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Review of Managed Aquifer Recharge (MAR) Experience in Africa and MAR Suitability Mapping for Ramotswa Transboundary Aquifer Area

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Executive Summary

Implementation of MAR can strengthen resilience in Africa, particularly in the semi-arid context in which Ramotswa is located. Climatic variability results in inadequate water supply and contributes to food insecurity in Africa particularly in rural dry land areas. Introducing surface runoff and wastewater into subsurface aquifers when it is available through Managed Aquifer Recharge (MAR) provides an opportunity to cope with such variability and mitigate adverse impacts. MAR addresses the temporal mismatch in demand and supply, reliability of water supply sources and creates wastewater re-use options. MAR also constitutes a strategy that can be used for adaptation to climate change. The feasibility and success of a MAR system, however, is not a given. Feasibility depends on soil and hydrogeological conditions. And success is likely to rely on not only the selection of a suitable site, but also ensuring a cost-effective and fit-for-purpose MAR type, and availability of surplus water for aquifer recharge.

No review of MAR experience in Africa, and no assessments of MAR potential in Ramotswa Aquifer have been undertaken. No research has been done so far that synthesises MAR practices in Africa or assesses MAR potential in the Ramotswa Aquifer. Through the joint initiative of IGRAC and TU Dresden, a web-based system known as Global MAR portal has been developed that show data from about 1200 MAR case studies from over 50 countries. The Global MAR portal inventory contains information on site name, coordinates, MAR type, year of operation, source of water, the final use and objective of the MAR. In this study, eight additional criteria that include climate, soil infiltration rate, unsaturated zone thickness, geology, aquifer characteristics, recharge volume, contribution to water supply, and design and operations challenges associated to MAR are reviewed. This effort aims to contextualize work in the Ramotswa Aquifer and increase awareness among African water managers for MAR development as a means to cope with water scarcity and strengthen resilience.

The objective of the present study is twofold:

1) Review and synthesize MAR practice in Africa

2) Develop MAR suitability map for the Ramotswa Aquifer Flight Area which encompasses the Ramotswa Transboundary Aquifer Area

Compiling and Classifying MAR case studies. We obtained more than 40 case studies, from eight African countries from the Global MAR portal and relevant literature. Case studies were classified according to 11 criteria including: objectives, MAR type, source of water, final use, climate, soil infiltration rate, unsaturated zone thickness, geology, aquifer characteristics, recharge volume, contribution to water supply, and design and operations challenges associated to MAR.

Determining MAR Suitability in Ramotswa Aquifer Flight Area Due to hydrogeological, environmental, social and cost limitations MAR may not be feasible at all sites. Among others, there is a need for evaluation of the intrinsic suitability of an aquifer for MAR. It is important to identify suitable areas where MAR practice can be implemented. MAR suitability assessment was carried out by applying a Multi-Criteria Analysis using Geographic Information System (GIS). The objective of the MAR suitability mapping was to enable initial assessment MAR in the Ramotswa transboundary Aquifer Area (RTBAA) and support the follow-up work of MAR feasibility assessment using hydrogeological model. Based on literature review and availability of data, four criteria including: lithology, soil, slope and land use and land cover were selected and used for the suitability mapping. The ranking methods were used for the linear weighted combination of the criteria maps. The weights calculated using the ranking methods were also compared with other methods and weights based on expert ratings. The suitability map produced in this report represents the intrinsic suitability purely based on the intrinsic characteristics of the biophysical parameters. Water source, demand, water quality issues and depth to groundwater are not considered. Results from the suitability mapping should be updated as new data become available, and need to be validated against field data.

MAR experiences in Africa: Findings In most of the reviewed case studies, the main objective of MAR is to maximize natural storage, and in some cases to improve either water quality or both water quality and quantity. With respect to MAR type, the surface spreading method is the most used method, followed by in-channel modification and well injection methods. The specific MAR type practiced in Africa ranges from small sand and subsurface dams to well injections. While sand dams are practiced widely in Kenya, well injection methods are more common in Southern Africa. The technology choices mainly depend on aquifer property and cost. Sand dams are mostly practiced in rural areas where there are seasonal rivers with coarse sandy sediments under laid by impervious material. Sand dams are low cost, easily constructed by local communities using locally available material. On the other hand, the design and implementation of injection well system requires significant hydrogeological site investigation, followed by a pilot scale operation with detailed monitoring and performance assessment, drilling, and installation, which make them more costly. Therefore, they are less applicable in the rural context, because of the level of sophistication and high operational costs required. Although little data exist to prove the efficiency and sustainability of sand dams, they are used to store sufficient quantity of water for domestic use to buffer seasonal variability in the rural areas. In view of their low capital cost, such technologies need to be supported with detailed hydrogeological knowledge and improved site selection method and design.

MAR experience: Broader Lessons There are good examples that have more than 30 years of MAR practice in Southern and Northern Africa. However, in many Sub-Saharan African countries where the option to use or store additional surface water still exists, MAR is not practiced as such. Overall, the extent of MAR practice in Africa is very low compared to the scale of increasing seasonality of river flows, water availability and climate change. Hence, exploration of MAR through an effective research and experimental program and systematically disseminating the experience gained from other case studies is critical for understanding and harnessing the potential of MAR practice in Africa.

Suitability for MAR in Ramotswa Aquifer Flight Area and Ramotswa Transboundary Aquifer Area Results of the suitability assessment shows that 52% of Ramotswa Aquifer Flight Area and 63% of Ramotswa Transboundary Aquifer Area are suitable for MAR. About 26% of the Ramotswa Aquifer Flight Area and 16% of the Ramotswa Transboundary Aquifer Area falls in the very suitable class. The Ramotswa Aquifer area offer a good potential for MAR due to their high transmissivity and their gentle gradient. The suitability analysis enabled us to identify potentially suitable sites for MAR application. However, results from the suitability mapping need to be updated as new data become available, and need to be validated against field data. In order to unlock the potential for MAR in the area, feasibility study is required.

Summing Up and Next Steps Initial experiences with MAR in Africa show potential for broader use of this approach. MAR has the potential to increase the reliability of water supplies and agriculture if it is practiced appropriately. The RTBAA would appear to be an area where MAR can play an important role in light of the climate variability and need to increase security of water supplies. And there appear ample sites that are suitable for MAR. Next steps are assessment of water resource availability for aquifer recharge and assess the feasibility of MAR using the hydrogeological model through scenario analysis. The forthcoming feasibility assessment, to be undertaken through the hydrogeological model scenario analysis, will help to determine the volume of water to be added to storage in the aquifer, groundwater level change and dynamics for additional recharge, and to determine the length of time the recharged water remain in storage in a particular area.

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Acronyms

ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage and Transfer Recovery
BGI	Botswana Geoscience Institute
DEM	Digital Elevation Model
DWA	Department of Water Affairs (Botswana)
DWS	Department of Water and Sanitation (South Africa)
GIS	Geographic Information System
HWSD	Harmonized World Soil Database
IGRAC	International Groundwater Resources Assessment Cen
IWMI	International Water Management Institute
LULC	Land Use/Land Cover
MAR	Managed Aquifer Recharge
MIF	Multi-Influencing Factor
RTBAA	Ramotswa Transboundary Aquifer Area
SADC	Southern African Development Community
SRTM	Shuttle Radar Topography Mission
USAID	United States Agency for International Development
WLC	Weighted Linear Combination
WLE	Water, Land and Ecosystems
WUC	Water Utilities Corporation (Botswana)

1. Introduction

Managed Aquifer Recharge (MAR) is an alternative water resource management option that is gaining attention as a means of storing water underground when there is excess during wet periods for use during dry period. MAR enables efficient use of groundwater resources, particularly in locations where resources are scarce and/ or expensive to produce. River runoff is unevenly distributed throughout the year and most of river runoff is generated during wet periods and necessitate reservoirs to regulate flows (Shiklomanov, 1998). However, storing water in reservoirs – the most common way to mitigate this uneven distribution – is challenged by high evaporation losses, sediment accumulation. Due to high evaporation rate from the surface of the reservoir in arid and semi-arid regions, lack of appropriate site for dam location and cost of construction storing water underground is a preferred option (Bouwer, 1999). Storing water underground provide wastewater reuse option by facilitating the storage of wastewater and by contributing to its purification. MAR has been identified in many places as both a practical and necessary strategy for achieving water recycling goals (Miller, 2006) and achieving water security (Dillon, 2005). For instance in Arizona, USA, MAR is fully integrated to water resources planning (Lluria, 2009). Additional advantages of MAR include flood control, protecting ecosystem, reducing land degradation etc. (Dillon, 2005). Increase in water level due to MAR may also lead to low energy costs and thus make groundwater abstraction less expensive and affordable to the poor. According to the World Bank (2011) report MAR is identified as one of the most significant adaptation solution for climate change and hydrological variability.

According to Dillon et al. (2009a) and Gale et al. (2006), MAR can be used for different purpose including:

a) as temporary storage of water in the aquifer for future use,
b) to balance the variations in supply and demand,
c) to raise the groundwater levels in over exploited aquifer,
d) for securing and enhancing water supplies,
e) for improving groundwater quality,
f) for maintaining environmental flows and,
g) for preventing seawater intrusions

MAR can be used to buffer against drought and climate variability and change (Megdal and Dillon, 2015). MAR is particularly important in arid and semi-arid areas where the control of very irregular surface runoff (erratic floods) is more difficult than elsewhere and protecting stored water against evaporation is most important. MAR also provides an opportunity to exploit underutilized aquifers with capacity to store water, including aquifers which are otherwise saline (Gale et al., 2002).

The status and potential of MAR in Africa: What do we know? There has been scant effort to explore MAR in Africa. Global MAR portal database https://www.un-igrac.org/ggis/mar-portal contains 42 case studies from Africa (after correcting misclassifications, n=39); yet, the contents of such case studies have not been examined to generate lessons and insights. More broadly, no research has been carried out that synthesizes MAR applications in Africa. Since MAR may not be feasible at all sites due to hydrogeological, environmental, social and cost limitations, it is important to identify suitable areas where MAR practice can be expanded. Evaluating the hydrogeological suitability of the aquifer leads to improved MAR assessment.

1.1 Objectives

The objectives of this report are:

1) To compile and synthesize MAR experiences in Africa

2) To develop MAR suitability map for Ramotswa Aquifer Flight Area which encompasses the Ramotswa Transboundary Aquifer Area

To develop MAR suitability map for Ramotswa Transboundary Aquifer the remainder of this report is organized as follows: First, background is provided on key terms used in this report as well as different MAR techniques, sources of water for MAR and hydrogeological factors affecting the performance of MAR are described briefly. Second, review of MAR practice in Africa and karst aquifers and lessons learned are presented. Third, hydrogeology of karst aquifers, MAR in karst aquifers and MAR case studies in karst aquifers are also described and presented in a box (Box 1). Fourth, Geographic Information System (GIS) based multi-criteria analysis is described. Fifth, MAR suitability mapping for the Ramotswa Transboundary aquifer is presented. Finally, conclusions are presented. Ultimately, review of MAR experiences will inform parameters of approaches proposed in the Aquifer. The *suitability* mapping will enable future assessment of MAR *feasibility* in the RTBAA.

2. Background

2.1 Defining Geographic boundaries and conceptualizing MAR terms

Before proceeding, it is necessary to define a set of key terms used throughout this report.

Ramotswa Aquifer Corresponds to the Ramotswa dolomitic aquifer extent mapped based on surface geology (Figure 1, Blue colour). The island left blank (in white) is the area where dolomite is not mapped in the geological map from the Council of Geoscience South Africa. However, based on airborne geophysics survey cross-section and the general geology we assumed that dolomite exist in that area.

