base map World Countries from ESRI. The datum and spheroid of this map were ‘world geodetic system 1984’. The layers used in the analysis, including resolution, publisher, timeframe and citation, are shown in Table 4.

Map of	**Publisher**	**resolution**	**link**	**Date range**	**Citation**
World countries	ESRI	Country	https://www.ArcMap.com/home/item.html?id=3864c63872d84aec91933618e3815dd2	current	(ESRI, DeLorme Publishing Company, Inc., 2014)
water stress	Aquaduct	River basin and country	http://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data	current	(Gassert et al., 2013)
Climate regions	Kottek et al, 2006.	0.5°	http://köppen-geiger.vu-wien.ac.at/present.htm	1950-2000	(Kottek et al., 2006)
Aridity	CGIAR-CSI	30arcsec	http://csi.cgiar.org/aridity/	1950-2000	(Zomer et al., 2006)
Precipitation	WorldClim	30arcsec	http://www.worldclim.org/current	1950-2000	(Hijmans et al., 2005)
Lithology (GLIM)	Pangaea	0.5°	https://doi.pangaea.de/10.1594/PANGAEA.788537	current	(Hartmann & Moosdorf, 2012)

Table 4: all layers used in ArcMap with additional information

Not all layers were directly in the right format, therefore, a transformation needed to be performed. The lithology layer (GLIM) was projected from raster to polygon by projection into the Geo_WGS 1984 frame and World Mercator projection.

The precipitation layer data was downloaded in monthly data. The twelve months were summed up with the field calculator in order to obtain the annual precipitation layer.

After having all the layers present, the Excel file with the worldwide MAR projects was loaded into ArcMap. Georeferencing was done by setting X and Y coordinates with latitude and longitude columns in the excel file.

One by one the values from the polygon layers were added to the attribute table of the MAR projects layer with the function Join. For the layers aridity and precipitation, as they were still raster format, extract value to point was performed with spatial analyst.

After having combined all the layers in the attribute table of the MAR projects layer, the table was downloaded and transformed into an Excel file.

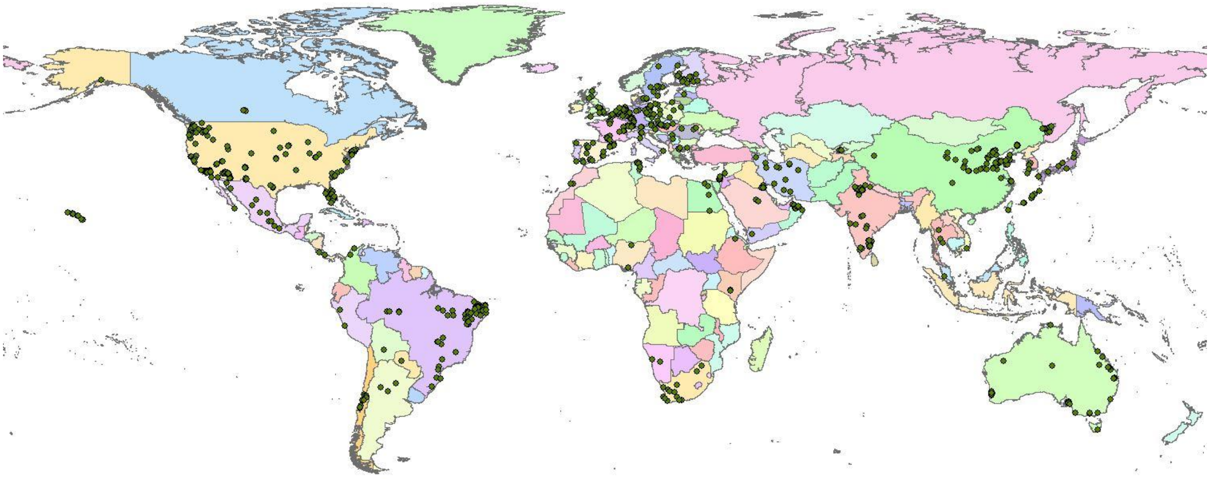


Figure 7: All MAR projects of the geodatabase on World Countries layer in ArcMap

In Excel

The geodata retrieved from ArcMap could not be analyzed before some adaptations. The most urgent action was to remove the cases with 'missing values', shown in Table 5. When values were deleted, the full row was removed in order to obtain a consistent, full, dataset. The cases of rainwater harvesting and subsurface dams were removed, as they are not considered as MAR in this study.

values deleted
no name
no specific MAR
Rainwater harvesting
Subsurface Dams
#N/A
-999

Table 5: values deleted in geodatabase from ArcMap

The case of Xiong was removed, as the latitude and longitude were switched, thus the wrong data was retrieved. In total 214 MAR projects were left out of the analysis due to missing values or applicability (rainwater harvesting and subsurface dams) in the study. The climate and lithology data were transformed from abbreviations to full lithology type names or climate types, shown in Appendix D and Appendix E.

To all the MAR projects the baseline water stress index from Aqueduct was added (Gassert et al., 2013). As the scope of this study is of a general and worldwide character, the water stress index is chosen above the water scarcity index. The water stress index is more applicable for this study as it includes a more inclusive and broader concept. The terms water stress and water scarcity are often used interchangeably; however, they are not the same. Water scarcity is only an index on volumetric availability, the water stress index has water scarcity and other factors included, shown in Figure 8 (Schulte, 2014).

Figure 8: Difference water scarcity and water stress. Adapted from Schulte (2014).

In ArcMap, the layer 'aqueduct global maps 2.0' is used, which contains among other information the baseline water stress index. "Baseline water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percentage of the total annual available blue water." Definitions of total annual water withdrawals and available blue water are shown in Table 6. Higher values indicate more competition among users.(Gassert et al., 2013).

Total withdrawal is the total amount of water removed from freshwater sources for human use.
Available blue water is the total amount of water available to a catchment before any are satisfied.

Table 6: Definitions for the 'baseline water stress' (Gassert et al., 2013).

At last, the latest Human Development Index values (of 2014) were added to the MAR projects in Excel. The data were downloaded from the United Nations Environmental Data Explorer (UNEP, 2016). The reason HDI was chosen instead of GDP, which has been a common economic indicator of development, is explained in the first step (Chapter 4), were HDI was found to possibly relate to MAR.

Once finalized the overview of data as chosen above, several analyses were performed. All the analyses were to perform descriptive statistics, such as the distribution of the values. Pie charts, bar charts, pivot charts, and box plots with whiskers were made. The boxplots were made with Excel 2016, as the instant boxplot option was not available in earlier versions. From these analyses it could then be determined if the hydrogeological, climate, socioeconomic and institutional conditions found around the current MAR projects are aligned with those hypothesized to be needed or favourable for the different MAR techniques (hypotheses can be found in paragraph 6.5).

4 First step: Why and where

In the first step the question why, for whom and where MAR is desired will be described. This implies an overview of the users with an interest in MAR and an overview of worldwide locations, regions and cities, where MAR might be desired.

4.1 General reasons for groundwater storage

Main drivers of the need for water storage are water scarcity, water demand and water use. Groundwater can play a meaningful role in water storage. These reasons for water storage were explained more in detail in the introduction (Chapter 1).

4.2 Groundwater users: domestic, agriculture, industry and ecosystems

The users of groundwater are a decisive group of potential beneficiaries of MAR. They are therefore described in the next paragraph. Groundwater as a natural resource does not exist without people to use it (Margat & Van der Gun, 2013). The factors that determine how people value (water) resources can be cultural backgrounds, views of nature, social change, resource scarcity, technological and economic factors.

There are four main sectors that use groundwater: domestic, agriculture, industry and ecosystems (Margat & Van der Gun, 2013). First, the domestic sectors are drinking water and other municipal water supply services. In many countries groundwater services for 100% the domestic water use. These countries include Denmark, Croatia, Montenegro, Austria, Pakistan, Yemen, Botswana and Iran. In addition, several cities in the world are entirely or for a substantial part serviced by groundwater. Second, water for irrigation in agriculture is a significant sector. Groundwater is in many cases the most 'easily and individually accessible' source of water for irrigation (Margat & Van der Gun, 2013). In addition, groundwater is in many cases the 'most flexible source in daily practice' and has the lowest exploitation costs (Margat & Van der Gun, 2013). In arid countries, groundwater is the largest contributor to irrigation water, but also in countries like Bangladesh, where surface water is difficult to control, groundwater is the main source for irrigation. Next to irrigation, groundwater is also a vital source for livestock farming and aquaculture (Margat & Van der Gun, 2013). Third, the industrial sector uses a large amount of groundwater, especially when the particular industry is not connected to public water supply services.

Globally, groundwater contributes to 35% (4300km^3/yr during 1998-2002) of freshwater withdrawals, shown in Figure 9 (Döll et al., 2012). This is per sector; 42% to the agricultural sector (irrigation), 36% to the domestic sector (households) and 27% to industry (manufacturing). This distribution is shown in Figure 10.

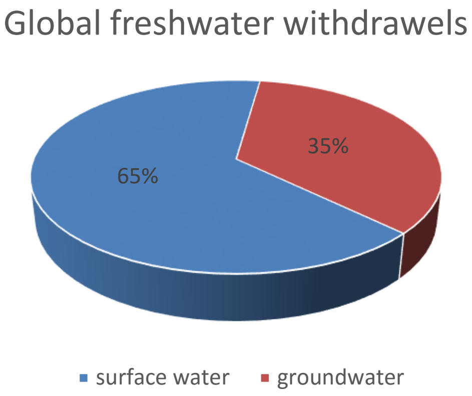


Figure 9: global freshwater withdrawals (1998-2002) (Döll et al., 2012)

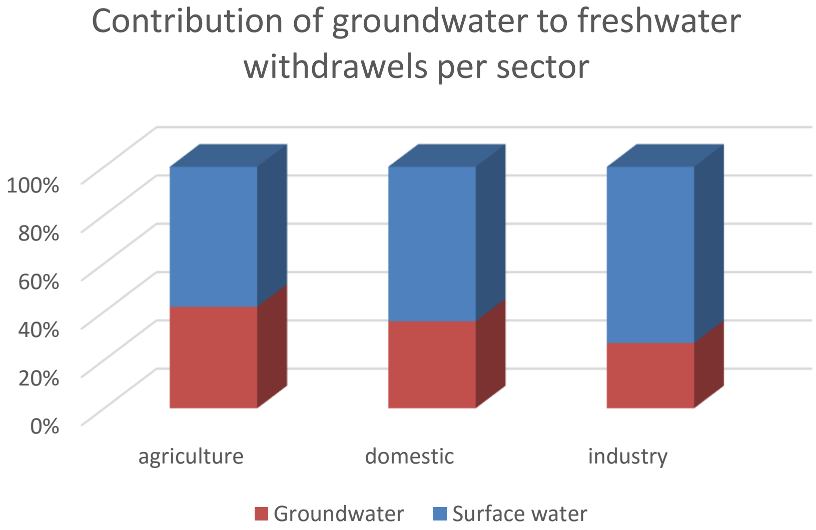
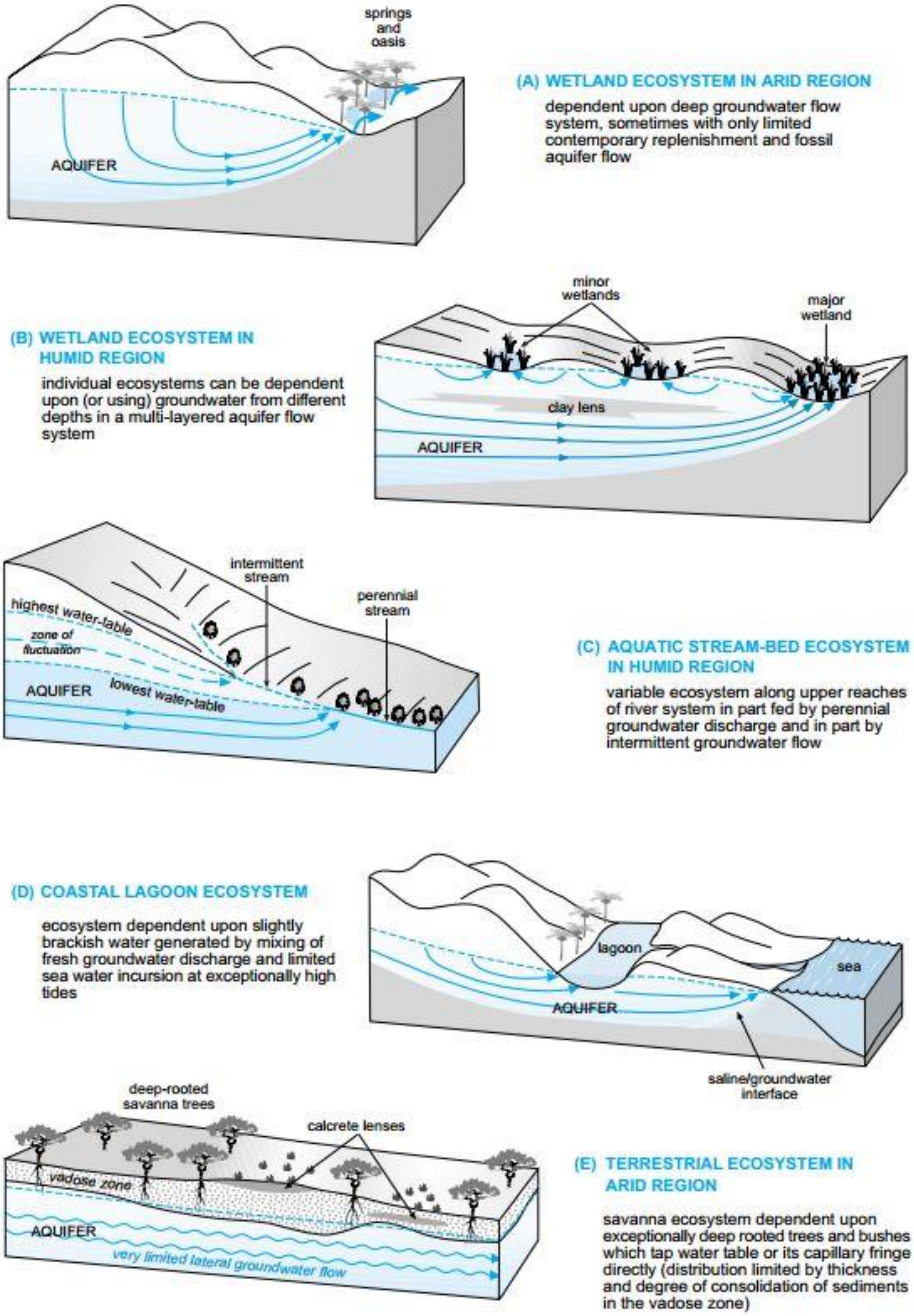


Figure 10: contribution of groundwater to freshwater withdrawals per sector(Döll et al., 2012)

Fourth, in addition to the three, human perspective based-sectors, the natural environment can be a beneficiary or user of groundwater. Groundwater is essential for the survival of several types of aquatic, terrestrial and coastal ecosystem such as wetlands, salt marshes, mangroves and terrestrial flora and fauna (Margat & Van der Gun, 2013). Groundwater-dependent ecosystems can be seen in Figure 11.



(A) WETLAND ECOSYSTEM IN ARID REGION

dependent upon deep groundwater flow system, sometimes with only limited contemporary replenishment and fossil aquifer flow

(B) WETLAND ECOSYSTEM IN HUMID REGION

individual ecosystems can be dependent upon (or using) groundwater from different depths in a multi-layered aquifer flow system

(C) AQUATIC STREAM-BED ECOSYSTEM IN HUMID REGION

variable ecosystem along upper reaches of river system in part fed by perennial groundwater discharge and in part by intermittent groundwater flow

(D) COASTAL LAGOON ECOSYSTEM

ecosystem dependent upon slightly brackish water generated by mixing of fresh groundwater discharge and limited sea water incursion at exceptionally high tides

(E) TERRESTRIAL ECOSYSTEM IN ARID REGION

savanna ecosystem dependent upon exceptionally deep rooted trees and bushes which tap water table or its capillary fringe directly (distribution limited by thickness and degree of consolidation of sediments in the vadose zone)

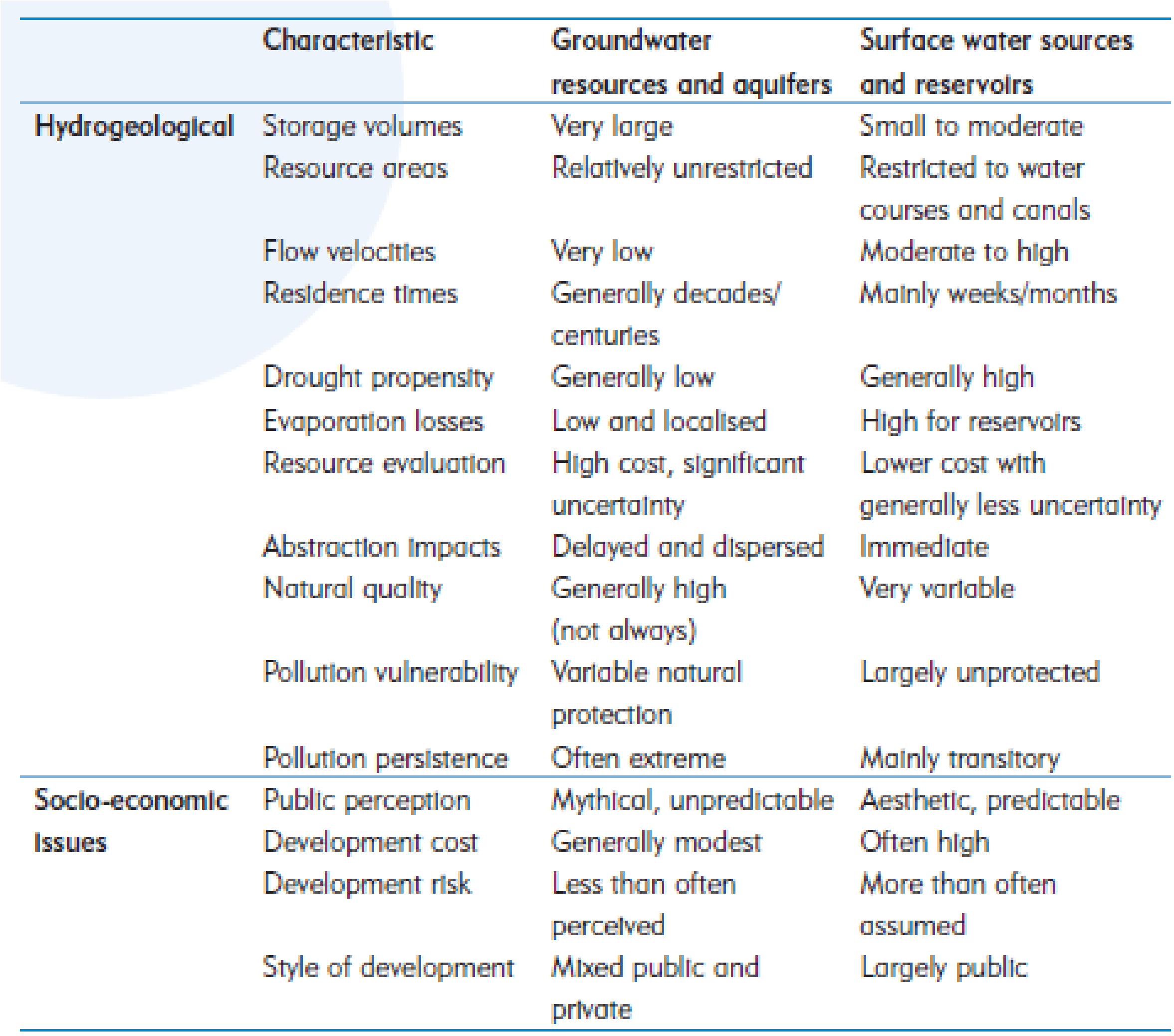
Figure 11: Groundwater dependent ecosystems (GW-MATE, 2006)

4.3 Impact of climate change on demand and recharge

The effects of future climate change on groundwater "may be greatest through indirect effects on irrigation water demand", as the agricultural sector is the largest user of groundwater (Taylor et al., 2013). Models estimate under emission scenarios A2 and B2 that by 2050 decreases of natural groundwater recharge of more than 70% could be seen in northeast Brazil, southwest Africa and the southern rim of the Mediterranean Sea. Increases of more than 30% could be seen in the Middle East, the Sahel, Siberia, northern China and the western United States (Taylor et al., 2013).The A2 emission scenario describes an almost completely heterogeneous world (Nakicenovic & Swart, 2000). It is characterized by slow and fragmented economic development. The scenario storyline is based on self-reliance and preservation of local identities under a growing global population. The B2 scenario describes a world where there are local solutions for economic, social and environmental issues. The population growth is lower than in A2. Focus is on environmental protection and social equity.

4.4 Comparison of different storage methods

There are considerable differences between groundwater and surface water. These essential differences, on hydrogeological and socioeconomic level, are shown in Table 7.

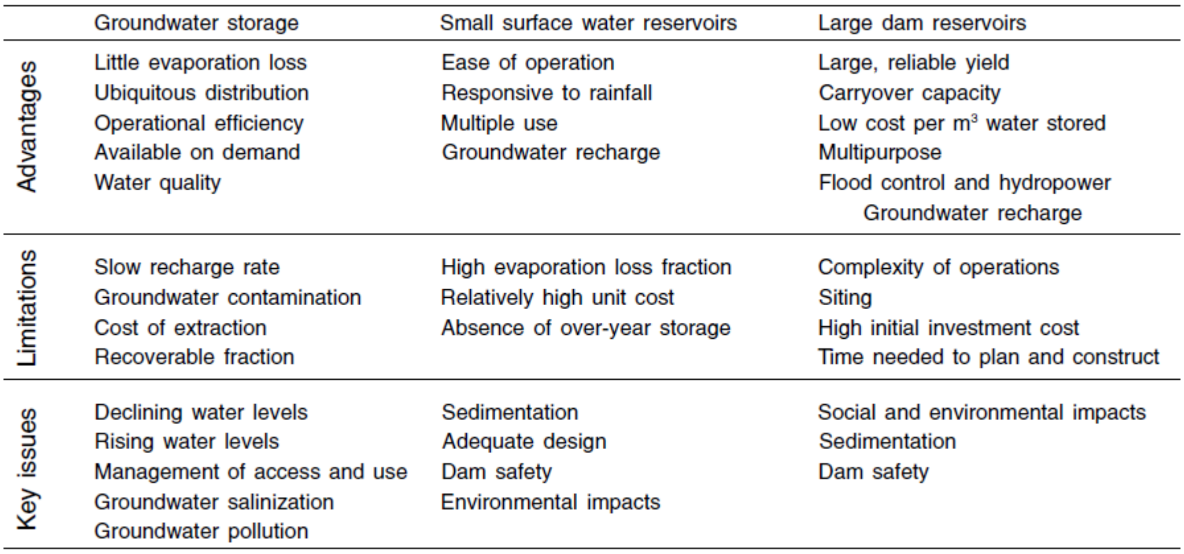


	Characteristic	Groundwater resources and aquifers	Surface water sources and reservoirs
Hydrogeological	Storage volumes	Very large	Small to moderate
	Resource areas	Relatively unrestricted	Restricted to water courses and canals
	Flow velocities	Very low	Moderate to high
	Residence times	Generally decades/ centuries	Mainly weeks/months
	Drought propensity	Generally low	Generally high
	Evaporation losses	Low and localised	High for reservoirs
	Resource evaluation	High cost, significant uncertainty	Lower cost with generally less uncertainty
	Abstraction impacts	Delayed and dispersed	Immediate
	Natural quality	Generally high (not always)	Very variable
	Pollution vulnerability	Variable natural protection	Largely unprotected
	Pollution persistence	Often extreme	Mainly transitory
Socio-economic issues	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

Table 7: Comparative advantages of groundwater and surface water from Tuinhof & Heederik (2003).

Limitation of dams

Surface water storage, with dams, has always been the most popular way of storing water (Bouwer, 2002). Both surface water and groundwater storage have their advantages and limitations. A comparison of groundwater, small and large surface water storage is given in Table 8. However, in the past decade, with population growth and higher competence for land, good dam sites have become scarce. Studies have shown the adverse effects and disadvantages of dams (Bouwer, 2002). In addition to Table 8: dams have high evaporation losses, about 2m/year in arid climates; there is sediment accumulation reducing storage (Wisser et al., 2013); danger of structural failure; more chances for human diseases such as malaria and schistosomiasis; and more undesired environmental and socioeconomic effects (Bouwer, 2002).



	Groundwater storage	Small surface water reservoirs	Large dam reservoirs
Advantages	Little evaporation loss	Ease of operation	Large, reliable yield
	Ubiquitous distribution	Responsive to rainfall	Carryover capacity
	Operational efficiency	Multiple use	Low cost per m^3 water stored
	Available on demand	Groundwater recharge	Multipurpose
	Water quality		Flood control and hydropower
			Groundwater recharge
Limitations	Slow recharge rate	High evaporation loss fraction	Complexity of operations
	Groundwater contamination	Relatively high unit cost	Siting
	Cost of extraction	Absence of over-year storage	High initial investment cost
	Recoverable fraction		Time needed to plan and construct
Key issues	Declining water levels	Sedimentation	Social and environmental impacts
	Rising water levels	Adequate design	Sedimentation
	Management of access and use	Dam safety	Dam safety
	Groundwater salinization	Environmental impacts	
	Groundwater pollution		

Table 8: Comparative advantages, limitations, and key issues associated with groundwater, small reservoir, and large dam water from Keller et al.,(2000).

4.5 Reasons for MAR

Barriers to using groundwater as a resource

Groundwater should not be used as a resource in cases of insufficient groundwater quality, technical exploitation difficulties, economic feasibility and environmental constraints (Margat & Van der Gun, 2013). Furthermore, groundwater should not be used at locations with non-renewable aquifers as they can only be depleted, as this is not sustainable.

Opportunities for using groundwater as a resource: objectives of MAR

An extended list of objectives for using MAR was composed of several sources (Gale, 2005; Gale et al., 2006; Holden et al., 2006; Maimone et al., 2011; Tuinhof et al., 2012; Xu et al., 2012; Zekri et al., 2014; Zuurbier et al., 2012)

1. Store water for long term storage
2. Buffer capacity for droughts/preparation for drought periods
3. Smooth out demand and supply fluctuations
4. Reduce evaporation loss
5. Improve water quality
6. Store excess storm/flood water
7. Manage saline intrusion
8. Manage land subsidence
9. Strategic reserve for emergency situations
10. Reducing runoff loss to oceans
11. Recharging groundwater (where the water table has lowered)
12. Store desalinated water
13. Improve and sustain ecosystems
14. Spare sewers of water overload
15. Conservation of archaeological sites
16. Provide water for domestic, agricultural and industrial use
17. Conserve wooden pile foundations

The list shows that there are 17 possible objectives to perform MAR. An overview of the objectives and the possible underlying threats is shown in Figure 12. In the list of objectives and in Figure 12, the objectives can be also seen as goals. It also must be noted that several of the objectives have overlap and can be applicable at the same time. Most objectives for MAR apply in regions where droughts occur. Four objectives of performing MAR were found to be applicable in all situations:

store water for long term storage, smooth out demand and supply, provide water for domestic, agricultural and industrial use, and improve water quality.

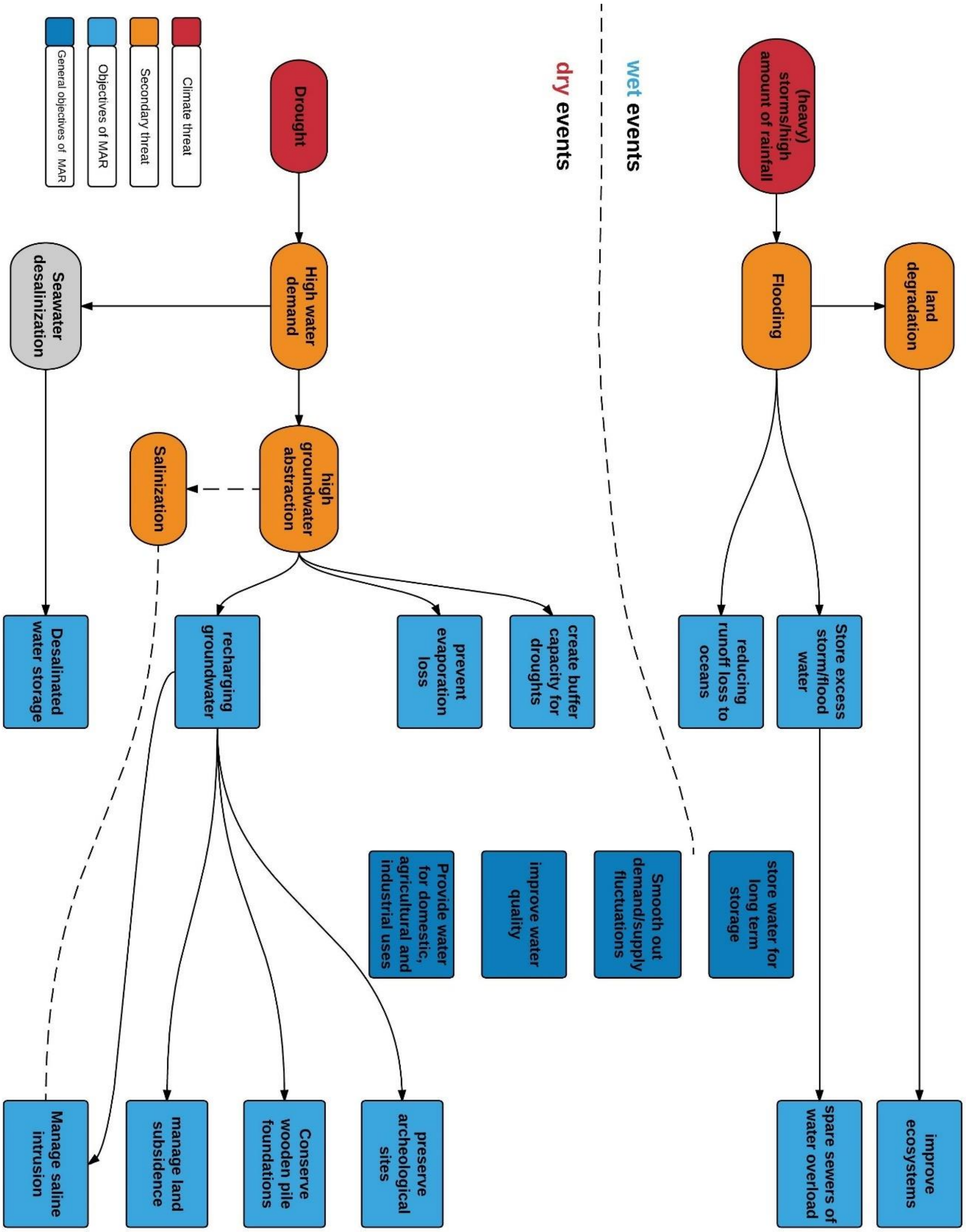
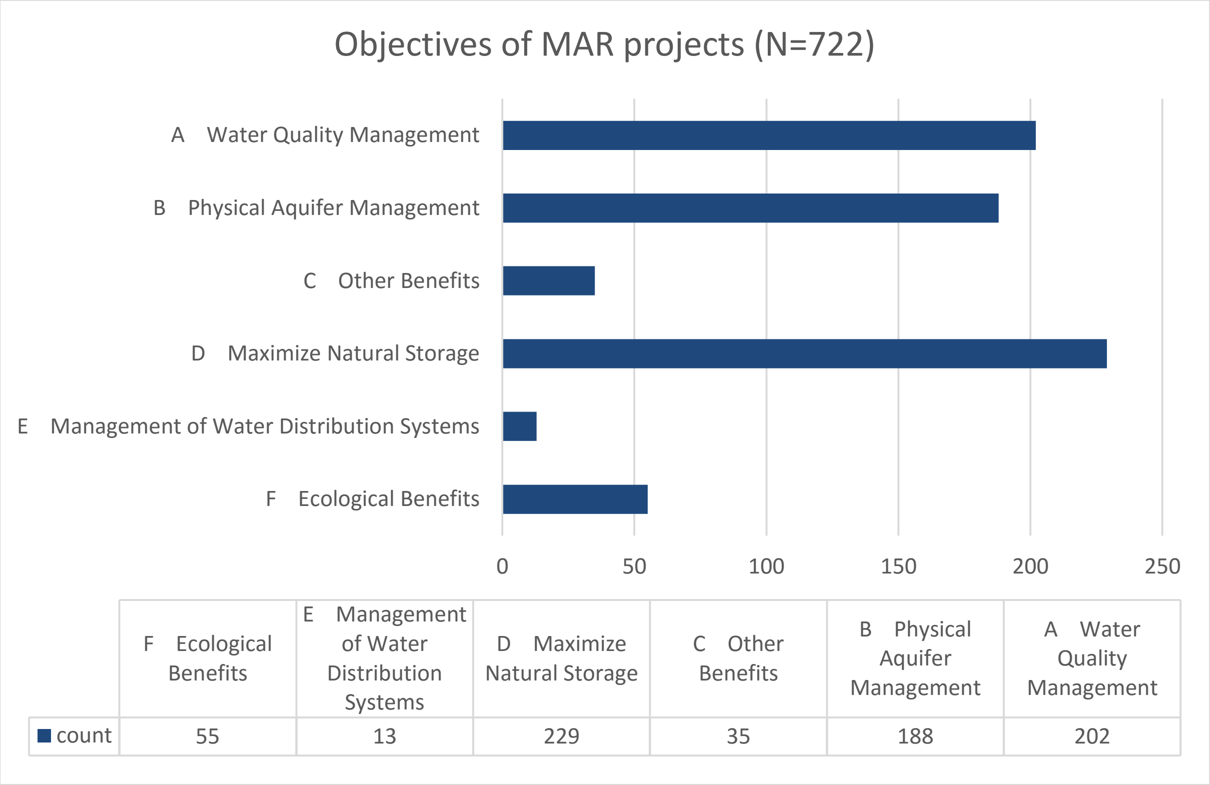


Figure 12: Flowchart of possible threats, objectives and goals for MAR

From the case studies studied in step 4 (Chapter 7), also information on objectives of MAR could be obtained. Six objectives are specified in the geodatabase. Of the 894 case studies, 172 did not mention the objective. The distribution 722 MAR case studies with objectives mentioned are shown in Figure 13. Maximize water storage, water quality management and physical aquifer management are the three most reported objectives of MAR case studies worldwide, respectively. The management of water distribution systems is least reported as an objective of MAR.



	F Ecological Benefits	E Management of Water Distribution Systems	D Maximize Natural Storage	C Other Benefits	B Physical Aquifer Management	A Water Quality Management
■ count	55	13	229	35	188	202

Figure 13: Objectives of MAR case studies from 894 case studies

If the objectives from the literature are combined with the objectives of the data, certain trends can be seen. It can be noticed that at least one of the following opposing goals for MAR do apply: Storing water for the long term versus rapid storage (after flooding events) and water quality management (managing water quality or nature) versus water quantity management. A possible distribution of the objectives into overarching goals is shown in Figure 14.

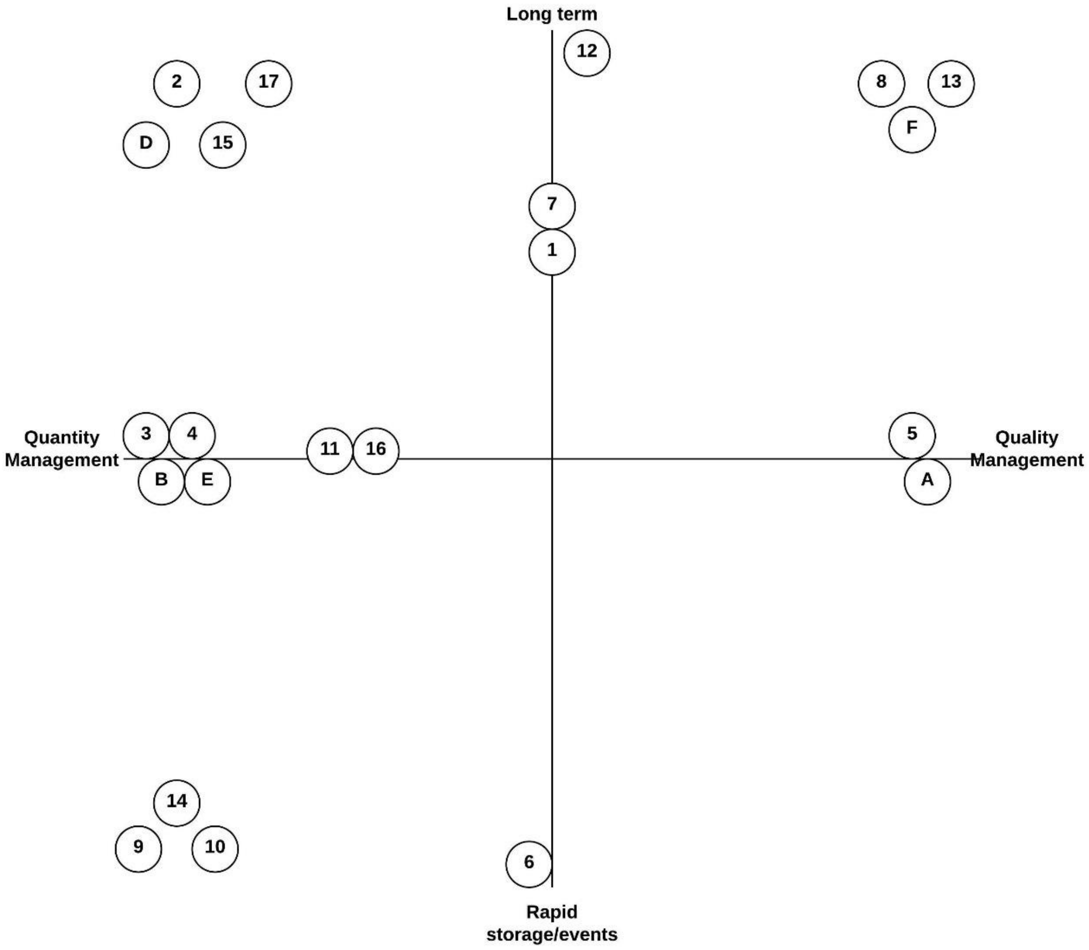


Figure 14: Possible distribution of objectives in the direction of overarching goals. When objectives are located directly at the label, it means that this is the main goal for this objective. If objectives are located elsewhere in the diagram, objectives serve a combination of goals.