Ramotswa Transboundary Aquifer Area (RTBAA) RTBAA is a slightly broader term than the strict aquifer boundary. RTBAA is used to capture areas in the subsurface that are hydrologically linked to the aquifer, but which lie outside the dolomitic aquifer boundaries delineated based on surface geology. The boundaries of the RTBAA extends beyond the boundaries of the Ramotswa Aquifer (Figure 1, Blue plus Grey colour). The boundaries were extended based dolomite sub crop and outcrop identified during the geophysics work (Genco and Pierce, 2016) and dolomite outcrop from the Google earth.

Ramotswa Aquifer Flight Area The flight area (area about 1,500 km2) was commonly used as an encompassing boundary within which the aquifer was found. It was used to overcome ambiguities of a precise boundary for the aquifer. Airborne geophysical surveys were conducted in phase 1 of the RAMOTSWA project within this flight area (Figure 1).

Gaborone Dam Catchment The catchment area located in the Upper Limpopo River Basin encompasses (Area ~4,318 km^2, Figure 2) reflects the immediate surface water boundaries within which the Ramotswa Aquifer is located. Given the linkages between surface and groundwater, the catchment is a very logical scale to use. Phase 2 of the RAMOTSWA project treats the Gaborone Dam Catchment as its project study area.

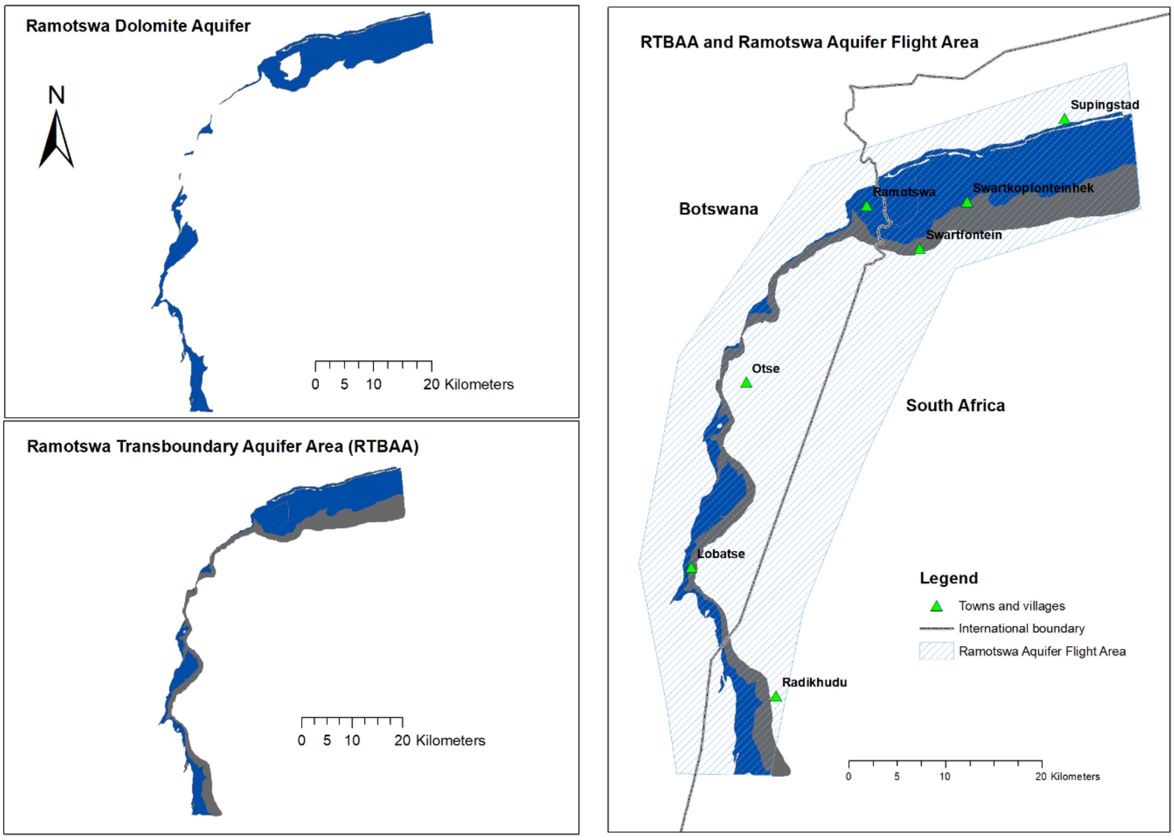

Figure 1: Ramotswa Aquifer, Ramotswa Transboundary Aquifer Area and Ramotswa Aquifer Flight Area

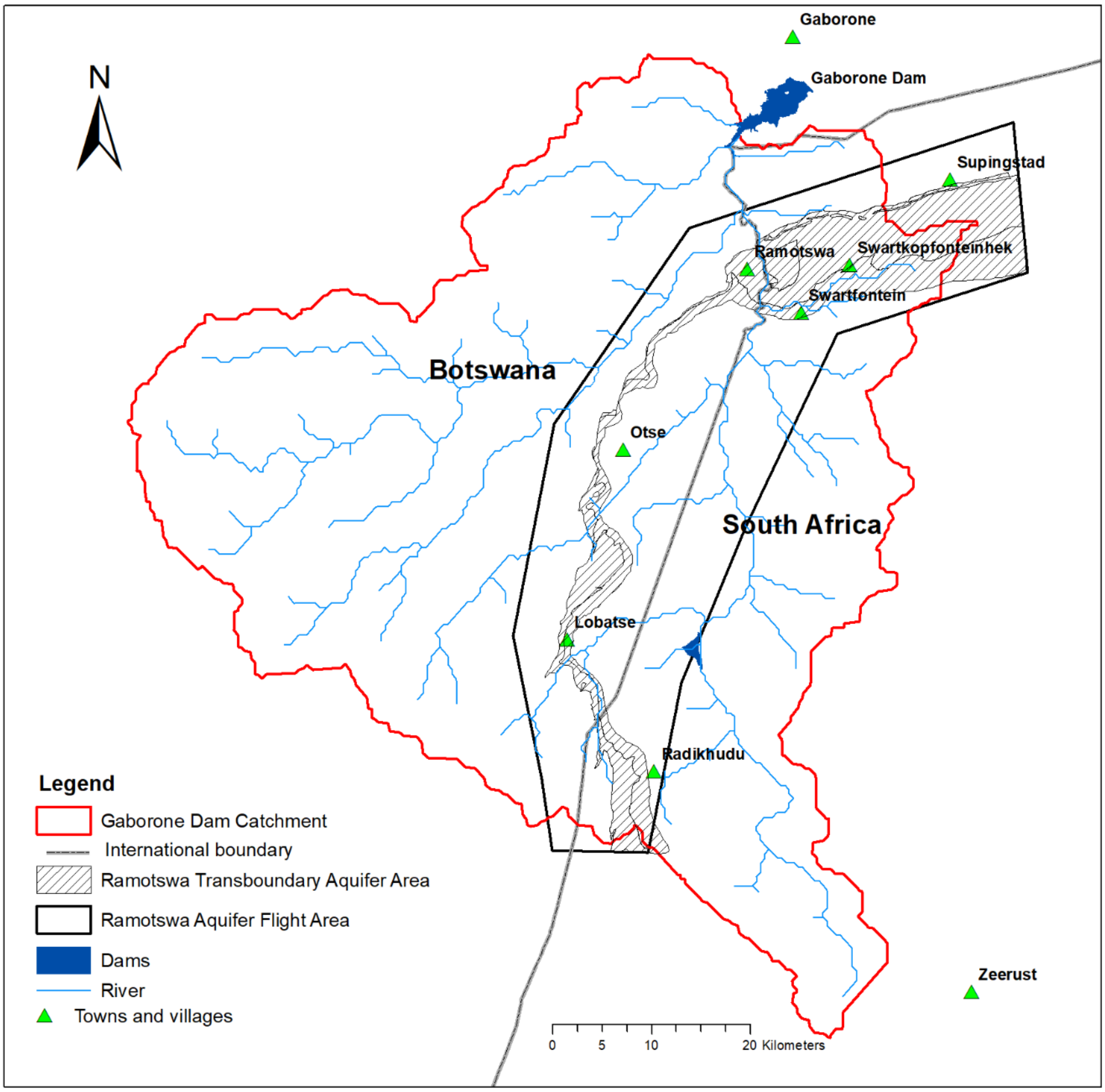

Figure 2: Gaborone Dam catchment

While no formal definition exist for following terms exist, preliminary definition for each term is provided below. See Figure 3 for the illustration.

MAR Suitability MAR suitability gauges the viability of implementing MAR in a geographic unit based on biophysical parameters (soil, geology, land use and other catchment characteristics etc.) as well as source of water using distance to source of water as proxy and subsurface characteristics like depth to groundwater.

MAR Feasibility is a slightly broader term than MAR suitability. MAR feasibility gauges the viability of undertaking MAR in a particular geography in terms of technical, availability of and potential demand for water resources and cost. The technical feasibility assessment include determination of the volume of water added to storage, aquifer dynamics to added recharge, and determination of recovery efficiency of recharged water.

MAR Potential: Potential is treated as a more open-ended term that implies satisfaction of all criteria used in the suitability assessment.

2.2 MAR Techniques

A number of different MAR techniques have been developed and used in the past. Gale (2005) has categorized the different MAR techniques into five groups namely: surface spreading method, in-channel modifications, induced bank filtration, well shaft and borehole recharge, and runoff harvesting. Different factors govern the selection MAR techniques such as the source and quality of water, aquifer types and properties, recovery methods and intended final use. Nearly similar classification as Gale (2005) was used in Global MAR portal. Table 1 summarizes the main and specific MAR types according to the classifications used in Gale (2005). Descriptions of the main MAR types and specific MAR types most practiced in Africa are provided below.

Table 1: MAR types according to the classification used in Gale (2005)

Main MAR type	Specific MAR classification
Spreading methods	Infiltration ponds and basins
	Soil Aquifer Treatment (SAT)
	Controlled flooding
	Incidental recharge from irrigation
In-channel modifications	Percolation ponds behind check- dams, gabions, etc.
	Sand storage dams
	Subsurface dams
	Leaky dams and recharge releases
Well, shaft and borehole recharge	Open wells and shafts
	Aquifer Storage and Recovery (ASR)/ASTR
Induced bank infiltration	Bank filtration
	Inter-dune filtration
Rainwater harvesting	Barriers and Bunds
	Trenches
	Roof-top rainwater harvesting

2.1.1 Surface spreading method/Surface infiltration

Surface spreading method/Surface infiltration uses constructed infiltration basins to recharge the aquifer system. Surface infiltration systems are often a preferred MAR option, because they offer the best opportunity for clogging control and the best soil-aquifer treatment if quality improvement of the water is important (Bouwer, 2002). Infiltration pond is a commonly used spreading method. Surface infiltration/spreading systems normally require permeable surface soils and huge tracts of land to get high infiltration rates, and therefore unsuitable where land area is restricted. The other drawback of this system is its high evaporation losses. These types of system also require unconfined aquifer so that infiltrated water recharges the aquifer without causing groundwater-mounding problem. The unsaturated zone should also be free of contaminants. Soil Aquifer Treatment (SAT) is a typical kind of surface spreading techniques for the purpose of water quality improvement. Sewage effluent will be treated while it passes through the soil and unsaturated zone. Typical schematic of infiltration pond and SAT is presented in Figure 3.

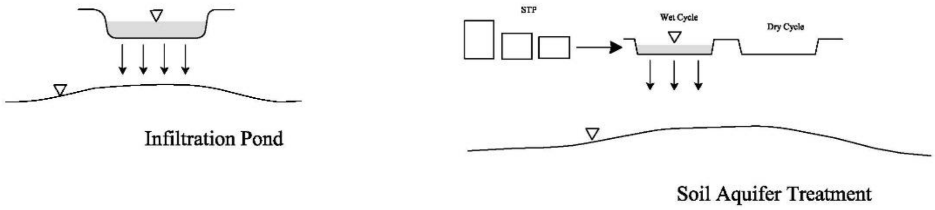

Figure 3: infiltration pond and soil Aquifer treatment techniques (modified from Dillon (2005))

2.1.2 Well, shaft and borehole recharge

In areas where evaporation is high, soils are impermeable, the aquifer is confined and sufficient land for surface infiltration is not available, surface infiltration systems may not be viable. In these cases depending on the depth of the impermeable layer, vadose zone wells, trenches or direct injection wells can be used (Bouwer, 2002). With regard to recovery of the injected water, injection well method can be classified as aquifer storage recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR) (Figure 4). ASR involves using the same well for injection and recovery, while ASTR uses different wells for injection and recovery. In most instances, injection and recovery from the same well is the preferred option for economic reasons (Pyne, 1995). It is typically less expensive to construct one dual-use well than dedicated injection and recovery wells. However, using separate injection and recovery wells may also be desirable to improve stored water quality by providing additional residence time and to allow aquifer filtration. ASTR technique is only be used in potable aquifer as there is mixing between the recharged water and native groundwater and recovery occur by wells located down gradient (Gale et al., 2002). For injections techniques the recharged water need to be highly treated, as this system is used to recharge directly into the aquifer. Sedimentation and pre-treatment of the recharged water and chlorination to prevent microbial growth is highly recommended (Gale, 2005). Geochemical modelling is a recommended approach to investigate the recharge water –rock aquifer interaction and possible chemical precipitation that may result from these reaction and contribute to clogging (Murray and Tredoux, 1998).

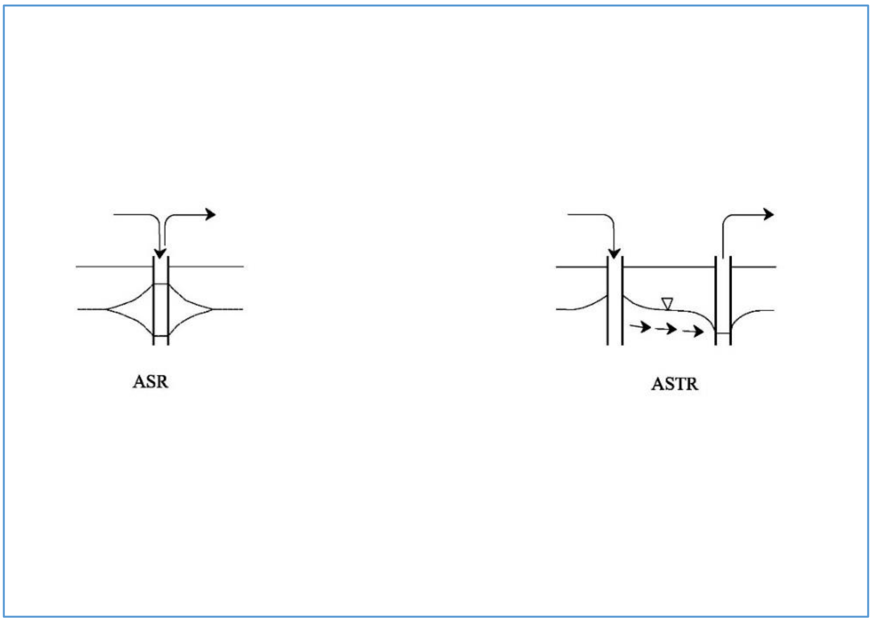

Figure 4: Aquifer storage recovery (ASR) and Aquifer Storage Transfer and Recovery (ASTR) (modified from Dillon (2005))

2.1.3 In-channel modification

In-channel systems consist of dams placed across ephemeral streams to detain flood water and allow percolation or slow release of water from the dam into the streambed downstream to match the capacity for infiltration (Bouwer, 2002) as shown in Figure 5 for Sand dams and subsurface dams (Figure 6). Sand dams and subsurface dams are typical examples of in channel modifications used in most rural areas. A subsurface dam is a dam constructed below ground level, and accumulates the natural groundwater flow, whereas a sand storage dam impounds water in sediments accumulate by the dam itself (Hanson and Nilsson, 1986).

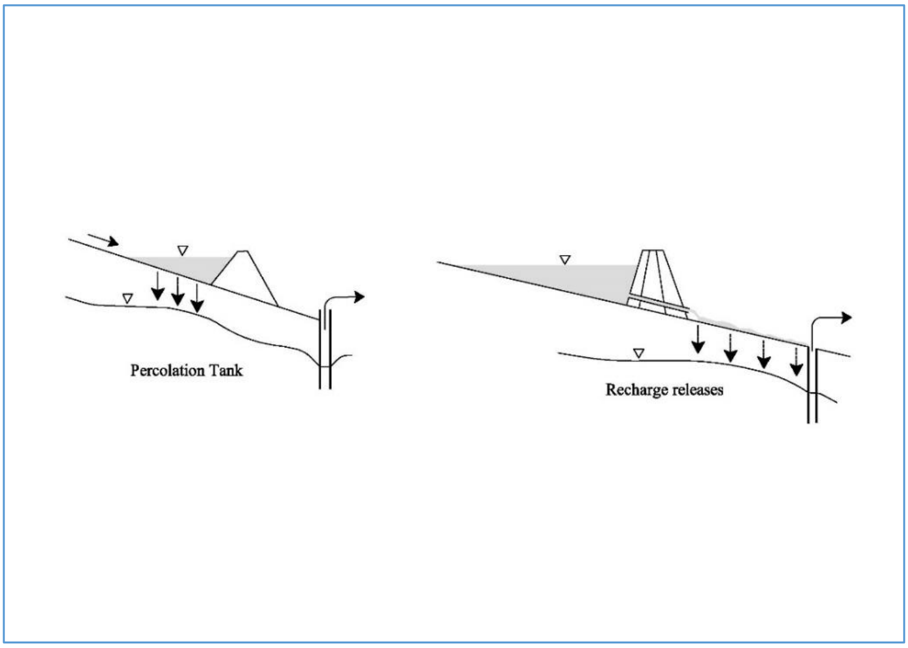

Figure 5: Percolation tank and recharge release dams (modified from Dillon (2005))

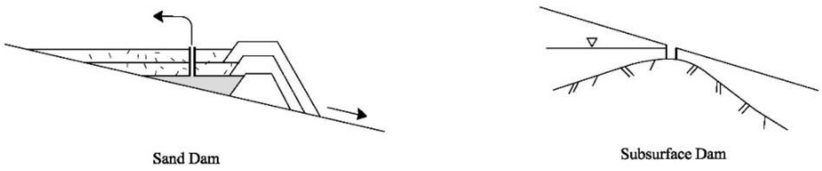

Figure 6: Sand dams and subsurface dams (modified from Dillon (2005))

2.1.4 Induced bank filtration

Induced bank filtration (Figure 7) is a process of inducing surface water infiltration into the aquifer by pumping from a nearby well (Dillon et al., 2002). This process is performed when the surface water quality needs improvement. The streambed and aquifer sediments are used as a medium for removing contaminants from the surface water bodies (Gollnitz et al., 2004). The technique is useful for removal of sediment from the surface water bodies, metals, pathogens and some other organic contaminants (Gollnitz et al., 2004). Pumping wells installed adjacent to the surface water bodies are used to induce recharge to the aquifer system (Dillon et al., 2002; Sprenger et al., 2017). To be feasible, this system has to be installed in perennial streams and lakes, which are in hydraulic connection to the adjacent aquifer system. The pumping well arrangement should allow sufficient travel time for purification. The recommended travel time for sufficient purification is 30 to 60 days (Gale, 2005)

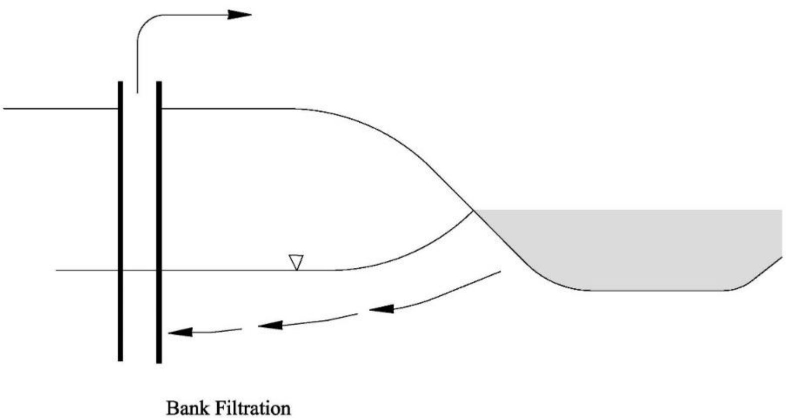

Figure 7: Induced bank filtration (modified from Dillon (2005))

2.2 Sources of water for MAR

Availability of water of sufficient quantity and quality is the pre-requisite for MAR application (Gale, 2005). Recharged water may be sourced from rainwater, storm water, treated wastewater, perennial streams, intermittent streams, storage dam, urban storm water, groundwater, and roof top rainwater harvesting. In recent years, there has been substantial interest in the use of treated wastewater as a source of water for MAR particularly in arid regions where freshwater resources are limited. Municipal wastewater has a predicted quantity and is available even during dry periods, but it may require significant treatment before used for recharge (Murray and Tredoux, 1998). Storm runoff may have high variability in quality particularly during the onset of the runoff, due contaminants from many sources such as industry, agricultural chemicals etc. On the other hand, roof runoff harvesting is good in terms of water quality except during the initial period of rain events that may result water quality degradation from the roof itself (Murray and Tredoux, 1998). Ephemeral streams may be valuable source of aquifer recharge in arid and semi-arid regions, but recharge water may contain a lot of suspended sediments that may require pre-treatment or sedimentation. The other problem is that, in ephemeral streams river flow occurs for few weeks in a year. Chemical difference between the injected and receiving aquifer may lead to some chemical reactions to take place. Therefore, it is important that the geochemistry of the recharged water, the native water and the aquifer rock be characterized to prevent anticipated degradation in water quality due physical, chemical or biological processes (Murray and Tredoux, 1998).

2.3 Hydrogeological factors affecting MAR

Hydrogeological factors that affect the performance of MAR are infiltration capacity of the soil, aquifer permeability, and storage properties (National Research Council, 2008). Storage properties are one of the most critical factors in selecting site for MAR. Storage coefficient of the aquifer determines the capacity of the aquifer to store water. Some of the factors that preclude further development of MAR are low aquifer storage, thin unsaturated zone thickness that do not allow sufficient travel time for degradation of contaminant in the recharged water, low hydraulic conductivity, the potential for clogging, loss of recharge water, and degradation of water quality (National Research Council, 2008). Understanding the dynamic hydrogeological response of the aquifer system to induced recharge is important to optimally site and operate MAR systems. For instance, in an unconfined aquifer, insufficient capacity may result in groundwater mounding, lateral movement of water to discharge points, and reduction of unsaturated zone thickness (Pyne, 1995). Unconfined aquifers with relatively deep water levels offer the largest storage capacity. While increasing groundwater levels is often a goal, rising groundwater levels may have negative impacts if landfills or structures such as nearby buildings, pipes are located adjacent to the recharging facilities. The aquifer permeability should not be too high either; otherwise, the added water would drain out of the aquifer too quickly. In a confined aquifer, the system's physical or chemical boundary conditions need to be sufficient to allow injection of the additional volume of water by displacing the native water (National Research Council, 2008).

The selection of an appropriate storage zone is an important consideration that affects costs, the ability to get water in and out of the storage zone, and the potential for water quality impacts. According to Murray and Tredoux (2002), availability of sustainable source of water for recharge both in quantity and quality, hydrogeological suitability, and hydraulic characteristics of the aquifer, and the potential for clogging of the recharging facility are some of the important pre-requisite for the implementation of MAR.

2.4 Success criteria for MAR and project development stages

According to Dillon et al. (2009b) the five critical element need to be considered for the success of MAR project are:

(i) sufficient demand for water,
(ii) adequate source of water for recharge,
(iii) suitable aquifer to store and recover the water,
(iv) sufficient space available for capture and treatment of the water(If treatment is required before injection or after it should be checked that open space available for construction of such facilities), and,
(v) Capability to design, construct and operate a MAR project.