Most of the objectives to use MAR have a long term and quantity management aspect. Least objectives lead to rapid storage and water quality management. It can be seen that the objectives long term storage and improve water quality are both seen in the objectives and the overarching goals.

4.6 Locations with need for MAR: Regions

From the list of objectives can be concluded that MAR is 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.

Appendix A, the line of reasoning is shown from the list of objectives to the conditions where MAR is desired.For each objective it was searched for in what type of region it applies.

In the next paragraphs, the conditions will be briefly discussed.

High seasonal rainfall peaks

Extreme rainfall events are seen in several different places. Due to enhanced climate change, the earth heats up and because warmer air holds more water, extreme rainfall events can be expected in more places (Harvey, 2000). The link between temperature increase and air water content is described by the Magnus approximation of the Clausius-Chapeyron equation, shown in equation 1 (Lehmann et al., 2015).

$$\mathrm{e_s}(T) = 6.1094 \cdot exp\left(\frac{17.625\,T}{T+243.04}\right) \qquad (1)$$

Regions with a high seasonality of rainfall are shown in Figure 15.

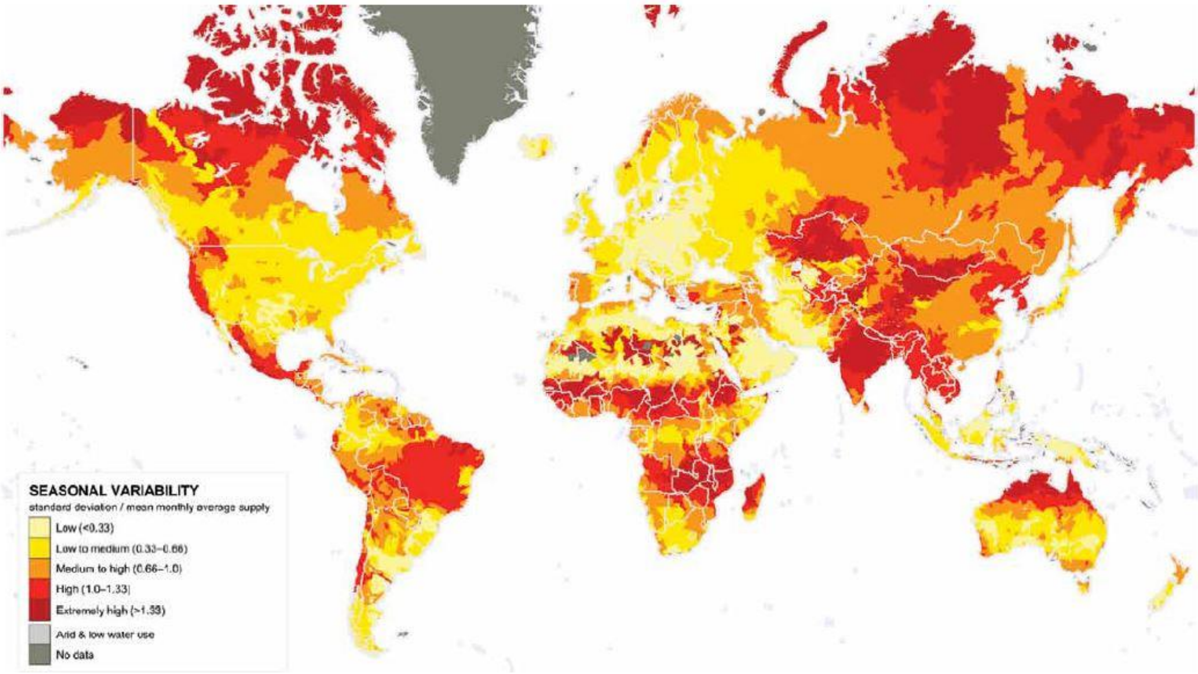


Figure 15: Map of seasonal variability of precipitation globally (calculated for a time period of 1950-2008) (Gassert et al., 2013)

Flooding

High rainfall often leads to (overland) floods; especially in areas where the surface has low infiltration capacity. These concerned regions are for example monsoonal, fully humid, hot arid or even warm temperate regions, as will be seen in the chapter on case studies. In flooding regions, the use of MAR could store the excess storm water and reduce freshwater runoff loss to the oceans. These regions can be identified with the global flood analyzer of the World Resources Institute (Winsemius & Ward, 2015). Regions that are vulnerable to floods and have seen flood occurrences in the past are shown in Figure 16.

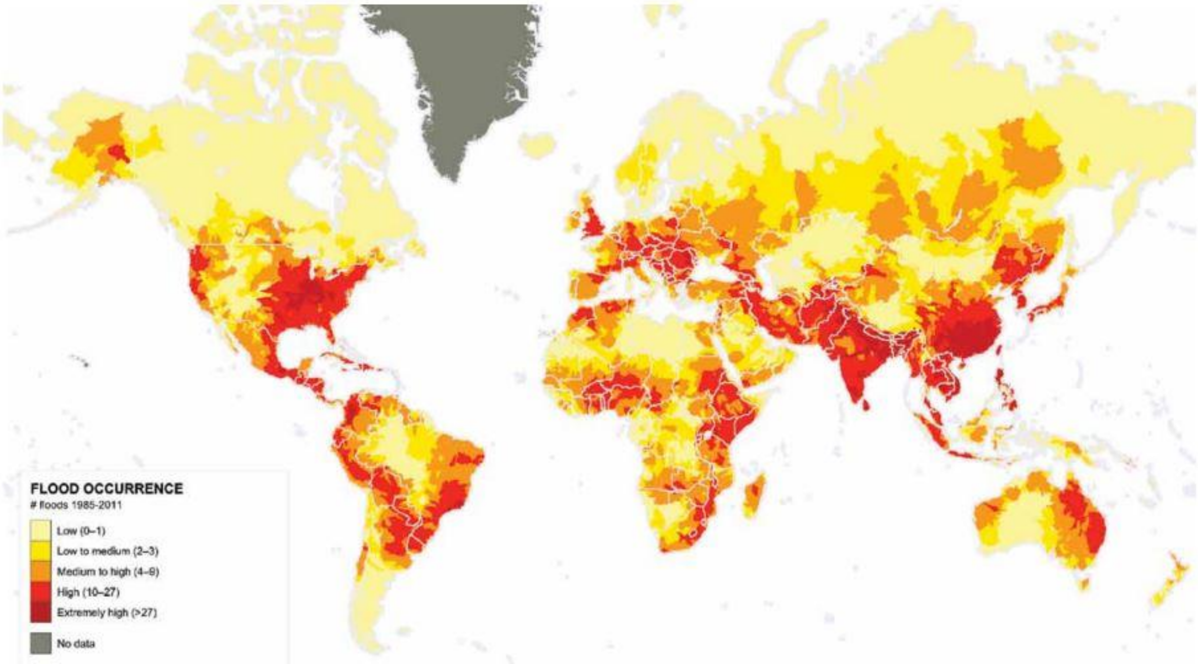


Figure 16: Map of flood occurrences globally from 1985-2011 (Gassert et al., 2013).

High evaporation

In regions with high evaporation, open surface water storage will lose large amounts of water through evaporation. Underground storage does not have this problem; therefore, MAR in regions with high evaporation rates will prevent evaporation loss and is therefore preferable.

Drought vulnerable

During drought, higher rates of groundwater abstraction can be expected. Therefore, drought triggers an increase in water demand. This can lead to famine and migration of people and livestock (Vrba & Verhagen, 2006). For ecosystems, degradation and desertification can be a consequence of drought. MAR can create a buffer capacity for droughts. A global map of drought severity is shown in Figure 17.

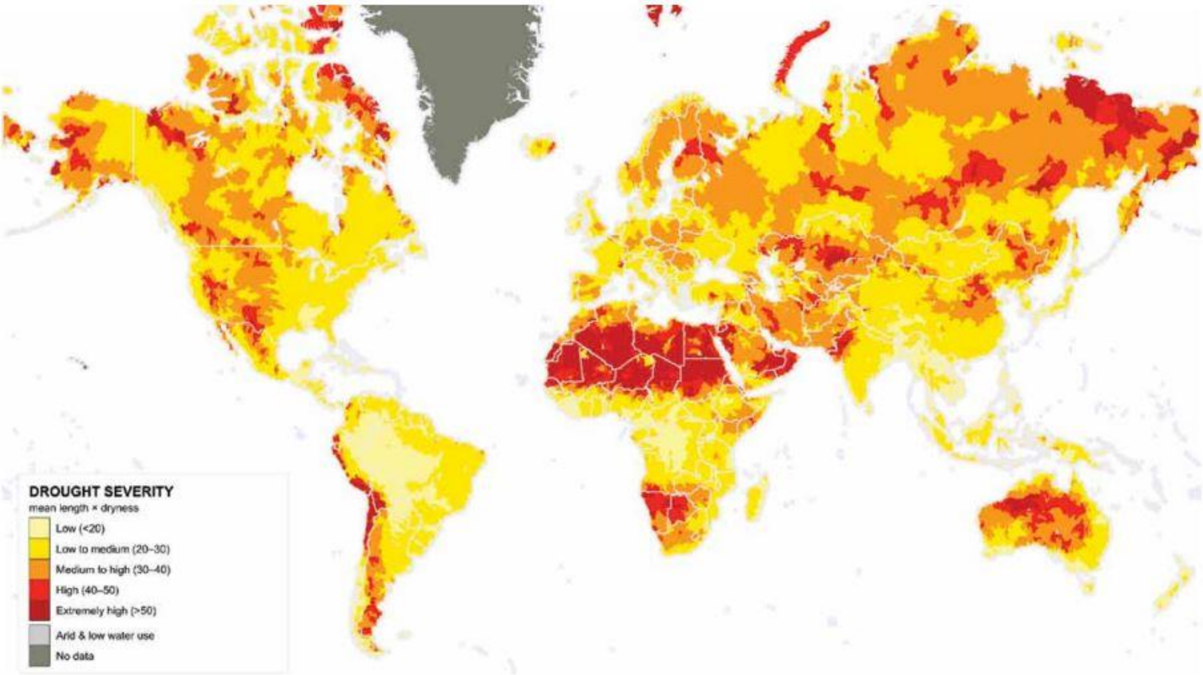


Figure 17: Global drought severity map (calculated in time frame 1901-2008) (Gassert et al., 2013)

Regions, where drought and floods occur more often than in other areas, are often linked to the El-Nino-Southern Oscillation (ENSO) (Vrba & Verhagen, 2006; Ward et al., 2014).

Over-exploited aquifers

Especially regions with over-exploited aquifers have a need for managed aquifer recharge (Dillon et al., 2012). These regions can also be called 'groundwater stressed', as withdrawals exceed replenishment (Gassert et al., 2013). In a global study, Gleeson et al. (2012) described, by use of the groundwater footprint, the over-exploited aquifers in the world, shown in Figure 18. Most of these aquifers are not bound by country borders, they are transboundary. Irreversible loss of storage can be a constraint for practicing MAR in over-exploited aquifers. When groundwater is abstracted at high rates, irreversible loss of storage can be a consequence (de Graaf et al., no date). The pore space which is in the 'normal' state filled with water, can be compacted. This has as direct result loss of pore space and subsidence. If the storage is lost, groundwater storage becomes difficult.

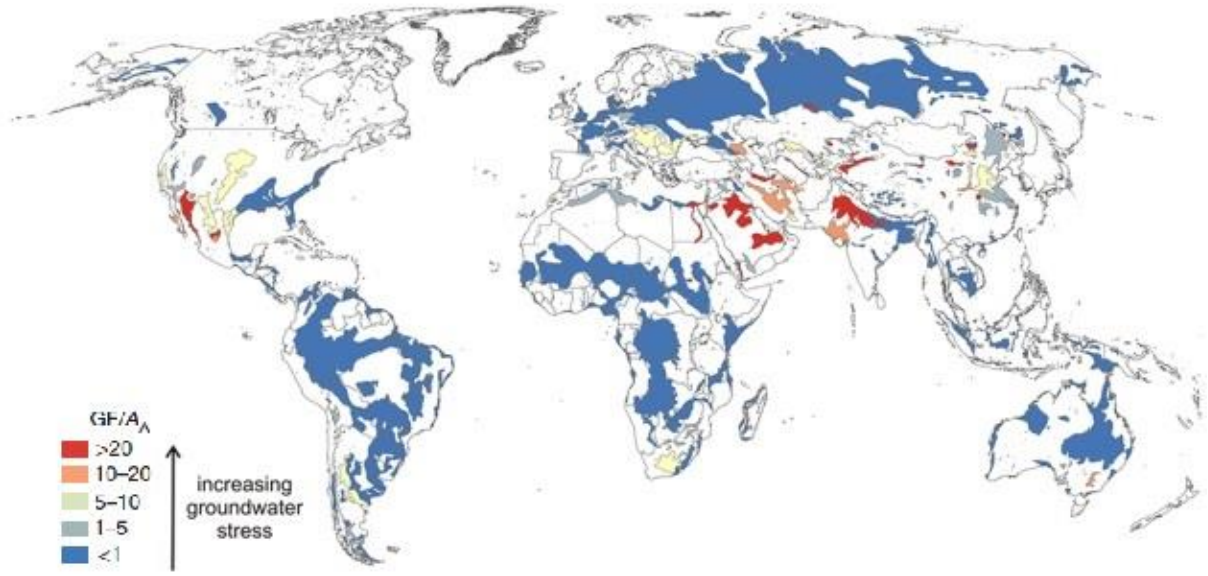


Figure 18: Groundwater footprint (GF) of aquifers worldwide (Gleeson et al., 2012). Groundwater footprint divided by the aquifer area, GF/Aa, gives an indication of the possible over-exploitation. Aquifers with GF/Aa>1 are being over-exploited. On the map, this is about 20% of the aquifers.

Land subsidence

One of the main reasons for land subsidence is high groundwater abstraction. High abstraction rates can lead to lowered fluid pressures and can then lead to compaction of the soil materials (Konikow, 2011). Especially organic-rich materials, in combination with micro-bacterial oxidation, will subside after lowered groundwater levels (Mount & Twiss, 2005). With MAR, groundwater levels can be raised and land subsidence can be halted. A global land subsidence map has not been produced yet but is currently developed by Deltares (H. Kooi, personal communication, July 11, 2016).

Salinization of groundwater

MAR can be an efficient technique to prevent saline groundwater intrusion. In saline groundwater environments, the fresh water lens on top of saline groundwater often increases in the winter and decreases in summer as abstraction rates increase (Tuinhof et al., 2012). If the saltwater reaches the root zone, it can damage crops and ecosystems. By recharging, a buffer against salinization is created and salinization can be prevented (Delsman et al., 2015). No global map on saline groundwater intrusion is available.

4.7 Locations with need for MAR: Cities

Data on the importance of freshwater provision for large cities are provided by McDonald et al. (2014). The growth of urban areas will experience water stress to cities as water supply doesn't hold up with the increasing demand. In Figure 19, a world map with ground and surface water-stressed cities can be seen. Cities with groundwater stress might especially be in need for MAR in order to alleviate the stress. However, cities with surface water stress might find MAR an option for water supply. Tables with both groundwater stressed and surface water-stressed cities, summarized from McDonald et al. (2014), can be found in Appendix B and Appendix C.

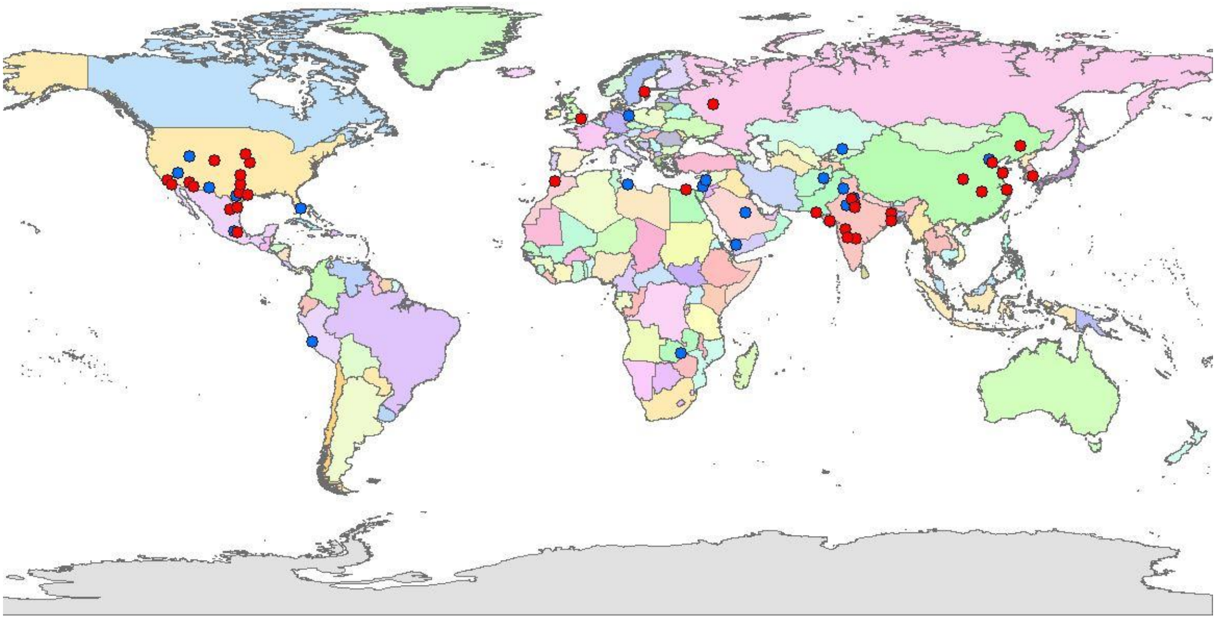


Figure 19: cities (with more than 750.000 people) with water stress adapted from McDonald et al., (2014).Blue dots are groundwater stressed cities and red dots are surface water stressed cities

Assuming that there is a higher need for storage in arid climates than in humid ones, where the opportunities for natural recharge are greater, MAR is most desired in arid and semi-arid countries (Dillon et al., 2012). Not only abundance, also seasonality of rainfall can play a role. This is because

MAR is often inter-seasonal storage. In Figure 21 and Figure 22, the vertical axis shows the seasonality of precipitation, with low values indicating a high seasonality and high values uniform precipitation throughout the year. The horizontal axis shows the aridity index, with low values indicating arid climates and high values humid climates. Cities in locations with high seasonality of rainfall (low values on the y-axis) and low water availability (low values on the x-axis) have the highest favourability for MAR, according to the theory of Dillon et al. (2012). Cities that fulfill this requirement can be seen in the lower left corner of Figure 21 and Figure 22.

Regions with high rainfall (>1000 mm) in combination with river basins with high water stress (baseline water stress index >3) can be seen in Figure 20 . These are regions with abundant precipitation however still high water stress. MAR is not widely practiced in those regions.

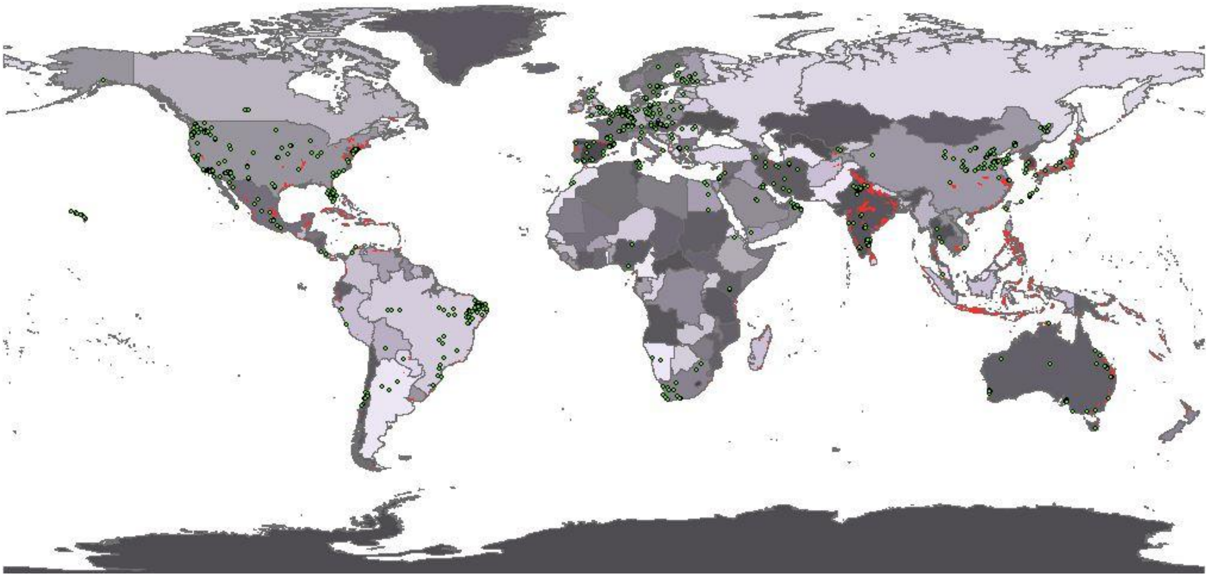


Figure 20: Map of areas (in red) with high rainfall in combination with high water stress. The green dots are current MAR projects. A full-size image of this map can be found in Appendix L.

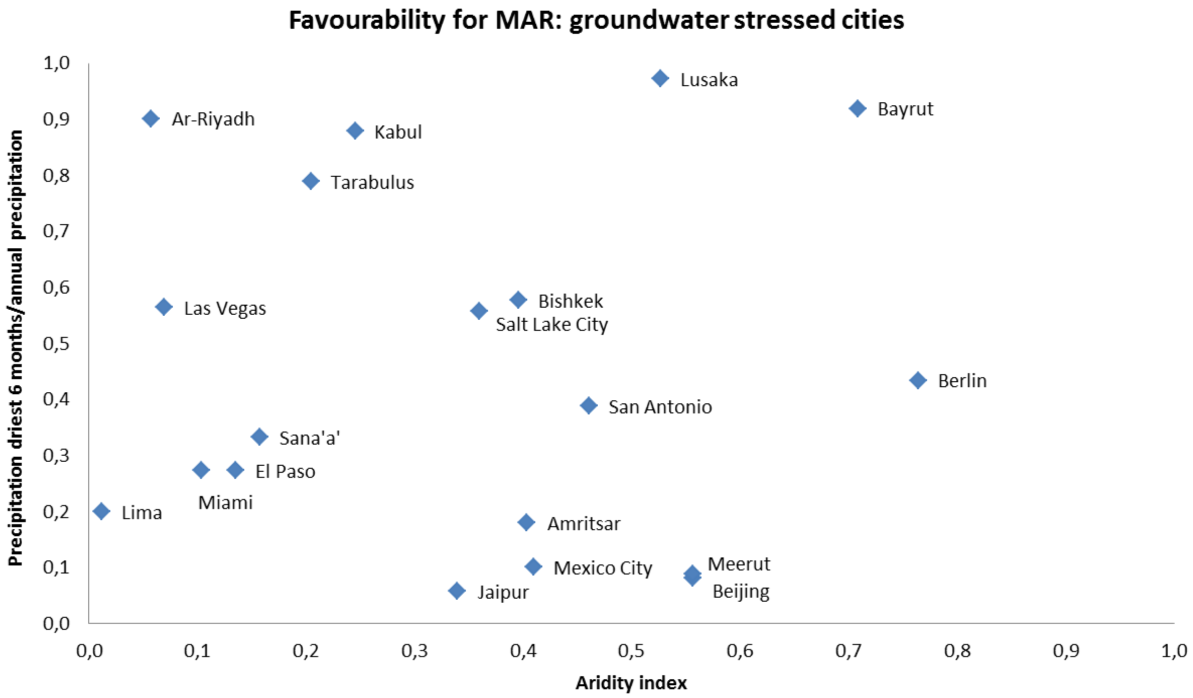


Figure 21: Climatic indicators of favourability for MAR of stressed groundwater cities

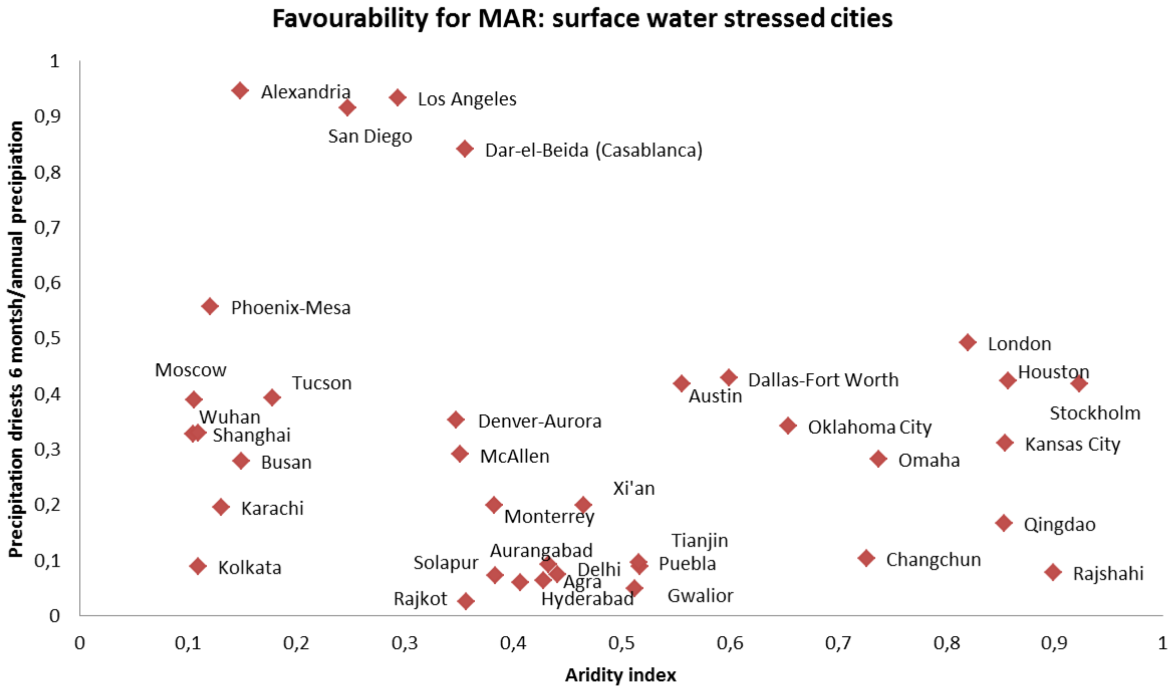


Figure 22: Climatic indicators of favourability for MAR of stressed surface water cities

5 Second step: overview of available MAR techniques

The seconds step consists of a historical overview and a state-of-the-art overview of the available MAR techniques.

According to the classification made by Gale (2005), there are 5 typical methods for MAR: spreading methods, recharge by well, shaft and boreholes, induced bank filtration, in-channel modifications and runoff harvesting. These types of methods and their sub-types will be described. In total 14 sub-types of MAR are described. Runoff harvesting is incorporated in spreading methods, as primarily the source water is the only difference. Spreading methods, well infiltration and induced bank infiltration have as a goal to infiltrate the water, whereas in-channel modifications and runoff harvesting are designed to first intercept the water, and then infiltrate.

5.1 History of MAR techniques from literature

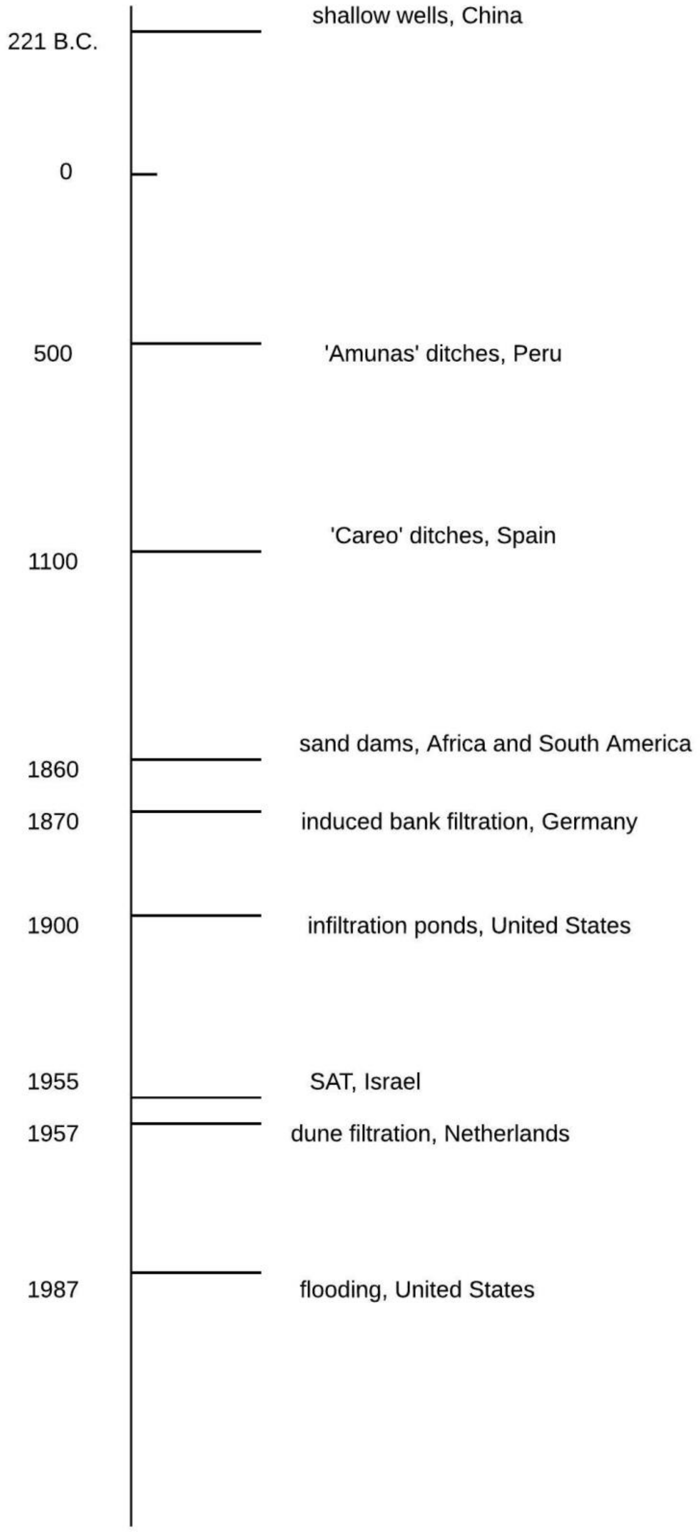


Figure 23: historical timeline of first use of MAR techniques, from literature

'Amunas' are probably the oldest notion of infiltration channels, from the 500 to 1000 A.D. in Peru, made by the Wari (a pre-Inca civilization) as water supply and runoff control. These were in fact infiltration channels which recharge the aquifers of the Andes (Gammie & De Bievre, 2015). These infiltration channels still exist and might be revived in order to aid Lima's current water crisis (Pierce, 2015)). Gammie & De Bievre (2015) showed the large and cost-effective benefits the restoration of Amunas can bring. In the 11th century in Spain, careo (infiltration channels), were created by the Arabs in the highest part of the Sierra Nevada (MEMOLA, 2014). The channels infiltrated water during peak flows to the aquifer so that in spring the base flow from the river originating partly from the aquifer was more constant. The channels were part of a larger, complex system, created for irrigation. The studies carried out by MEMOLA, were to maintain the traditional careo systems. Sand dams have a long history, in Africa but also for at least since 1860 in South-America (Maliva & Missimer, 2012). River bank filtration (RBF) in the lower Rhine has been practiced since 1870, which is probably the earliest practice of RBF (Schubert, 2002). In California, U.S., around 1900, infiltration ponds for storm runoff started to be used and this artificial recharge technique was widely used around the 1930s (Weeks, 2013). In Australia, the longest operating and still largest (up to 45 Mm^3/yr) groundwater infiltration basin was created in the 1960's on the Burkedin Delta (Dillon et al., 2009b). The earliest notice of SAT found is SAT in Israel, which was started in 1955 (Pervin, 2015). Dune infiltration has at least been practiced in Europe and the United States since the 1960's (Missimer et al., 2011). In the Netherlands, Amsterdam has been provided with dune filtrated water since 1853 (Van Der Meulen & Wanders, 1985). From 1957, these infiltration channels have been recharged with river water, as the quantities of rainwater could not hold up with the demand of Amsterdam. Flooding was the last MAR technique that was found in literature as indicated as aquifer recharge method. Dokoozlian et al. (1987) found that flooding as recharge technique in vineyards in the San Joaquin Valley in California, US was a viable recharge method.

5.2 History of MAR techniques in case studies

MAR projects with starting years from 1810 to 2015 are present among the 894 case studies used in Step 4 (Chapter 7) from IGRAC (IGRAC, 2016a). When the case studies (MAR projects) were first noticed is shown in Table 9.

MAR techniques	starting year data	starting year literature
ASR/ASTR	1880	-
Barriers & Bunds	1940	-
Channel Spreading	1965	-
Ditch & Furrow	1979	500
Dug Well/ Shaft/ Pit Injection	1951	221 B.C
Excess Irrigation	1875	-
Flooding	1911	1987
Induced Bank Filtration	1810	1870
Infiltration Ponds & Basins	1883	1900
Recharge Dam	1939	-
Reverse Drainage	1980	-
Sand Storage Dams	2007	1860
Trenches	1978	-
SAT	-	1955
Dune filtration	-	1957

Table 9: second column: First notice of MAR techniques from the used cases from the geodatabase from IGRAC, third column, first notice of MAR techniques from literature.

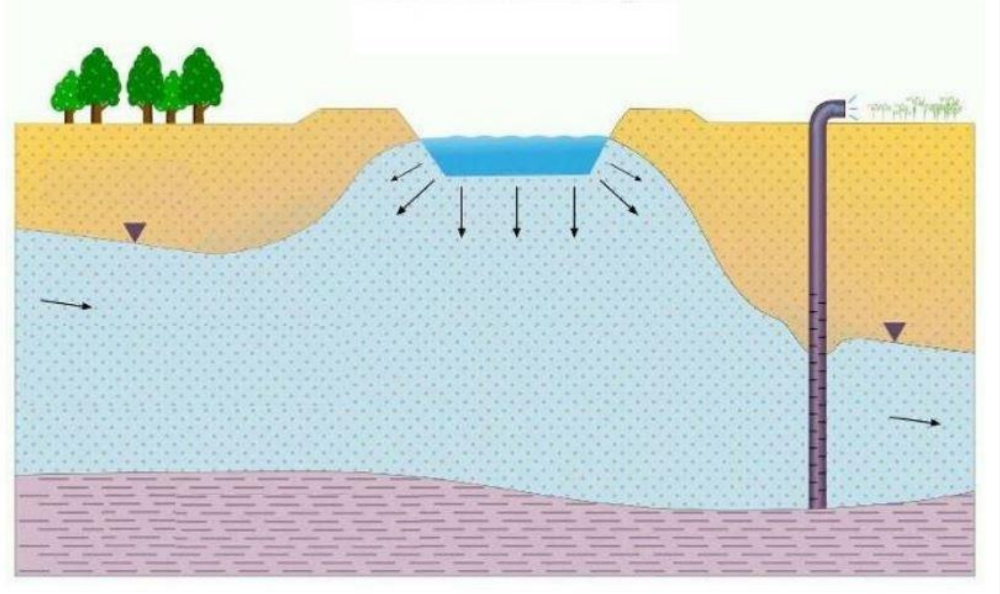
Flooding, induced bank filtration and infiltration ponds all have earlier MAR projects noticed in the case studies than found in the literature, see Table 9. Ditch and furrow, dug well/shaft/pit injection and sand storage dams have earlier MAR projects noticed in the literature than in the case studies.

5.3 Spreading methods

Water spreading methods are techniques that directly infiltrate water at the surface into the subsurface through spreading. Spreading methods are the most simple and most used MAR technique (Maliva & Missimer, 2012). Several hydrogeological conditions are required. They require a highly permeable surface (Central Ground Water Board, 2007; Gale, 2005). Also, the vadose zone has to be free of low permeable layers in order to prevent perched groundwater conditions. Furthermore, it is essential that the water table should not be too high, in order to prevent the rising water table after infiltration to reach the surface. If however, the water table is too deep, water might never reach the aquifer (Central Ground Water Board, 2007). Finally, the aquifer should be unconfined (Central Ground Water Board, 2007).