The 10 success critera for implementation of MAR, and MAR project development stages and activities, from Murray (2007) are listed in Table 2 and 3, respectivley.

Table 2: The ten sucesses crteira and related questios for the implmenation of MAR (souce Murray (2007))

CRITERIA	SOME KEY QUESTIONS
1) The need for the scheme	• Is MAR necessary? • Could you not increase your groundwater yield by expanding the wellfield or by managing existing wellfields better?
2) The source water	• What volume of water is available for recharge, and when is it available?
3) Aquifer hydraulics	• Will the aquifer receive and store the water?
4) Water quality	• Is the quality of the source water suitable for artificial recharge?
5) Engineering issues	• How will the water be transferred into the aquifer?
6) Environmental issues	• What are the potential environmental benefits, risks and constraints?
7) Legal and regulatory issues	• What type of authorisation is required?
8) Economics	• How much will the scheme cost, how much will it cost to operate it, and what will the cost of supplied water per m^3 be?
9) Management and technical capacity	• What skills are required to operate the scheme, and are they available?
10) Institutional arrangements	• Who will be responsible for supplying the source water and ensuring its quality is suitable for recharge? • Are there other users of the aquifer? • Who will regulate the use of the scheme?

Table 3: MAR project development stages (souce Murray (2007))

PROJECT STAGE	KEY ACTIVITIES

Pre-feasibility Stage	• Identify the potential MAR project and describe the information currently available. • Based on existing information, comment on the feasibility of the project. • Describe the work required for the Feasibility Stage and estimate the cost of undertaking the feasibility study. • Establish authorisation requirements from relevant government departments.
Feasibility Stage	• If needed, obtain authorization (e.g. a water use license and environmental authorisation) for the recharge tests. • Conduct the Feasibility Study. This should include testing (example, injection tests, infiltration tests, pumping tests, water quality assessments, etc.). • Develop a preliminary infrastructure design. • Identify the project implementation phases if a phased approach is necessary (example, starting small and expanding after successive recharge cycles). • Estimate the costs of the project. • Identify funding sources. • Compile a detailed project implementation plan.
Implementation Stage	• Obtain the necessary authorization to construct the scheme. • Drill and test new injection and abstraction boreholes or infiltration basins. • Set up the groundwater and recharge water-monitoring system • Develop a detailed infrastructure design, carry out the tendering processes, and construct the scheme. • Compile monitoring, operation & maintenance procedures.
Operation and Maintenance Stage	• Carry out performance monitoring during production. • Modify operation & maintenance procedures based on scheme performance. • Develop final operating, monitoring and reporting system.

3. Review of MAR experience in Africa

3.1 Case study collection

Global MAR portal database documented over 1200 case studies from over 50 countries (Stefan and Ansems, 2015). The portal contains 42 case studies for Africa. Three misclassified case studies were removed. One case study was from Yemen (Al-Qubatee et al., 2009), and the other two case studies are Northern Cape, South Africa (Smit, 1978) and Kitui district, Kenya (Foster and Tuinhof (2004). The study by Smit (1978) deal with natural groundwater recharge assessment while the study by Foster and Tuinhof (2004) provided general assessment of the experience in sand storage dams in Kitiu district, Kenya and subsurface dam in Brazil. This reduces the total number of case studies in Africa from 42 to 39. Two additional case studies from Tunisia were found through literature search. The additional literature search often results similar case studies covering different aspects of the MAR project. Hence, the total case studies reviewed in this study are 41. According to the Global MAR portal database, at present only eight African countries are practicing MAR.

3.2 Case study compilation

The African case studies in Global MAR portal are mostly compiled from peer reviewed publication and Technical governmental documents accounting for 46%, conference presentations and proceeding 29%, MSc Thesis 20%, and web source 5%. The Global MAR portal is one of the very good initiative with regard to MAR, but it should not be viewed as 100 percent coverage of all MAR applications worldwide (Stefan and Ansems, 2015). Particularly, this is true for Africa where data is difficult to obtain. For example, Gijsbertsen and Groen (2007) reported that in Kenya Kitui District only, more than 500 sand storage dams have been constructed by Local NGO called SASOL (Sahelian Solution Foundation) and by the communities since 1994. However, the Global MAR portal contains eight case studies of Sand dams form the whole country. The lack of data in some countries does not necessarily indicate an absence of MAR practice in those countries but rather may be due to lack of references which in most cases documented as governmental technical reports.

3.3 Case study classification

The Global MAR portal contains information on site name, coordinates, MAR type, year when the scheme came into operation, source of water, final use, and the main objective of the MAR scheme. Additional key variables are found to be necessary to be reviewed. The eight key additional variables used for the literature review are climate, soil infiltration rate, unsaturated zone thickness, geology, aquifer properties, recharge volume, contribution to overall water supply, and challenges. For instance, the infiltration capacity of the soil is one of the factors that affect the performance of MAR (National Research Council, 2008), it control the amount of recharge water entering into the aquifer and the rate of clogging (Pavelic et al., 2011). For the purpose of completeness, the present review not only included key variables already documented in Global MAR portal but also corrected numerous miss classification errors. Table 4 presents the summary of key variables used in this review. It is worthwhile to acknowledge that other factors such as cost and water quality are very important; however, these were not captured, as there are no information available.

Table 4: Summary of criteria used in this review

- Country and site
- Year operation start
- Annual rainfall and evaporation
- MAR objective
- Specific MAR type
- Source of water for MAR
- Soil infiltration rate
- Final use
- Unsaturated zone thickness
- Geology
- Aquifer characteristics
- Recharge rate and volume
- Contribution to the total water supply
- Challenges
- Other information (e.g., economics)

4. Results of Review of MAR experience in Africa

Most MAR experience is located in areas facing or approaching physical water scarcity. The 41 case studies reviewed in this study overlaid with water security map obtained with IWMI data portal (http://waterdata.iwmi.org/) and Transboundary aquifer map from UNESCO (http://ihp-wins.unesco.org/layers/geonode:tba_map2015) are shown in Figure 8. Not surprisingly, most MAR experience is found in areas facing scarcity. Nonetheless, MAR experience is also found in some other areas like Nigeria, Kenya and Ethiopia. While underlying factors are not immediately apparent, it may be that such regions – despite sufficient average annual water availability – face challenges with inter and intra annual variability in water availability. The number of MAR case studies per country is presented in Figure 9. Relatively few (Five out of the 41) case studies are located in a transboundary aquifer. Three case studies from Egypt (El Bustan Extension Area, Toushka Khoure, Sidfa Riverbank Filtration) are located in the Nubian Sandstone Aquifer System, one case study from Ethiopia (Koraro-01) is located in the Mereb basin shared between Ethiopia and Eritrea, and one case study from Nigeria (Kano River irrigation Project (KRIP)) is located in the Lake Chad Basin.

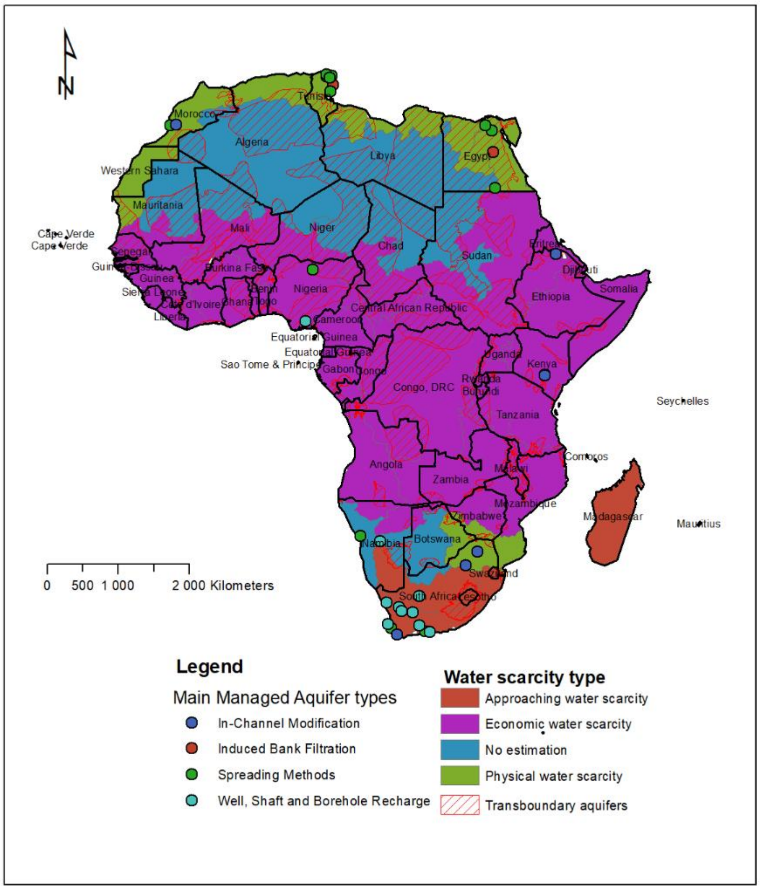

Figure 8: Location of 41 MAR case studies in Africa per MAR type overlain by Water Scarcity and Transboundary Aquifer map layers of Africa

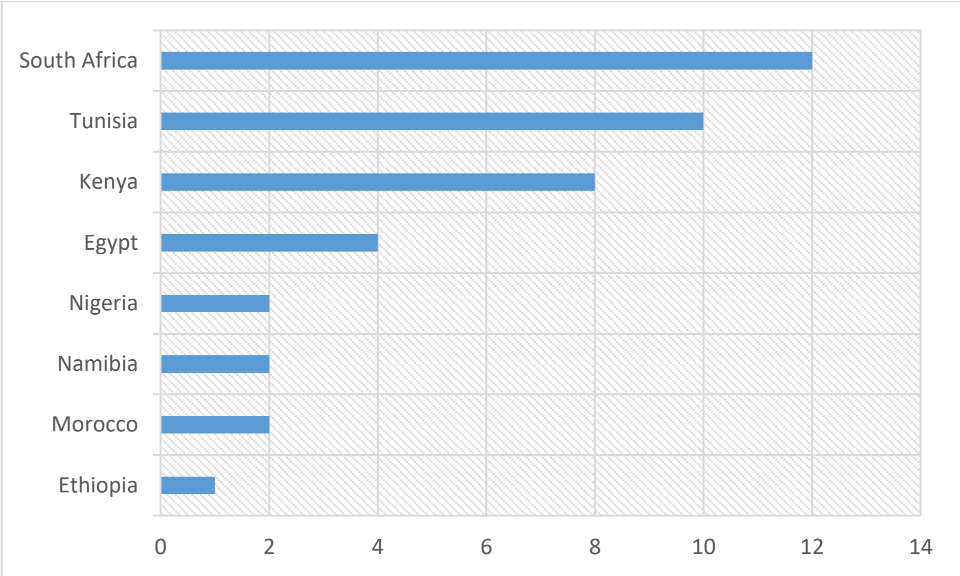

Figure 9: Number of MAR case studies in Africa per country from the Global MAR portal

4.1 Historical development of MAR in Africa

MAR practice is increasing over time in Africa Information on year where MAR operation start is available only for the 27 case studies. The number of case studies, and year of commencement, are presented in Figure 10. According to the UNEP online report[1] accessed on Nov 8, 2017). MAR in North Africa started in 1958, and Morocco was the first North African country that used the technology as a water supply source for the Tanga City. In Tunisia MAR has been practiced as experimental operations in the period between 1970-1988 using infiltration basins like trenches, river beds, well borehole and farm lands as a part of conventional water and soil conservation works (Chaieb 2012, 2014b). According to Nissen-Petersen (2006) the first sand demands in Kenya were built by a District Agricultural Officer, Eng. Classen, as part of a development project called African Land Development Board. According to Nissen-Petersen (2006), Manzui sand dam at Kyuso, Kenya is presented as one of successful sand dams built in 1950's, which still functional, despite lack of maintenance.

However, more detail information about these case studies is not available and this review focuses only on the case studies that are in the Global MAR portal and two additional case studies found in literature search. As can be seen in the Figure 10, the first MAR type in Africa is Spreading method. The Soukra case study, Tunisia is the first spreading method in Africa that started in 1965 (Chaieb 2014a). This was followed by the Atlantis case study in South Africa which was started in 1979 (Tredoux and Cain, 2010). Sand storage dams, which is an in channel modification has been constructed in the Kitui district in Kenya in 1994 by cooperation between, local NGO, SASOL and the communities (Gijsbertsen and Groen, 2007). According to Gijsbertsen and Groen (2007) to date more than 500 sand storage dams have been constructed in the Kitui District only, Kenya. In 1971 injection method using dam water was tested in Teboulba aquifer system, Tunisian (Bouri and Dhia, 2010). In 1995 Kharkams, case study in South Africa was piloted as the first case study, which uses an injection method. A year later in 1996 a large-scale injection MAR type was implement in Windhoek city, Namibia. The Sidaf induced bank infiltration, Egypt started in 2004 is the only induced bank filtration case study implemented in Africa.

[1] http://www.unep.or.jp/ietc/Publications/TechPublications/TechPub-8f/B/Groundwater1.asp,

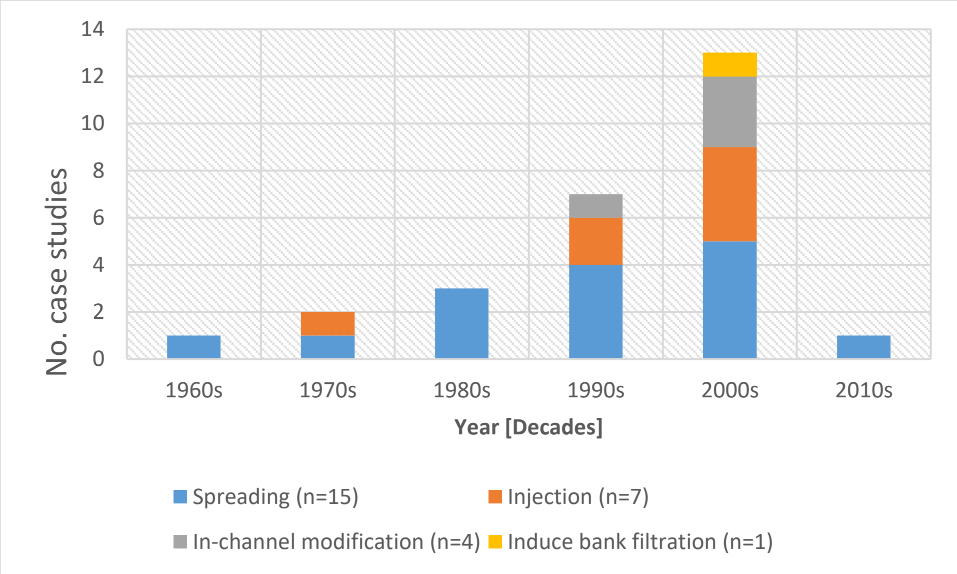

Figure 10: Historical development of MAR in Africa for 27 MAR case studies out of the 41 where starting year for the MAR operation data is reported[2]

4.2 MAR types practiced in Africa

The number of case studies per main MAR types per country in Africa are presented in Table 5. The most common MAR type is the spreading method, the second is in channel modification, and the third is the Well, Shaft and Borehole Recharge method. In channel-modification using sand dams is one of the most practiced MAR type in Kenya, spreading method in Tunisia and well injection in South Africa. The only induced bank filtration case study is found in Egypt. The mean annual rainfall across MAR sites ranges from 20 - 500 mm/a (Figure 11).

Table 5: Main MAR types per country

Country	Spreading Methods	In-Channel Modification	Induced Bank Filtration	Well, Shaft and Borehole Recharge
Egypt	3	-	1	-
Ethiopia	-	1	-	-
Kenya	-	8	-	-
Morocco	1	1	-	-
Namibia	1	-	-	1
Nigeria	1	-	-	1
South Africa	4	1	-	7
Tunisia	6	3	-	1
Total	**16**	**14**	**1**	**10**

[2] 2010s reflect data from 2004

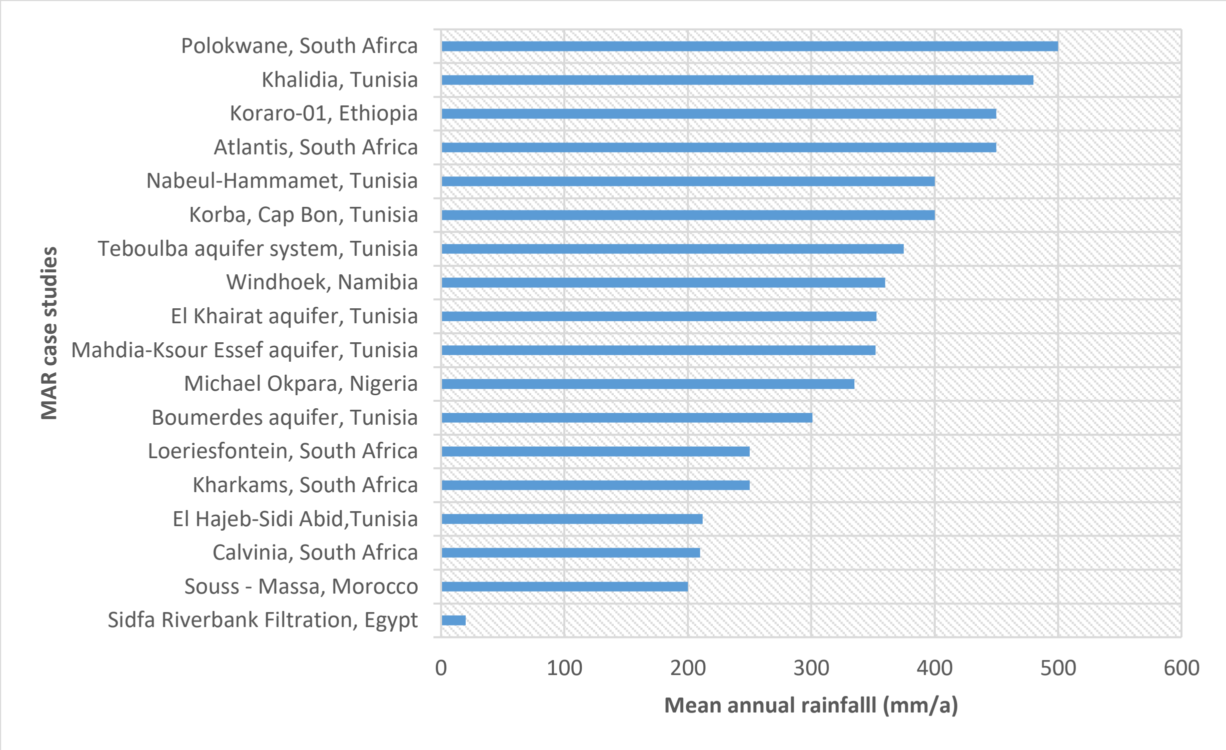

Figure 11: Mean annual rainfall for 18 case studies where annual rainfall data is available

4.3 Objectives of MAR in Africa

The main objective of MAR in Africa is to maximizing natural storage. Number of case studies per MAR objectives is presented in Figure 12. The objectives of maximizing natural storage of groundwater includes increasing groundwater availability to meet rural domestic demand during dry periods (example, sand dams in Kenya), to meet summer peak demand (example, Prince Albert, and Plettenberg, South Africa), to meet emergency and drought supplies (example, Calvinia, South Africa), and water banking for seasonal peak demands and emergency supplies (example, Windhoek, Namibia). Maximizing natural storage and physical aquifer management refers to storing water to meet domestic demand and preventing seawater intrusion (example, Atlantis case study, South Africa). The objective of water quality improvement refers to water quality improvement during infiltration process to filter poor quality water (example, Ben Sergao, case study, Morocco).

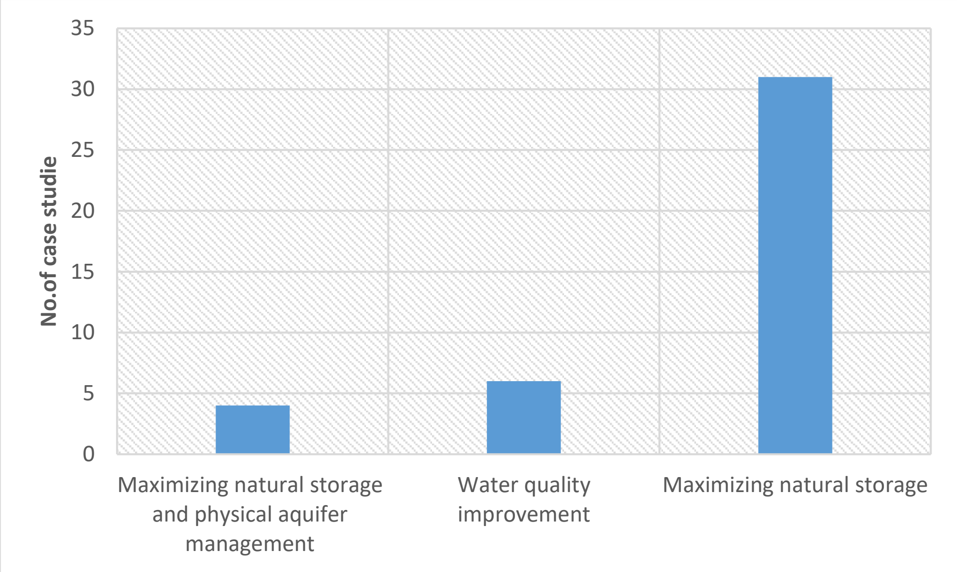

Figure 12: Number of case studies per MAR objectives in Africa

4.4 Source of water for MAR and final uses

Recharge water for MAR in Africa is sourced from river water, treated wastewater, storm runoff, roof runoff, and groundwater from adjacent compartment (Figure 13). About 63% of recharge water is from river water and about 28% is sourced from treated wastewater. Treated wastewater is used in countries with limited water resources such as Tunisia for agricultural uses. The Willsion case study, South Africa, is a unique example of using groundwater from another compartment to recharge aquifer compartment used for domestic water supply. The final use of the recovered MAR water per case studies is presented in Figure 14. The largest use of MAR is to support domestic water supply. Sand dams are used especially in remote rural areas where local community maintain their own water supplies. Agriculture and domestic use represent case studies that have dual purposes.