One of the most acknowledged problems with spreading methods is the issue of clogging. This results from the formation of an organic-rich layer or a deposition of suspended sediments on the land surface (Maliva & Missimer, 2012). Clogging rates can be made much lower when the water is treated before infiltration.

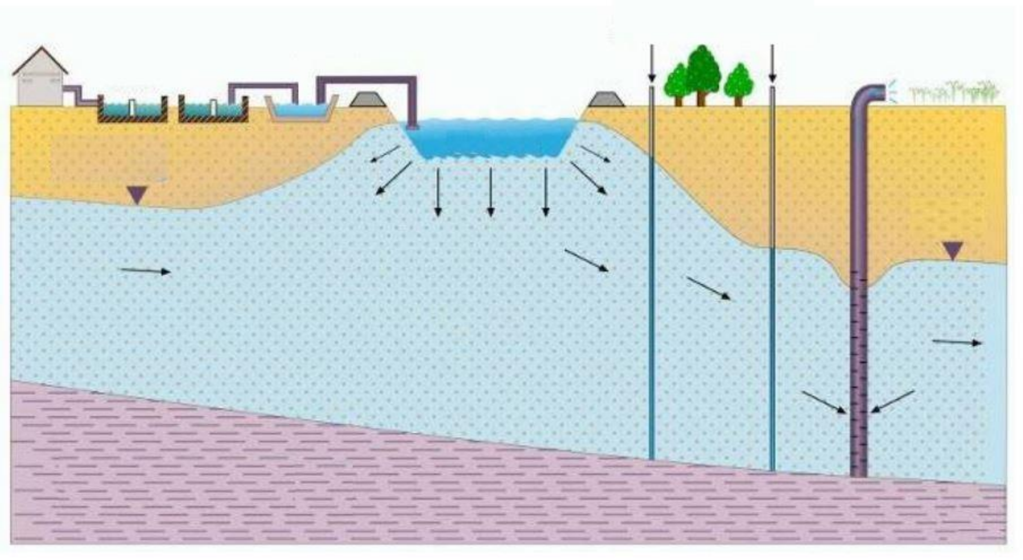
Infiltration ponds

synonyms	infiltration basin, retention pond, wet pond, spreading basin
schematic image	 *Figure 24: schematic image of an infiltration pond (Escalante, 2010)*
description	Infiltration ponds can be ponds surrounded by levees or dikes but can also be excavated in the surface. The source water is retained in the pond until it has infiltrated through the floor of the pond (Maliva & Missimer, 2012). If these infiltration ponds are placed within ephemeral streams in monsoon regions, the monsoon flow can be captured to recharge the aquifer. The widely used term for this in India is 'percolation tanks' (Dillon, 2005; Maliva & Missimer, 2012).
capacity	Ranging from small to large (up to 45 Mm^3/yr) (Dillon et al., 2009b). In Israel, a current research project had infiltration rates of 5000 m^3/hr of desalinated seawater (MARSOL, 2016).
Costs	MAR surface infiltration techniques in Spain which included infiltration ponds and infiltration channels, had an average cost of 0.23 USD/m^3 (Escalante et al., 2014).
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	Essential procedures: According to Gale (2005), in order to prevent or halt clogging and keep up infiltration rates it is necessary to have infiltration ponds change between filled and empty (wet and dry). For infiltration ponds that use stormwater, this happens automatically. If this is not the case, larger basins could be divided into smaller cells, so that some can be filled while other dry. Necessary information for designing infiltration ponds is that the shape of infiltration

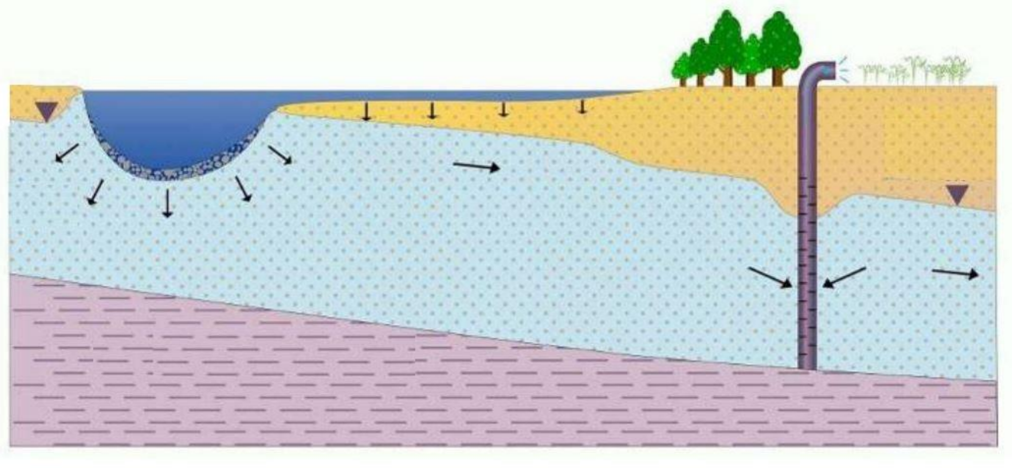
pond affects the hydrologic response of the aquifer (Gale, 2005). Specific shapes (circular/rectangular) can be desirable for different conditions.

Advantages include the easy maintenance and simple anti-clogging measures for the infiltration system (IGRAC, 2007; Tuinhof et al., 2012). Constraints are the large land area required, the potential for surface water diseases and the potential high evaporation.

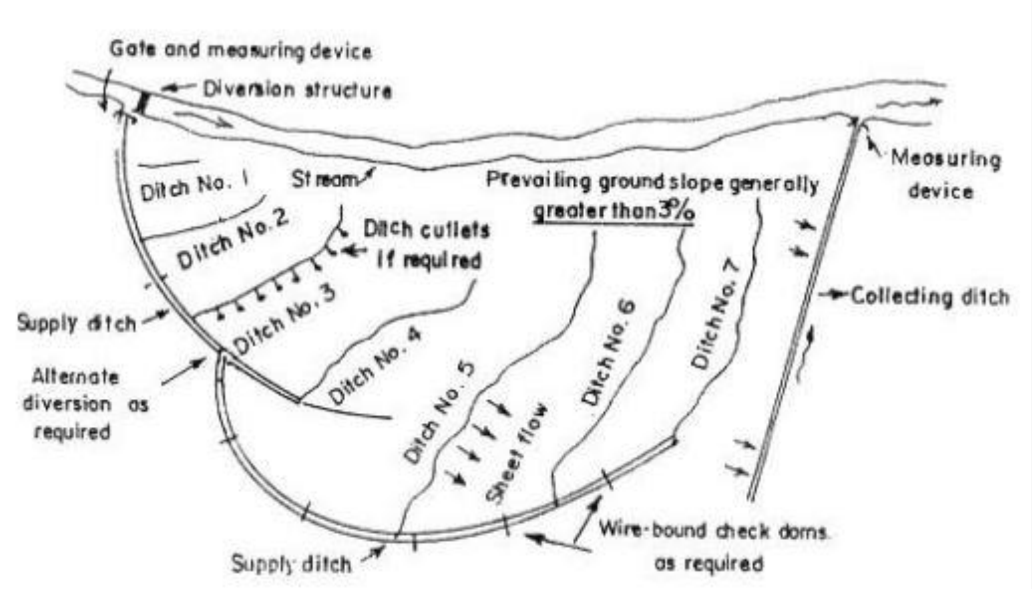
Soil aquifer treatment (SAT)

synonyms	SAT is a type of infiltration pond
schematic image	 *Figure 25: schematic image of an SAT system (Escalante, 2010)*
description	The technique for using reclaimed (treated) wastewater in infiltration ponds is called 'soil aquifer treatment' (SAT) (Dillon, 2005). SAT works well for removal of pathogens and nutrients. Essential in design for SAT systems is that the infiltrated water is well controlled between infiltration and recovery so that the groundwater is not contaminated. As said before, the reclaimed water should be treated before infiltration on suspended solids to prevent clogging.
capacity	The capacity of SAT systems is relatively small compared to normal wastewater treatment plants and land requirements can be large (Gale, 2005). One of the largest SAT plants in the world is operated in Israel, having an infiltration capacity of 110-130 Mm^3/yr (Wolf et al., 2007).
costs	SAT systems are a relatively simple and low-cost water treatment method (Gale, 2005).
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	For the infiltration part, the same advantages and constraints as for 'normal' infiltration pond systems.

Flooding

synonyms	Infiltration fields
schematic image	 *Figure 26: schematic image of a flooding system (Escalante, 2010)*
description	Water is at low velocities thinly spread on the surface (Maliva & Missimer, 2012).
capacity	Not available
costs	Flooding is the MAR method with the lowest costs (Central Ground Water Board, 2007).
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	Constraints are that a large land area is required, the potential for surface water diseases and the potential for high evaporation (IGRAC, 2007; Tuinhof et al., 2012).

Ditches, furrow, and drains

synonyms	Infiltration channels, channel infiltration, reverse drainage, trenches, soakaways, infiltration gallery, trenches
schematic image	 *Figure 27: Schematic image of an example ditches and furrows infiltration system (Central Ground Water Board, 2007).*
description	Water is distributed through shallow, closely spaced ditches/trenches/furrows. The ditches/trenches can also be filled with coarse gravel to reduce water velocity to increase infiltration (Maliva & Missimer, 2012). Perforated drainage pipes can be added to enable water infiltrating into the soil. Trenches are often combined with check dams and ‘barriers and bunds’ see paragraphs on ‘recharge dams’ and ‘barriers and bunds’.
capacity	**-**
costs	0,1-0,3 USD/m^3 (IGRAC, 2007).
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	An advantage of ditches/trenches is that more water can be infiltrated than with flat surfaces, as the vertical walls create a larger wetting area (Gale, 2005). The vertical walls experience also fewer issues with clogging, as sediments do not settle well on vertical surfaces. When using drains, an advantage is that there is no interference with land use (IGRAC, 2007; Tuinhof et al., 2012). Ditches however, can have a large interference with land use and have a potential for surface water diseases. Companies have also designed trench systems that are filled with other materials

than gravel. For example, Bekele et al. (2009) showed, using the Atlantis® Infiltration Tank System that although capital costs are higher, O&M costs are lower. Also, the change for clogging was reduced, water quality was improved before infiltration in the soil and the infiltration rates were higher. Looking at these more sophisticated systems might, therefore, be worthwhile.

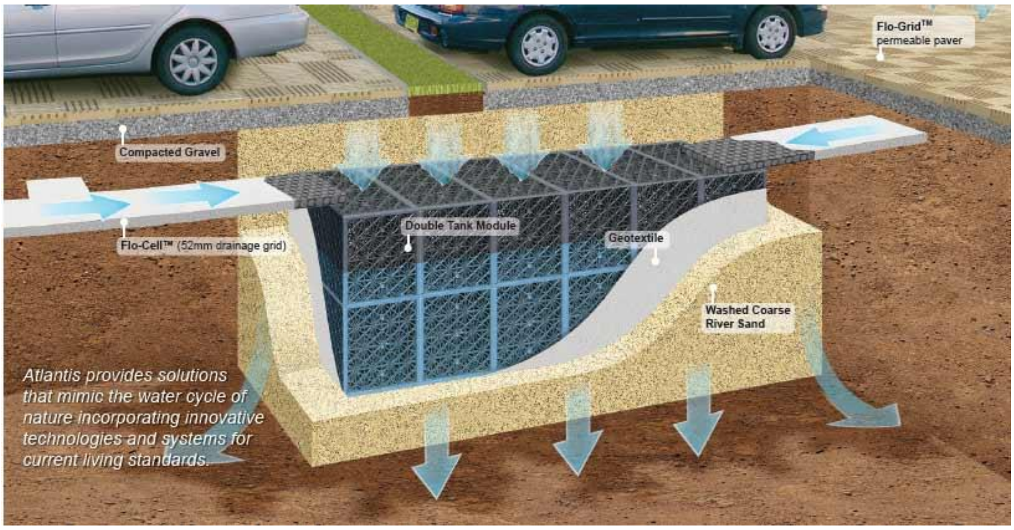
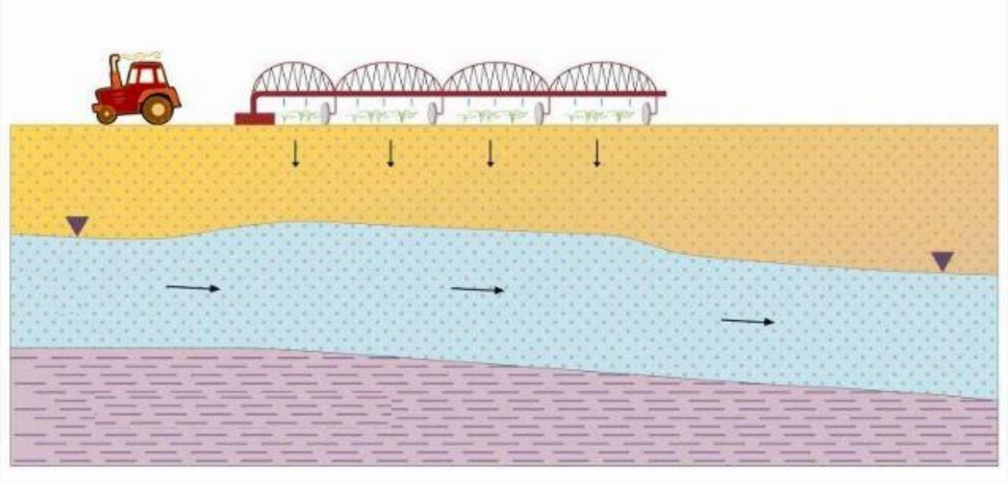
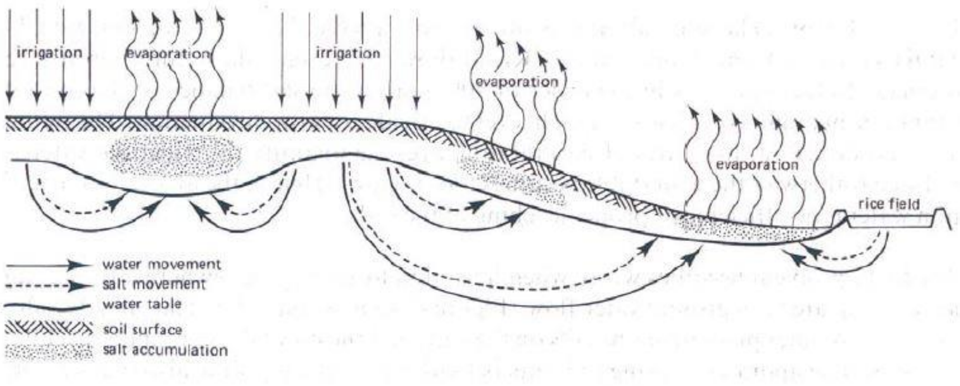


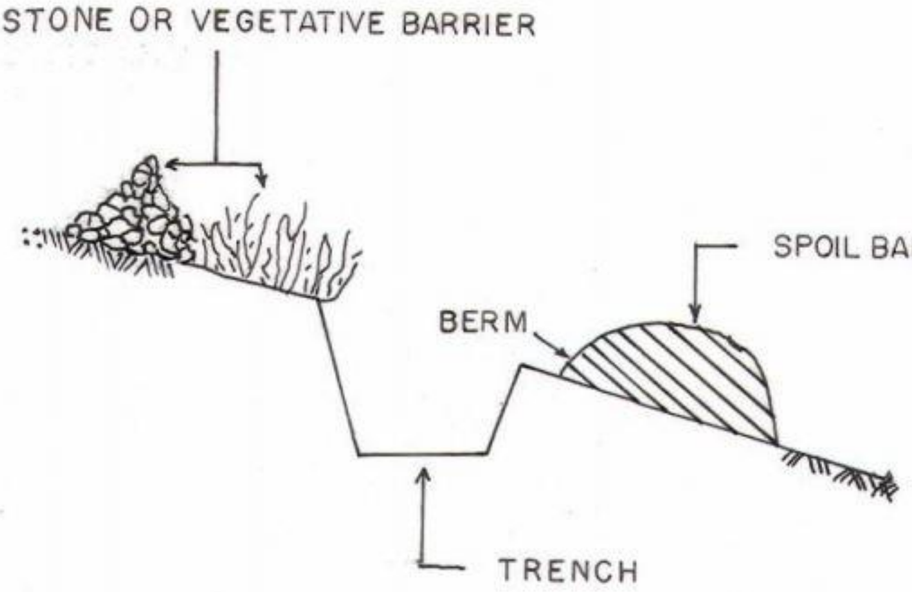
Figure 28: The Atlantis Flo-tank storm water capture system (Atlantis, 2014)

Good examples of controlled drainage in areas with saline seepage, to prevent the capillary rise of the saline water, are the Drains2buffer system, collector drains, the Freshmaker and creek ridge filtration (Delsman et al., 2015).

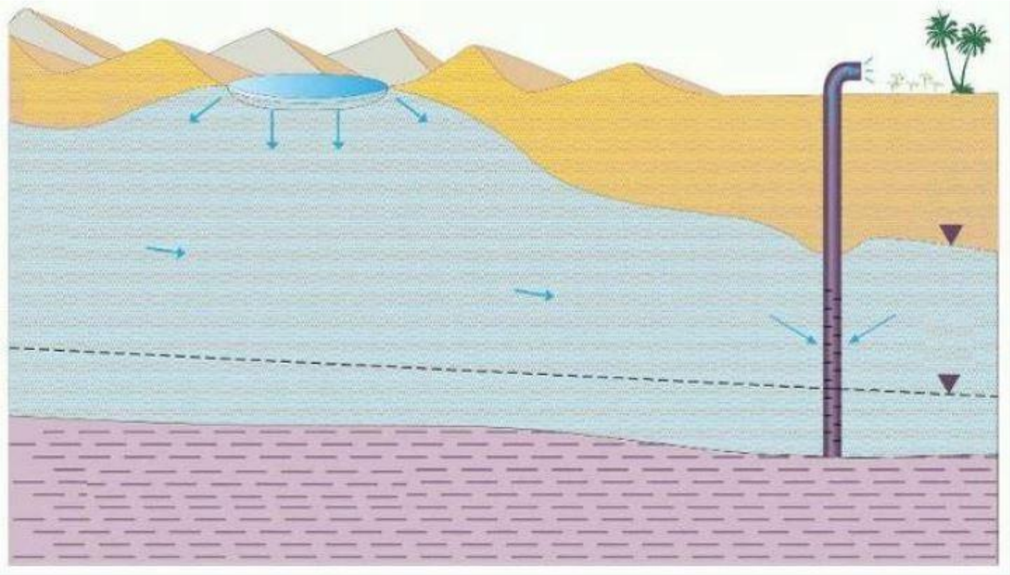
Excess irrigation

synonyms	-
schematic image	 *Figure 29: schematic image of excess irrigation (Escalante, 2010)*
description	On purpose, more irrigation water will be distributed than required to saturate the root zone (Maliva & Missimer, 2012). Excess irrigation water will be percolated to the aquifer when the unsaturated zone becomes saturated.
capacity	Not applicable
costs	Not applicable
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	The main threat for aquifers is salt leaching from the soil, which travels with percolation to the aquifer (Oosterbaan, 1988). Salt leaching can degrade the aquifer water quality. Related to this phenomenon are two well-known issues for agriculture with excess irrigation; waterlogging and salinization. Waterlogging in agriculture is the issue that the water table is too high to grow crops. Waterlogging prevents the salts in the soil from leaching which can result in an accumulation of salts in the soil. Groundwater flow can also enhance the problem of salinization, as is shown in Figure 30.  *Figure 30: Salinization of the soil enhanced by groundwater flow.*

Barriers and bunds

synonyms	Contour bunds
schematic image	 *Figure 31: Schematic image of barriers and bunds, combined with trenches (Bhalerao & Kelkar, 2013).*
description	Structures to obstruct the overland flow, slow downstream velocities and therefore infiltrating the water into the soil. This is a method of runoff harvesting that is made for water retention of (Hortonian) overland flow (Maliva & Missimer, 2012).
capacity	Relatively small quantities (IGRAC, 2007; Tuinhof et al., 2012).
costs	0,1-0,3 USD/m^3 (IGRAC, 2007)
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	Rainfall in the region is preferably less than 1000 mm/yr (Central Ground Water Board, 2007). Main advantages are seen in the simple design, operation and maintenance, and the capabilities in preventing soil erosion (IGRAC, 2007; Tuinhof et al., 2012).

Dune filtration

synonyms	Inter-dune filtration
schematic image	 *Figure 32: schematic image of dune filtration (Escalante, 2010)*
description	If water is infiltrated by infiltration ponds, flooding or ditches in dunes, the technique is called dune filtration (Dillon, 2005; Maliva & Missimer, 2012). When reclaimed water is used, it can also be called 'soil aquifer treatment' (SAT), see paragraph on SAT.
capacity	Dune filtration for Amsterdam filters 70 Mm^3/yr, on a dune area of 3400 ha (Waternet, 2016). A groundwater recharge plant in the Veurne region, Belgium, has an infiltration capacity of 2,5 Mm^3/yr per year using wastewater as source water (Van Houtte & Verbauwhede, 2008). The water is infiltrated by using an infiltration pond of 18000 m^2.
costs	-
aquifer type	Sandy unconsolidated, alluvium, sandstone, carbonate aquifers
additional information	In the filtration dunes for Amsterdam, the water has a minimal residence time in the soil of 60 days (Natuurwegwijzer.nl, 2016).

5.4 Well, shaft and borehole recharge

With well, shaft or borehole recharge methods water is infiltrated into an aquifer at a deeper level than the surface. The most primary method is deep well infiltration, where the water is directly infiltrated into the aquifer (Gale, 2005). Usually, the reason for this is that an impermeable layer, often a clay layer, lies above the aquifer. AS(T)R can be performed under gravity or under pressure (Maliva & Missimer, 2012).

Well, shaft or borehole recharge methods are the preferred MAR technique for regions with specific hydrogeological conditions. These conditions are 1) where low permeability strata are present above the aquifer, 2) for confined aquifers, 3) where the water table is far below the land surface and 4) where surface infiltration suffers from high evaporation loss (Maliva & Missimer, 2012). Where lateral flow is not confined, the use of horizontal flow barriers might be an option in order to create a confined aquifer system (Maliva & Missimer, 2012). Apart from hydrogeology, another condition is related to land availability. In regions where surface spreading is not feasible due to land availability, for example due to contaminated land or high land costs, well, shaft or borehole recharge methods are preferred (Maliva & Missimer, 2012).

Drawbacks are clogging (mechanical, gas-air binding, chemical precipitation and biological growth). These processes fill the pore space thus reduce hydraulic conductivity (Bouwer, 2002). Therefore, the source water should be of adequate quality, preferably close to native aquifer quality (Maliva & Missimer, 2012). Other factors that determine the performance of injection wells beside the source water quality are design and operation and a rehabilitation program. An institutional barrier for well, shaft or borehole recharge methods is regulation. Regulation is usually stricter for wells than for surface infiltration (Maliva & Missimer, 2012).

Aquifer storage and recovery (ASR)

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 well infiltration.

schematic image

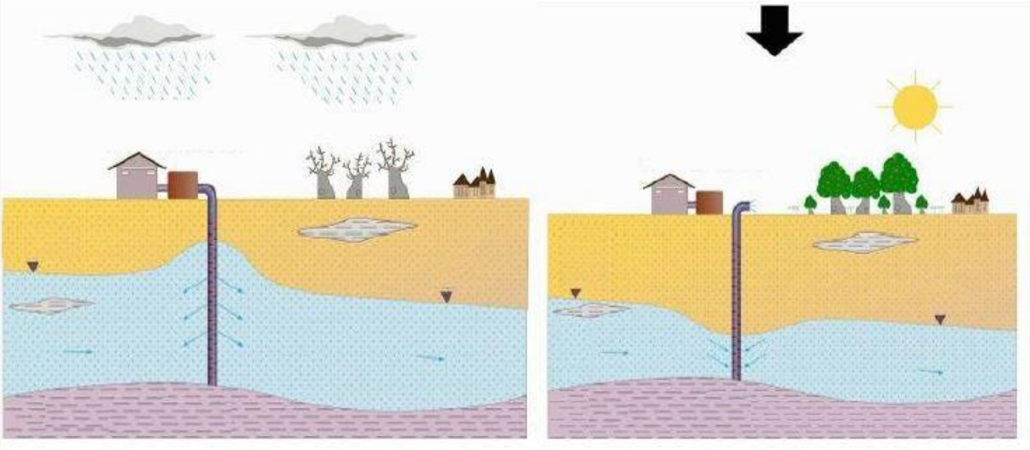


Figure 33: schematic image of an ASR system with infiltration during wet periods and abstraction in dry periods (Escalante, 2010)

description

With this technique water in injected and recovered from the same well (Gale, 2005).

capacity

An ASR system at Parafield, Australia, by using stormwater as source water, has an abstraction up to 2.1 Mm^3/yr (IGRAC, 2007). The injection rate is 35l/s, and the stormwater catchment is 1600 ha.

aquifer type

Limestone, and usually deep and clay covered aquifers

costs

ASR is a relative expensive MAR technique; however, it has lower costs than ASTR, as only one well is required, see paragraph 5.2.2 on ASTR (Escalante et al., 2014; Maliva & Missimer, 2012). Also, costs per m^3 stored are usually lower than for surface storage.

Costs of ASR in Spain are shown in Table 10 (Escalante et al., 2014).

Well depth (m)	**Capital cost (USD)**	**Cost over lifetime USD/m^3**
50	192.900	0.26
500	648.500	0.65

Table 10: costs of shallow and deep ASR wells

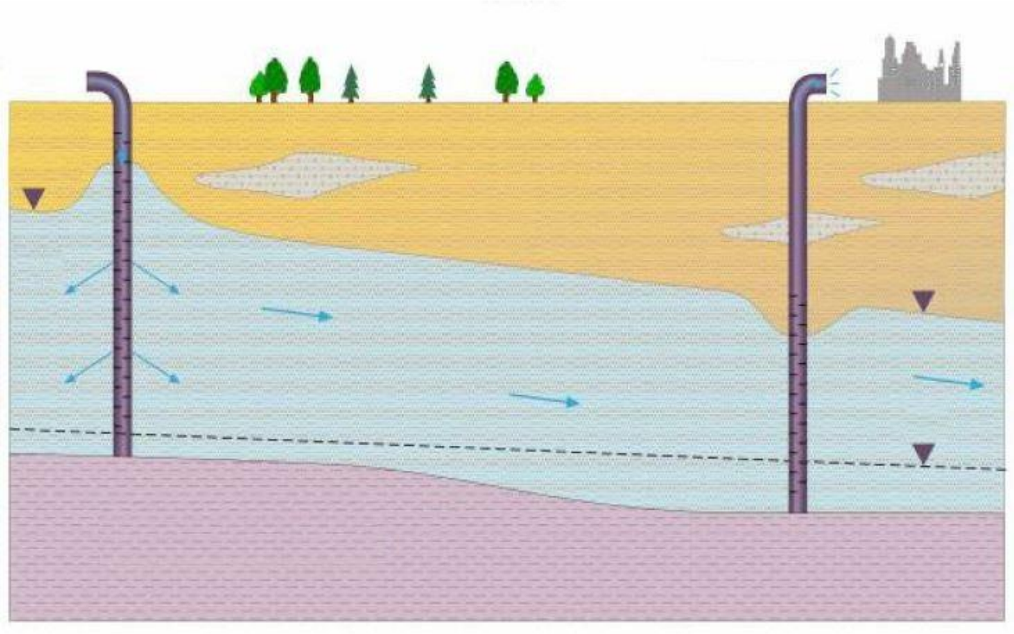
For the Parafield ASR system, see 'capacity', costs were USD 2.9 million. (well depth 160-180m).

additional

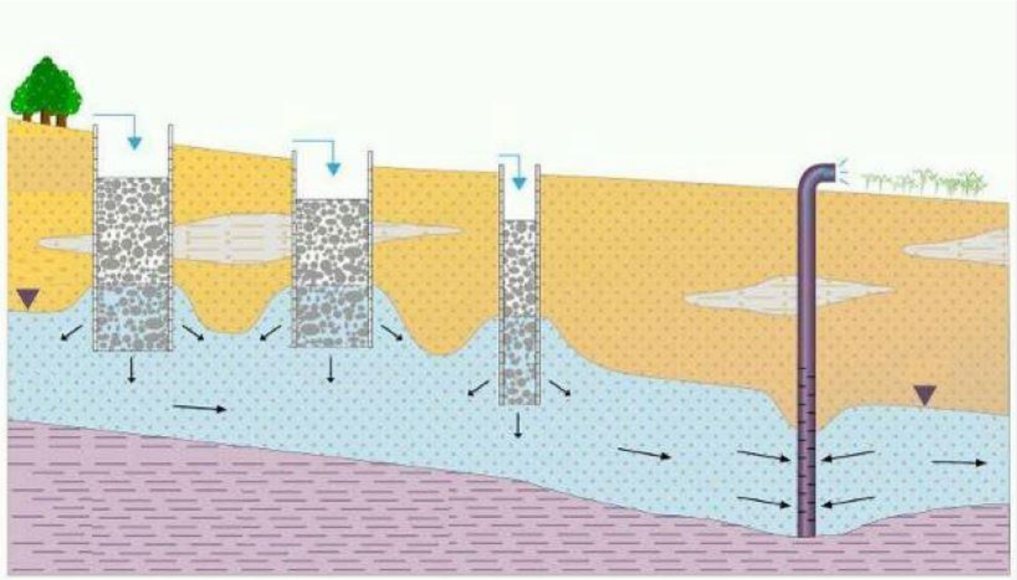
Most of the ASR wells in the world provide seasonal storage and therefore might work

information	well for regions with extreme rainfall events and extreme dryness (Maliva & Missimer, 2012). ASR has numerous advantages. Compared to surface storage, ASR has less: 1) land required, 2) evaporation loss, 3) contaminations (Maliva & Missimer, 2012). A main disadvantage of ASR can be a low recoverability of the stored water in the aquifer (Maliva & Missimer, 2012). Also, when recovery is an important goal, ASR should not be used for aquifers with a strong vertical or lateral gradient, as water will migrate from the well. The amount of water recovered will be much lower. More constraining factors include complex design, complex operation and maintenance (O&M), the high potential for well screen clogging, and close monitoring required (IGRAC, 2007; Schmidt et al., 2003; Tuinhof et al., 2012). The performance of ASR is mainly dependent on hydrogeology (Maliva & Missimer, 2012). There has been a large increase in the number of ASR wells in the US, between 1999 and 2009 the number of wells quadrupled. In 2009 there were approximately 1200 AR and ASR wells in the US (Environmental Protection Agency (EPA), 2016).

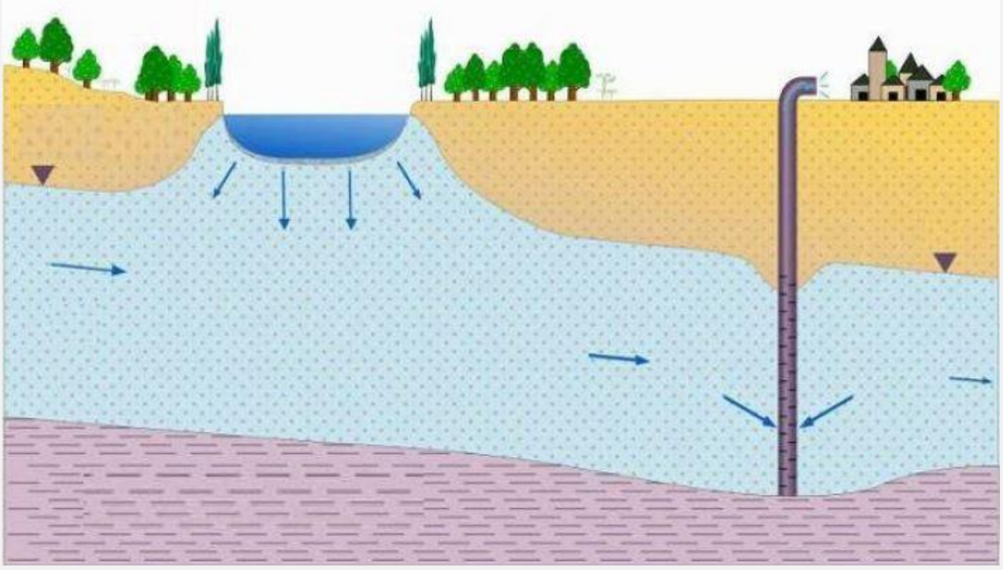
Aquifer storage transfer and recovery (ASTR)

synonyms	-
schematic image	 *Figure 34: schematic image of an ASTR system (Escalante, 2010)*
description	This technique injects water at a certain place with a well (AS, aquifer storage) and can be recovered from another well not far from the injection well.
capacity	-
costs	Similar as ASR but more costs as two wells are required and close monitoring is essential (Maliva & Missimer, 2012).
aquifer type	Limestone, and usually deep and clay covered aquifers
additional information	Monitoring is an essential aspect in the planning of an ASTR project, as infiltration and recovery rates are related (Maliva & Missimer, 2012).

Shallow well/borehole/shaft recharge

synonyms	**-**
schematic image	 *Figure 35: schematic image of shallow well shaft systems (Escalante, 2010)*
description	Shallow wells infiltrate water into shallow aquifers and unconfined aquifers. The type where recharge is above the water table is called vadose zone recharge, and does not directly infiltrate water in the aquifer (Gale, 2005).
capacity	-
costs	0,1-0,3 USD/m^3 and always lower costs than deep wells (Gale, 2005; IGRAC, 2007).
aquifer type	limestone
additional information	Vadose-zone recharge is mainly used for stormwater disposal (Maliva & Missimer, 2012). Main advantages and reasons for shallow well infiltration are that the unsaturated zone functions as a buffer zone (increased residence time) which improves quality; therefore, the source water has lower quality requirements. However, chances for clogging are higher than for deep wells and are more difficult to rehabilitate (Maliva & Missimer, 2012).

Induced bank filtration

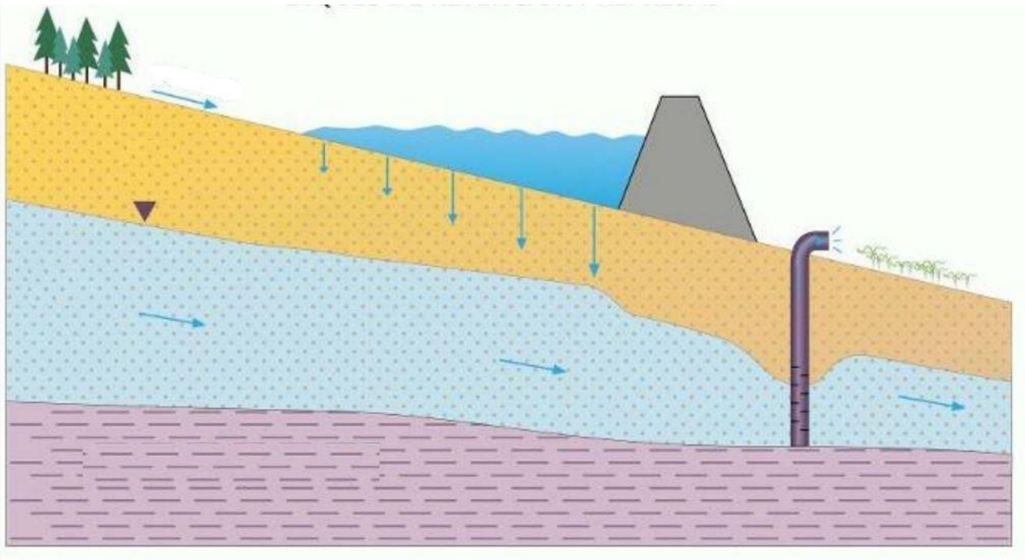
synonyms	River bank filtration, lake bank filtration
schematic image	 *Figure 36: schematic image an induced bank filtration system (Escalante, 2010)*
description	Induced bank filtration is a system where close to a surface water body, wells are installed to abstract water, therefore lowering the water pressure or water table at the lake or river bank, and therefore inducing the water to infiltrate into the aquifer between the water body and the pumping (abstraction) wells.
capacity	The Csepsel Island Bank filtration system at the Danube in Hungary, which provides 40% the drinking water for Budapest, has an infiltration capacity of 146 Mm^3/yr (IGRAC, 2007). Several studies name the large capacity of induced bank filtration as the main advantage (IGRAC, 2007; Schmidt et al., 2003; Tuinhof et al., 2012).
costs	Compared to other MAR techniques, costs are relatively high. However, costs compared to other drinking water supply methods (in Germany) can be classified as 'moderate' (Schmidt et al., 2003).
aquifer type	Sandy unconsolidated
additional information	Constraints are the complex design, complex operation and maintenance (O&M), the high potential for well-screen clogging, and close monitoring.

5.5 In-channel modifications

In-channel modifications intercept water where it runs off in order to have water retention and storage. It can in a way be seen a large-scale version of rainwater harvesting (Maliva & Missimer, 2012). This method is especially used for flooding events. In-channel modifications are MAR by enhancement of natural aquifer recharge processes. There are several structures that can be made.

Numerous studies mention underground dams/subterranean dikes/groundwater dams as a MAR technique (Escalante, 2010; Escalante & Sauto, 2012; Gale, 2005; Maliva & Missimer, 2012). However, according to the definition used for this study by Topper (2004), MAR should infiltrate water into an aquifer. This is not the case for underground dams; there is no additional recharge of water. Therefore, these dams are not further discussed in this study.