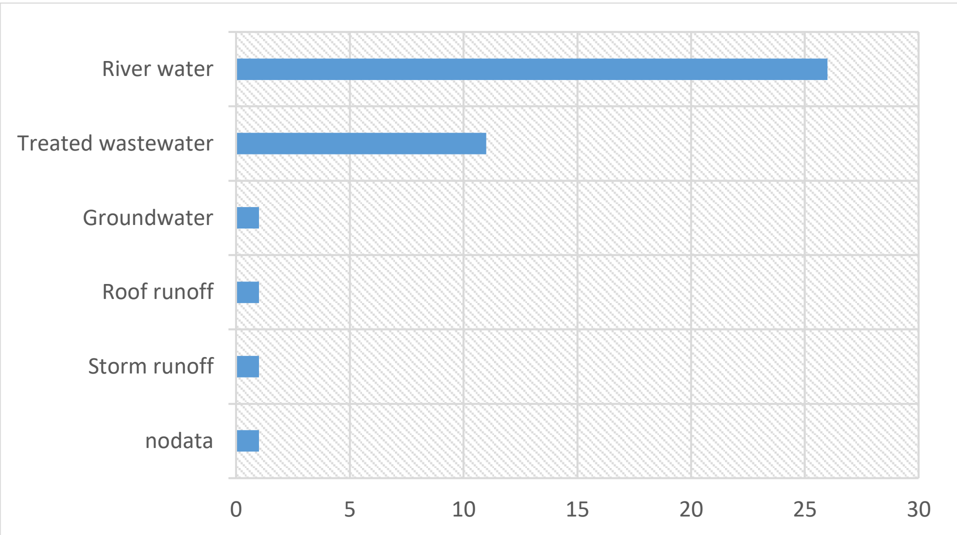

Figure 13: Number of case studies in Africa per water source for MAR

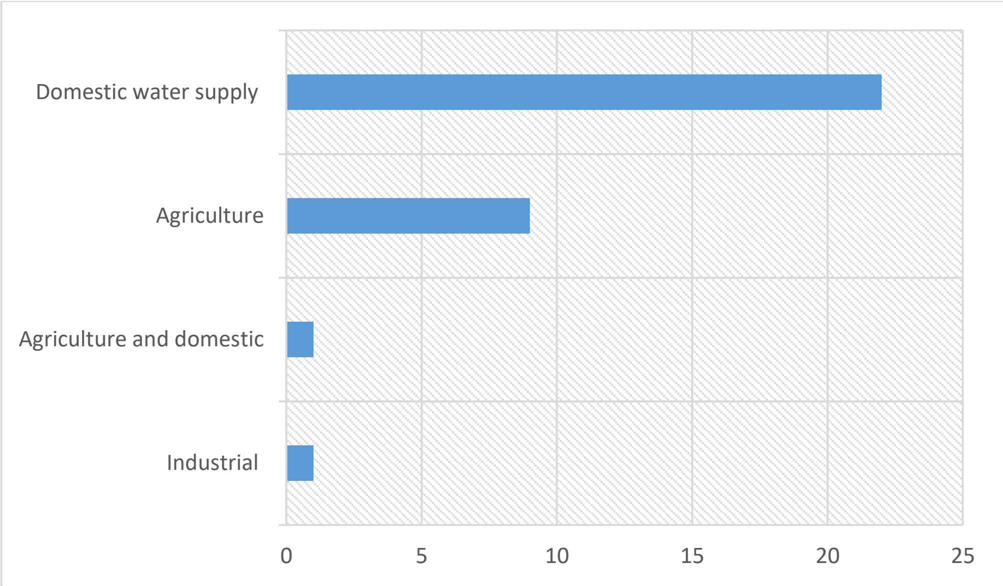

Figure 14: Number of case studies per final use of MAR water (in 8 cases there were no data so these were excluded from the figure)

4.5 Soil properties and unsaturated zone thickness

From the 41 case studies, only five case studies had soil infiltration rates reported (Table 6). The soil infiltration rate ranges from 0.01 m/d -24.5 m/d respectively for the Atlantis case study, South Africa and Abu Rawash case tudy, Egypt.

Unsaturated zone thickens is one of the important factor for the implementation of the MAR schemes. It affects the travel time for degradation of contaminant in the recharged water and storage capacity of the aquifer for the additional recharge. The unsaturated zone thickness is site specific. For example, Atlantis, case study in South Africa, infiltration basin 12 has unsaturated zone thickness of 10.5, while infiltration basin 7 has 1.5 m. Five case studies reported unsaturated zone thickness (Table 7). The unsaturated zone thickness ranges from 1.5 m -12 m respectively for the Atlantis case study, South Africa and Nabeul-Hammamet, case study, Tunisia.

Table 6: Soil infiltration rates

Case study	Country	Soil infitration rate (m/a)
Atlantis	South Africa	0.01-0.16
Korba, Cap Bon	Tunisia	0.5
Souil Wadi, Nabelul	Tunisia	0.19
Abu Rawash	Egypt	1.4-24.5
Koraro-01	Ethiopia	0.864-8.64

Table 7: Unsaturated zone thickness

Case study	Country	Unsaturated zone thickness (m) below the ground
Atlantis	South Africa	1.5-10.5
Korba, Cap Bon	Tunisia	15.0
Hermanus	South Africa	2.5
Nabeul-Hammamet	Tunisia	12.0
Sidfa Riverbank Filtration	Egypt	3.0

4.6 Geology

As shown in Figure 15, majority of MAR sites are situated in Siliclastic Sedimentary rocks followed by Metamorphic Rocks and Unconsolidated sediments. Siliclastic Sedimentary rocks are rocks composed of silicate particles from weathering of rocks and comprises of sandstones, mudstones (shale) and conglomerate. MAR sites situated in Siliclastic Sedimentary rocks are found mainly in South Africa and Tunisia. MAR sites situated in Metamorphic Rocks are found mainly in kitui district Kenya. Sand dams in Kitui district, Kenya are located in crystalline rocks, which mainly consist of gneisses, granulites, schists, migmatites, with minor intrusive overlaid by more recently aged quaternary and tertiary deposits consist of alluvium aquifers and Quaternary deposits (Gijsbertsen and Groen, 2007). Other examples in Metamorphic Rocks are found in Nigeria and Namibia. MAR sites located in unconsolidated sediments are found in Egypt, Morocco and Tunisia. MAR sites situated in Carbonate sedimentary are found in Egypt, Ethiopia, South Africa and Tunisia. MAR sites situated in Acid plutonic Rocks and Basic Volcanic Rocks are found in South Africa.

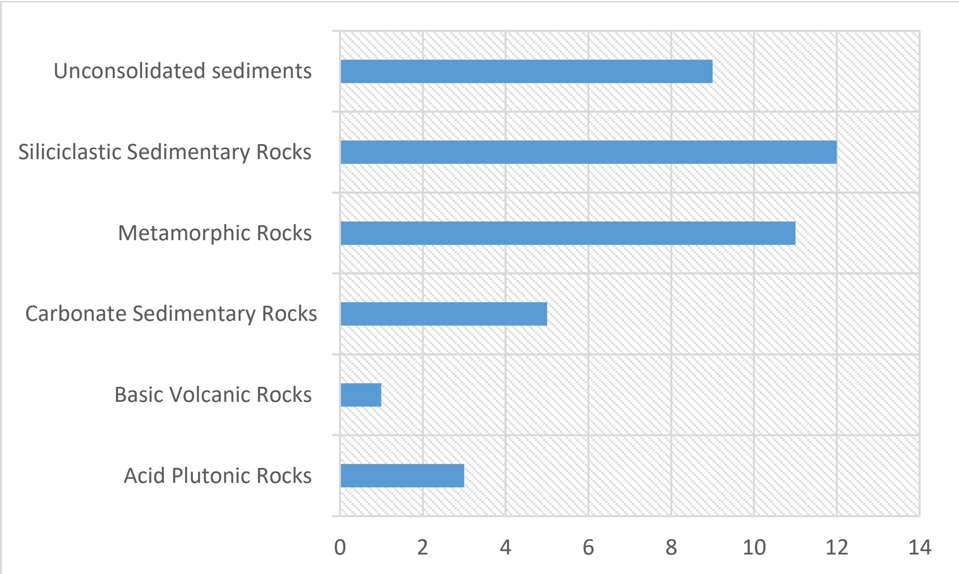

Figure 15: Number of case studies per geology type (based on Global Geologic map by Hartmann and Moosdorf (2012))

4.7 Aquifer properties

Aquifer permeability and storage properties are the two main hydrogeological factors that affects the performance of MAR (National Research Council, 2008). Storage properties of the aquifer determine the capacity of the aquifer to store water. Storage coefficients are not reported for all case studies. However, hydraulic conductivity estimates are reported at least in four case studies and transmissivity values for two MAR sites (Table 8). The hydraulic conductivity values ranges from 0.864 -120 m/d respectively, for the Souil Wadi, Nabelul, Tunisia and Sidfa Riverbank filtration, Egypt.

Table 8: Horizontal hydraulic conductivity

Case study	Country	Hydraulic conductivity (m/a)
Souil Wadi, Nabelul	Tunisia	0.864-8.64
Michael Okpara University of Agriculture	Nigeria	3.15
Polokwane	South Africa	0.896
Sidfa Riverbank Filtration	Egypt	60-110
El Khairat aquifer	Tunisia	86.4 - 605 (transmissivity m^2/d)

Teboulba aquifer system	Tunisia	17.3 (transmissivity m^2/d)

4.8 Recharge volume

Recharge volumes estimates are only available for 17 case studies out of 41 (Table 9). The recharge volume ranges from 492 - 9 x 10^6 m^3/a. The highest recharge volume was achieved at the Omaruru Delta site, Namibia and the lowest recharge volume was for the Koraro-01 subsurface dam, Ethiopia. Chaieb (2014b) presented annual recharge volume for the period of 1992-2012 for Tunisia. According to Chaieb (2014b) the annual recharge volume for the whole Tunisia ranges from 6.2 - 66.2 x10^6 m^3/a, with mean of 37.8 x10^6 m^3/a and standard deviation of 17.1 x10^6 m^3/a.

Table 9 Recharge volume per annum

Case study	Country	Recharge volume (m^3/a)
Atlantis	South Africa	2.7X10^6 and additional 1.5x10^6 high salinity water discharged at the coast for seawater control
Korba, Cap Bon	Tunisia	0.5x10^6
Khalidia	Tunisia	0.8x10^6
El Khairat aquifer	Tunisia	3.3 x10^6
Teboulba aquifer system	Tunisia	0.21 x10^6
Kharkams	South Africa	4906
Polokwane	South Africa	4.5X10^6
Calvinia artificial recharge scheme	South Africa	0.8x10^6
Plettenberg Bay	South Africa	0.315X10^6
Omaruru Delta (OMDEL)	Namibia	9x10^6
Sedgefield	South Africa	0.47x10^6
Hermanus	South Africa	1.5x10^6
Williston	South Africa	0.1X10^6
El Hajeb-Sidi Abid	Tunisia	0.1x10^6
Sidfa Riverbank Filtration	Egypt	2.2x10^7
Souss – Massa	Morocco	1x10^8
Koraro-01	Ethiopia	492

4.9 Challenges

4.9.1 Clogging problem

Multiple sites have experienced some form of clogging problem. Clogging is the process of restricting the volume of water that can infiltrate or be injected into the target aquifer (Martin, 2013). Clogging of the MAR system may occur due to chemical, physical, mechanical and biological process, as well as a combination of these (Martin, 2013; Murray and Tredoux, 1998; Rice, 1974). Clogging may take place at the infiltration surface, unsaturated zone, or in the aquifer. The consequence of clogging is reducing the amount of recharged water, which leads to complete failure of the scheme. In the case of injection, clogging may block the fractures leading away from the borehole (Murray and Tredoux, 1998). For Atlantis case study, South Africa the infiltration rate decreased noticeably due to clogging over the years in Basin 7 (the original recharge basin), biofouling and the natural occurrence of iron in the groundwater has contributed to problem of borehole clogging (Gideon and Julia, 2010). It was reported that maximum pumping rate to meet the higher demand results in air entering the system and stimulated the over-growth of microorganisms in the soil. This problem was addressed by blended chemical, heat treatment and rehabilitation of the boreholes (Tredoux and Cain, 2010). The use of chemical and heat treatment in addition to borehole rehabilitation shown to be useful at the Atlantis case study to destroy bacteria that results biological clogging of the system. According to Tredoux and Cain (2010), elevated iron and sulphate in the groundwater caused biological iron-related clogging rather than physical clogging of individual boreholes. To prevent clogging, Basin 7 is cleaned every 15 years. In addition subdividing Basin 7 to allow alternate wetting and drying cleaning every 20 to 30 years was recommended (Tredoux and Cain, 2010). Similarly, the Omaruru Delta (OMDEL) infiltration basin Namibia the surface of the basin need to be scraped from time –to-time in order to maximize infiltration (Murray, 2009). In the Abu Rawash case study, Egypt the major problem observed in the clay basin is the very low infiltration rate (El-Fakharany, 2013).