(Permeable) Recharge dams

synonyms	If the recharge dam is small (often made of earth) and permeable it is called a ‘check dam’ (Gale et al., 2006) If the recharge dam is constructed in ephemeral streams (wadies), in order to retain flood water for storage can be called a ‘wadi dam’ (Maliva & Missimer, 2012). When this water retention structure is made out of stone baskets it can be called a ‘gabion’ (Ramli et al., 2013).
schematic image	 *Figure 37: schematic image of a recharge dam (Escalante, 2010).*
description	Works as any other dam, however, the reservoir of the dam works as a percolation pond. Water can also be distributed with pipes to infiltrate at the downstream river bed (Maliva & Missimer, 2012).
capacity	Check dams (N=4) in the Gujarat province, India, have a capacity of 6400-27600 m^3 (Gale et al., 2006). The increase of recharge, at several check dam projects in India, compared to natural recharge was 2-23%. A more elaborate, worldwide, study on the increase of recharge by recharge dams was done by Renganayaki and Elango (2013). The Siwaqa dam in Jordan has an infiltration capacity of 9,3 Mm^3/yr (Wolf et al., 2007). Rates of daily recharge dependent on the water level within the dam and can be up to 1 m/day.
costs	The construction of Wadi Dams is expensive. The total capital costs can be between 250 million and 1 billion USD (Missimer et al., 2015).

aquifer type	Alluvial (Gale et al., 2006).
additional information	The major problem with small dams for aquifer recharge is that their reservoirs may accumulate sediment (Pereira et al., 2002). This can be prevented by land erosion management and sediment traps. It can also be done on purpose, creating sand dams, see paragraph 5.3.2 on sand dams. Recharge dams have been proven to be efficient in recharge, as can be seen in Figure 38.

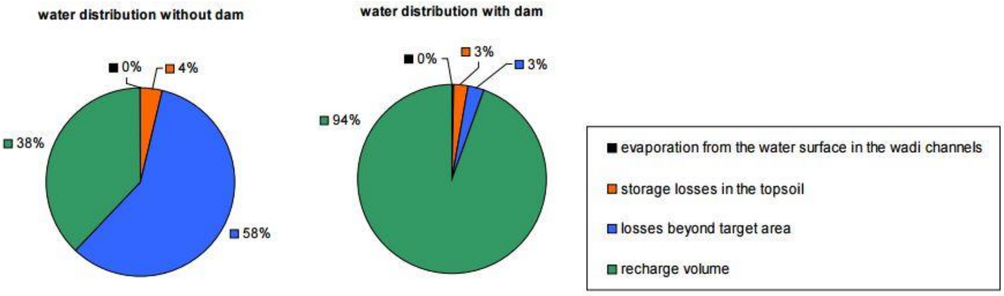


Figure 38: Recharge efficiency of recharge dams (Haimerl, 2004).

Sand dams

synonyms

Trap dams

schematic image

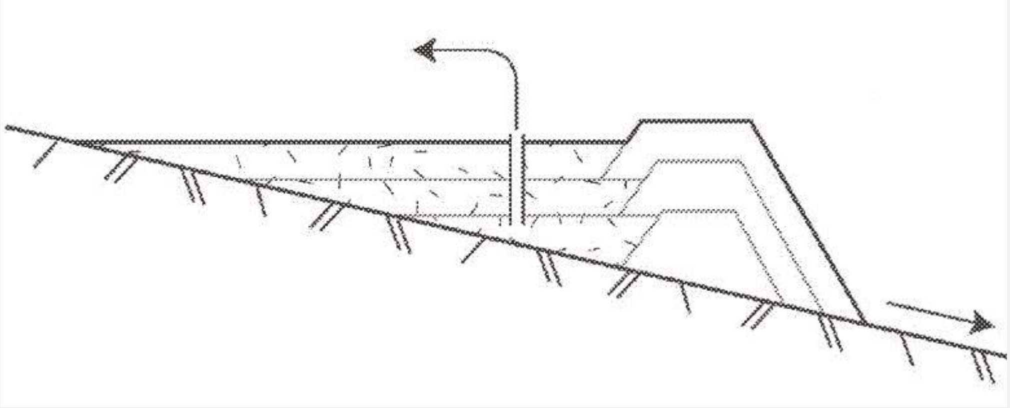


Figure 39: schematic image of a sand dam system (Dillon, 2005)

description

Sand dams are structures creating a new water holding formation (aquifer) (Gale, 2005). The dam will let sediments accumulate against the dam creating a new, highly permeable soil layer. This layer is an artificially created aquifer as the sediments have a high water holding capacity. Sand dams are commonly 4 to 6 meters in height.

capacity

The capacity of sand dams (from cases in Kenya) is 2000-30.000 m^3 in storage (Maddrell, 2016)). Lasage & Verburg (2015) provided in their study on rainwater harvesting techniques in Ethiopia quantitative data on sand dams. According to their study, the average sand dam has a capacity of around 1000 m^3. The sand dam experiences (Madrell) and studies (Lasage & Verburg) are compared in Table 11.

Author(s)	Madrell	Lasage &Verburg
Capacity	2000-30.000 m^3	200-2700 m^3

Table 11: Capacity comparison of sand dam studies

costs

Low cost (Maliva & Missimer, 2012). Two studies (explained under capacity) are compared on costs in Table 12.

Author(s)	Madrell	Lasage &Verburg
Construction costs	15.000 to 45.000 USD	900-25.000 USD
Cost per /m^3 over lifetime	-	0.4 USD/m^3

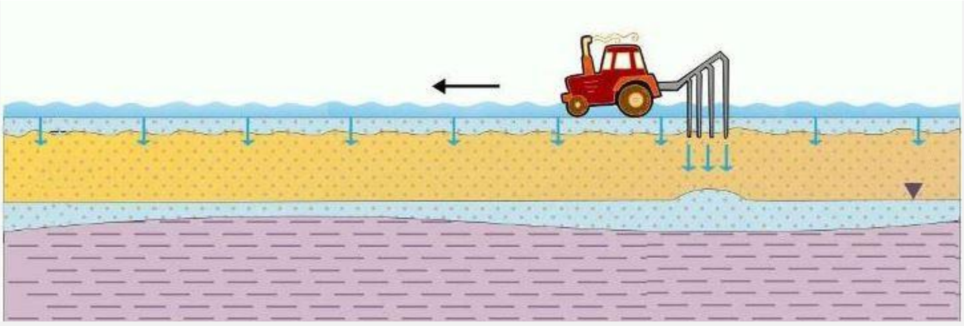
Table 12: Cost comparison of sand dam studies.

aquifer type

Coarse sand

additional information	Advantages of sand dams are low maintenance and a low engineering sophistication-level (Maliva & Missimer, 2012). An essential advantage is that sand dams greatly reduce evaporation losses connected to dam reservoir storage (Maliva & Missimer, 2012). Moreover, sand dams directly remove pathogens through sand filtering. The most significant required hydrogeological conditions for a sand dam are: river width (no more than 25 meters), river slope (preferably 2-4%), availability of coarse sediments in the river catchment and the river bank height should be high enough, even during flood events (Maliva & Missimer, 2012). There are also several socioeconomic aspects. Sand dams tend to need high public acceptance, as are the shared commitment of an organization and a community. They are only preferable for small scale water storage and recovery, such as small villages (Maliva & Missimer, 2012).

Channel widening

synonyms	Riverbed scarification, channel spreading
schematic image	 *Figure 40: schematic image of riverbed scarification (Escalante, 2010).*
description	With channel widening, a stream or a river is widened or dredged in order to increase the wetted surface, and therefore increasing infiltration. One type of dredging is riverbed scarification; a dredging method where the impermeable top layer of the river is removed in order to increase recharge (Escalante & Sauto, 2012).
capacity	Not available
costs	Not available
aquifer type	-
additional information	-

5.6 Combined capacity and cost overview of MAR techniques

MAR technique	capacity quantitative (in Mm3/yr)	costs quantitative (in USD/m3)	cost qualitative
infiltration ponds	45	0,23	low
soil aquifer treatment	110-130	-	high
flooding	-	-	lowest
ditches, furrows, drains	-	0,1-0,3	low
barriers and bunds	-	0,1-0,3	low
dune filtration	2,5-70	-	high
ASR	2,1 (abstraction)	0,26-0,65, (190.000-2.500.000)	high
ASTR	-	-	high
Shallow well infiltration	-	0,1-0,3, (190.000)	-
induced bank filtration	146	-	high
recharge dams	0,0064-9,3	(250 to 1000 million for Wadi dams)	-
sand dams	0,0002- 0,03	0,4 (900-45.000)	low

Table 13: Overview of quantitative information found on capacity and cost of which the latter also qualitative information is provided. For quantitative costs, when found, capital costs are indicated between brackets.

Induced bank filtration is the MAR technique with the largest infiltration capacity, followed by soil aquifer treatment (SAT). Sand dams are the MAR technique with the lowest cost, although flooding is said to be having the lowest costs but no quantitative data to prove this was found. The MAR technique with the highest cost per m3 is ASR, the MAR technique with highest capital costs are wadi dams. As seen in the complete overview of the techniques (paragraph 5.3, 5.4 and 5.5), a lot of data is missing.

6 Third step: Hydrogeological, climatic, socioeconomic and institutional conditions

6.1 Hydrogeological conditions

Assessing the subsoil is a prerequisite for the role of groundwater. In general, this means assessing the composition of the subsoil in terms of rock properties and the regional structures (Margat & Van der Gun, 2013). The composition determines for example porosity, permeability and solubility; all properties that define the capacity of water storage (Margat & Van der Gun, 2013). The regional structure determined by for example thickness and depth of the aquifer defines the physical framework where the groundwater can be stored (Margat & Van der Gun, 2013).

There are several definitions of what an aquifer is. One that seems to link to MAR by seeing it as a groundwater reservoir is described by Margat & Van der Gun (2013) in their book Groundwater around the world: “An aquifer system is a three-dimensional continuous subsurface domain that serves as both a reservoir for groundwater and a preferential natural conduit for groundwater flow (‘subsurface highway’)” (Margat & Van der Gun, 2013).

An aquifer can be confined or unconfined (Hendriks, 2010). Aquifer systems can be large and small, ranging from a few to more than one million square kilometers (Margat & Van der Gun, 2013). Also, their thickness varies, ranging from a few meters to several kilometers (Margat & Van der Gun, 2013).

In general, the desired type of aquifer for MAR is one that absorbs large quantities of water and releases the water when it is abstracted (Central Ground Water Board, 2007).

The unsaturated (or vadose) zone has hydrogeological conditions that must be considered especially for spreading methods, as they must first pass through this zone before reaching the aquifer. Permeability rate of this zone is the crucial factor for how much an aquifer can store, followed by the hydraulic characteristics (for example transmissivity) of the aquifer (Gale, 2005).

When the aim of MAR is to quickly store large amounts of water, with no direct intention to use it again, unconfined aquifers are best to use (Margat & Van der Gun, 2013). In unconfined aquifers spreading methods, induced bank infiltration and in-channel modifications are best to use, especially for shallow unconfined aquifers (Arsad et al, 2014). Confined aquifers are better when the aim is to reduce water pressure in an aquifer or to stop land subsidence. Another reason to use confined aquifers is that, especially in urban areas, water quality is better protected than with unconfined aquifers (Dillon et al., 2010). However, a disadvantage of confined aquifers is that their capacity is lower and their depth usually requires (deep) well injection techniques (Margat & Van der Gun, 2013)

Third, there are four types of aquifers for MAR described by Gale, (2005). These are alluvial, fractured hard rock, consolidated sandstone and carbonate aquifers. Alluvium formations can be composited of fluvial, lake and marine deposits. Alluvial sediments can be impermeable fine-grained silt to permeable coarse gravel. Fractured hard rock formations can be composited of metamorphic, igneous and volcanic bedrock. They are usually largely impermeable and have low storage capacity. Still, they do store water and might be the only source of groundwater in a region. Especially when groundwater abstraction from saturated hard rock aquifers is performed, this can drain the alluvial layers above. Consolidated sandstone aquifers consist of sandstone which is porous and highly permeable. They usually have large storage capacity and high transmissivity. These aquifers are sometimes over-abstracted on purpose in the dry season in order to ‘create storage’ for the wet season. The last type is carbonate aquifers which can be composited of limestone. In these aquifers, storage and transmissivity depend on the type of limestone (porous or karstic).

Alluvium, sandstone and sometimes carbonate aquifers are suitable for especially spreading methods. Especially for shallow aquifers which are not covered by a clay layer, these methods are possible (Tuinhof et al., 2012). Deep and clay covered aquifers can best be recharged by (deep) well infiltration. River bank infiltration should be applied at either dry rivers with (subsurface) dams/sand dams or at perennial rivers or streams with adjacent permeable sand layers (Tuinhof et al., 2012). The suitable aquifers for these three types of MAR are also shown in Table 14. For all the MAR techniques, suitable aquifer types are given in Step 2 (Chapter 5).

MAR technique	**Aquifer type**
spreading methods	Alluvium, sandstone and sometimes carbonate aquifers
(deep) well infiltration	Deep and clay covered aquifers
Induced bank infiltration	dry rivers with (subsurface) dams/sand dams or at perennial rivers or streams with adjacent permeable sand layers

Table 14: Suitable aquifers for several MAR techniques.

It depends on the type of MAR method what hydrogeological factors are relevant (Maliva & Missimer, 2012). This is particularly the case when comparing the suitability for spreading methods and well infiltration methods. By using deep well injection, a large part of the soil is passed by. Therefore, for deep well injection, it is more important to know the hydrogeological conditions of the aquifer and its direct environment. The following two paragraphs, therefore, focus on the upper part (including the unsaturated zone) and the lower part of the soil.

At the point of infiltration, considered one of the most critical factors to MAR spreading methods is surface permeability (Mahdavi et al, 2011, Maliva & Missimer, 2012 p. 190). The permeability of the topsoil determines the infiltration rate for a large amount. After infiltration, there are several vital factors determining the infiltration towards the aquifer. These have been, among others, investigated by Gau (2006).With the groundwater model FEMWATER, factors influencing the arrival time of recharge water to the groundwater level were studied. Especially when sources or time do not allow a full soil assessment, the following factors were found to be necessary to take into account, in the following order: displacement of recharge water (Dg (m)), potential for movement of the recharge water (θe, fraction), capacity to store water (Dp (m)) and the ability of soil to transport water (Ks (m/h))(Gau et al., 2006). One factor that is related to the factors found by Gau (2006) are the macroporosity features, such as fractures (Maliva & Missimer, 2012). Other factors found to be named as essential to surface infiltration methods are groundwater level and confinement (Arshad et al., 2014; Mahdavi et al., 2013; Margat & Van der Gun, 2013). All the hydrogeological factors relevant for surface infiltration methods are shown in Table 15. The aquifer properties are also relevant to surface infiltration methods, they determine storage capacity and movement of the infiltrated water. For water recovery, the same factors are of importance as for deep well infiltration, which will be discussed in the next paragraph.

Hydrogeological factor	**Reference**
Surface permeability	(Mahdavi et al., 2013; Maliva & Missimer, 2012)
Groundwater level	(Mahdavi et al., 2013)
Confinement	(Arshad et al., 2014; Margat & Van der Gun, 2013)
Soil hydraulic conductivity	(Gau et al., 2006)

Table 15: overview of relevant hydrogeological factors for MAR spreading methods

For well injection, especially deep well injection, other factors than for surface infiltration are considered as relevant. Aquifer thickness and transmissivity (which is the hydraulic conductivity integrated over aquifer thickness) are essential information for well injection MAR techniques (Gale, 2005; Mahdavi et al., 2013). Thick aquifers have potentially higher storage capacity than thinner aquifers. Well injection is usually performed at confined aquifers, as surface infiltration methods do not work there (Cisneros et al., 2008; Margat & Van der Gun, 2013). Also, the quality of the aquifer material and the aquifer water needs to be known. One of the main parameters of the quality of the aquifer water is salinity (Wolf et al., 2007). When the water is infiltrated, the movement of groundwater is largely dependent on the storativity, the lateral hydraulic gradient and the hydraulic conductivity of the aquifer (Central Ground Water Board, 2007; Cisneros et al., 2008). When the lateral hydraulic gradient is gentle, the infiltrated water stays closer to the point of infiltration. In addition, connections with other aquifers can also play a serious role in the movement of the aquifer water (Arshad et al., 2014). For recovery, groundwater quality and mineralogy is meaningful information, as recharged water can react with minerals. Salinity of the groundwater can determine the recovery efficiency (Wolf et al., 2007). Aerobic conditions can have high rates of inactivation of pathogens and endocrine disrupting chemicals, while anaerobic conditions can have high rates of biodegradation of trihalomethanes (Cisneros et al., 2008). Table 16 shows the relevant aquifer properties for deep well injection techniques of MAR.

Hydrogeological factor	**characteristics**
Confinement	-confined -unconfined
Permeability	-low -moderate -high
Thickness	-thick -thin
Unconformity of hydraulic properties	-heterogeneous -homogeneous
Groundwater quality: salinity	-fresh -brackish -saline
Groundwater quality: redox state	-aerobic -anaerobic
Lateral hydraulic gradient	-none -gentle -steep
Consolidation	-unconsolidated -consolidated
Mineralogy	-reactive with infiltrated water -unreactive with infiltrated water

Table 16: Overview of relevant aquifer properties for deep well injection techniques of MAR (Cisneros et al., 2008; Wolf et al., 2007).

For both surface infiltration and well infiltration techniques, the aquifer properties are essential information for considering a MAR project. These properties are largely determined by the lithology (Hartmann & Moosdorf, 2012). Lithology type can be the boundary condition for recharge (Sanford, 2002). All hydrogeological factors shown in Table 16, except maybe groundwater quality, are dependent on lithology. Therefore, looking at what lithology is present gives valuable information on the opportunities for MAR.

Essential hydrological factors before infiltration

Second to the first location assessments, it is required to evaluate the locations on their proximity to water sources (Mahdavi et al., 2013). A location can be perfect for recharge, but when there is no water source available (such as a stream) then there is no use for a further feasibility study.

Also, before infiltration, for several surface infiltration methods, slope is a crucial factor (Mahdavi et al, 2011). Some techniques require no slope while others need a specific range of slope.

The importance of the source of water that will be infiltrated mentioned in several studies (Bouwer, 2002; Rahman et al., 2012). The source water should be of adequate quality in order to prevent clogging of the soil surface and clogging of the unsaturated zone. Clogging in these regions is caused by deposition of suspended solids such as algae, sediments and sludge (Bouwer, 2002). On the surface, clogging is expressed by the accumulation of matter (biomass).

Other factors found to be of importance before infiltration were land use, land cover and irrigation practices (Maliva & Missimer, 2012).

6.2 Climatic conditions

MAR can be applied in several different climates. Arid and semi-arid climates have most need for water storage techniques; in these climates MAR is especially useful (Dillon, 2005). However, as MAR is also a technique to store excess stormwater or to manage water quality, humid climates could also be a place to implement MAR projects. This is supported by Dillon et al., (2009b).

Several studies consider rainfall as an influential climatic condition for MAR (Central Ground Water Board, 2007; IGRAC, 2007). From experiences with different amount of rainfall in India, a classification can be made of the amount of rainfall and the effect it can have on MAR potential (Central Ground Water Board, 2007). This is shown in Table 17. It must be noted however that this study is clearly mainly focused on MAR techniques with runoff/storm water as a source for infiltration.

Amount of rainfall	**Effects on MAR**
High (1000-2000 mm/y) to very high (>2000 mm/y)	5-10% infiltrates. However also rejected recharge may occur. In both cases, most of the water has to be stored in surface storage before it can be used for MAR.
Moderate (750-1000 mm/y)	10-15% infiltrates. Not much runoff water available after the wet season, so MAR mainly possible during the rainy season.
Low to moderate (400-700 mm/y)	15-20% infiltrates. Runoff only in wet season.
Low (<400 mm/y)	Infiltration small. No MAR by runoff as water source possible.

Table 17: effects of amount of rainfall to MAR potential

6.3 Socioeconomic factors

Social factors: public acceptance

Water reuse can benefit from MAR as it disconnects the not well-accepted 'toilet-to-tap' connection (Bouwer, 2002). By having waste water first treated by the soil and the aquifer, water quality improves. Recharge also can alleviate religious taboos which exist in for example some Islamic countries.

In public acceptance (in a study with as water source storm water) five policy related variables can play a role: fairness, trust, effectiveness, importance of communication and importance of safety assurances (Mankad & Walton, 2015). Policy-makers of groundwater management/MAR projects worldwide should especially communicate 1) trust in the water authorities 2) perceptions of fairness and 3) effectiveness of MAR programs as they are robust predictors of public acceptance (Mankad & Walton, 2015).

Socioeconomic status

The human development index (HDI) can be an indicator of socioeconomic status (SES). Socioeconomic status (SES) is an indicator of a person's economic and social status, quantified by education, income and occupation (Baker, 2014). HDI has been used in other studies to assess socioeconomic status at national level (Zhu et al., 2014). Since the 90's, it was recognized that income or GDP should not solely be used as a measure of human development and socioeconomic status (Neumayer, 2001). Therefore, the United Nations introduced a new indicator based on income, health and educational factors, each given the same weight. These factors form the human development index. A schematic visualization of the components of the human development index is shown in Figure 41.

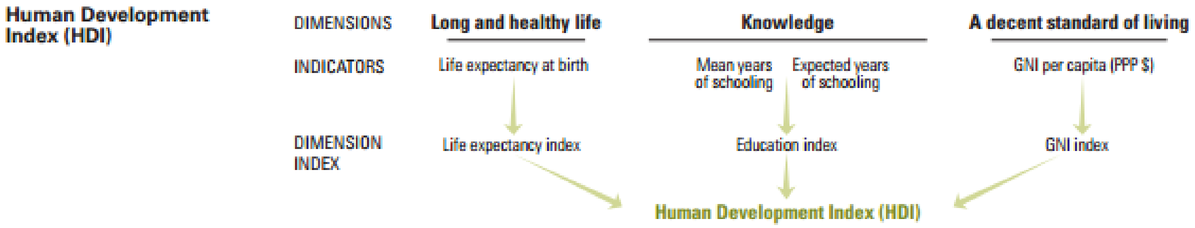


Figure 41: Components of the human development index

The relationship between HDI and MAR can be found in the sustainable development goals (SDG's). These goals are part of a recent program, started in 2015, of the United Nations to 'shape the development discourse and policies over the next 15 years' (United Nations, 2015). Sustainable development goal 6 is to ensure availability and sustainable management of water and sanitation for all. This includes aquifer protection and restoration. According to the UN, HDI can be aligned to SDG's and can be used to measure development and progress. Therefore, when relating MAR projects to the HDI, one can, for example, look for relationships of specific MAR techniques in countries with a certain HDI. The relationship between MAR and HDI is shown schematically in Figure 42.

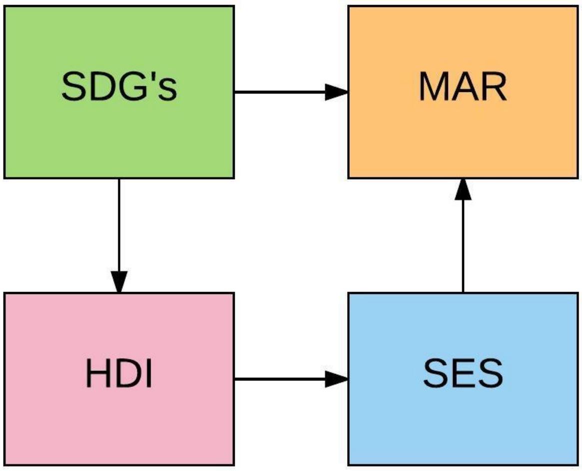


Figure 42: link of HDI to MAR: SDG's have a focus on protecting aquifers (MAR) and are aligned to HDI. HDI can be used to assess SES in a country, which gives then the socioeconomic context of a MAR project.

Economic factors: costs

In general, "water has an economic value only when its supply is scarce relative to its demand" (Maliva, 2014). Scarcity increases competition among water users which let water take an economic value. According to Tuinhof et al. (2012), there is only a small amount of studies on the financial and economic benefits of aquifer recharge. However, several studies were found that discussed economic conditions and frameworks for MAR. In order to know whether MAR should be chosen above other storage methods (see paragraph 1.3), a reliable cost estimate should be made for a recharge site or MAR techniques (Zekri et al., 2014). Costs of MAR vary significantly between MAR techniques.

The capital costs are mainly the cost of construction. Operations and maintenance (O&M) are the cost for running the aquifer recharge (and recovery) system. For most projects, an estimate of total cost is given per m^3. Not always the timespan of cost analyses is clear neither whether they only refer to recharge, or to recharge and recovery.

The numerous factors on which the costs of a MAR project are dependent are shown in Table 18 (Arshad et al., 2014; Maliva, 2014; Rahman et al., 2012; Zekri et al., 2014). The cost factors are taken from different studies.

General costs

- size/scale of the MAR project (including capacity)
- type of MAR technique
- lifespan of the project
- recharge and extraction depth
- opportunity cost of water
- interest rate

Capital costs

- land
- testing and feasibility analyses
- consulting services for the design
- consulting for permitting
- permits
- environmental impact assessment
- consulting for supervision of the construction
- construction costs such as roads, piping, controls, instrumentation and pretreatment systems

O&M costs

- labor
- energy
- consulting services/studies/legal fees
- testing
- maintenance
- pre-treatment
- post treatment
- source water costs
- infiltration, injection and recovery rates

Table 18: Factors were costs can depend on in a MAR project.

There are several methods to monetize the benefits of MAR (Maliva, 2014). One example of monetizing benefits is the method of calculating and estimating 'damage cost'. This means that the benefits are estimated in damage costs that are avoided such as flood damage or health impacts due to water shortage. All of the methods to monetize the benefits of MAR are described in a study by Maliva et al. (2014).

Specific attention in cost-benefit analyses (CBAs) for MAR is drawn from some experiences. In the province of Gujarat, India, a MAR strategy was designed by a government authority, the Taskforce on managed aquifer recharge (constituted in 2008). According to Shah (2014), some basic economic concepts were over-looked by this task force. The concepts that could be overlooked for regions worldwide are 1) criticality of opportunity costs, 2) partial versus total solutions and 3) the irrelevance of sunk cost. The first two both state a similar issue. The cost and benefit analysis is often narrow and should take alternative courses of action and all actors into account. With all actors is meant that instead of only the water sector, all stakeholders should be involved in the cost-benefit analysis of MAR, also in how they contribute. Often too much a one party (the government) view is taken. The third issue indicated by Shah is the irrelevance of sunk cost. In many cases, decision makers tend to take past investments too much into account. In addition, Maliva et al. (2014), support this by pointing out that sunk cost should not be included in the cost-benefit analysis (CBA) of a MAR project. In the case of Gujarat, previous investments in surface water storage should not be prioritized for allocation of runoff if groundwater has become the most prevalent source for agriculture and the domestic water supply (Shah, 2014).

Economic factors: funding

Financing MAR, in general, is dependent on the size of the system, the financial benefits, the socioeconomic conditions and the beneficiary (Tuinhof et al., 2012). Financial constraints are often most severe in poor areas of developing countries (Maliva, 2014).

Funding of MAR projects by government takes place through 1) revenues from the sale of water, 2) general tax revenues, 3) property tax (ad valorem tax) and 4) direct assessment (Maliva, 2014). MAR projects can also be funded by external parties, such as international agencies and non-governmental organizations (NGOs) (Maliva, 2014). Although funding seems a vital part of economic studies on MAR, attention to the funding parties seems lacking in the literature.

6.4 Institutional factors

Stakeholders and authorities

In an extensive study by Brunner et al., (2014), a stakeholder analysis was done for MAR in the Chennai City, India (formerly Madras). MAR stakeholders at national, regional and local levels were identified. These were government agencies, companies, organizations and action groups such as the National Green Tribunal, the State Government of Tamil Nadu, the Hindu Religious & Charitable Endowment Board and residents of the city (Brunner et al., 2014).

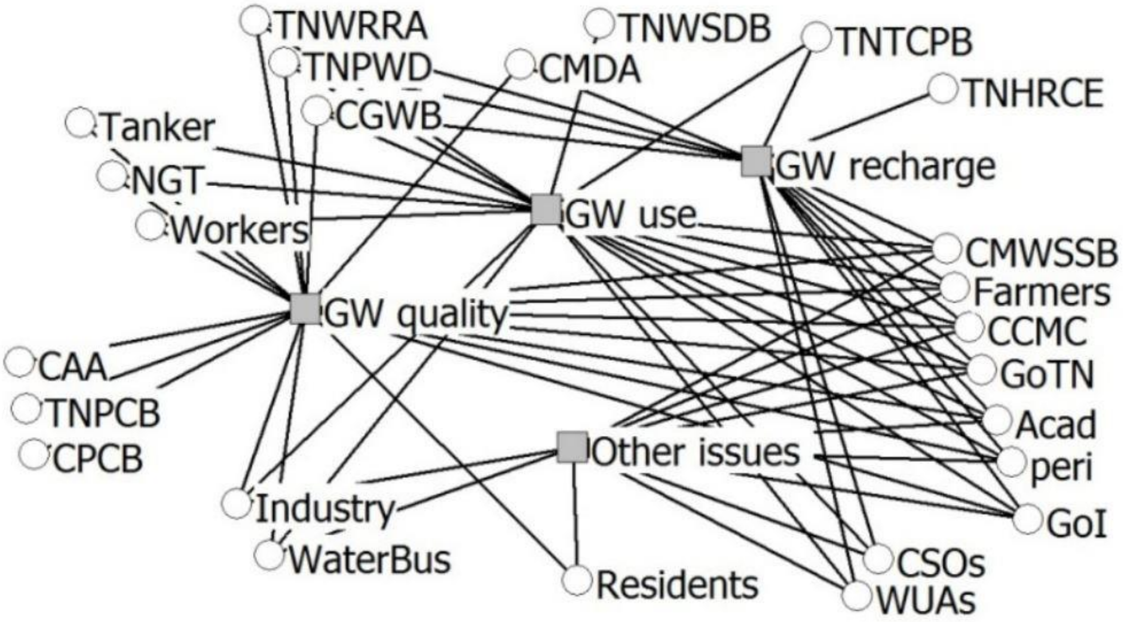
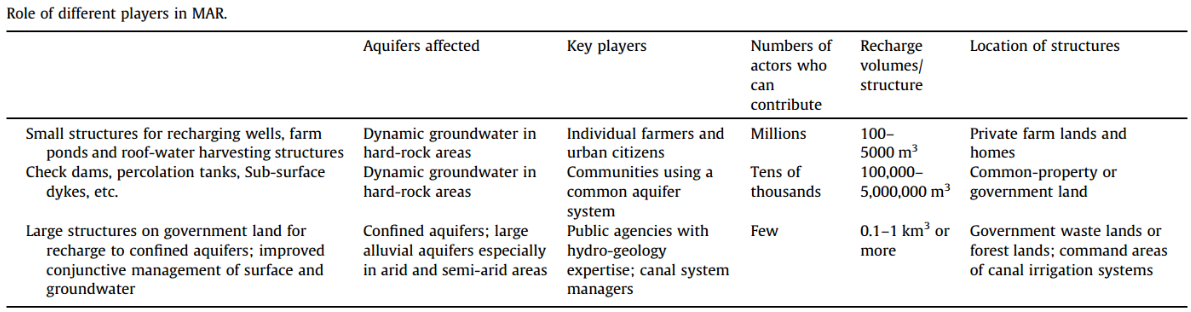


Figure 43: Stakeholders and their groundwater related interests for Chennai City, India (Brunner et al., 2014). Abbreviations are explained in Appendix H.

As can be seen in Figure 43, stakeholders in Chennai City have different interests. The users of groundwater often do not have a direct interest in groundwater recharge. In the study of Brunner et al., (2014) a coordination problem, due to this conflict of interests, between stakeholders for MAR in Chennai City was found. As a solution, all stakeholder representatives supported the idea to form a government authority with the specific task of 'licensing groundwater extraction and overseeing MAR' (Brunner et al., 2014).



Role of different players in MAR.

	Aquifers affected	Key players	Numbers of actors who can contribute	Recharge volumes/ structure	Location of structures
Small structures for recharging wells, farm ponds and roof-water harvesting structures	Dynamic groundwater in hard-rock areas	Individual farmers and urban citizens	Millions	100–5000 m^3	Private farm lands and homes
Check dams, percolation tanks, Sub-surface dykes, etc.	Dynamic groundwater in hard-rock areas	Communities using a common aquifer system	Tens of thousands	100,000–5,000,000 m^3	Common-property or government land
Large structures on government land for recharge to confined aquifers; improved conjunctive management of surface and groundwater	Confined aquifers; large alluvial aquifers especially in arid and semi-arid areas	Public agencies with hydro-geology expertise; canal system managers	Few	0.1–1 km^3 or more	Government waste lands or forest lands; command areas of canal irrigation systems

Table 19: Role of different players in the province of Gujarat, India. From Shah (2014)

In Table 19, from MAR experiences in the province of Gujarat, India several things can be seen. First, the key players have different type of aquifers they use for MAR. Secondly, although the recharge volumes for farmers and urban citizens are relatively small, the amount of farmers that can contribute are enormous and can, therefore, create a lot of recharge. Third, different key players use different MAR techniques.

Legislation

As most freshwater is found in aquifers and given the importance of freshwater for the well-being of society, the regulation of aquifers and MAR cannot be neglected. Reasons for regulation can be the protection of the environment, stable groundwater levels (for agriculture), increase or reduce recharge and pollution control (Margat & Van der Gun, 2013). The basics of groundwater law can be found in ownership. Water can be privately (landowner), commonly (everybody) and state-public (authorities) owned (Margat & Van der Gun, 2013). Ownership might be a limitation to the implementation of MAR. Types of regulation commonly seen for MAR focus on wells and groundwater abstraction (Margat & Van der Gun, 2013). Wells might require studies on the possible side effects and permits. Monitoring can also be mandatory. Groundwater abstraction regulation is mainly about thresholds for abstraction rates. On the international scene, there is the UN Convention on the Law of Non-Navigational Uses of International Watercourses (1997) known as the UN Watercourse Convention (United Nations, 1997). However, this convention appears limited in its scope as it only considers groundwater related to surface water flowing to a common terminus (Stephan, 2009). It is under the UNESCO´s International Hydrological Program that the need for legal and institutional tools to manage transboundary aquifers has been expressed. This led to the preparation of draft articles on the law of transboundary aquifers that have been annexed to a UN General Assembly Resolution (A/RES/63/124) and were adopted in December 2008. The draft articles touch amongst others on an equitable and reasonable utilization of transboundary aquifers, on the obligation to cooperate, to take all appropriate measures to protect and preserve and manage ecosystems (Stephan, 2009). In Africa, there are different international agreements on transboundary aquifers, like the one between Egypt, Libya and Sudan of 1992 on the Nubian sandstone Aquifer System. From a national perspective, three countries are touched upon: the US, India and the Netherlands.

Under article 4 of the European Water Framework Directive (2000/60/EC), the Netherlands is to implement the measures necessary to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater, such as aquifers (European Commission, 2000). In addition, the European Groundwater Directive 2006/118/EC has been developed in response to the requirements of Article 17 of the Water Framework Directive which requires criteria for a good groundwater chemical status which is specified in annex V of the directive. There are several emission limits and minimum requirements, sometimes dependent on the groundwater body. There are also reporting requirements to the authorities. In the Dutch legislation, MAR is mainly regulated under the regulation on infiltration of the soil under the ‘Water Act’ (Hoogvliet et al., 2016).

In India, groundwater use is the highest in the world (World bank, 2010). An increasing number of aquifers in India are threatened by overexploitation. There is a lot of discussion on the status of regulation on groundwater in India. Besides national legislation, the 610 districts have their district regulation. In 2007 the planning commission concluded that: “no change in basic legal regime relating to groundwater seems necessary because the problem of groundwater overexploitation does not arise from inadequate legislation and therefore cannot be solved through legislative remedies” (World bank, 2010). Yet the scene indicates that there are still conflicting regulations or missing regulations on groundwater and MAR.

In the US, ASR techniques are regulated by regulation of the Environmental Protection Agency (EPA) and on state level (Environmental Protection Agency (EPA), 2016). Water sources for MAR and recovered water from MAR are regulated by state water criteria. Nine states require that water used for ASR injection be potable or meet national or state drinking water standards. The regulation of the EPA where MAR performed by wells is regulated is the ‘U.S. Environmental Protection Underground Injection Control’ regulation (Maliva & Missimer, 2012)

6.5 Hypotheses

Hypotheses for different hydrogeological, climatic and socioeconomic conditions are shown below.

Hydrogeological

The following techniques are expected to have a sandy unconsolidated lithology: Induced bank infiltration, ditches/furrows and drains, flooding, dune filtration, infiltration ponds, SAT and barriers and bunds.

Climate

MAR is primarily seen in arid and semi-arid countries.

Socioeconomic

As AS(T)R is one of the most expensive MAR techniques, this technique will only be found in highly developed countries (very high HDI, > 0.8).

7 Fourth Step: Case Studies

7.1 Basic analysis

For the case studies, the global MAR database of MAR projects of IGRAC is used (IGRAC, 2016a). This database provides data on MAR projects around the world which can be analyzed under different climatic, hydrogeological, and socioeconomic conditions. An institutional analysis on a global scale is not possible, as no significant institutional factors were found in the literature which can be analyzed on a global scale. Also, it must be noted that the MAR projects do not comprise all the MAR cases worldwide.

Country distribution

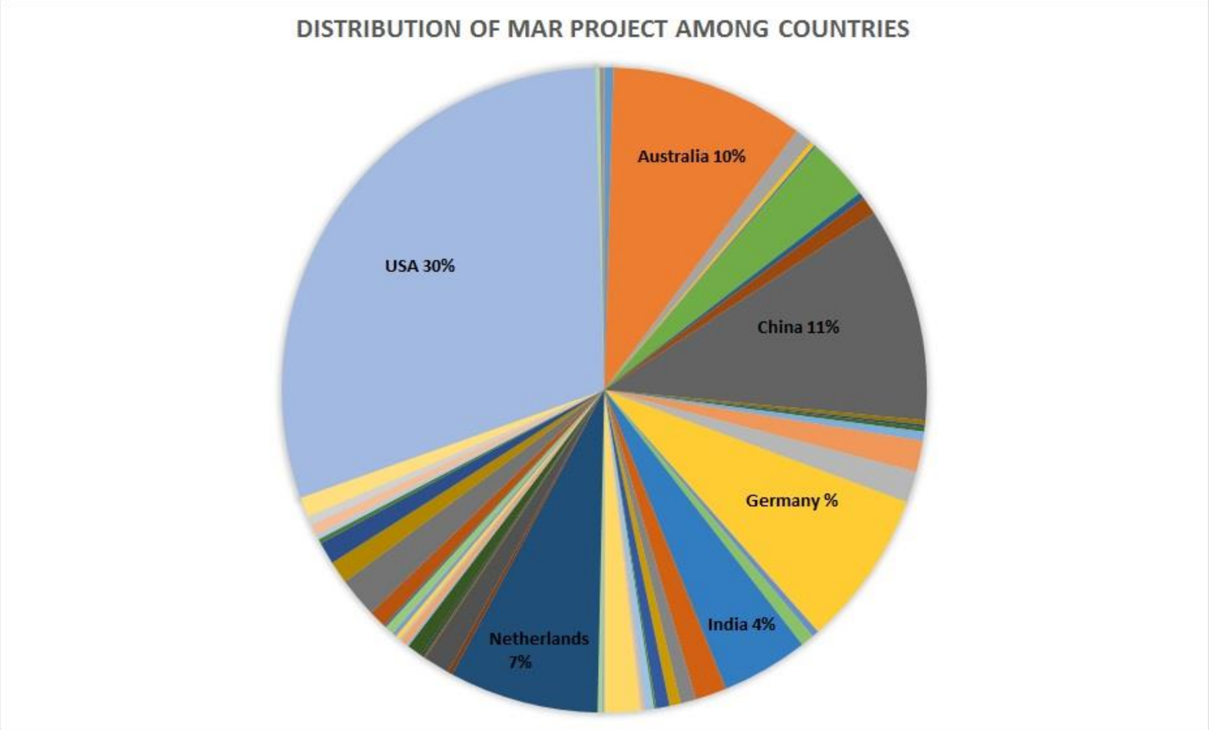


Figure 44: Country distribution of 894 MAR projects in 56 countries. The 6 countries with the most cases are labeled, for with full legend, see Appendix K.

General statistics are created of the global MAR database. In Figure 44, the distribution of reported MAR projects in the world is shown.

Of the 894 projects in 56 countries, most projects, i.e. 30%, stem from the United States. The countries with the most MAR projects after the United States are China, Australia, Germany, the Netherlands and India.

In addition, in Appendix J, the country distribution per MAR technique is shown. This shows that some techniques were only reported in a few different countries and other in many different countries. This information is important if comparisons are made between MAR techniques.

MAR technique distribution

The distribution of different MAR techniques is created to obtain an overview of the MAR projects, see Figure 45.

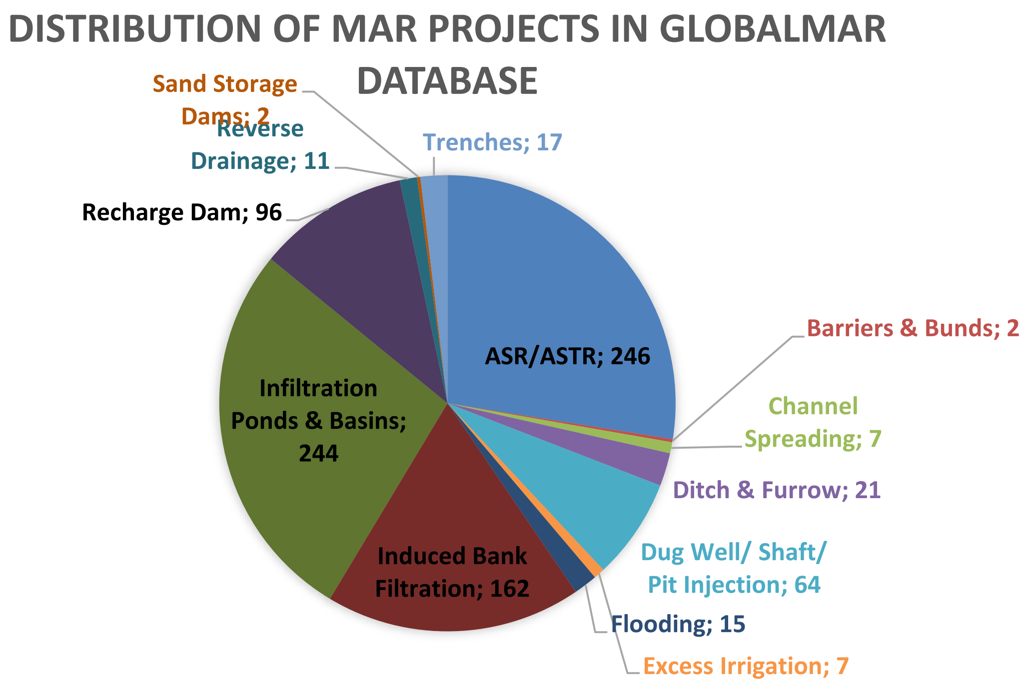


Figure 45: Distribution of MAR projects in MAR projects database (number of MAR projects indicated after label name)

The most used techniques are AS(T)R, induced bank filtration and infiltration ponds. Barriers and bunds (2), sand dams (2), channel spreading (7) and excess irrigation (7) all have less than 10 MAR projects reported in the geodatabase.

Water stress

Water stress was analyzed, as one of the most important objectives of MAR is water provision. The baseline water stress map is shown in Appendix F. The results of water stress among MAR techniques are shown in Figure 46. The World Resources Institute (WRI) made a classification of the water stress values, shown in Table 20 (Gassert et al., 2013).

0-1	1-2	2-3	3-4	4-5
Low (<10%)	Low to medium (10-20%)	Medium to high (20-40%)	High (40-80%)	Extremely high (>80%)

Table 20: classification of water stress (Gassert et al., 2013)

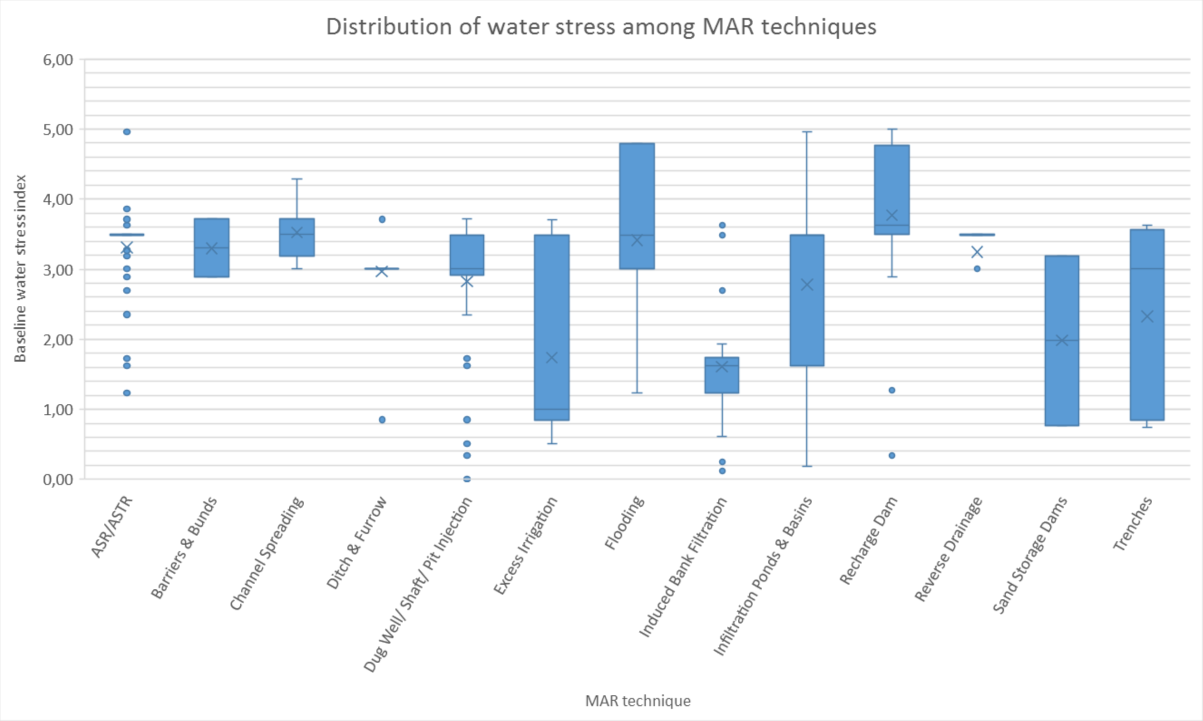


Figure 46: Box and Whisker plot of the distribution of water stress among MAR techniques.

A Box and Whisker plot of the distribution of water stress among MAR techniques is shown in Figure 46. An explanation of Box and Whisker plots is given in Appendix G.

The baseline water stress is very different for the 14 MAR techniques, see Figure 46. Infiltration ponds and basins have the widest spread in baseline water stress (outliers excluded). Most of the MAR techniques seem to be located in areas with high water stress (3-4). Infiltration ponds and basins, excess irrigation and induced bank filtration have a lot of MAR projects in areas with a low to medium (<1-2) baseline water stress. Flooding, recharge dams and infiltration ponds and basins have respectively most MAR projects in areas with an extremely high (4-5) baseline water stress.

7.2 Hydrogeological

Lithology

For the lithology analysis, the global lithological map database (GLiM) is used from Hartmann & Moosdorf (2012). The map is shown in Appendix F.

Of all MAR techniques the lithology composition is presented in pie diagrams, see figures below. This allows for a comparison that is not dependent on the number of MAR projects reported. This visualization helps, therefore, to standardize the number of MAR projects.

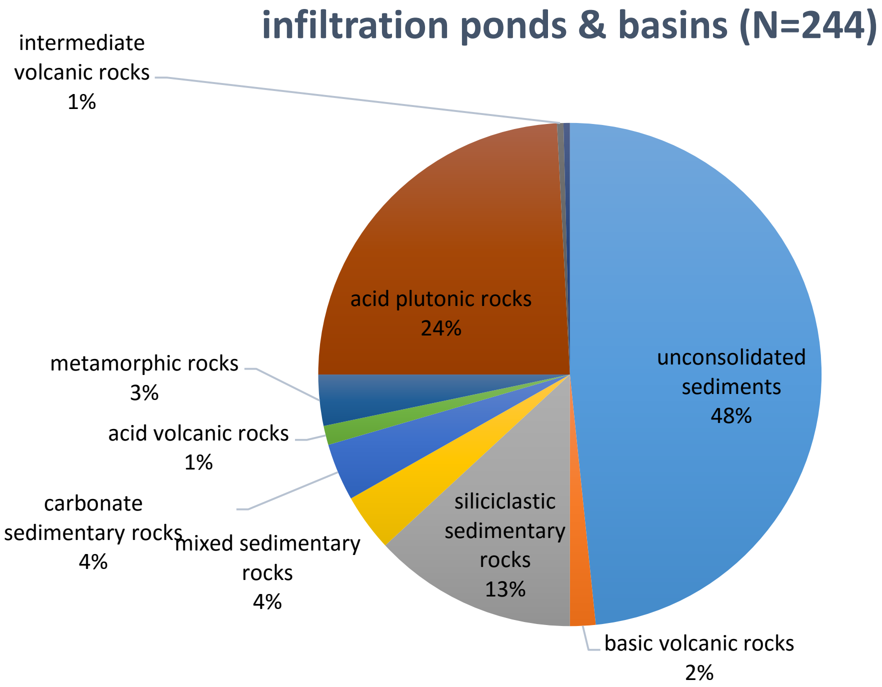


Figure 47: Lithology distribution of infiltration ponds & basins

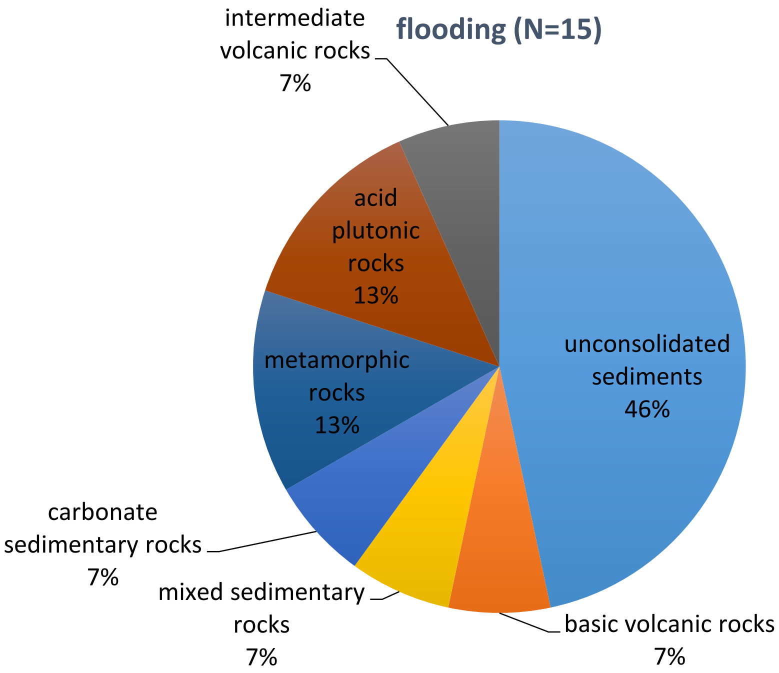


Figure 48: Lithology distribution of flooding (N=15)

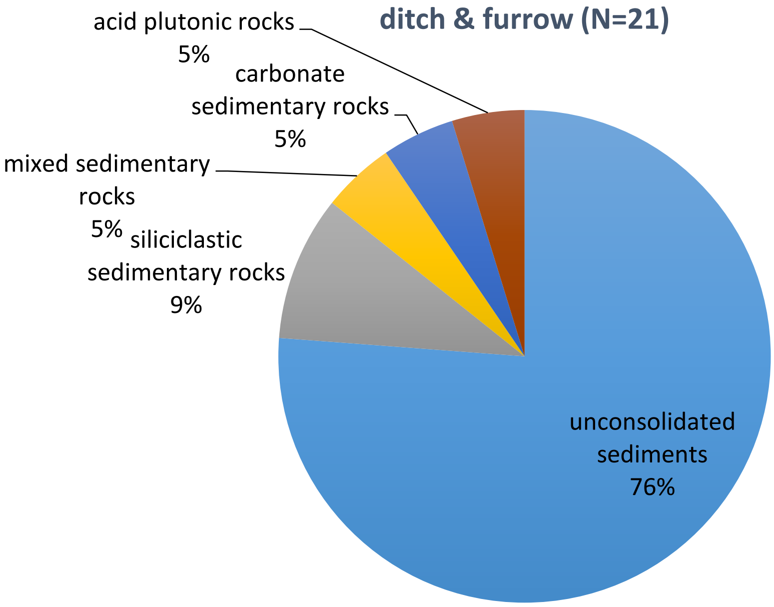


Figure 49: Lithology distribution of ditch & furrow (N=21)

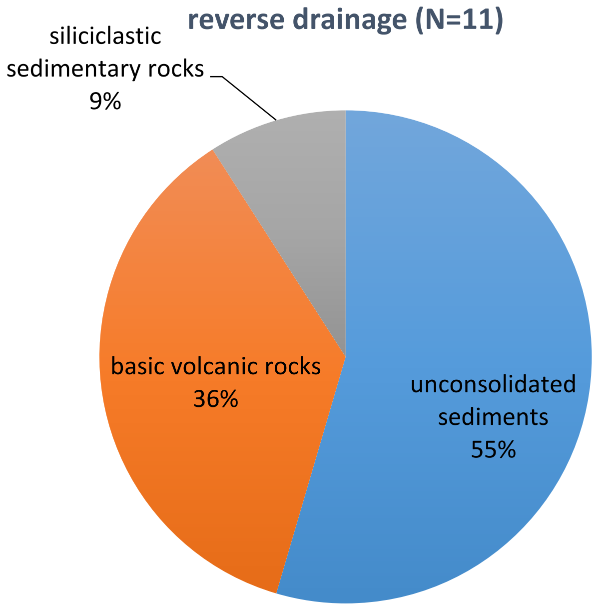


Figure 50: Lithology distribution of reverse drainage (N=11)

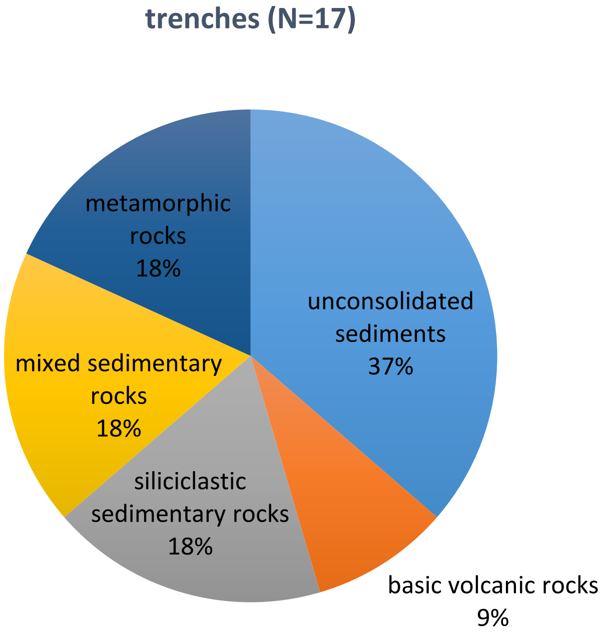


Figure 51: Lithology distribution of trenches (N=17)

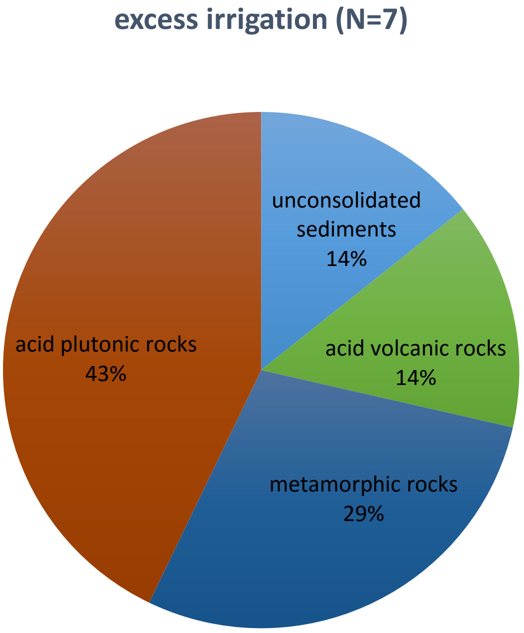


Figure 52: Lithology distribution of excess irrigation (N=7)

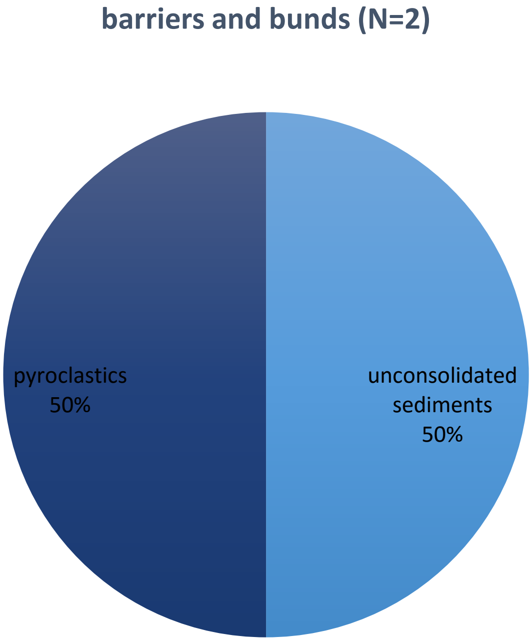


Figure 53: Lithology distribution of barriers and bunds (N=2)

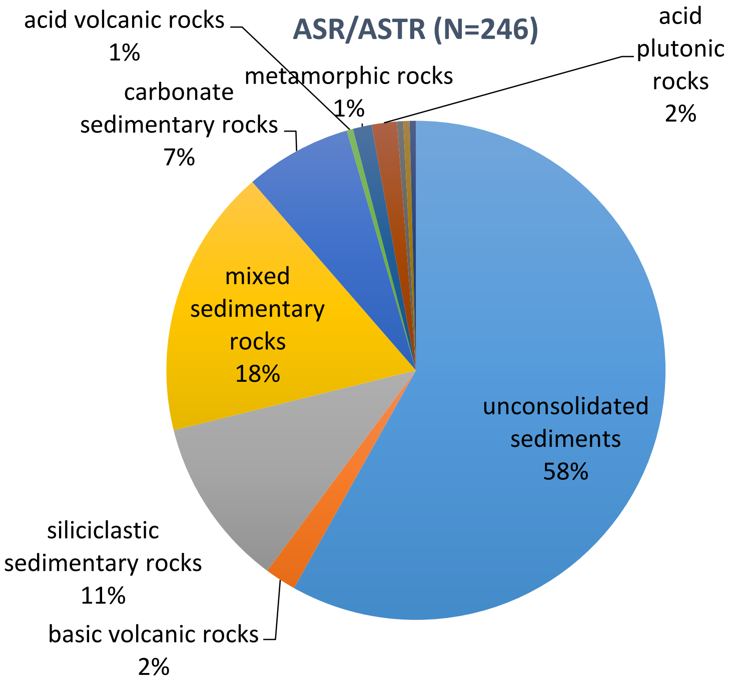


Figure 54: Lithology distribution of ASR/ASTR (N=246)

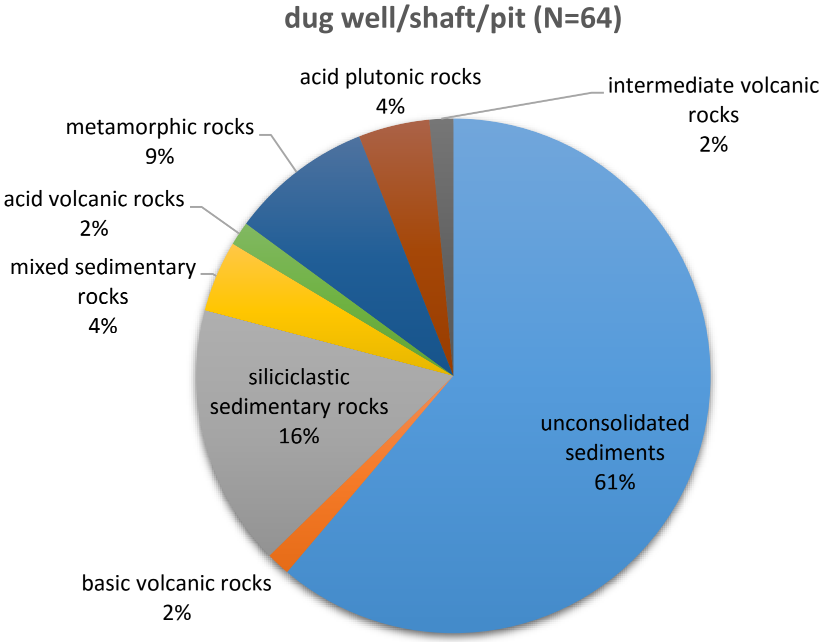


Figure 55: Lithology distribution of dug well/shaft/pit (N=64)

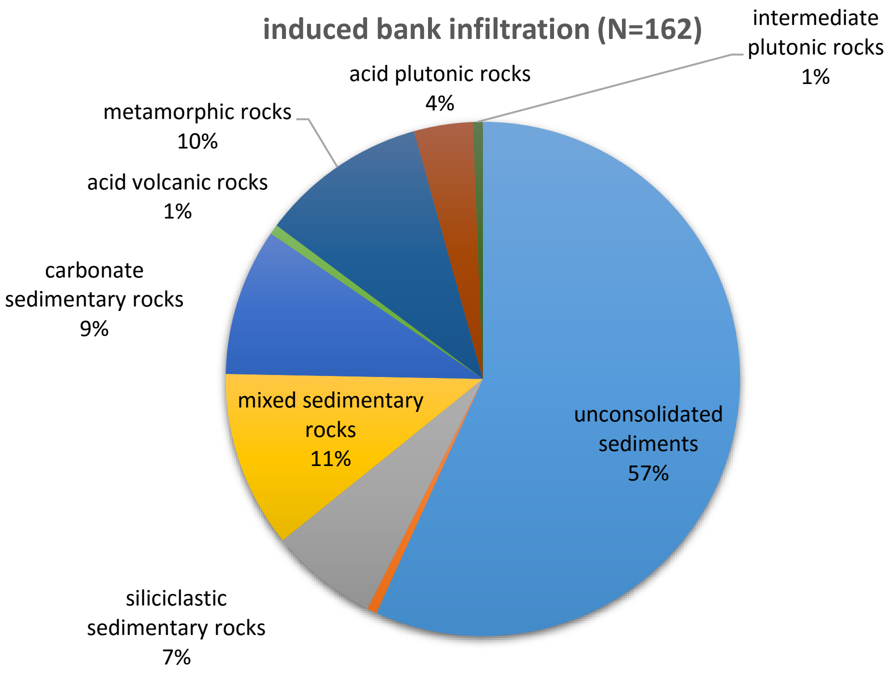


Figure 56: Lithology distribution of induced bank infiltration (N=162)

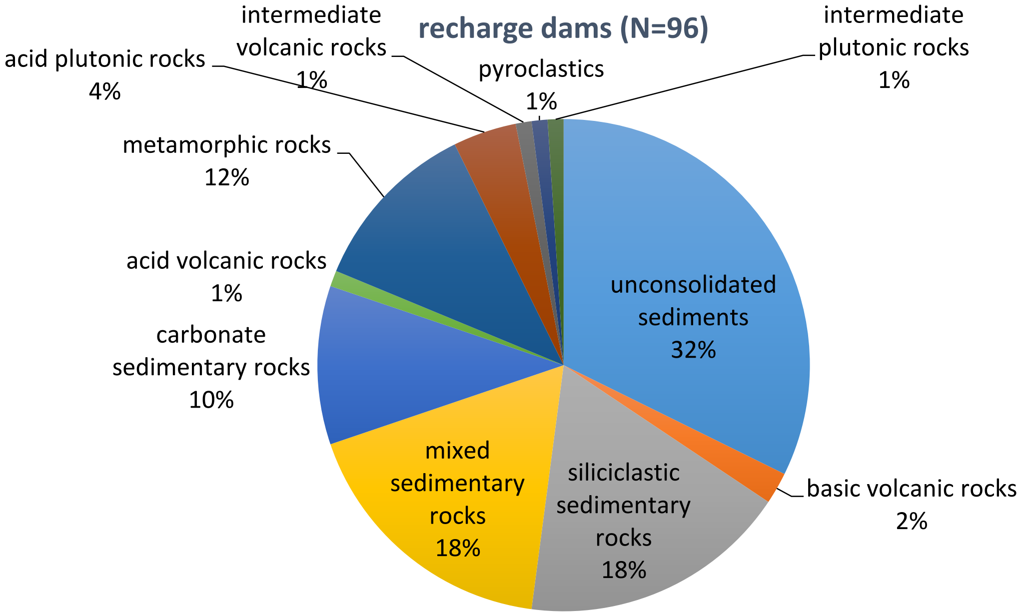


Figure 57: Lithology distribution of recharge dams (N=96)

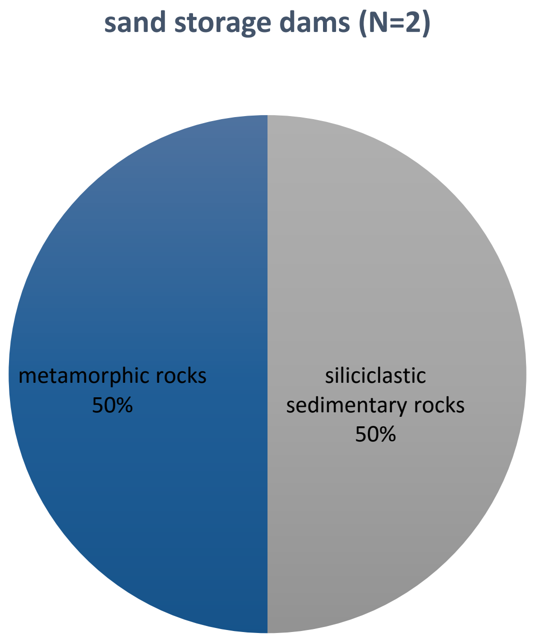


Figure 58: Lithology distribution of sand storage dams (N=2)

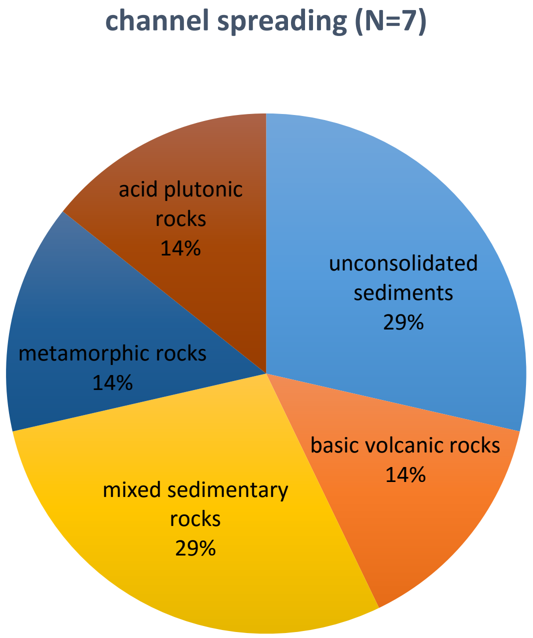


Figure 59: Lithology distribution of channel spreading (N=7)

Unconsolidated sediments are for each technique, except sand dams and excess irrigation, the most seen lithology type where the MAR project is located on. For barriers and bunds and channel spreading, this 'first place' is shared with pyroclastics and mixed sedimentary rocks, respectively.

ASR is the MAR technique with the largest variety of lithology types.

7.3 Climate

Three maps considering climate are being used: the Köppen-geiger classification, global aridity and global annual precipitation.

Köppen-geiger

For climate regions, the Köppen-geiger classification is used as being the most prominent climate classification available. The map is shown in Appendix F.

An overview of the distribution of global MAR projects in the main climate types is shown in Figure 60.

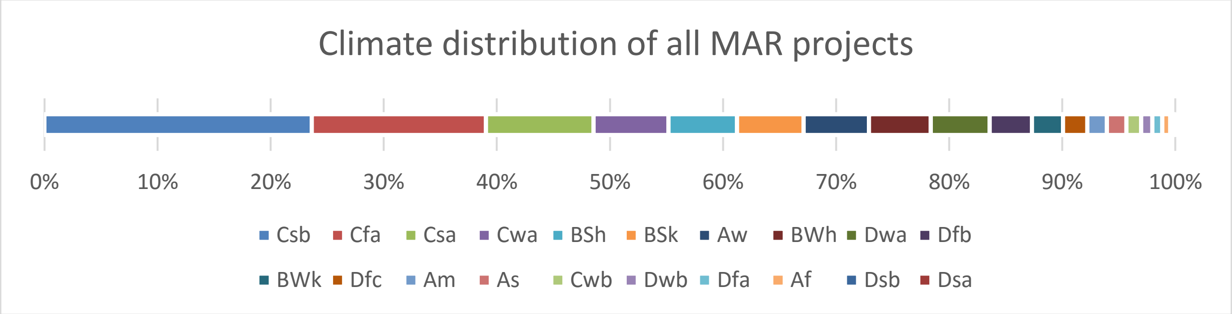


Figure 60: Climate distribution of all MAR projects

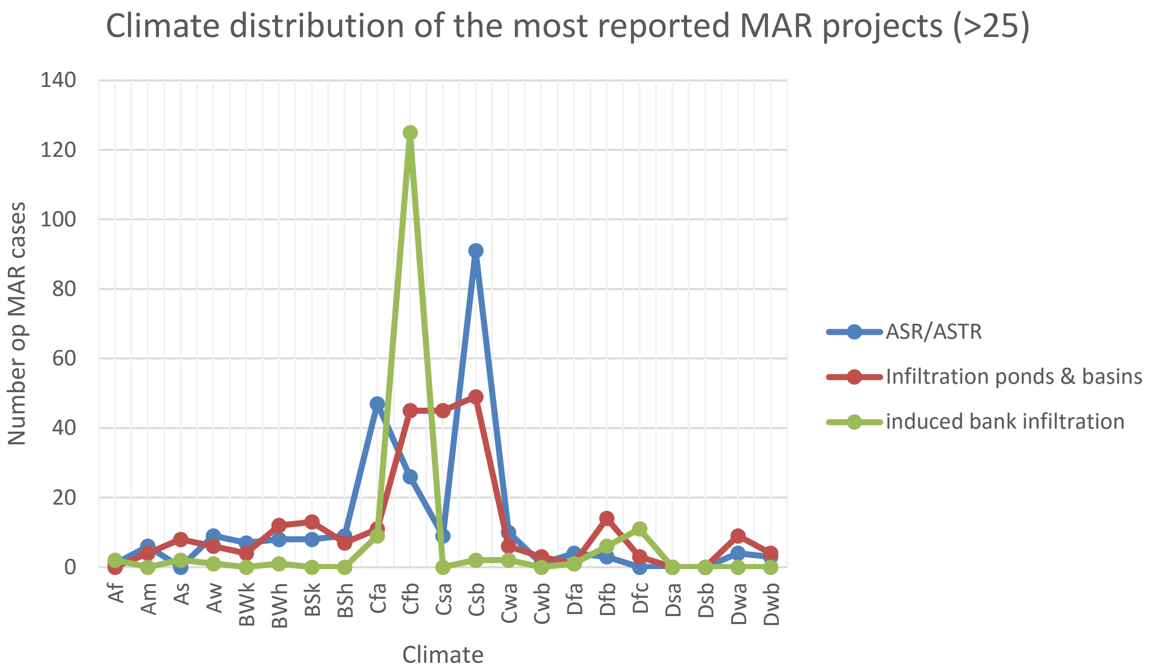


Figure 61: Climate distribution of the most reported MAR projects (>25)

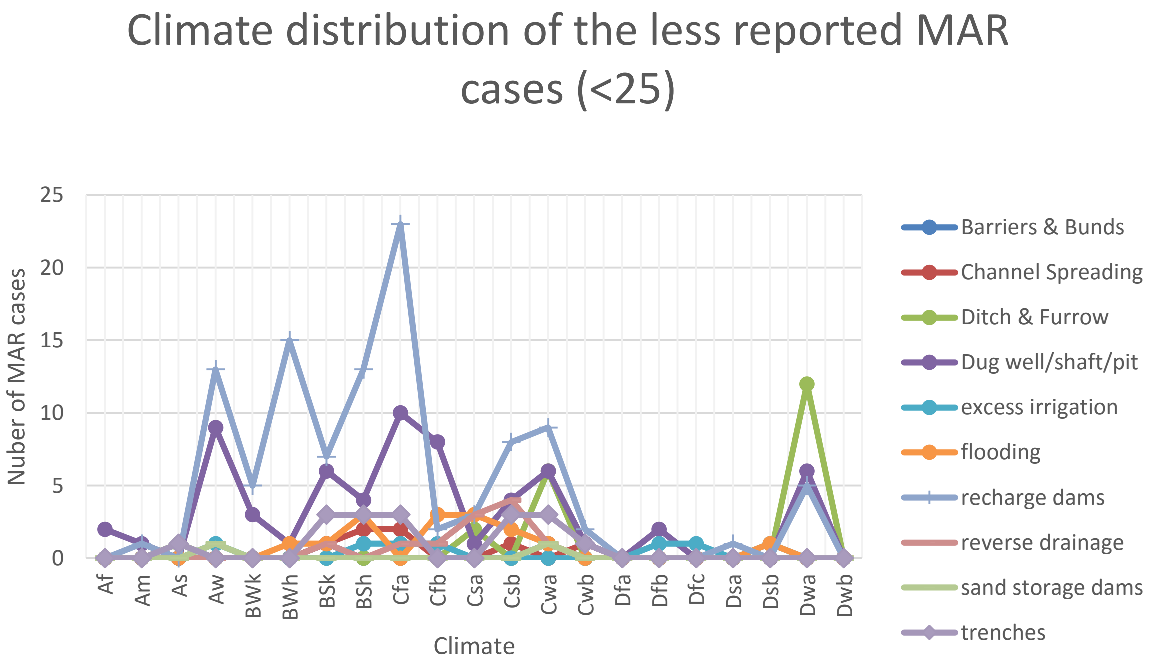


Figure 62: Climate distribution of the less reported MAR projects (<25)

The three largest climates are Induced bank filtration is most seen in a Cfb (temperate, warm summer, without dry season) climate, Dfc (cold, cold summer, without dry season) climate on the second place. Infiltration ponds and basins are most seen in Csb (temperate, dry warm summer), Cfb (temperate warm summer without dry season), Csa (temperate dry hot summer) and Dfb (Cold, warm summer, without dry season) climates respectively. ASR/ASTR is most seen in Csb (temperate, dry warm summer) and Cfa (temperate hot summer without dry season) respectively.