4.9.2 Unsaturated zone

The ability of the unsaturated zone to provide adequate purification depends on the thickness of the unsaturated zone and its permeability. The unsaturated zone thickness at Basin 7 Atlantis case study, South Africa is extremely small and hence the unsaturated zone will be fully saturated during the rainy season (Tredoux and Cain, 2010). In the Polokwane case study, South Africa due to lack of unsaturated zone thickness that assist in purification of the recharged water it is suspected that some bacteria, viruses or parasites could survive the bank infiltration process and contaminates the groundwater (Murry and Tredoux, 2002).

4.9.3 Site selection and design problems

One of the most difficult problems in the planning of sand dams for a rural community is the lack of criteria upon which an engineering design can be based. Most recently design guidelines for sand dams are begin developed (MWI, 2015; RAIN, 2011). According to Nissen-Petersen (2006) around 200 sand dams have been constructed since the early 1970s in Machakos, Makueni, Kitui, Mwingi,Embu and Meru areas, Kenya. However only about 5% of the dams built during the last 40 years were functional. The main reason mentioned was the lack of design experience by young engineers who lack the fundamental knowledge of course that deal with sand dams, subsurface dams and weirs.

Some of the reasons for the failure of many sand dams in Kenya were (DE TRINCHERIA et al., 2015; Foster and Tuinhof, 2004; Gijsbertsen and Groen, 2007):

i. Errors in site selection resulting insufficient storage potential,
ii. Insufficient depth to reach relatively impermeable bedrock
iii. Seepage through the layer on which dam is founded or leakage underneath the dam wall decrease the efficiency of the sand storage dams
iv. Location in a soil type with very low infiltration capacity
v. Sediment accumulation behind the dam is too fine grained which decrease infiltration rates and groundwater storage and extraction,
vi. Low yielding abstraction wells due to poor construction
vii. Location in a soil type that could lead to sever ground water salinization
viii. Longer time required for reach full potential. Some dams take more than 9 years to fill completely.

The subsurface dam constructed near the village of Koraro, Ethiopia was reported to be affected by flooding problem as a result of catastrophic rain events and breached an above situated percolation dam due to uncontrolled flow over its crest. Hence, it was recommended to avoid sand storage dams above the riverbed due to the erosive nature of the highland catchment. The other problem reported for the Koraro case study was significant reduction in the efficiency of the reservoir about by 38% due to evaporation and seepage losses. The estimated efficiency of the scheme is about 62%.

Box 1: MAR in karstic Aquifers

Hydrogeology of karst aquifers

How karst aquifers form? Karst aquifers are found throughout the world and include notable aquifers such as Florida Aquifer, Florida, USA, Edwards Aquifer, central Texas, USA, the Almyros and Trifilia aquifers, Greece, Far West Rand, South Africa, North West Dolomitic, South Africa X, Y and the Ramotswa. Karst aquifers contribute 72% of groundwater in Greece, 18% in Austria, 17% in Italy, 11% in Spain and 6% Portugal (Koreimann et al., 1996). Karst is a special type of landscape that is formed by the dissolution of soluble rocks, including limestone and dolomite under the process called karstification (Zwahlen, 2003). The rain water collect atmospheric carbon dioxide (CO_2) in the atmosphere and in the soil during infiltration and if the underlying bedrock is composed of carbonate rock, its CO_2 will dissolve the bedrock material. In this way, karst develops over tens of thousands of years, creating a landscape with specific surface and subsurface features (Hartmann et al., 2014). Karst typically develops from carbonate rocks, such as limestone (consisting of the mineral calcite, $CaCO_3$) and dolomite rock or dolostone (consisting of the mineral dolomite, $CaMg(CO_3)_2$) (Hartmann et al., 2014). The dissolution process creates complex networks of preferential flow pathways that are difficult to locate. A karst aquifer is typically characterized by sinkholes, caves, springs, conduits, and underground drainage systems (Bakalowicz, 2005; Hartmann et al., 2014).

Karstic aquifer recharge could occur as concentrated or diffuse, and flow velocity ranges from Darcian to Turbulent. According to Hartmann et al. (2014) the hydrological behaviour of karst systems exhibits duality in its process and storage dynamics. In karst aquifers, permeability may be associated with three types of system porosity: matrix, fractures, and conduits (Hartmann et al., 2014; Mifflin and Hess, 1979). The occurrence and movement of groundwater in karst aquifer is different from hard rock or non-karst aquifer, primarily because of the presences of conduits that permit relatively rapid transmission of groundwater (Mull et al., 1988). Conduits are underground pipes formed by dissolution of carbonate rocks that carry water from the recharge area to an outlet spring. Karst aquifers are highly vulnerable to pollution, once contaminants enter the groundwater they travel rapidly through the aquifer towards the spring or well (Zwahlen, 2003). Flow within the Karst aquifer ranges from Darcian to turbulent flow depending upon the relative contribution and interplay of matrix, fracture and conduit permeability. Natural recharge in karst aquifer occur as concentrated or diffuse, recharge from precipitation falling on non-carbonate portion of the basin, and recharge that occurs directly on the karst surface and entering the aquifer as infiltration (Taylor and Greene, 2008; White, 2002). Figure 16 illustrates typical features of the Karstic aquifers.

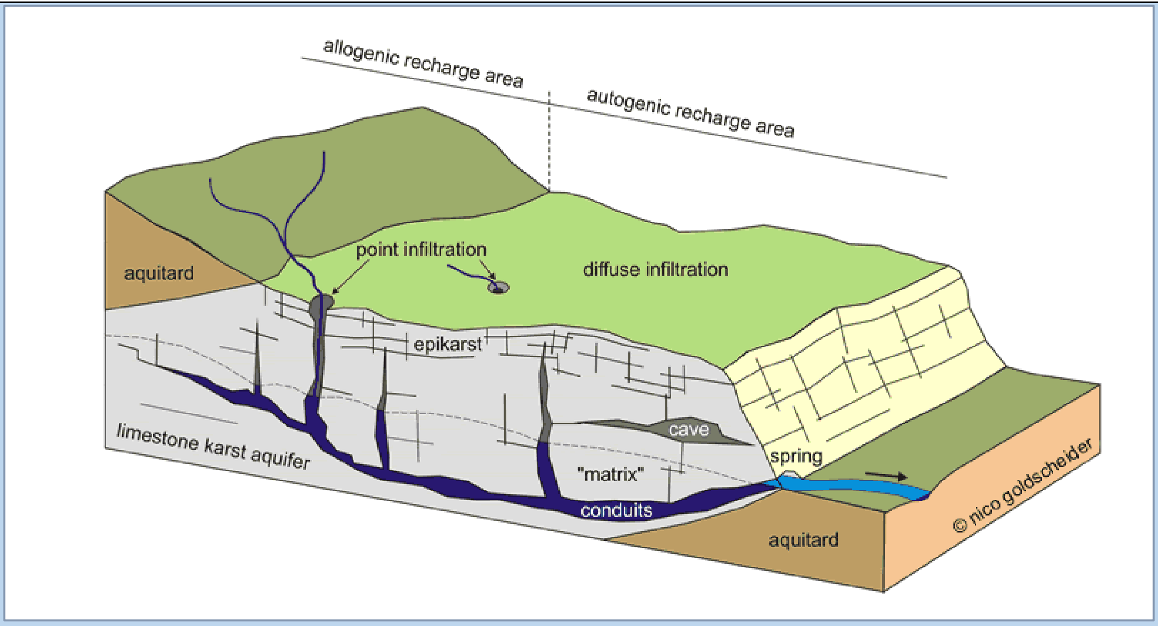

Figure 16: Typical aquifer system illustrating the duality of recharge mechanisms (Source: http://karst.iah.org/karst_hydrogeology.html

MAR in Karst Aquifers

Due to the high degree of heterogeneity, aquifer recharge in karst aquifer is very challenging. Karst processes at the surface and underground affect the infiltration process (Daher et al., 2011). The presence of conduits that quickly drain the recharged water without significant storage and its vulnerability to contamination makes MAR in karst aquifer challenging (Daher et al., 2011). Understanding how karst features control ground-water flow and respond to varying hydrologic conditions is critical for effective planning and implementation of MAR (Green et al., 2006), because groundwater management options appropriate for other aquifer may not be adequate for karst aquifers. Hence, MAR must be approached in an appropriate and rational manner to ensure the success of MAR in karst aquifers (Daher et al., 2011).

Recharge to karst aquifers be should be operated in such a way that concentrated flow through sinkholes and conduits are avoided, otherwise, the filtering capability of the soil will be compromised, recharged water will be lost through spring discharges. Daher et al. (2011) recommended to aim the epikarst zone for potential MAR application mainly for two reasons: (i) spreading the injected water preferably through slow and diffuse infiltration, and (ii) favouring natural treatment process, which could decrease the project operational cost. An epikrast is a term introduced to refer the highly weathered carbonate rock below the soil layer and typically 3-10m deep but in some cases it may extends to 30 m or more (Ghasemizadeh et al., 2012; Williams, 2008).The high porosity and permeability of the epikarst is due to its proximate to the main source of carbon dioxide in the soil that results dissolution of carbonate (Williams, 2008). Epikrast zone play significant role in recharge regulation that allow slow and delayed infiltration and it has the potential of distributing the recharge water into different infiltration process (Daher et al., 2011) such as: fast infiltration though large openings, slow infiltration through fine cracks and rock porosities. Under natural conditions some of the recharge may pass through the concentrated flow paths such as sink holes. MAR operation in Karst aquifers must be operated in such a way that water flow though concentrated fast infiltration flow paths are avoided (Daher et al., 2011). It is strongly recommended that water be injected far from karst features such as vertical shafts or closed depressions, which are generally connected to the conduit system, so as to ensure that the recharge water spreads towards the phreatic zone through diffuse and slow flow conditions (Daher et al., 2011).

MAR case studies in Karst Aquifers

Application of MAR in karst aquifer is very limited. The recent inventory of MAR sites in Europe by Sprenger et al. (2017) found no application of MAR in European countries. However, some pilot studies under the European MARSOL (Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought) project were carried out in Portugal, and Italy in karstic aquifer settings. In total five case sudies were identified and reviewed. This review generated several key messages:

Karst aquifers have the potential to store large volume of water during aquifer recharge. According to Daher et al. (2011) ASR operation in Beruit, Lebanon was first proposed in 1970s and the first test injection was carreidout in early 2000s. The purpose of the ASR operation was to prevent seawater intrusion using water from Beriut River. The system works 6 months a year with a 12,000m^3/d injection rate into asinlge well. The the Wala reservoir Jordan is another largest MAR site, where flood water is recharged in carbonate aquifers, with a mean annual recharge of around 6.7 million cubic meters (2002–2012) (Xanke, 2017; Xanke et al., 2015). This recahrge volume corresponds to about 60 % of the yearly average abstraction of about 11.7 million m^3 Period of operation start 2002. MAR is accomplished using percoaltion reservoirs and injection wells (Xanke, 2017). Water is recharged mainly by natural seepage from the reservoir and small amounts via recharge wells (since 2011) and then recovered at Hidan wellfield. The wellfield serves as an important drinking-water supplier of the cities of Amman, Madaba and nearby communities.

Aquifer recharge through sinkholes In Nardo, Italy, karst sinkholes were used to recharge large volume of treated wastewater into the aquifer (Kazner et al., 2009; Masciopinto and Carrieri, 2002). This is in contrary to Daher et al. (2011), recommendation to avoid recharge in sinkholes. The Nardò aquifer comprises of the limestone rock formations that are significantly fractured and very permeable (Masciopinto et al., 2008). The natural sinkhole located near Nardo has been used since 1991 for treated wastewater injection of about 12,000m^3/d derived from the Galatone and Naro municipal wastewater treatment plants. After injection started the water table rasie 1.5m and seawater extent reduced by 2km. After 10 years, the injection has increased the volume of the available resource for agriculture and drinking water use, without any potable decrease in the pre-existing groundwater quality (Masciopinto and Carrieri, 2002).