The following climates have no reported MAR projects: Dwc, Dwd Dsc, Dfd, Cfc, Cwc, Csc, EF and ET.

Aridity

The global aridity index combines two vital factors determining the water availability, precipitation and evapotranspiration. For this map aridity is calculated as follows (Zomer et al., 2006):

Aridity Index (AI) = MAP / MAE

Where MAP = Mean Annual Precipitation and MAE = Mean Annual Potential Evapotranspiration

The data is from the period 1950-2000. The map is shown in Appendix F. A classification of the aridity index is shown in Table 21. The results of the aridity index distribution among MAR techniques are shown in Figure 63.

Value	Climate Class
< 0.03	Hyper Arid
0.03 – 0.2	Arid
0.2 – 0.5	Semi-Arid
0.5 – 0.65	Dry sub-humid
> 0.65	Humid

Table 21: classification of the aridity index (Zomer et al., 2006)

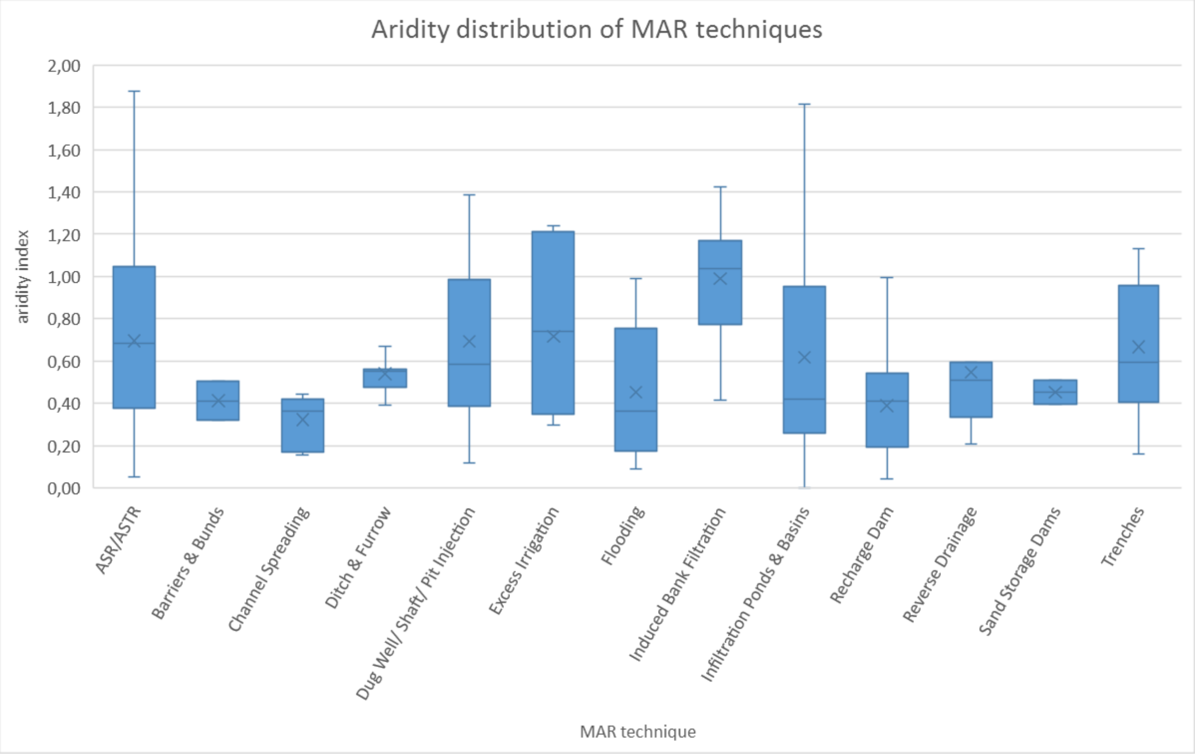


Figure 63: Box and Whisker plot of aridity distribution among MAR techniques

The aridity distribution shows that most techniques operate in arid to humid regions, the values are well distributed. MAR techniques that are mainly seen in arid and semi-arid regions are barriers and bunds, channel spreading, flooding, recharge dams and reverse drainage. MAR techniques that mostly operate in humid regions are AS(T)R, Ditch & Furrow, ‘dug well/shaft/pit injection’, excess irrigation, induced bank filtration and trenches.

Precipitation

As rainfall is seen as one of the main climate factors for MAR, a global precipitation map has been used. This map, made with data from WorldClim, is shown in Appendix F.

Boxplots with and without outliers have been created. The results of the distribution of precipitation among MAR techniques (without outliers) are shown in Figure 64. The results with outliers are shown in Figure 65.

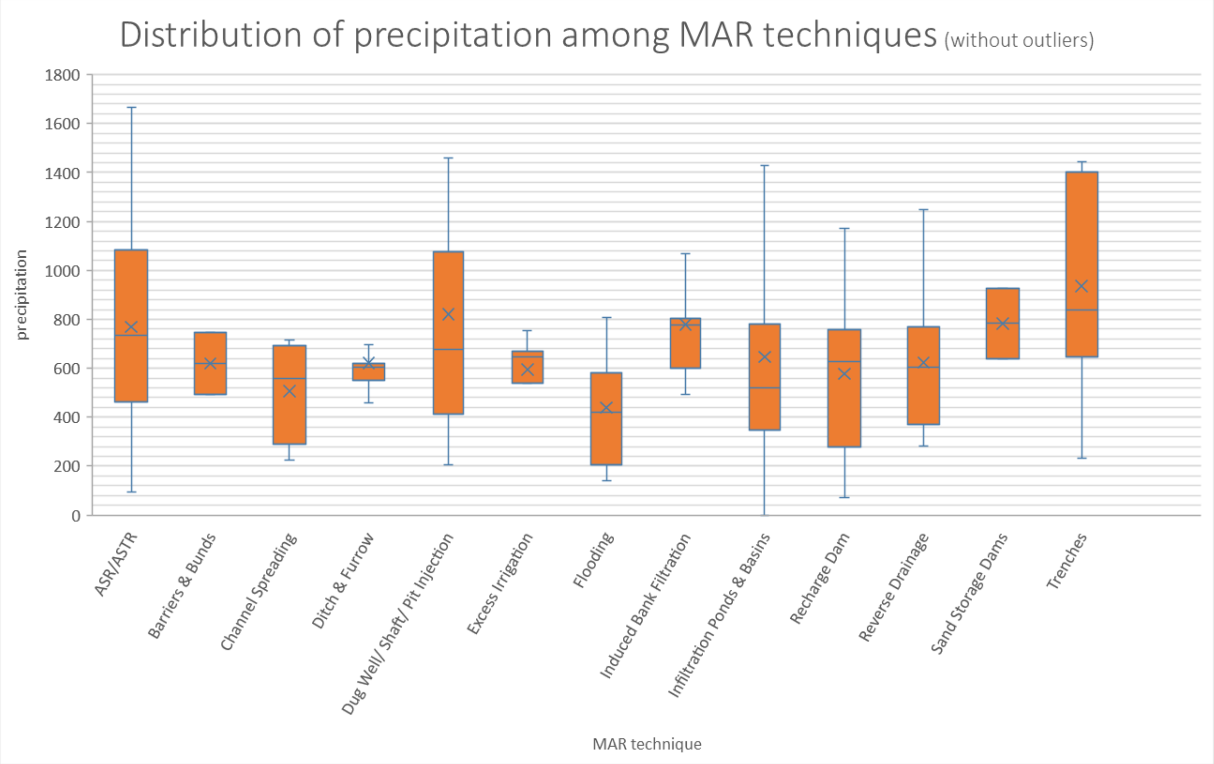


Figure 64: Box and Whisker plot (without outliers) of the distribution of precipitation among MAR techniques.

MAR techniques are located in areas with a wide variety of annual precipitation values. The largest spread is seen for AS(T)R and for infiltration ponds and basins. Trenches stand out in being located in comparison to the other techniques in areas with high rainfall. In areas with low rainfall, flooding techniques stand out.

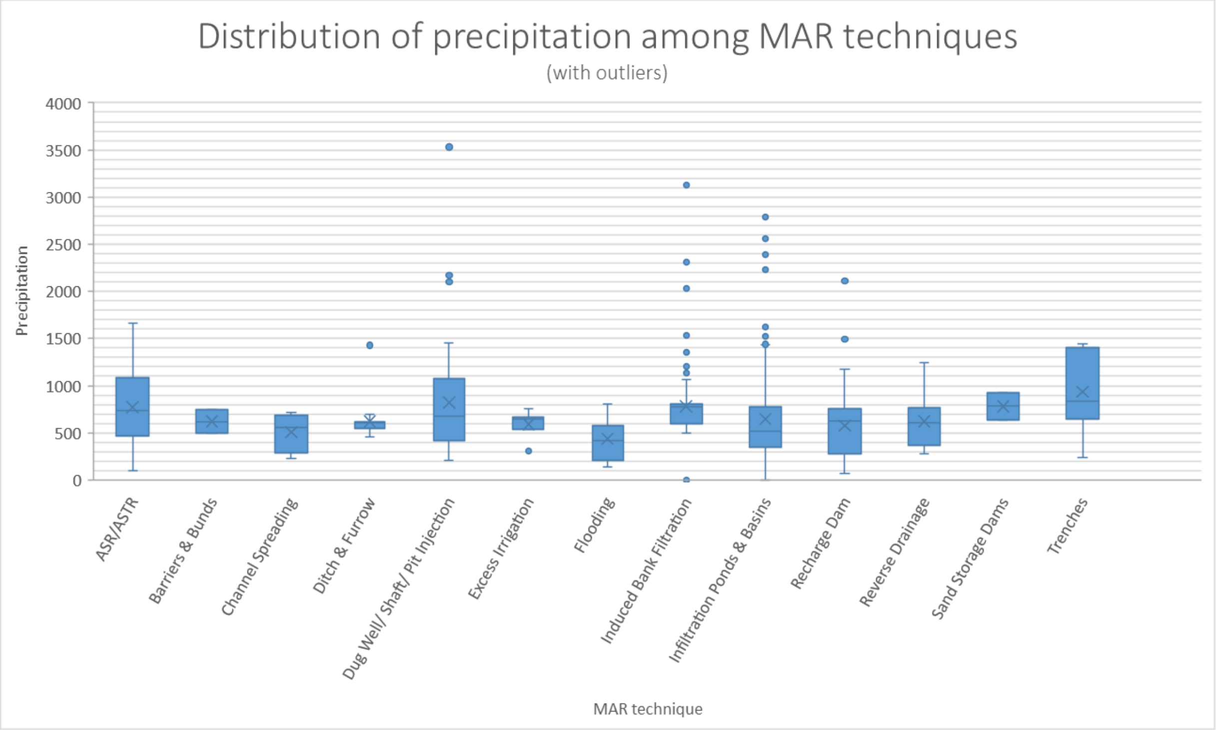


Figure 65: Box and Whisker plot (with outliers) of the distribution of precipitation among MAR techniques.

Outliers with a high annual precipitation are seen for ‘dug well/shaft/pit injection’, induced bank filtration and infiltration ponds and basins.

7.4 Socioeconomic

The results of the human development (HDI) distribution are shown Figure 66. The classification of the HDI, made by the United Nations Development Programme (UNDP), is shown in Table 22.

Level of human development	HDI range
Low (underdeveloped)	0- 0.550
Medium (developing)	0.550–0.699
High (developed)	0.700–0.799
Very high (developed)	0.800-1

Table 22: Classification of the human development index (UNDP, 2015)

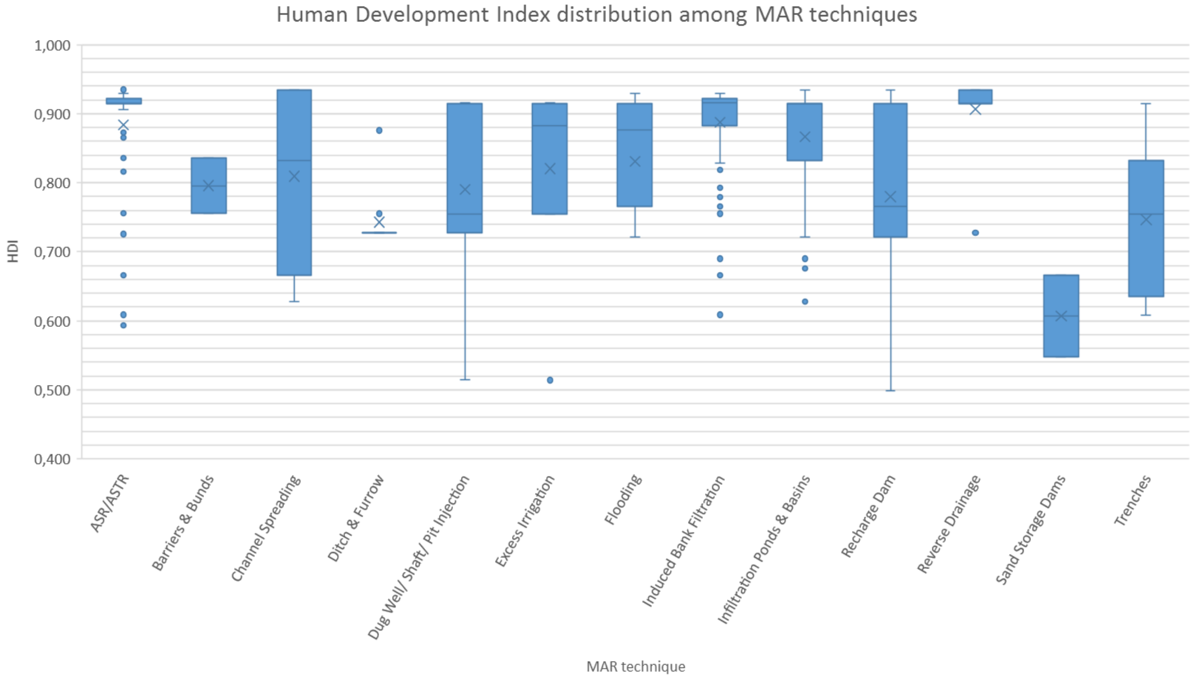


Figure 66: Box and whisker plot of HDI distribution among MAR techniques

The human development index is high among all techniques, except sand dams. The largest spread in HDI values is seen for dug well/shaft/pit injection and for recharge dams. For both of these techniques, HDI values are skewed to the top. AS(T)R and reverse drainage techniques are particularly found in countries with a very high HDI.

8 Discussion

In paragraph 8.1, 8.2 and 8.3 the results of the first three research steps will be discussed and the barriers and opportunities found in these steps will be described. In paragraph 8.4, the hypotheses formed after the literature study (step 1-3) will be discussed in the light of the results from the case studies (step 4). In paragraph 8.5, 8.6, 8.7 the reliability of the results, the policy implications and the scientific implications will be discussed respectively.

Opportunities are mostly chances that are currently unused. Above that, they are ways to overcome barriers and they can show the benefits of using/not using a certain factor. Barriers are factors that obstruct implementation or block opportunities.

8.1 First Step: Why and where

General interpretation and most significant findings

Climate change will have a large impact on natural recharge; strong decreases but also (less strong) increases could be seen by 2050.

Groundwater storage is to prefer over surface water storage on the following hydrogeological factors: storage volumes, resource areas, flow velocities, residence times, drought vulnerability, evaporation losses and pollution vulnerability. Surface water storage has the preference in the factors resource evaluation and abstraction impacts. For socioeconomic factors, groundwater storage has the preference over surface water storage in relation to development costs and development risk. Surface water storage scores better on public acceptance.

When performing MAR, there are 17 objectives that can lead to the major goals of MAR: improved quantitative and qualitative groundwater management solving long and short term water issues. The list of objectives composed of several sources should be looked at as an example. Several of the mentioned objectives overlap and MAR projects can have multiple objectives at the same time.

The objectives were linked to underlying threats that can trigger MAR. Several more links could be applicable and were not shown. Drought can be directly linked to land degradation. Also, high water abstraction does not always lead to salinization; this process can be triggered by several other factors.

There were 8 conditions identified that are typical for regions were an increased demand for groundwater storage and therefore MAR might be desired. These regions are characterized by having a large shortage of water or a large abundance of water. The regions with over-exploited aquifers, land subsidence and saline intrusion share that these conditions were created by high groundwater abstraction rates.

Barriers and opportunities

The use of MAR for cities and countries all over the world can meet the needs and interests of the four groundwater sectors; domestic, agriculture, industry and ecosystems. Looking at water storage in general, a great opportunity is the increasing water demand and use and the ensuing increasing water scarcity. These are seen as main driving forces of water storage. Together with more storage required, MAR could be more used. As groundwater is often the 1) most easily, 2) best accessible, 3) cheapest, 4) and most flexible water source for agriculture, improved management of groundwater, which could include MAR, might be the ideal solution for the agricultural sector. Other opportunities for using more groundwater are where surface water is difficult to control or when industry and households are not connected to public water services. Groundwater storage will probably gain more popularity due to the decreased popularity of the main surface water storage technique, large dam reservoirs. Dam reservoirs have negative effects and due to population growth and higher competition for land, dam reservoirs are a less and less popular option for water storage. This trend gives opportunities for MAR. There are several objectives for using MAR, for water storage and if desired as a recovery technique. MAR might be used more if it is clear what goals it can achieve. Therefore, well-argumented reasoning could give further opportunities for MAR within the overall water resource equation. The real opportunities are in regions that fulfill one or more of the eight regional conditions. MAR could also play an (if not already performed, a larger) role, in 20 large cities (more than 750.000 inhabitants) with groundwater stress and 36 large cities with surface water stress. Other major opportunities are in regions is abundant rainfall however also high water stress. Retaining and storing water in those regions could decrease water stress. Finally, the greatest need for MAR is in arid and semi-arid climates where there are water stress and a high seasonality of rainfall. MAR could have a large impact in those climates.

Barriers to MAR could be seen in that water resources do not have the same value for different water users. This could lead to conflicts between groundwater users and therefore, MAR projects. There are several reasons why groundwater should not be used and therefore are barriers to MAR. These constraints to groundwater use are insufficient groundwater quality, technical exploitation difficulties, low economic feasibility and undesired influences on the natural environment. The barriers to using groundwater or performing MAR seem to be highly site-specific and therefore have to be analyzed at the first location assessments for a MAR project. A specific barrier, seen in regions with over-exploited aquifers, is an irreversible loss of storage caused by high net water abstraction rates. Therefore, in some over-exploited aquifers, MAR is no longer a solution.

8.2 Second Step: overview of available MAR techniques

General interpretation and most significant findings

MAR techniques have been well classified in the literature and 14 types of MAR techniques were found. However, these main 14 types could again be divided into more sub-types. For example, recharge dams can be wadi dams, check dams, permeable dams and gabions. They can differ in size and material composition. Sand dams are seen as one type of recharge dam but are probably categorized as a different sub-type because they are different in water storage and design.

Barriers and opportunities

It was seen in literature that certain MAR techniques were discussed, but other closely related techniques were not mentioned. Therefore, it could be that the full extent of MAR techniques is not always known, and a knowledge database including all information could provide more suitable MAR techniques.

MAR techniques have existed for a long time, from which opportunities can arise. Lessons can be drawn from long experiences with certain MAR techniques. Also, as was seen, old MAR techniques in place might be revived, as the ‘Amunas’ in the Andes, Peru. The most can be learned from the history of infiltration ponds, ‘ditches, furrows and drains’, sand dams and induced bank filtration. These are the longest existing techniques, going far as back as 221 B.C.

Most opportunities for spreading methods are at locations where there is a highly permeable surface, a vadose zone free of low permeable layers, a water table not too high or too deep and an unconfined aquifer. If these properties are not present, they could pose barriers to the use of spreading methods as MAR technique. In case of surface spreading, clogging is often a barrier to MAR. There is an opportunity, as clogging rates can be made much lower, when the water is treated before infiltration. Most opportunities for ‘well, shaft and borehole methods’ are at locations where there are low permeability strata present above the aquifer and where there are confined aquifers. Also, where there is a deep water table, limited land availability and at locations where surface infiltration suffers from high evaporation loss, opportunities ‘well, shaft and borehole methods’ for could be present.

Opportunities and barriers for the 14 MAR techniques are summarized in Table 23. Several gaps can be seen, as without certain doubt opportunities and/or barriers were not found.

Technique	**Opportunities**	**Barriers**
Infiltration ponds	- large range in capacity - relatively low cost - simple anti-clogging measures - easy maintenance	- need to change between filled and empty to keep up infiltration rates - large land area required - potential for surface water contamination - potential for high evaporation
Soil aquifer treatment (SAT)	- Relatively simple water treatment method - Relatively low cost water treatment method	- capacity small relatively to normal wastewater treatment plants - large land area required
Flooding	-low costs	- large land area required - potential for surface water contamination - potential for high evaporation
Ditches, furrows and drains	-low costs -more water infiltrated than with flat surfaces - fewer clogging issues than with flat surfaces -controlled drainage (for saline lens control) -drains have no interference with land use	-ditches might have interference with land use -ditches have potential for surface water contamination and potential for high evaporation
Excess irrigation	-	-
Barriers and bunds	-simple design, operation and maintenance -can prevent soil erosion	Rainfall is preferably less than 1000mm/yr
Dune filtration	- large capacity	-
Aquifer storage and recovery (ASR)	- compared to surface storage less land required, no evaporation loss and less contaminations	- High costs - potentially low recoverability - not to use in aquifers with steep lateral or vertical

		gradients. -complex design, operation and maintenance -close monitoring
Aquifer storage transfer and recovery (ASTR)	-	- High costs, higher than ASR
Shallow well/ borehole/shaft recharge	- Unsaturated zone can improve water quality -low source water requirements	-more clogging than deep wells
Induced bank filtration	- large capacity	-high costs -complex design, operation and maintenance -close monitoring
(permeable) Recharge dams	-	-sediment accumulation
Sand dams	-low costs -low maintenance -simple design -reduce evaporation	- tend to need high public acceptance - only preferable for small scale
Channel widening	-	-

Table 23: Opportunities and barriers for the MAR techniques

In Table 23, it can be seen that most opportunities and barriers are seen in the following factors: costs, capacity, operation and maintenance (including clogging and monitoring), land requirement, sophistication of the technique and factors that compare to surface storage (evaporation and contamination).

8.3 Third Step: Hydrogeological, climatic, socioeconomic and institutional conditions

General interpretation and most significant findings

Hydrogeological

Although 4 types of aquifers were found to be suitable for MAR, alluvial and consolidated sandstone are probably preferred as they are highly permeable and have a large storage capacity. However, when these types are not available, MAR in fractured hard rock and carbonate aquifers should probably be the next choice. The choice of MAR technique is dependent on the aquifer type, as for example ASR is preferred for deep and clay covered aquifers and spreading methods are preferred in alluvial, sandstone and sometimes carbonate aquifers.

For surface infiltration methods, such as infiltration ponds, fewer hydrogeological factors were found to be of importance than for deep well infiltration. This can be the case as deeper aquifers are more complex or, it can be the case that the literature only describes infiltration; recovery is a less discussed topic. At least nine hydrogeological factors, all aquifer properties, were found to be of relevance to deep well injection techniques of MAR.

Hydrogeology is the study of the water and its environment beneath the land surface. This means that factors before infiltration are not part of hydrogeology. However, in the scientific literature often factors as land slope and proximity to water sources are seen as hydrogeological factors. The importance of the factors before infiltration, such as the water source, is significant. Therefore, in the list of hydrogeological, climatic, socioeconomic and institutional factors, also environmental factors should be taken into account when assessing MAR.

Socioeconomic

Public acceptance was the only social factor found in the literature to be linked directly to MAR. There are 23 possible economic factors, divided into general, capital and O&M costs, were the costs are dependent on the MAR project.

Institutional

The main issue on the institutional aspects is the issue of stakeholder conflicts. Authorities and other stakeholders have different interests; the users of groundwater have no direct incentive to recharge groundwater. This is a typical case of the ‘tragedy of the commons’. It means that a shared resource (groundwater) which is a common good, is depleted by users with only self-interest. This leads to aquifer depletion. A solution to solve this issue, found in India, was to form an authority completely focused on sustainably managing aquifers and MAR. On the regulation side, use of (international) legal texts on equitable and reasonable utilization of common use of aquifers might be helpful in this as well for national as for local authorities. This might be used as a prerequisite by financing agencies.

Barriers and opportunities

Hydrogeological

It was found that unconfined aquifers are an opportunity if the aim is to store large amounts of water quickly. Confined aquifers are an opportunity if the aim is to stop land subsidence. Also, confined aquifers have better-protected water quality than unconfined aquifers. Thick aquifers have potentially a large storage capacity, which is an opportunity to MAR. Opportunities for MAR with recovery as an essential aspect, are in aquifers with a gentle lateral hydraulic gradient. A steep gradient causes infiltrated water to travel away from the point of infiltration which could reduce the recovery rate. It was found that both aerobic and anaerobic conditions have different opportunities, depending on the goal. If it is necessary to inactivate pathogens and endocrine disrupting chemicals, aerobic conditions are preferred, if biodegradation of trihalomethanes is required, anaerobic conditions are best.

Confined aquifers can be a barrier to MAR, as they can have a lower storage capacity. Also, for confined aquifers usually (more expensive and more complex) deep well techniques are required as surface infiltration methods do not work for confined aquifers. Thin aquifers can be a barrier to MAR as their storage capacity is potentially lower than thick aquifers. Groundwater salinity can be a barrier to recovery.

Climatic

The only climatic factor found to relate to MAR was rainfall. The amount of rainfall can be a barrier and an opportunity to MAR (with storm runoff as source). At low to moderate (400-700 mm/yr) rainfall rates, recharge is the highest. Therefore, low to moderate rainfall is probably the ideal amount of rainfall for MAR.

Socioeconomic

An opportunity, especially in countries with a low trust in the water authorities, is that MAR can disconnect the toilet-to-tap connection for MAR techniques using wastewater. In addition, it can alleviate religious taboos. Therefore, in countries with public distrust in using wastewater, MAR has opportunities. As cost-benefit analyses are done for most water projects around the world, it can be essential to value benefits of the implementation of a (water) project. There are several ways to monetize the benefits of MAR, which could provide substantiated arguments for policy makers to the economical aspect of MAR.

The cost of MAR can be dependent on numerous factors, which can make the cost inventory complex. There are three economic concepts that are easily overlooked: criticality of opportunity costs, partial versus total solutions and the irrelevance of sunk costs. If these economic concepts are not considered, costs of MAR can be higher than necessary. Another economic barrier to MAR is that in cost-benefit analyses, often a government perspective is taken. This top-down approach might lead to stakeholder conflicts.

Institutional

Institutional barriers are that the users of groundwater do not often have a direct interest in groundwater recharge, that government authorities on groundwater/MAR can be missing and that stakeholder conflicts exist. In extrapolating this study to worldwide managing of MAR projects, probably for most MAR projects stakeholder conflicts do indeed exist. Therefore, a pressing question is if the public domain is sufficiently involved in water management. From that, the question emerges: which countries do have public water authorities? Are there water authorities focusing on managing groundwater or MAR projects? This might be an indicator for the success of MAR projects.

8.4 Fourth step: case studies

General interpretation

Barriers and bunds, sand dams, channel spreading and excess irrigation all have less than 10 MAR projects reported in the geodatabase. They should, therefore, all be left out of analyses or treated with caution, as conclusions may be founded on too low numbers.

Not all MAR techniques found in the literature do exist in the MAR projects used from the global MAR database of IGRAC. Also, some techniques do have different names. Ditch furrow, reverse drainage and trenches are in the discussion taken as part of ‘ditches, furrow and drains’. An overview of all the differences between the names of the techniques in literature and the data can be found in Appendix I.

The names of the literature study will be used where possible; otherwise, the names from the data will be used.

The hypotheses formed after the literature study (step 1-3) will now be discussed in the light of the results from the case studies (step 4).

Hydrogeological

Hypothesis: *The following techniques are expected to have a sandy unconsolidated lithology: Induced bank filtration, ditches/furrows and drains, flooding, dune filtration, infiltration ponds, SAT and barriers and bunds*.

MAR technique in literature	**MAR technique in database**	**Percentage unconsolidated sediments**
Induced bank filtration	Induced bank filtration	57%
Ditches, furrows and drains	Ditch and furrow	76 %
	reverse drainage	55 %
	trenches	37 %
flooding	flooding	46 %
Dune filtration	-	-
Infiltration ponds	Infiltration ponds and basins	48 %
SAT	-	-
Barriers and bunds	Barriers and bunds	50%

Table 24: MAR techniques with expected sandy unconsolidated lithology

For discussing the first hypothesis, sandy unconsolidated is seen as the same as unconsolidated sediments. In Table 24 can be seen that, for most of the techniques where a sandy unconsolidated lithology is expected, they do show close to 50% or over 50% of the MAR projects having this type of lithology. The technique where sandy unconsolidated lithology is seen the least are trenches. Reasons for this are unclear, however, the number of cases assessed was low (N=17), therefore single cases influence the data to a large extent. The country distribution was heterogeneous (5 countries). Other lithology types for trenches were sedimentary, volcanic and metamorphic rocks. For almost all MAR techniques (not only the ones stated in the hypothesis), also the techniques with less than 50%, the most seen type of lithology is sandy unconsolidated. The explanation for the high percentage sandy unconsolidated lithology for ‘ditch and furrow’ might be due to the homogenous country distribution of this MAR technique, as 90% of the cases are in China. The MAR techniques which do not have their lithology made up of the largest part of sandy unconsolidated lithology are barriers and bunds, channel spreading, sand dams and excess irrigation. They will not be discussed as these MAR techniques do not have enough data present. SAT and dune filtration techniques are not present in the data.

Climate

Hypothesis: *MAR is primarily seen in arid and semi-arid countries*.

Most MAR projects are seen in warm temperate (C) climates. If this hypothesis is true, MAR has to be primarily seen in BWk and Bwh (arid) climates and in BSk and Bsh (semi-arid) climates. However, B (arid) climates make up only 140 MAR projects of the 905 MAR projects (or 15% of the total) with assigned climates. The reason that there are in total 905 MAR projects with assigned climates, instead of the 894 MAR projects analyzed, is probably that 11 projects have 2 climates assigned to them in ArcMap. Therefore, MAR is not primarily seen in arid and semi-arid countries, it is primarily seen in warm temperate climates. Linking this trend to the other data results, the same trend is seen in water stress, precipitation and aridity. The latter could bring confusion, as most of the techniques have MAR projects in arid regions. Looking at the number of cases per technique however, shows that the largest techniques (infiltration ponds, AS(T)R and induced bank filtration) have most of their cases located in more humid regions. The reason that MAR is primarily seen in more humid regions can be the case due to several factors. It could be that MAR is less practiced in arid and semi-arid regions because they are in general less developed. From the HDI distribution in the results it follows that it is high for almost all MAR techniques. Lower development could pose financial constraints to MAR. Another factor could be that the MAR projects in arid and semi-arid regions are less reported in the database of IGRAC.

Dwc, Dwd Dsc, Dfd, Cfc, Cwc, Csc, EF and ET climates might be seen as barriers or opportunities for MAR as no MAR projects around the world were found in these climates.

Socioeconomic

Hypothesis: *As AS(T)R is one of the most expensive MAR techniques, this technique will only be found in highly developed countries (very high HDI, > 0.8).*

Almost all AS(T)R techniques are in highly developed countries, as all values except the outliers are located above an HDI of 0,9. Country distribution is essential information for the HDI analysis, as HDI is at country level. As most of the projects are located in developed countries, the HDI will be higher in general. The uneven country distribution of MAR projects globally, has a large effect on the HDI results in this study, and should be looked at with caution. Most ASR techniques are located in the USA and in Australia, both highly developed countries. At the AS(T)R boxplot several low outliers can be seen. In further research these outliers could be analyzed in order to find out if a low HDI (developing countries) might pose opportunities for MAR.

8.5 Overview of barriers and opportunities to MAR

A summarization of all the discussed hydrogeological, climatic, socioeconomic and institutional barriers and opportunities is shown in Table 25.

Type of factor	Factor	Barrier	Opportunity
Hydrogeological	Groundwater quality/salinity	to recovery, if low quality	-
	Influences on the natural environment	If undesired	If positive; to rehabilitate ecosystems
	Irreversible loss of storage	to practice MAR	Can be prevented if timely
	Technical exploitation issues	to practice MAR	-
	Clogging	to lifespan MAR project	As water can be treated before infiltration
	Highly permeable surface	-	for spreading methods
	Low permeable strata in the vadose zone	for spreading methods	for deep well infiltration
	Deep water table	for spreading methods	for deep well infiltration
	High, but not too high, water table	for deep well infiltration	for spreading methods
	Unconfined aquifer	-	for spreading methods if aim is to store large amount
	Confined aquifer	for spreading methods possible lower storage capacity	to stop land subsidence protected water quality
	Aquifer thickness	If thin; lower storage capacity	If thick, large storage capacity
	Hydraulic gradient	If steep; lower recovery	If gentle; higher recovery
	(An)aerobic conditions	-	Aerobic; inactivate pathogens and endocrine disrupting chemicals Anaerobic; biodegradation of trihalomethanes
	Capacity	If low	If high
	Operation and maintenance (including clogging and monitoring)	If highly needed	-
	Sophistication of the technique	If high	If low

Climatic	Rainfall	If too low or too high	If moderate If seasonality is strong
	aridity		High need, low practice
Socioeconomic	Valuating of water resources	If values differ	-
	Costs	Many different cost factors Top down-approach	Monetizing benefits possible Low-to-high cost range of techniques
	Public acceptance	If low, lack of trust	Disconnects toilet-to-tap and alleviates religious taboos for wastewater MAR
	Knowledge on MAR techniques	If not	If yes
	Increasing water demand and use		Because of need for storage and aquifer management
	Land requirement	If high	If low
Institutional	Stakeholder involvement	If conflicts	-
	Legislation	If missing	-
	Long term/short term, quality, quantity water issues	-	17 objectives for MAR

Table 25: Hydrogeological, climatic, socioeconomic and institutional barriers and opportunities found in the study.

8.6 Reliability of the results

The methodology used in this thesis is unique, in that the 4 steps of research are not based on an existing framework of investigation. They derive their logic from the exploratory character of the research, which required a broad scope. At the same time, this broad scope is probably the largest issue with the methodology as most results are based on literature study and therefore, general and with limited depth. The general character of the study also might have led to a not completely objective attention to some parts of the study. This can be seen in that the opportunities tend to have got more attention than the barriers. Another choice of literature search might have led to more barriers. When discussing barriers and opportunities it still needs to be noticed that most opportunities, if turned the other way around, can be conceived as barriers to MAR. Therefore, objectively defining opportunities and barriers is difficult.

In the study, the same data and literature were used multiple times. Authors that were cited the most: Maliva & Missimer (2012), Dillon et al. (2009), Dillon et al. (2012) and Margat & van der Gun (2013). Topics like stakeholder analyses, were composed of one or few sources. This can lead to a low external validity, if these 'examples' are generalized to the world. The same argument counts for the studies on MAR techniques that use storm water as a water source (Central Ground Water Board, 2007; Mankad & Walton, 2015). It is essential before generalizing the results used from these studies to all MAR projects, to check what water source is used for infiltration. Another discussion point of unreliability of the sources are the non-scientific (and not peer reviewed) sources. These 'grey' sources can provide useful information but are not always completely objective.

The global MAR database created recently by IGRAC was used extensively for this study. The database consists of a lot of MAR projects. It is however, still a sample of all MAR projects around the world. It is unclear how representative this sample is for all MAR project worldwide.

8.7 Policy implications

For MAR policy makers, several useful 'products' resulted from the study. Policy makers could use a list of objectives to substantiate arguments for planning and implementing a MAR project. Economists in the field of MAR can use a detailed list of possible costs factors; it is up to them to decide which factors be taken into account. For hydrologists the list of hydrogeological factors might be useful preventing them to overlook relevant factors.

The recommendation resulting from this research study is that MAR should be considered more frequently wherever in the world. The advantages do clearly out-weigh the disadvantages. More importantly, MAR has the ability to fulfill humankind's basic needs for safe and clean water.

Therefore, it is paramount to bring the topic of groundwater storage to the attention of policy makers by showing the importance and the (economic) opportunities. In education programs attention to the importance of groundwater and its reservoir will make people better aware of its benefits for people and ecosystems. Moreover, an (online) knowledge network or community, exchanging knowledge and experiences on MAR would be valuable.

8.8 Scientific implications

This study was for a large part an overview study. It combined literature sources and created new insights by combining different literature and data sources in a four-step framework. The study also created the first historical overview of MAR techniques worldwide. By comparing this overview with data, it showed that the historical overview of MAR in the available literature is incomplete. Literature with data comparison also showed that even though most studies are focused on arid and semi-arid climates, only a small part of the MAR projects are in those climates. The lists with combined state-of-the-art information composed from several sources on hydrogeological factors, cost factors and objectives for MAR add clarity to science, as this information was up till now more fragmented.

Further research

It is recommended that all the knowledge gaps created by this study should be studied further. Several gaps were seen in the structured overview of the techniques. More quantitative information is required on the costs and capacities of the 14 MAR techniques. In further research into MAR, it can be useful if a map of groundwater resources is used. This map could provide insights in the currently available groundwater and annual natural recharge. UNESCO and BGR (2008) made a global groundwater resources map; however, this map was unfortunately not used (WHYMAP, 2008). No aquifer thickness map was obtained, which is an essential hydrogeological factor. A review of an aquifer thickness and permeability map under development was done by De Graaf et al. (no date). Also, this map could be used in future research in assessing the potential for MAR. Furthermore, it is recommended to create a potential map of the opportunities and barriers worldwide. This study could provide a basis for potential mapping of MAR. Although this study showed that local factors are important, global MAR potential mapping might show new opportunities and barriers.

Recommendations for improvements on the global MAR projects database are to add for all projects capacity and costs. Dune filtration and SAT, now included in the category infiltration ponds, could be categorized as own categories, in order to show their use.

More studies that are recommended should touch upon the following topics: Reasons that MAR is less practiced in arid and semi-arid regions, historical studies, mapping need for authorities on groundwater/MAR and financing of (relatively expensive) AS(T)R projects in developing countries.

9 Conclusions

This multi-disciplinary study looked for solutions for water scarcity and groundwater management issues worldwide. The main research question was: *What are the barriers and opportunities for managed aquifer recharge in different climatic, hydrogeological, institutional and socioeconomic settings that exist around the world*? In the discussion, all the barriers and opportunities for MAR were concluded from the results of the study. In total, 22 barriers and 22 opportunities in different climatic, hydrogeological, institutional and socioeconomic settings were found.

The hydrogeological barriers and opportunities comprise the following factors: groundwater quality/salinity, influences on the natural environment, irreversible loss of storage, technical exploitation issues, clogging, highly permeable surfaces, low permeable strata in the vadose zone, deep water tables, ‘high, but not too high’ water tables, confinement of the aquifer, aquifer thickness, hydraulic gradient, (an)aerobic conditions, capacity, operation and maintenance and sophistication of the techniques. Climatic barriers and opportunities are related to the factors rainfall and aridity. Socioeconomic barriers and opportunities revolve around the following factors: valuating of water resources, costs, public acceptance, knowledge on MAR techniques, increasing water demand and use, and land requirement. Institutional barriers and opportunities are seen in stakeholder involvement, legislation and ‘long /short term and quality/quantity water issues.

The study revealed two main insights: First, while the highest need for MAR is in arid and semi-arid regions, currently only a small number of the total MAR projects are in arid and semi-arid regions. Therefore, the greatest opportunities are located in regions with arid and semi-arid regions. This does not mean that there are fewer opportunities in other climates. Humid regions, especially with excess water issues can also have a major need for MAR. Second, no specific additional barriers were found.

Policy recommendations resulting from this study leads to a clear message: for meeting the growing needs of fresh water, there are few reasons that MAR should not be used and thus should it be a standard item into all environmental programs. Policy makers should incorporate MAR in their programs, as should the education and academic sector. Recommendations for scientists include multi-disciplinary studies on MAR and further search of the potential for MAR.

The influences of the different settings around the world on MAR show that it is strongly bound to local and regional conditions. Therefore, although MAR can offer solutions to water scarcity and groundwater management issues around the world, local and regional conditions have to be considered.

References

Aeschbach-Hertig, W. & T. Gleeson. (2012), Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience 5(12), pp.853-861.

Arshad, M., J.H. Guillaume & A. Ross. (2014), Assessing the feasibility of managed aquifer recharge for irrigation under uncertainty. Water 6(9), pp.2748-2769.

Assmuth, T., A. Simola, T. Pitkänen, J. Lyytimäki & T. Huttula. (2016), Integrated frameworks for assessing and managing health risks in the context of managed aquifer recharge with river water. Integrated Environmental Assessment and Management 12(1), pp.160-173.

Atlantis. (2014). FLO-TANK® MODULES (online). Retrieved 07-06-2016. Available on the world wide web: <http://www.atlantis-america.com/index.php/product-menu/modular-water-tanks/flo-tank-module>.

Baker, E.H. (2014). Socioeconomic status, definition. The Wiley Blackwell Encyclopedia of Health, Illness, Behavior, and Society. John Wiley & Sons, Ltd.

Bekele, E., S. Toze, B. Patterson, B. Devine, S. Higginson, W. Fegg & J. Vanderzalm. (2009), Design and operation of infiltration galleries and water quality guidelines-Chapter 1. Determining the Requirements for Managed Aquifer Recharge in Western Australia.

Bhalerao, S.A. & T.S. Kelkar. (2013), Artificial recharge of groundwater: A novel technique for replenishment of an aquifer with water from land surface. International Journal of Geology, Earth and Environmental Sciences 3, pp.165-183.

Bouwer, H. (2002), Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeology Journal 10(1), pp.121-142.

Brunner, N., M. Starkl, P. Sakthivel, L. Elango, S. Amirthalingam, C.E. Pratap, M. Thirunavukkarasu & S. Parimalarenganayaki. (2014), Policy preferences about managed aquifer recharge for securing sustainable water supply to chennai city, India. Water 6(12), pp.3739-3757.

Central Ground Water Board. (2007). manual on artificial recharge of ground water (online). Faridabad: Ministry of water sources.

Chinnasamy, P., G. Misra, T. Shah, B. Maheshwari & S. Prathapar. (2015), Evaluating the effectiveness of water infrastructures for increasing groundwater recharge and agricultural production – A case study of Gujarat, India. Agricultural Water Management 158, pp.179-188.

Cisneros, B. E. J., Jiménez, B. & Asano, T. (2008). Water reuse: an international survey of current practice, issues and need.IWA publishing.

Connor, R. (2015). The United Nations world water development report 2015: water for a sustainable world.UNESCO Publishing.

de Graaf, I.E., R.L. van Beek, T. Gleeson, N. Moosdorf, O. Schmitz, E.H. Sutanudjaja & M.F. Bierkens. A global-scale two-layer transient groundwater model: development and application to groundwater depletion.

Delsman J., J.M. De Paz, M. De Klerk, L. Stuyt, P. De Louw, F. Visconti, M. Del Longo & S. Pecora. (2015). Application of the FWOO method in the Vega Baja Segura catchment: Potential for local solutions to optimize fresh water supply in European regions under increasing water stress (online No. 1220325-000) Deltares.

Dillon, P. J., Escalante, F. E. & Tuinhof, A. (2012). Management of Aquifer Recharge and Discharge Processes and Aquifer Storage Equilibrium: IAH Contribution to GEF-FAO Groundwater Governance Thematic Paper 4. CSIRO.

Dillon, P.J., P. Pavelic, D. Page, H. Beringen & J. Ward. (2009), Managed aquifer recharge. An introduction Waterlines Report Series(13)

Dillon, P., S. Toze, D. Page, J. Vanderzalm, E. Bekele, J. Sidhu & S. Rinck-Pfeiffer. (2010), Managed aquifer recharge: rediscovering nature as a leading edge technology. Water Science and Technology 62(10), pp.2338.

Dillon, P. (2005), Future management of aquifer recharge. Hydrogeology Journal 13(1), pp.313-316.

Dillon, P., I. Gale, S. Contreras, P. Pavelic, R. Evans & J. Ward. (2009a), Managing aquifer recharge and discharge to sustain irrigation livelihoods under water scarcity and climate change. IAHS Publication 330, pp.1-12.

Dillon, P., P. Pavelic, D. Page, H. Beringen & J. Ward. (2009b), Managed aquifer recharge. An introduction Waterlines Report Series.(13)

Dokoozlian, N., V. Petrucci, J. Ayars, C. Clary & R. Schoneman. (1987), artificial ground water recharge by flooding during grapevine dormancy.

Döll, P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg & B. Scanlon. (2012), Impact of water withdrawals from groundwater and surface water on continental water storage variations. Journal of Geodynamics 59, pp.143-156.

Dolowitz, D.P. & D. Marsh. (2000), Learning from abroad: The role of policy transfer in contemporary policy-making. Governance 13(1), pp.5-23.

EIP Water. (2016). MAR Solutions - Managed Aquifer Recharge Strategies and Actions (AG128) (online). Retrieved 03/21, 2016. Available on the world wide web: <http://www.eip-water.eu/MAR_Solutions>.

Environmental Protection Agency (EPA). (2016). Aquifer Recharge and Aquifer Storage and Recovery (online). Retrieved 23-05-2016. Available on the world wide web: <https://www.epa.gov/uic/aquifer-recharge-and-aquifer-storage-and-recovery#main-content>.

Escalante, E. F. (2010). La gestión de la recarga artificial de acuíferos en el marco del desarrollo sostenible desarrollo tecnológico. Madrid: Grafinat.

Escalante, E.F., R.C. Gil, San Miguel Fraile, María Á & F.S. Serrano. (2014), Economic Assessment of Opportunities for Managed Aquifer Recharge Techniques in Spain Using an Advanced Geographic Information System (GIS). Water 6(7), pp.2021-2040.

Escalante, E.F. & J.S.S. Sauto, eds. (2012), rechargable sustainability: the key is the storage. Spain: TRAGSA. <http://www.dina-mar.es/pdf/DM-Rechargeable%20sustainability-en-sp.pdf>

ESRI, DeLorme Publishing Company, Inc. (2014). World Countries, ESRI. <https://www.arcgis.com/home/item.html?id=3864c63872d84aec91933618e3815dd2>

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, (2000).

Gale, I. (2005). Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas.UNESCO.

Gale, I., D. Macdonald, R. Calow, I. Neumann, M. Moench, H. Kulkarni, S. Mudrakartha & K. Palanisami. (2006), Managed aquifer recharge: an assessment of its role and effectiveness in watershed management: Final report for DFID KAR project R8169, Augmenting groundwater resources by artificial recharge: AGRAR.

Gammie G. & B. De Bievre. (2015). Assessing Green Interventions for the Water Supply of Lima, Peru (onlineForest Trends. Retrieved 09-05-2016. <http://www.forest-trends.org/documents/files/doc_4896.pdf>

Gassert, F., M. Landis, M. Luck, P. Reig & T. Shiao. (2013), Aqueduct global maps 2.0. Water Resources Institute (WRI): Washington, DC

Gau, H., C. Hsieh & C. Liu. (2006), Application of grey correlation method to evaluate potential groundwater recharge sites. Stochastic environmental research and risk assessment 20(6), pp.407-421.

Ghayoumian, J., M.M. Saravi, S. Feiznia, B. Nouri & A. Malekian. (2007), Application of GIS techniques to determine areas most suitable for artificial groundwater recharge in a coastal aquifer in southern Iran. Journal of Asian Earth Sciences 30(2), pp.364-374.

Gleeson, T., Y. Wada, M.F. Bierkens & L.P. van Beek. (2012), Water balance of global aquifers revealed by groundwater footprint. Nature 488(7410), pp.197-200.

Hartmann, J. & N. Moosdorf. (2012), The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophysics, Geosystems 13(12)

Harvey, L. D. (2000). Global warming, the hard science. United Kingdom: Pearson Education Limited.

Hendriks, M. (2010). Introduction to physical hydrology. Oxford University Press.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones & A. Jarvis. (2005), Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25(15), pp.1965-1978.

Holden, J., L.J. West, A.J. Howard, E. Maxfield, I. Panter & J. Oxley. (2006), Hydrological controls of in situ preservation of waterlogged archaeological deposits. Earth-Science Reviews 78(1), pp.59-83.

Hoogvliet M., H. Van Meerten, M. Paalman, M. Van der Schans, R. Stuurman & K. Broks. (2016). Ondergronds bergen en terugwinnen van water in stedelijk gebied: een verkenning van mogelijkheden (online No. 1). Amersfoort: STOWA.

IGRAC. (2007). Artificial Recharge of Groundwater in the World.IGRAC.

IGRAC. (2016a). Global MAR inventory (online). Retrieved 24-02-2016. Available on the world wide web: <https://ggis.un-igrac.org/ggis-viewer/viewer/globalmar/public/default>.

IGRAC. (2016b). Managed Aquifer Recharge (MAR) (online). Retrieved 01-03-2016. Available on the world wide web: <http://www.un-igrac.org/node/35>.

Kalbus, E., T. Kalbacher, O. Kolditz, E. Krüger, J. Seegert, G. Röstel, G. Teutsch, D. Borchardt & P. Krebs. (2012), Integrated water resources management under different hydrological, climatic and socio-economic conditions. Environmental Earth Sciences 65(5), pp.1363-1366.

Keller A., R. Sakthivadivel & D. Seckler. (2000). Water Scarcity and the Role of Storage in Development (Research report No. 39). Colombo Sri Lanka: International Water Management Institute (IWMI).

Konikow, L.F. (2011), Contribution of global groundwater depletion since 1900 to sea-level rise. Geophysical Research Letters 38(17)

Kottek, M., J. Grieser, C. Beck, B. Rudolf & F. Rubel. (2006), World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15(3), pp.259-263.

Krajcik, J. S. & Blumenfeld, P. C. (2006). Project-based learning.na.

Lasage, R. & P.H. Verburg. (2015), Evaluation of small scale water harvesting techniques for semi-arid environments. Journal of Arid Environments 118, pp.48-57.

Lehmann, J., D. Coumou & K. Frieler. (2015), Increased record-breaking precipitation events under global warming. Climatic Change 132(4), pp.501-515.

Maddrell, S. (2016), Securing water supplies with sand dams. Ingenia, (66)

Mahdavi, A., S. Tabatabaei, R. Mahdavi & M. Nouri Emamzadei. (2013), Application of digital techniques to identify aquifer artificial recharge sites in GIS environment. International Journal of Digital Earth 6(6), pp.589-609.

Maimone, M., D. O'Rourke, J. Knighton & C. Thomas. (2011), Potential impacts of extensive stormwater infiltration in Philadelphia. Environmental Engineer 14, pp.29-39.

Maliva, R.G. & T. Missimer. (2012). Managed aquifer recharge. Arid Lands Water Evaluation and Management.pp. 559-630.Springer.

Maliva, R.G. (2014), Economics of managed aquifer recharge. Water 6(5), pp.1257-1279.

Mankad, A. & A. Walton. (2015), Accepting managed aquifer recharge of urban storm water reuse: The role of policy-related factors. Water Resources Research 51(12), pp.9696-9707.

Margat, J. & Van der Gun, J. (2013). Groundwater around the world: a geographic synopsis. CRC Press.

MARSOL. (2016). DEMO Site 7: Menashe Infiltration Basin, Hadera, Israel (online). Retrieved 14-06- 2016. Available on the world wide web: <http://www.marsol.eu/19-0-Menashe-.html>.

McDonald, R.I., K. Weber, J. Padowski, M. Flörke, C. Schneider, P.A. Green, T. Gleeson, S. Eckman, B. Lehner, D. Balk, T. Boucher, G. Grill & M. Montgomery. (2014), Water on an urban planet: Urbanization and the reach of urban water infrastructure. Global Environmental Change 27, pp.96-105.

Mekonnen, M.M. & A.Y. Hoekstra. (2016), Four billion people facing severe water scarcity. Science advances 2(2), pp.e1500323.

MEMOLA. (2014). historical/current water use (online). Retrieved 05-02-2016. Available on the world wide web: <http://www.memolaproject.eu/sierra-nevada/wateruse>.

Missimer, T.M., J.E. Drewes, R.G. Maliva & G. Amy. (2011), Aquifer recharge and recovery: groundwater recharge systems for treatment, storage, and water reclamation. Ground Water 49(6), pp.771-771.

Missimer, T.M., W. Guo, R.G. Maliva, J. Rosas & K.Z. Jadoon. (2015), Enhancement of wadi recharge using dams coupled with aquifer storage and recovery wells. Environmental Earth Sciences 73(12), pp.7723-7731.

Mount, J. & R. Twiss. (2005), Subsidence, sea level rise, and seismicity in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science 3(1)

Nakicenovic, N. & R. Swart. (2000), Special report on emissions scenarios. Special Report on Emissions Scenarios, Edited by Nebojsa Nakicenovic and Robert Swart, pp.612.ISBN 0521804930.Cambridge, UK: Cambridge University Press, July 2000. 1

Natuurwegwijzer.nl. (2016). Amsterdamse Waterleidingduinen (online). Retrieved 11-06-2016. Available on the world wide web: <http://www.natuurwegwijzer.nl/route/amsterdamse-waterleidingduinen/detail_gebied=1005_000000_000000_000167>.

Neumayer, E. (2001), The human development index and sustainability — a constructive proposal. Ecological Economics 39(1), pp.101-114.

NRWM. (2015). Restoration of natural infiltration to groundwater (online). Retrieved 04-06-2016. Available on the world wide web: <http://www.nwrm.eu/measure/restoration-natural-infiltration-groundwater>.

Oosterbaan, R. (1988), Effectiveness and social/environmental impacts of irrigation projects: A critical review. ILRI Annual Report 1988, pp.18-34.

Pachauri, R.K., M. Allen, V. Barros, J. Broome, W. Cramer, R. Christ, J. Church, L. Clarke, Q. Dahe & P. Dasgupta. (2014), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Peel, M.C., B.L. Finlayson & T.A. McMahon. (2007), Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences Discussions Discussions 4(2), pp.439-473.

Pereira, L.S., I. Cordery & I. Iacovides. (2002), Coping with water scarcity. Technical Documents in Hydrology, no. 58.

Pervin, M. (2015). Potential and challenges of managed aquifer recharge in an over exploited aquifer of Dhaka City. Unpublished Master, Dhaka University of Engineering and Technology.

Pierce, F. (2015), Pre-Inca canals may solve Lima's water crisis (online). New Scientist

Rahman, M.A., B. Rusteberg, R. Gogu, J.L. Ferreira & M. Sauter. (2012), A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. Journal of environmental management 99, pp.61-75.

Ramli, M., T.J.r. Karasu & E.T. Dawood. (2013), The stability of gabion walls for earth retaining structures. Alexandria Engineering Journal 52(4), pp.705-710.

Renganayaki, S.P. & L. Elango. (2013), A review on managed aquifer recharge by check dams: a case study near Chennai, India. International Journal of Research in Engineering and Technology 2(4), pp.416-423.

Richey, A.S., B.F. Thomas, M. Lo, J.T. Reager, J.S. Famiglietti, K. Voss, S. Swenson & M. Rodell. (2015), Quantifying renewable groundwater stress with GRACE. Water Resources Research 51(7), pp.5217-5238.

Sanford, W. (2002), Recharge and groundwater models: an overview. Hydrogeology Journal 10(1), pp.110-120.

Scheibler F., S. Hannappel, C. Sprenger, N. Hartog, G. Grützmacher, C. Reger, A. Huber, Rejman-Rasinska, M. Hernandez Garcia & E. Vilanova. (2015). Overview of European Managed Aquifer Recharge (Online). presentation Demeau-fp7.

Schmidt, C.K., F. Lange, H. Brauch & W. Kühn. (2003). Experiences with riverbank filtration and infiltration in germany. Paper presented at the International Symposium on Artificial Recharge of Groundwater. K-WATER, Daejon, Korea, pp.117-131.

Schubert, J. (2002), Hydraulic aspects of riverbank filtration—field studies. Journal of Hydrology 266(3–4), pp.145-161.

Schulte, P. (2014). Defining Water Scarcity, Water Stress, and Water Risk: It’s Not Just Semantics (online). Retrieved 02-06-2016. Available on the world wide web: <http://pacinst.org/water-definitions/>.

Shah, T. (2009), Climate change and groundwater: India’s opportunities for mitigation and adaptation. Environmental Research Letters 4(3), pp.035005.

Shah, T. (2014), Towards a Managed Aquifer Recharge strategy for Gujarat, India: An economist’s dialogue with hydro-geologists. Journal of Hydrology 518, pp.94-107.

Stephan R. M. (2009). Transboundary aquifers: managing a vital resource (online). Paris: UNESCO.

Stuyfzand, P. (2015). Managed Aquifer Recharge and Storage (online). Retrieved 24-02-2016. Available on the world wide web: <http://www.hydrology-amsterdam.nl/researchpages/Recharge.html>.

Sukhija, B. (2008), Adaptation to climate change: strategies for sustaining groundwater resources during droughts. Geological Society, London, Special Publications 288(1), pp.169-181.

Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. Van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti & M. Edmunds. (2013), Ground water and climate change. Nature Climate Change 3(4), pp.322-329.

Topper, R. E. (2004). Artificial recharge of ground water in Colorado: A statewide assessment.Colorado Geological Survey.

Tuinhof, A. & Heederik, J. P. (2003). Management of Aquifer Recharge and Subsurface Storage. Making Better Use of Our Largest Reservoir.Secretariat National Committee IAH: TNO-NITG.

Tuinhof, A., Van Steenbergen, F., Vos, P. & Tolk, L. (2012). Profit from Storage. The costs and benefits of water buffering. Wageningen, The Netherlands: 3R Water Secretariat.

UNAM. (2016). 9th international symposium on managed aquifer recharge (online). Retrieved 10-07-2016. Available on the world wide web: <http://www.ismar9.org/>.

UNDP. (2015). Human Development Report 2015: Work for Human Development. New York: United Nations Development Programme (UNDP).

UNEP. (2016). Environmental Data Explorer (online). Retrieved 18-04-2016. Available on the world wide web: <http://geodata.grid.unep.ch/>.

Convention on the Law of the Non-Navigational Uses of International Watercourses, 51/229, 51. Cong. (1997).

United Nations. (2012). The United Nations World Water Development 42 Report 4: Managing Water under Uncertainty and Risk. Paris: Unesco. Retrieved 11-06-2016.

Transforming our world: the 2030 Agenda for Sustainable Development, Resolution 70/1. U.S.C. (2015).

United Nations, Department of Economic and Social Affairs, Population Division. (2014). World Urbanization Prospects: The 2014 Revision (cd-rom)

Van Der Meulen, F. & E. Wanders. (1985). Dynamics and management of some coastal dune woodlands near the hague, the netherlands. Ecology of coastal vegetation.pp. 457-465. Springer.

Van Houtte, E. & J. Verbauwhede. (2008), AQUAREC 2006 CHEMECA 2006 Operational experience with indirect potable reuse at the Flemish Coast. Desalination 218(1), pp.198-207.

Veldkamp, T.I.E., Y. Wada, H. de Moel, M. Kummu, S. Eisner, J.C.J.H. Aerts & P.J. Ward. (2015), Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydro-climatic variability. Global Environmental Change 32, pp.18-29.

Vrba J. & B.T. Verhagen. (2006). Groundwater for emergency situations–A framework document, International Hydrological Programme VI, Series on Groundwater No. 12 (online No. 14). Paris: Unesco. Retrieved 10-05-2016.

Wada, Y., L.P. van Beek, C.M. van Kempen, J.W. Reckman, S. Vasak & M.F. Bierkens. (2010), Global depletion of groundwater resources. Geophysical Research Letters 37(20)

Wang, W., X. Sun & Y. Xu. (2010). Recent advances in managed aquifer recharge in china. Paper presented at the Challenges in Environmental Science and Computer Engineering (CESCE), 2010 International Conference On, 2, pp.516-519.

Ward, P.J., B. Jongman, M. Kummu, M.D. Dettinger, F.C. Sperna Weiland & H.C. Winsemius. (2014), Strong influence of El Nino Southern Oscillation on flood risk around the world. Proceedings of the National Academy of Sciences of the United States of America 111(44), pp.15659-15664.

Waternet. (2016). Amsterdamse Waterleidingsduinen (online). Retrieved 11-06-2016. Available on the world wide web: <https://awd.waternet.nl/>.

Weeks, E. P. (2013). A Historical Overview of Hydrologic Studies of Artificial Recharge in the U.S. Geological Survey (online). Retrieved 08-03-2016. Available on the world wide web: <http://water.usgs.gov/ogw/pubs/ofr0289/epw_historical.html>.

WHYMAP. (2008). Groundwater resources of the world, 1: 40 000 000, 1 : 25 000 000. BGR, UNESCO. <http://www.whymap.org/whymap/EN/Downloads/Global_maps/globalmaps_node_en.html>

Winsemius H.C. & P.J. Ward. (2015). Global Flood Risk Maps, World Resources Institute. <http://www.wri.org/resources/data-sets/aqueduct-global-flood-risk-maps>

Wisser, D., S. Frolking, S. Hagen & M.F. Bierkens. (2013), Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs. Water Resources Research 49(9), pp.5732-5739.

Wolf, L., H. Werz, H. Hoetzl & M. Ghanem. (2007). Exploring the potential of managed aquifer recharge to mitigate water scarcity in the lower jordan river basin within an IWRM approach. Paper presented at the Proceedings of the 6th International Symposium on Managed Artificial Recharge of Groundwater, ISMAR6, Phoenix, AZ

World bank. (2010). Deep wells and prudence : towards pragmatic action for addressing groundwater overexploitation in India (online). Washington D.C.: world bank.

World bank. (2016). Data (online). Retrieved 12-06-2016. Available on the world wide web: <http://data.worldbank.org/country/>.

Xu, Y., L. Ma, Y. Du & S. Shen. (2012), Analysis of urbanisation-induced land subsidence in Shanghai. Natural Hazards 63(2), pp.1255-1267.

Zekri, S., M. Ahmed, R. Chaieb & N. Ghaffour. (2014), Managed aquifer recharge using quaternary-treated wastewater: an economic perspective. International Journal of Water Resources Development 30(2), pp.246-261.

Zhang, W., Y. Huan, D. Liu, H. Wang, X. Jiao, X. Wu & S. Du. (2016), Influences of microbial communities on groundwater component concentrations during managed artificial recharge. Environmental Earth Sciences 75(1), pp.1-8.

Zhu, J., T. Yan, C. Yu, X. Wan, Y. Wang & Y. Li. (2014), Is national socioeconomic status related to prevalence of irritable bowel syndrome? Journal of gastroenterology and hepatology 29(8), pp.1595-1602.

Zomer, R., Trabucco, A., van Straaten, O. & Bossio, D. (2006). Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. IWMI.

Zuurbier K. G., M. Paalman & E. Zwinkels. (2012). Haalbaarheid Ondergrondse Waterberging Glastuinbouw Westland No. 2012.003. Nieuwegein: KWR Watercycle Research Institute.

Appendices

Appendix A

Concluding conditions from objectives for MAR

Reason for MAR	**Regions with these conditions**
Store water for long term storage	Everywhere
Buffer capacity for droughts/preparation for drought periods	Drought vulnerable
Smooth out demand and supply fluctuations	Everywhere
Reduce evaporation loss	High evaporation
Improve water quality	Everywhere
Store excess storm/flood water	High seasonal rainfall peaks, flooding
Manage saline intrusion	salinization of groundwater
Manage land subsidence	land subsidence
Strategic reserve for emergency situations	High seasonal rainfall peaks, flooding, drought vulnerable
Reducing runoff loss	High seasonal rainfall peaks, flooding
Recharging groundwater	Over-exploited aquifers, land subsidence
Store desalinated water	*Desalinization plants*
Improve and sustain ecosystems	Everywhere
Spare sewers of water overload	*Cities*
Conserve archeological sites	Everywhere
Provide water for domestic, agricultural and industrial use	Everywhere
Conserve wooden pile foundations	*Cities*

Table 26: concluding reasons from objectives for MAR

In bold are locations instead of regions.

Appendix B

surface water stressed cities

Country	Urban Agglomeration	Latitude	Longitude	Groundwater Footprint	WBM	WaterGap	HDI	Population (in thousands)				country income class
								2015	2020	2025	2030	
Bangladesh	Rajshahi	24,37	88,6	Not	Stressed	Stressed		844	943	1 087	1 240	lower middle
China	Changchun	43,87	125,3	Not	Stressed	Stressed		3 762	4 130	4 480	4 742	upper middle
China	Qingdao	36,07	120,38	Not	Stressed	Stressed		4 566	5 139	5 601	5 920	upper middle
China	Shanghai	31,23	121,47	Not	Stressed	Stressed		23 741	27 137	29 442	30 751	upper middle
China	Tianjin	39,09	117,17	Not	Stressed	Stressed		11 210	12 816	13 955	14 655	upper middle
China	Wuhan	30,58	114,28	Not	Stressed	Stressed		7 906	8 364	8 970	9 442	upper middle
China	Xi'an	34,26	108,94	Not	Stressed	Stressed		6 044	6 869	7 493	7 904	upper middle
Egypt	Alexandria	31,2	29,92	Not	Stressed	Stressed		4 778	5 225	5 733	6 313	lower middle
India	Agra	27,18	78,02	Not	Stressed	Stressed		1 966	2 224	2 501	2 793	lower middle
India	Aurangabad	19,86	75,36	Not	Stressed	Stressed		1 344	1 526	1 720	1 925	lower middle
India	Delhi	28,67	77,22	Not	Stressed	Stressed		25 703	29 348	32 727	36 060	lower middle
India	Gwalior	26,22	78,18	Not	Stressed	Stressed		1 221	1 365	1 534	1 718	lower middle
India	Hyderabad	17,38	78,47	Not	Stressed	Stressed		8 944	10 279	11 527	12 774	lower middle
India	Kolkata	22,5	88,33	Not	Stressed	Stressed		14 865	15 726	17 285	19 092	lower middle
India	Rajkot	22,3	70,78	Not	Stressed	Stressed		1 599	1 838	2 076	2 322	lower middle
India	Solapur	17,68	75,92	Not	Stressed	Stressed		986	1 049	1 167	1 307	lower middle
Mexico	Monterrey	25,66	-100,31	Not	Stressed	Stressed		4 513	4 875	5 194	5 471	upper middle
Mexico	Puebla	19,04	-98,21	Not	Stressed	Stressed		2 984	3 217	3 433	3 628	upper middle
Morocco	Dar-el-Beida (Casablanca)	33,59	-7,62	Not	Stressed	Stressed		3 515	3 736	4 056	4 361	lower middle
Pakistan	Karachi	24,87	67,05	Not	Stressed	Stressed		16 618	19 230	22 009	24 838	lower middle
Republic of Korea	Busan	35,1	129,04	Not	Stressed	Stressed		3 216	3 174	3 213	3 264	High: OECD
Russia	Moscow	55,75	37,62	Not	Stressed	Stressed		12 166	12 474	12 382	12 200	high: non OECD
Sweden	Stockholm	59,33	18,05	Not	Stressed	Stressed		1 486	1 589	1 678	1 757	High: OECD
United Kingdom	London	51,5	-0,12	Not	Stressed	Stressed		10 313	10 849	11 207	11 467	High: OECD
United States	Austin	30,3	-97,75	Not	Stressed	Stressed		1 684	1 938	2 079	2 182	High: OECD
United States	Dallas-Fort Worth	32,71	-97,31	Not	Stressed	Stressed		5 703	6 130	6 430	6 683	High: OECD
United States	Denver-Aurora	39,73	-104,97	Not	Stressed	Stressed		2 599	2 771	2 916	3 048	High: OECD
United States	Houston	29,76	-95,38	Not	Stressed	Stressed		5 638	6 151	6 474	6 729	High: OECD
United States	Kansas City	39,1	-94,61	Not	Stressed	Stressed		1 604	1 675	1 759	1 846	High: OECD
United States	Los Angeles	34,09	-118,38	Not	Stressed	Stressed		12 310	12 454	12 835	13 257	High: OECD
United States	McAllen	26,22	-98,24	Not	Stressed	Stressed		864	970	1 039	1 096	High: OECD
United States	Oklahoma City	35,47	-97,52	Not	Stressed	Stressed		926	978	1 033	1 089	High: OECD
United States	Omaha	41,26	-95,94	Not	Stressed	Stressed		780	826	874	922	High: OECD
United States	Phoenix-Mesa	33,44	-111,95	Not	Stressed	Stressed		4 063	4 386	4 614	4 808	High: OECD
United States	San Diego	32,78	-117,15	Not	Stressed	Stressed		3 107	3 228	3 373	3 522	High: OECD
United States	Tucson	32,21	-110,92	Not	Stressed	Stressed		913	969	1 025	1 081	High: OECD

Table 27: surface water stressed cities

Appendix C

Groundwater stressed cities

Country	Urban Agglomeration	Latitude	Longitude	Groundwater Footprint	WBM	WaterGap	HDI	Population (in thousends)				country income class
								2015	2020	2025	2030	
Bangladesh	Rajshahi	24,37	88,6	Not	Stressed	Stressed	0,57	844	943	1 087	1 240	lower middle
China	Changchun	43,87	125,3	Not	Stressed	Stressed	0,73	3 762	4 130	4 480	4 742	upper middle
China	Qingdao	36,07	120,38	Not	Stressed	Stressed	0,73	4 566	5 139	5 601	5 920	upper middle
China	Shanghai	31,23	121,47	Not	Stressed	Stressed	0,73	23 741	27 137	29 442	30 751	upper middle
China	Tianjin	39,09	117,17	Not	Stressed	Stressed	0,73	11 210	12 816	13 955	14 655	upper middle
China	Wuhan	30,58	114,28	Not	Stressed	Stressed	0,73	7 906	8 364	8 970	9 442	upper middle
China	Xi'an	34,26	108,94	Not	Stressed	Stressed	0,73	6 044	6 869	7 493	7 904	upper middle
Egypt	Alexandria	31,2	29,92	Not	Stressed	Stressed	0,69	4 778	5 225	5 733	6 313	lower middle
India	Agra	27,18	78,02	Not	Stressed	Stressed	0,61	1 966	2 224	2 501	2 793	lower middle
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India	Delhi	28,67	77,22	Not	Stressed	Stressed	0,61	25 703	29 348	32 727	36 060	lower middle
India	Gwalior	26,22	78,18	Not	Stressed	Stressed	0,61	1 221	1 365	1 534	1 718	lower middle
India	Hyderabad	17,38	78,47	Not	Stressed	Stressed	0,61	8 944	10 279	11 527	12 774	lower middle
India	Kolkata	22,5	88,33	Not	Stressed	Stressed	0,61	14 865	15 726	17 285	19 092	lower middle
India	Rajkot	22,3	70,78	Not	Stressed	Stressed	0,61	1 599	1 838	2 076	2 322	lower middle
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Mexico	Monterrey	25,66	-100,31	Not	Stressed	Stressed	0,76	4 513	4 875	5 194	5 471	upper middle
Mexico	Puebla	19,04	-98,21	Not	Stressed	Stressed	0,76	2 984	3 217	3 433	3 628	upper middle
Morocco	Dar-el-Beida (Casablanca)	33,59	-7,62	Not	Stressed	Stressed	0,63	3 515	3 736	4 056	4 361	lower middle
Pakistan	Karachi	24,87	67,05	Not	Stressed	Stressed	0,54	16 618	19 230	22 009	24 838	lower middle
Republic of Korea	Busan	35,1	129,04	Not	Stressed	Stressed	0,90	3 216	3 174	3 213	3 264	High: OECD
Russia	Moscow	55,75	37,62	Not	Stressed	Stressed	0,80	12 166	12 474	12 382	12 200	high: non OECD
Sweden	Stockholm	59,33	18,05	Not	Stressed	Stressed	0,91	1 486	1 589	1 678	1 757	High: OECD
United Kingdom	London	51,5	-0,12	Not	Stressed	Stressed	0,91	10 313	10 849	11 207	11 467	High: OECD
United States	Austin	30,3	-97,75	Not	Stressed	Stressed	0,91	1 684	1 938	2 079	2 182	High: OECD
United States	Dallas-Fort Worth	32,71	-97,31	Not	Stressed	Stressed	0,91	5 703	6 130	6 430	6 683	High: OECD
United States	Denver-Aurora	39,73	-104,97	Not	Stressed	Stressed	0,91	2 599	2 771	2 916	3 048	High: OECD
United States	Houston	29,76	-95,38	Not	Stressed	Stressed	0,91	5 638	6 151	6 474	6 729	High: OECD
United States	Kansas City	39,1	-94,61	Not	Stressed	Stressed	0,91	1 604	1 675	1 759	1 846	High: OECD
United States	Los Angeles	34,09	-118,38	Not	Stressed	Stressed	0,91	12 310	12 454	12 835	13 257	High: OECD
United States	McAllen	26,22	-98,24	Not	Stressed	Stressed	0,91	864	970	1 039	1 096	High: OECD
United States	Oklahoma City	35,47	-97,52	Not	Stressed	Stressed	0,91	926	978	1 033	1 089	High: OECD
United States	Omaha	41,26	-95,94	Not	Stressed	Stressed	0,91	780	826	874	922	High: OECD
United States	Phoenix-Mesa	33,44	-111,95	Not	Stressed	Stressed	0,91	4 063	4 386	4 614	4 808	High: OECD
United States	San Diego	32,78	-117,15	Not	Stressed	Stressed	0,91	3 107	3 228	3 373	3 522	High: OECD
United States	Tucson	32,21	-110,92	Not	Stressed	Stressed	0,91	913	969	1 025	1 081	High: OECD

Table 28: groundwater stressed cities

Appendix D

climate conversion table

Composed from Kottek et al. (2006).

climate code	abbreviation	basic climate	Specific climate (with help of Peel et al.(2007))
11	Af	Equatorial	Tropical rainforest
12	Am	Equatorial	Tropical monsoon
13	As	Equatorial	Tropical Savannah with dry winter
14	Aw	Equatorial	Tropical savannah
21	BWk	Arid	Arid cold desert
22	Bwh	Arid	Arid hot desert
26	BSk	Arid	Arid Steppe Cold
27	Bsh	Arid	Arid steppe hot
31	Cfa	Warm temperate	Temperate hot summer without dry season
32	Cfb	Warm temperate	Temperate warm summer without dry season
33	Cfc	Warm temperate	Temperate cold summer without dry season
34	Csa	Warm temperate	Temperate dry hot summer
35	Csb	Warm temperate	Temperate dry warm summer
36	Csc	Warm temperate	Temperate dry and cold summer
37	Cwa	Warm temperate	Temperate dry winter hot summer
38	Cwb	Warm temperate	Temperate dry winter warm summer
39	CWc	Warm temperate	Temperate dry winter and cold summer
41	Dfa	Snow	Cold hot summer without dry season

42	Dfb	Snow	Cold warm summer without dry season
43	Dfc	Snow	Cold cold summer without dry season
44	Dfd	Snow	Cold, very cold winter without dry season
45	Dsa	Snow	Cold hot summer dry summer
46	Dsb	Snow	Cold dry and warm summer
47	Dsc	Snow	
49	Dwa	Snow	Cold dry winter and hot summer
50	Dwb	Snow	Cold dry winter and warm summer
51	Dwc	Snow	Cold dry winter and cold summer
52	Dwd	Snow	Cold dry and very cold winter
61	EF	Polar	Polar frost
62	ET	Polar	Polar tundra

Appendix E

Lithology conversion table

Composed from Hartmann & Moosdorf (2012).

Number	Lithology name
1	unconsolidated sediments
2	basic volcanic rocks
3	siliciclastic sedimentary rocks
4	basic plutonic rocks
5	mixed sedimentary rocks
6	carbonate sedimentary rocks
7	acid volcanic rocks
8	metamorphic rocks
9	acid plutonic rocks
10	intermediate volcanic rocks
11	water bodies
12	pyroclastics
13	intermediate plutonic rocks
14	evaporites
15	no data
16	ice and glaciers

Appendix F

Maps of used layers in ArcGIS

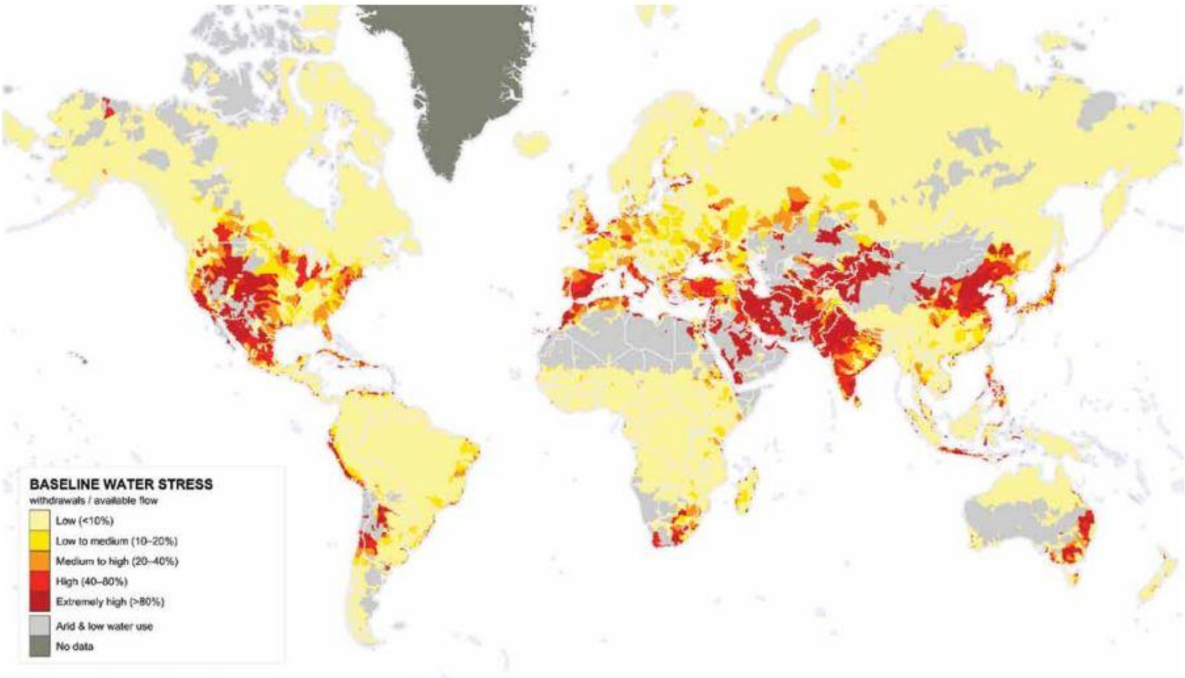


Figure 67: global map of baseline water stress (Gassert et al., 2013)

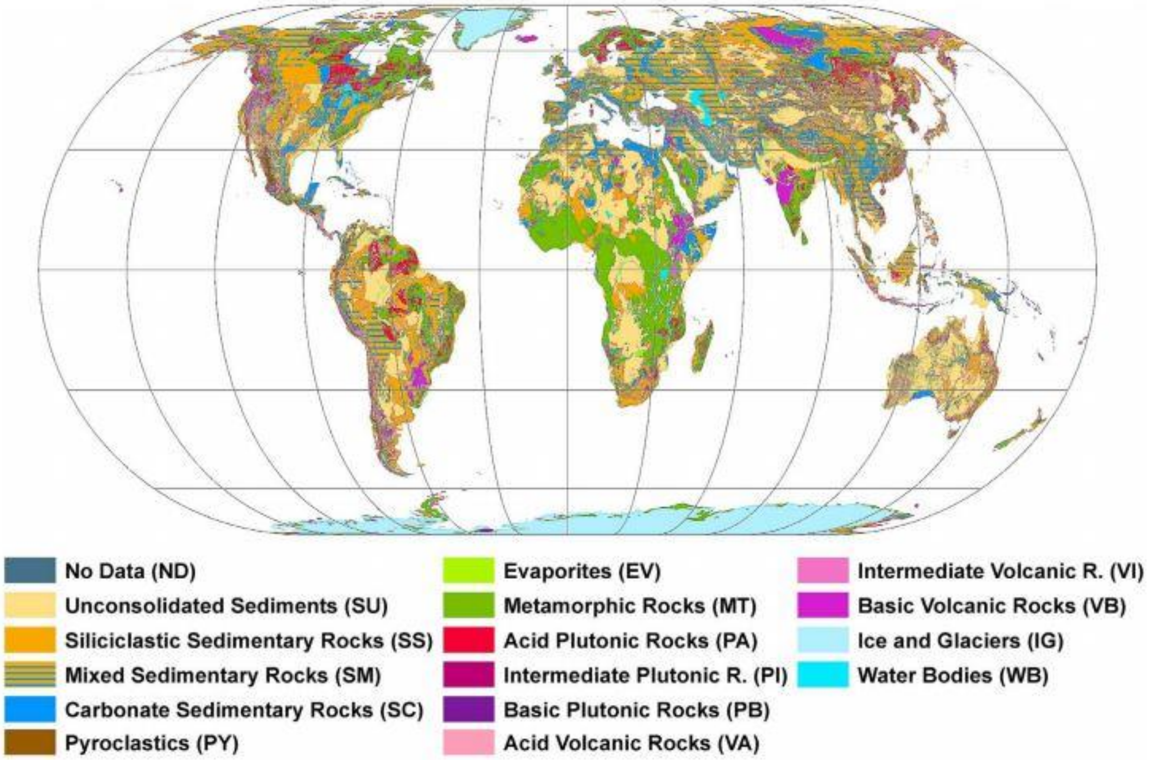


Figure 68: the global lithological map showing the basic lithological classes (Hartmann & Moosdorf, 2012).

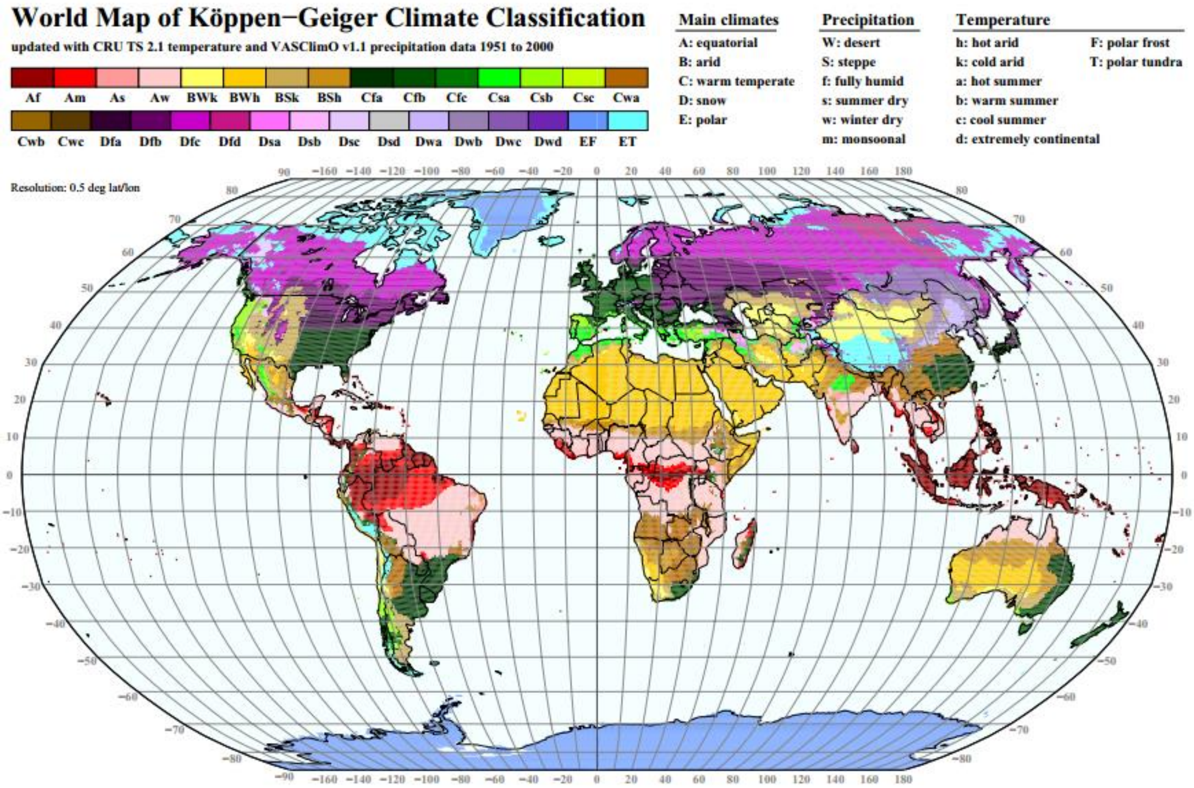


Figure 69: world map of köppen-geiger classification (Kottek et al., 2006)

Figure 70: Global aridity map (Zomer et al., 2006)

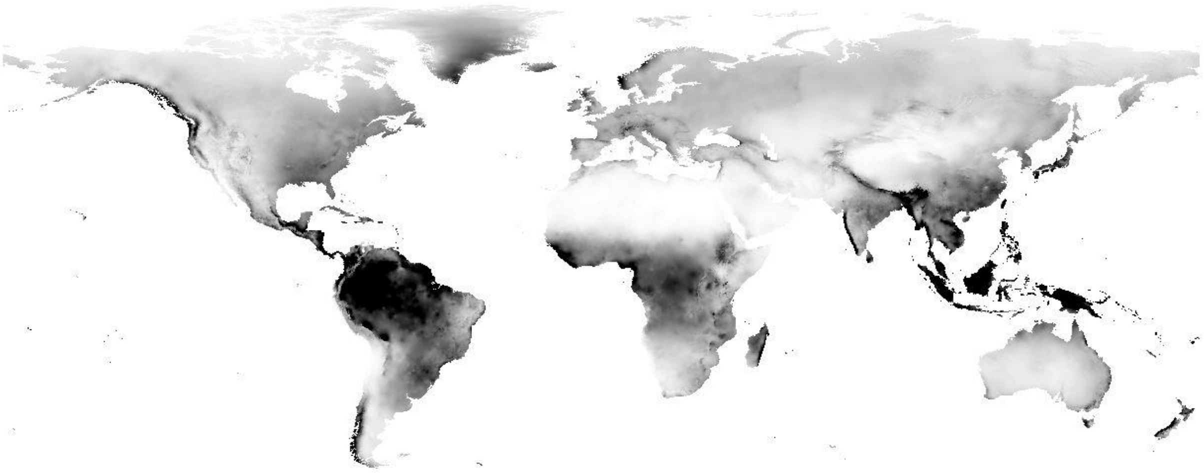


Figure 71: total annual precipitation global map (made in ArcMap, data from (Hijmans et al., 2005))

Appendix G

Explanation of Box & Whisker plots

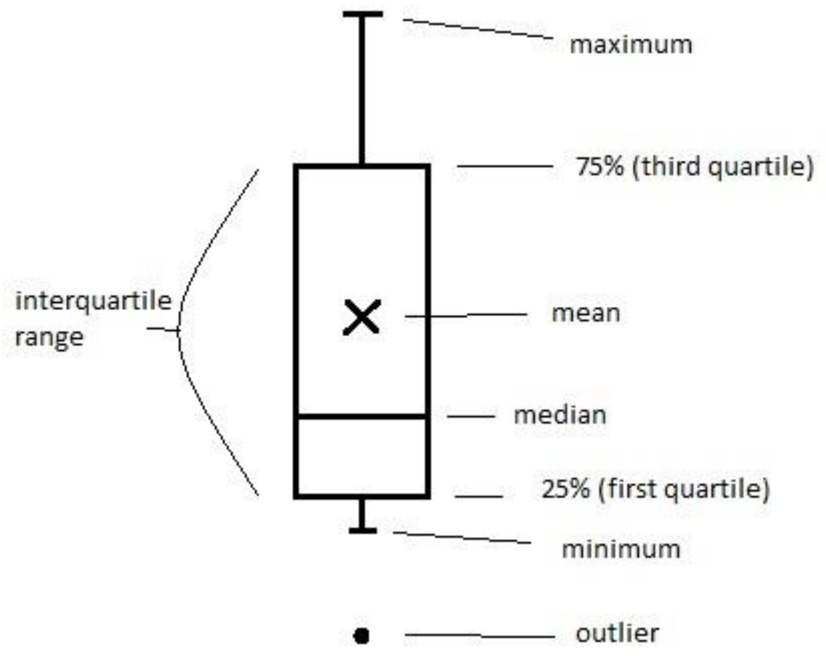


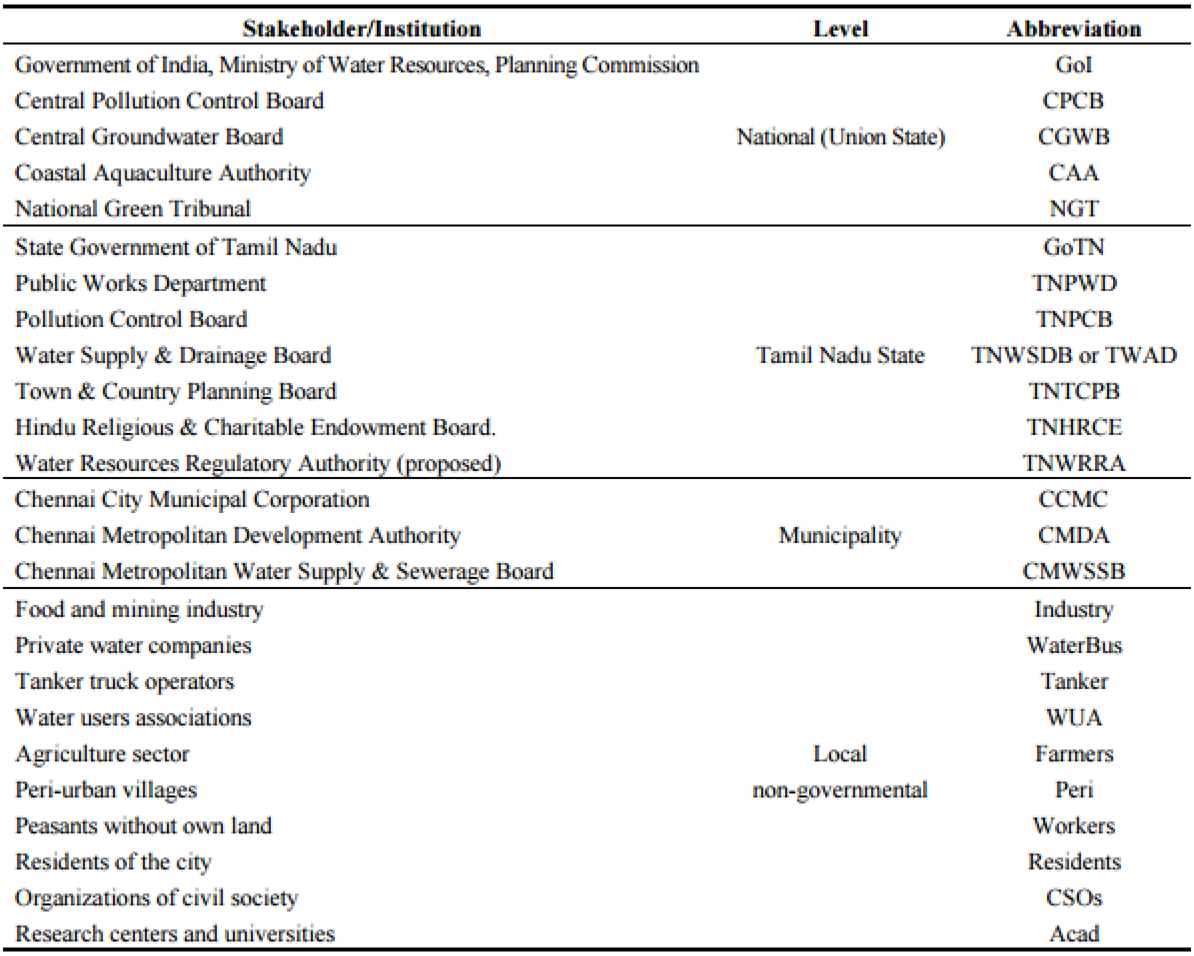
Figure 72: boxplot explanation

A boxplot shows the distribution of values. Outliers are 1.5 times the length of the interquartile range.

Appendix H

list of stakeholders of MAR in Chennai City

From Brunner et al., (2014)



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

Appendix I

Names of MAR techniques in literature and data

MAR techniques in literature	MAR techniques used from geodatabase
Infiltration ponds	Infiltration ponds and basins
SAT	-
Flooding	Flooding
Ditches, drains and furrows	Ditches and drains Reverse drainage Trenches
Excess irrigation	Excess irrigation
Barriers and bunds	Barriers and bunds
Dune filtration	-
ASR	ASR/ASTR
ASTR	
Shallow well/borehole/shaft recharge	Dug well/shaft/pit injection
Induced bank filtration	Induced bank filtration
Recharge dams	Recharge dams
Sand dams	Sand storage dams
Channel spreading	Channel spreading

Appendix J

Country distribution per MAR technique

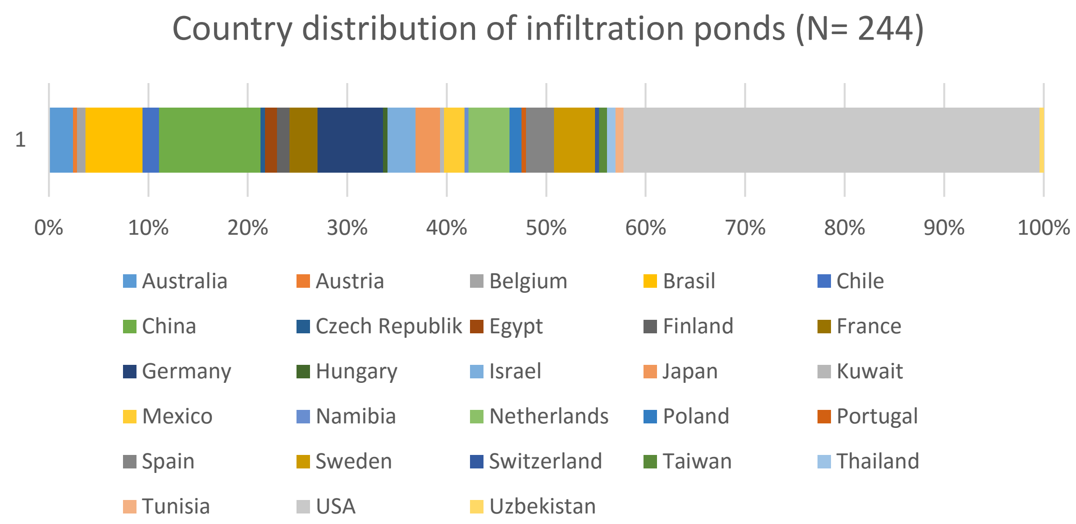


Figure 73: Country distribution of infiltration ponds (N= 244)

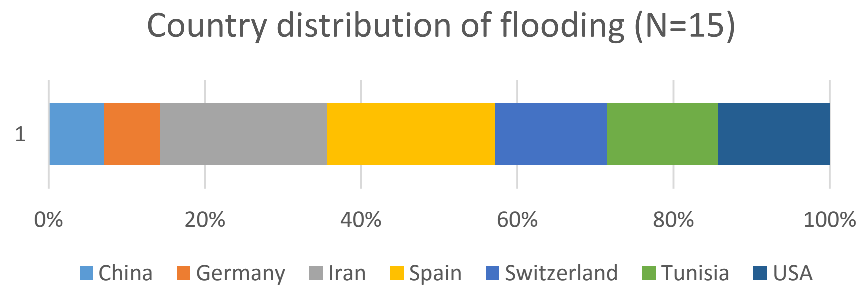


Figure 74: Country distribution of flooding (N=15)

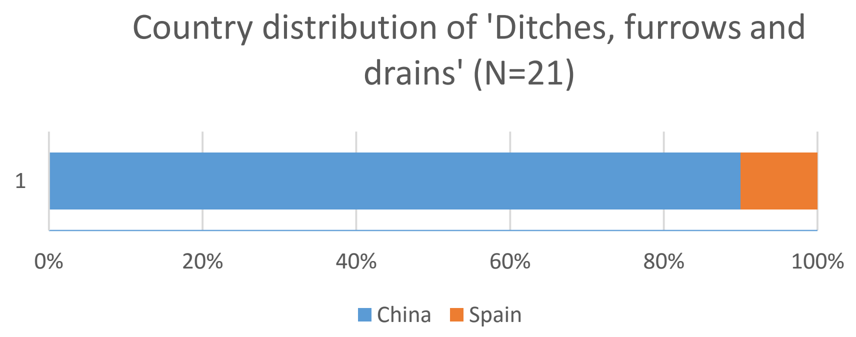


Figure 75: Country distribution of 'Ditches, furrows and drains' (N=21)

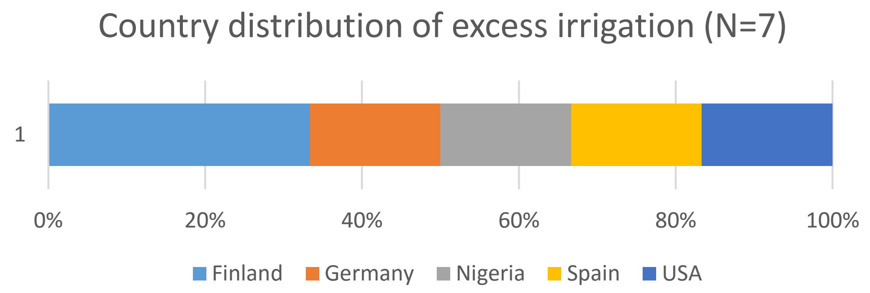


Figure 76: Country distribution of excess irrigation (N=7)

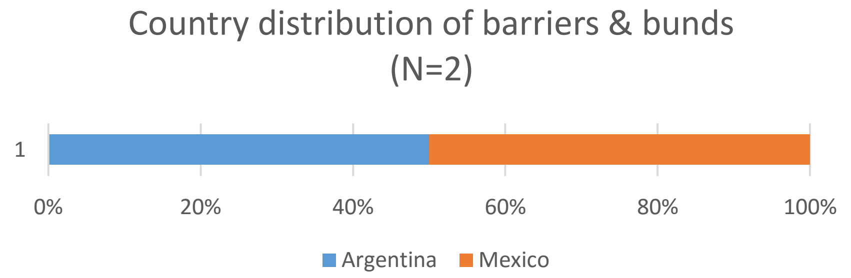


Figure 77: Country distribution of barriers & bunds (N=2)

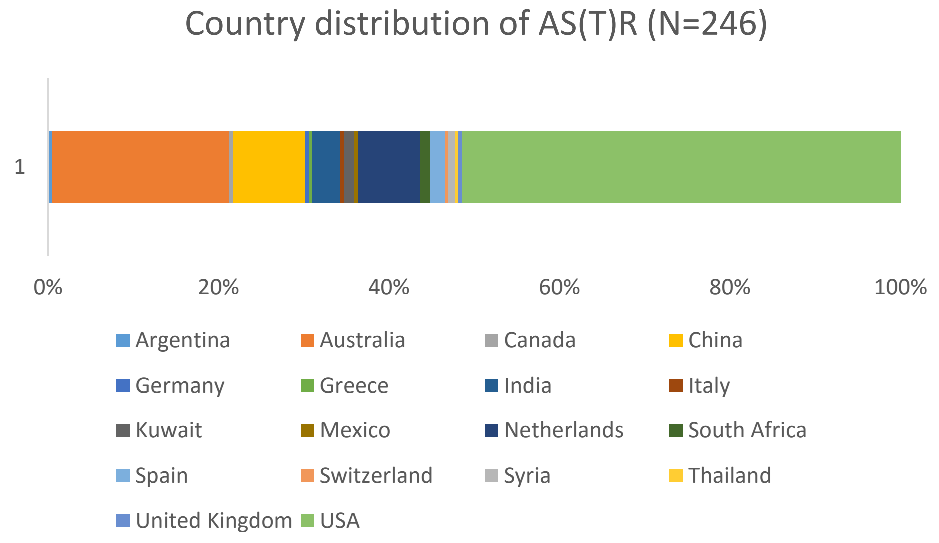


Figure 78: Country distribution of AS(T)R (N=246)

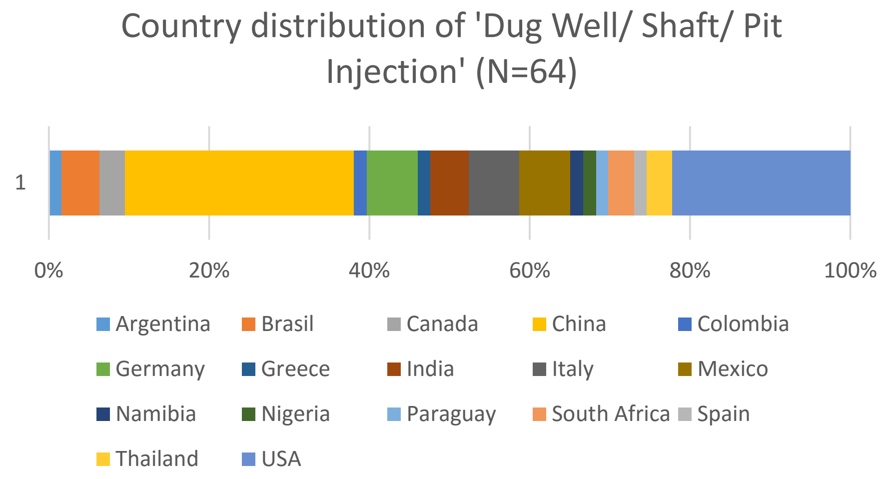


Figure 79: Country distribution of 'Dug Well/ Shaft/ Pit Injection' (N=64)

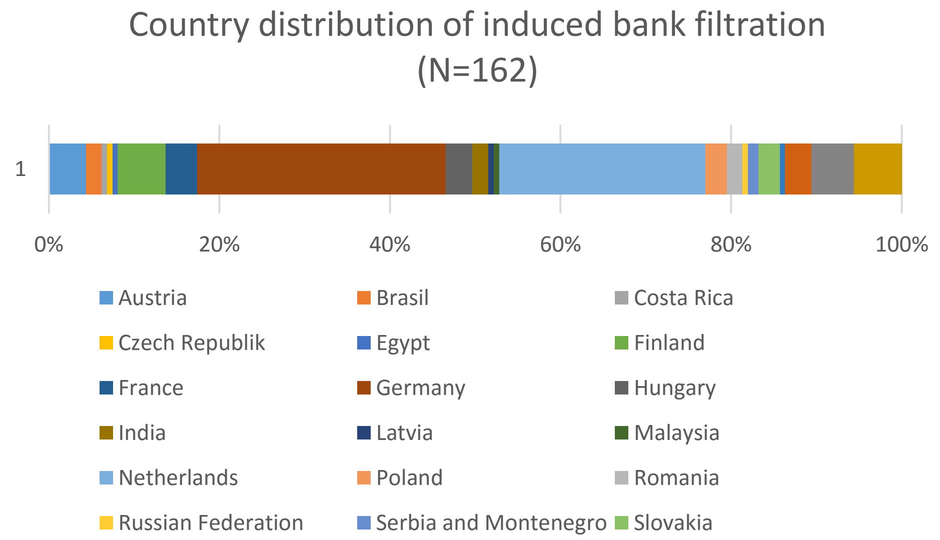


Figure 80: Country distribution of induced bank filtration (N=162)

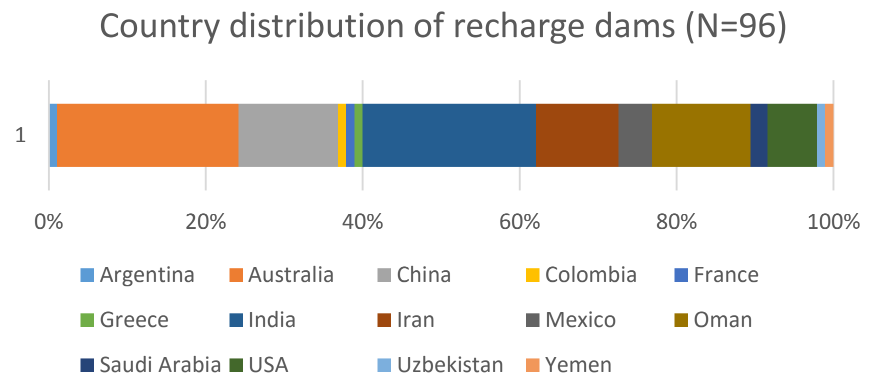


Figure 81: Country distribution of recharge dams (N=96)

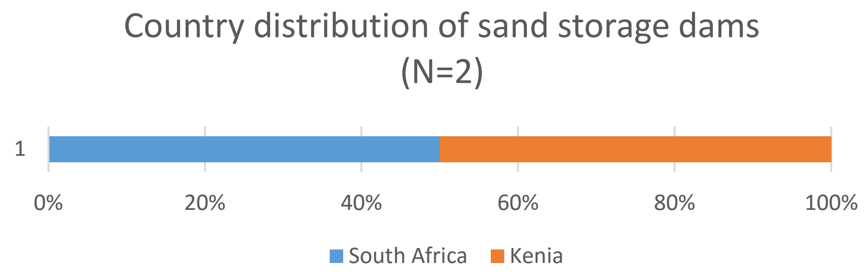


Figure 82: Country distribution of sand storage dams (N=2)

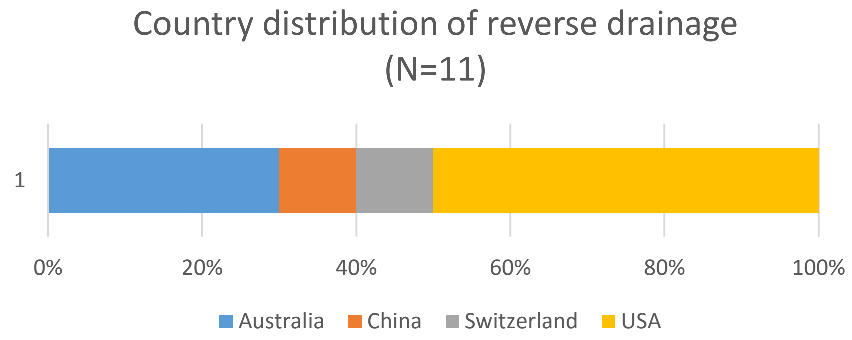


Figure 83: Country distribution of reverse drainage (N=11)

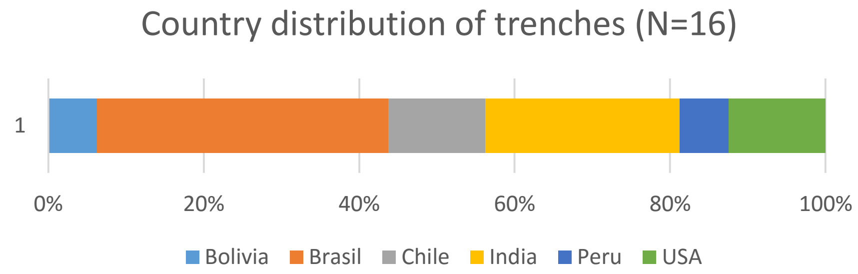
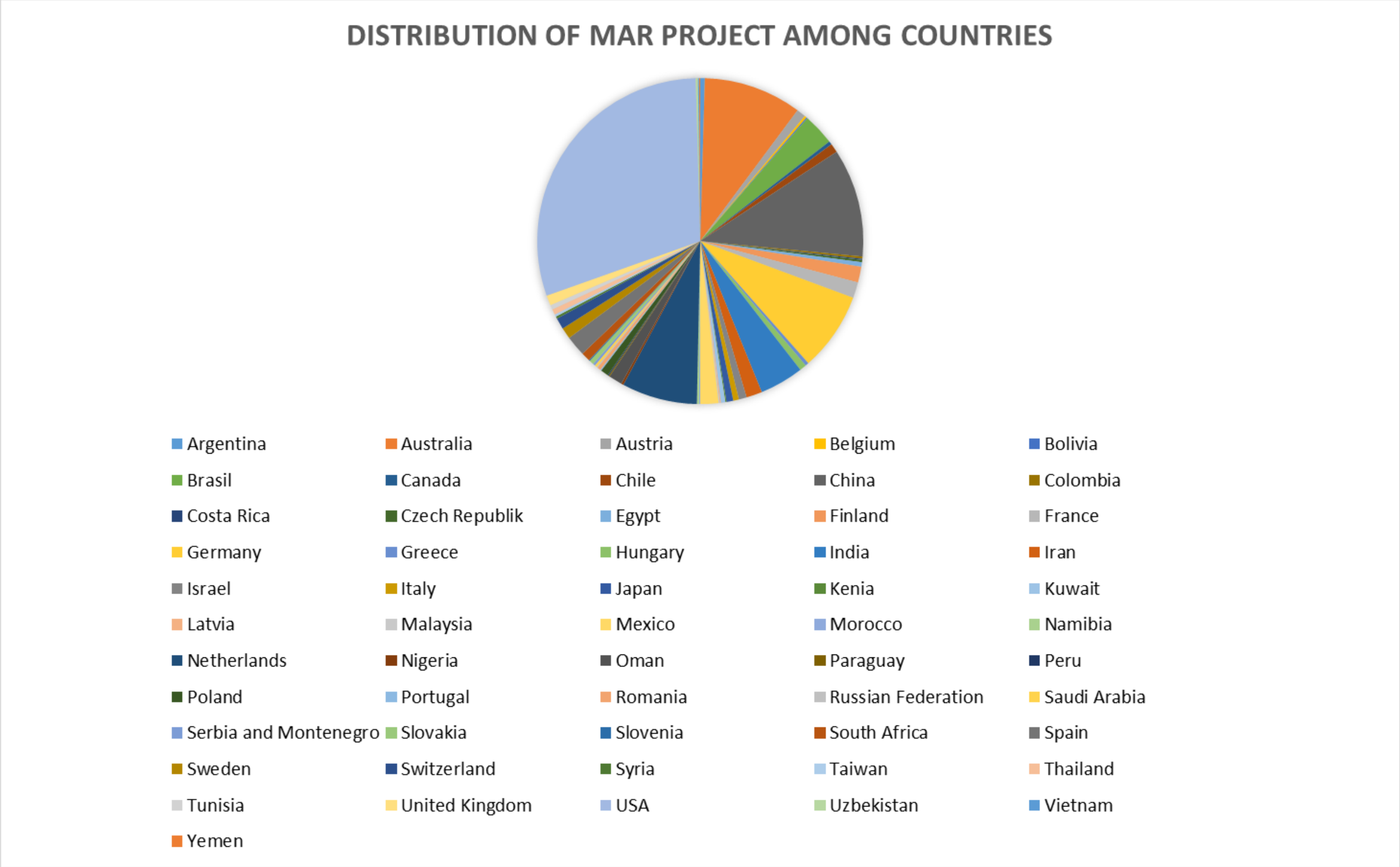


Figure 84: Country distribution of trenches (N=16)

Appendix K


DISTRIBUTION OF MAR PROJECT AMONG COUNTRIES

Appendix L