Protecting karst aquifers' water quality and ensuring water availability. The Querença-Silves limestone karstic aquifer system is the largest and most important groundwater body in the Algarve region and under the Eruopean MARSOL project two-MAR demonstration activities were undertaken (Leitão et al., 2017; Schüth, 2017). The main goals of the two pilot projects are: 1) to improve the the waste water treatment plant effluent quality, prior to its discharge into Ribeiro Meirinho, a stream which naturally recharges the karstic aquifer in part of its river bed, 2) to increase groundwater storage at Cerro do Bardo karstic area using wet years surface water surplus stored in Águas do Algarve water supply Odelouca and Funcho reservoirs to increase the water availability in dry years and facilitate downstream water supply. To achive the first objective two infiltration basins were constructed to monitor the fate of pharmaceuticals. According to Schüth (2017) although no direct proof of degradation was obtained, analyses of the sediment in the basins showed no detection of pharmaceuticals, indicating that biodegradation may have occurred. The second objective was achieved through infiltration into a rehabilitated a 2m diameter and 34 m depth infitration dug well, for which a pipeline of more than 1300 m length was constructed to supply water to the well. Although infiltration rates decreased exponentially over time it showed a prinical means to rechrge the aquifer.

ASR systems could be operated in karstic aquifers using turbid storm water without significant clogging problems. Pavelic et al. (2006) conducted a pilot study at the Andrews Farm site in Adelaide, South Australia to investigate the nature and extent of well clogging using ASR with urban storm water in a brackish limestone aquifer. The authors used hydrological data in conjunction with a mass balance approach using physico-chemical and microbial data to investigate the clogging extent. Microbial clogging was investigated through sampling of recovered water and comparing this with water sample before injection. Their results shows that clogging during the storm water injection partly reversed by an increase in porosity due to the dissolution of calcite. The trial test showed a successful case study where turbid storm water could be used for aquifer recharge using ASR system. According to Pavelic et al. (2006) the success story of this trial test has led to a series of storm water ASR schemes implementation in the Adelaide region.

5. Discussion on MAR experience in Africa

5.1 Discussion

Injection wells are more often used for urban domestic supply and sand storage dams for rural. There are substantial differences among types of MAR implementation in terms of municipal water uses in the rural and urban contexts. Sand dams in Kenya and subsurface dams in Ethiopia are used for domestic water use for the rural water supply. In view of their low capital costs, sand storage dams and subsurface dams have relevance to the poor communities although there is little data to prove the efficiency of this method and some question about sustainability due to silting-up. The cost of each sand dams built in Kitiu district, Kenya ranges from 8,000-12,000 US$ (Foster et al., 2012). On the other hand, injection wells type of MAR schemes are used widely for supplying domestic water for urban areas in South Africa and Namibia. Injection wells generally have relatively high costs, due to deep drilling and high pumping lifts. The option of aquifer recharge via boreholes is not considered economic in the rural context, because of the high level and cost of operational treatment required. The cost of a cubic meter of recovered water is a function of the source water quality, ambient groundwater quality, geochemical reactions, and the water treatment required to meet regulatory standards (Brown, 2006).

MAR Contribution to aggregated domestic demand is unclear. In the majority of the reviewed case studies the contribution of MAR to overall drinking water supply is lacking. Only few case studies reported the contribution of MAR to overall water supply. A good example is the Atlantis case study, South Africa where approximately 25-30% of the town water supply is supplemented using MAR (Tredoux and Cain, 2010). For the Calvina case study, South Africa MAR reported to have the potential to supplement at least two to three month of the town water supply (Murry and Tredoux, 2002). Subsurface dam in Koror, Ethiopia supply domestic water for user group consisted of 150 to 170 people at a rate of 15l/d/head over a time span of 89 days (Mohn et al., 2012). Sand dams in Kenya provide a perennial source of water to 150-200 people for drinking, food production, and livestock watering (Foster et al., 2012). According to SASOL each sand dams are designed to serve at least 20 households (Gijsbertsen and Groen, 2007). Sand dams are a useful alternative water source in dryland areas that can be managed and operated independently by low income communities (Hussey, 2007). The river sediment stored behind the dam acts as slow sand filter system and hence there is less water quality problem or no algae growth as there is no direct sunlight contact (Hussey, 2007). The Sidfa Riverbank Filtration case study found in Nile Valley, Egypt produces drinking water for the city of Sidfa for the population of around 30,000 (Shamrukh and Abdel-Wahab, 2008).

The role for MAR in the context of increasing agricultural water use. At present 10 case studies from three countries – Tunisia, Morocco and South Africa – are using MAR for agricultural uses. Among the three countries, Tunisia is the major user of MAR for agriculture (n=7) followed by Morocco (n=2) and South Africa (n=1). The Polokwane cases study, South Africa is used for both agricultural and domestic water supply purposes. Seven out of the 10 case studies use treated wastewater as their water source for MAR while the other three case studies use river water. MAR is accomplished through the spreading method (n=5), in channel modification mainly channel spreading and dam release (n=4) and well injection (n=1). Total recharge volume information is available only for the six cases studies out of the ten. The annual rate of recharge across the six case studies ranges from $1x10^5$- 4.5 $x10^6$ m^3/a, with mean value of 1.6 x 10^6 m^3/a. Even if their main purpose is domestic water supply, Sand dams in Kenya are also used for garden agriculture to grow vegetables, and support food security. With this few examples, we can see the contribution of MAR for agriculture. If expanded and used properly MAR may have a role to play for securing water to improve the productivity and reliability of water for irrigation in Africa.

The main issues of MAR application in karst aquifers are risk of contamination problem and loss of recharged water through conduits (Box 1). The hydrogeology of karst aquifers is very complex and highly heterogeneous. Duality is the common property of karst aquifers. Duality in recharge and duality in flow. Recharge occur as concentrated and diffuse. The major source of concentrated recharge is surface runoff draining to sinkhole depressions. There are three type of porosity in karst aquifer: matrix porosity, porosity related to fractures and porosity related to solution enlarged channels or conduits. Pores that are not connected to other pore or conduits cannot provide much water. Compared to other aquifers those composed of sand, groundwater in karst aquifers may not stay in storage for later use. This is because flow in karst aquifer behaves differently from other aquifers. The flow in porous media is mainly governed by Darcian flow, however, in karst aquifer both Darcian and Turbulent flow exist. The Turbulent flow is mainly due to the presence of conduit that carry water at a faster rate from recharge area to an outlet spring. Because of this the flow and transmission of water in karst aquifer may vary significantly within a short distance depending on the jointing and dissolution (Coakley et al., 2017). Due to this fast transfer of water and the existence of sink holes or large opening at the surface that favour the entrance of contaminant into the aquifer, karst aquifers are highly vulnerable to contamination problem. Contaminant entering into the karst aquifer has little opportunity for degradation due to short residence time. MAR operations in Karst aquifer therefore must be prevented water flowing through these concentrated fast infiltration flow paths because of potential contamination risks and rapid transfer of water to springs through conduits. As presented in previous section (Box 1) the Nardo, Italy case study uses the natural sinkhole for recharge, but detailed understanding of how the natural sinkhole function is needed and hence caution in inferring such cases. MAR using spreading method is the preferred option. The spreading method should target the Epikrastic zone. Epikrastic provide soil infiltration and slow and diffused infiltration. But, as Williams (2008) pointed out the Epikrastic zone in some cases many not developed or it has been removed. If injection method is used with treated wastewater as a source, it need to be treated to very high level as there is little opportunity for the recharge water undergo further purification.

5.2 Lessons learned

- ***Separating domestic and industrial wastewater and storm water runoff are important for aquifer recharge.*** For example, the Atlantis case study, South Africa, separate the domestic and industrial wastewater, storm runoff based on their salinity and recharges the low salinity water into the aquifer used for domestic supply, and high saline water is recharged at the coast to prevent seawater intrusion (Tredoux et al., 1999).
- ***Complex, fractured rock aquifers can be used for MAR*****.** Storage and permeability in fractured rock aquifers depend on secondary porosity and affected by the size and depth of fracture opening, fracture spacing, and interconnection of fractures. In most cases, formations targeted for recharge are usually sedimentary (carbonate, gravel and sand), and fractured rock aquifers are regarded as less favourable (Dillon and Pavelic, 1996). However, the Windhoek case study, Namibia is a very good example that demonstrated the success of large-scale municipal use MAR scheme in fractured rock aquifer settings. During injection, water levels were observed to raise at observation boreholes located up to 1.3 km from the injection site, which confirm the geology is highly fractured and jointed and the potential to store large volume of water. However, detailed hydrogeological assessments are required to understand the groundwater flow system in such a aquifers (Murray, 2009). According to Murray (2007) when fully developed, the water banking through Windhoek MAR case study is expected to provide security for three years as the main water resource for the city during the drought conditions.
- ***Groundwater transfer using MAR within an aquifer is a preferred option to reduce cost.*** When aquifers are compartmentalized by impermeable or less permeable geological structures like dykes, groundwater extraction from one aquifer compartment does not necessarily draw water from the adjacent aquifer system. While the compartment developed for use show significant decline in groundwater level, the adjacent aquifer compartment remains fully saturated. The Williston, case study South Africa demonstrate a very good example where groundwater from the adjacent compartment is used to recharge another compartment used for domestic water supply. According to Murray and Harris (2010) the town of Williston, Western Karoo relies on groundwater for its domestic supplies and abstraction over the years has been in excess of the natural recharge. Therefore, ASTR scheme was designed to recharge the aquifer compartment used for domestic water supply using groundwater from the adjacent compartment. The existing groundwater pumping scheme is located approximately 4km from the aquifer recharge point. Therefore, the MAR system was aimed to reduce additional cost of infrastructure such as additional pipeline work and installation of new pumping boreholes for direct use of groundwater from the unused compartment. Similarly, the Calvinia, case study, South Africa, demonstrated breccia tubes to store treated surface water from dams via injection (Murry and Tredoux, 2002). Breccia pipes are formed as a result of hydrothermal explosions and are highly impermeable.
- ***Use of abandoned mining and quarry sites reduce cost of infrastructure for MAR.*** The Eland Platinum Mine case study, South Africa, demonstrates the use of an abandoned mining site for MAR aiming to reduce the risk of production loss due to water shortage (Botha and Maleka, 2011; Botha, 2009). Khalidia case study, Tunisia also demonstrated the use of abandoned sand stone quarry site for aquifer recharge (Mhamdi and Heilweil, 2007). The use of such facility may reduce costs associated to MAR infrastructure and can be used as a sustainable water resources management strategy for minimizing groundwater declines. However, risk of water quality problem from the mining activities should be investigated very carefully.

- ***Proper filter design for river flow intake structure is important for reducing clogging problem.*** For example, filter design problems was an issue in Kharkams, case study South Africa (Murry and Tredoux, 2002). The Kharkams, case study South Africa rely on empheral flow for its MAR. Ephemeral stream are known to carry large silt load during flooding. Due to problem in the filter design, sand was entering the injection borehole, resulting in a clogging problem. The sand filter was re-designed to avoid this problem. The main new features of the new filter design were: an appropriately sized screen at the base of the filter, correctly sized filter sand, grading from the coarse at the base to relatively fine at the surface, a heightened filter wall and gabions at the entrance to the filter to prevent debris from entering the filter.

- ***Subsurface and sand dams provide reliable sources of water for communities living in remote, rural areas.*** Subsurface and sand dams are low cost, easily constructed using locally available material. They are instrumental for water supply for the rural population who has the responsibility to find their own water supply sources. For example, in Koraro, Ethiopia subsurface dam is used to supply domestic water for 150-170 people at a rate of 15 litre per capita per day over a time span of 89 days (Mohn et al., 2012) which enable water security during the dry period. Sand dams in Kitiu district of Kenya have been used for a very long time for rural domestic water supply and garden agriculture to provide water to vulnerable rural communities in harsh dryland areas. In the kitui area in general, SASOL have built consecutive dams at 0.5-1.0 km intervals along water courses, and nearly 200,000 households have benefited through cutting the average time spent on water collection (primarily by women) from more than 5 hours/day to less than 1 hours/day (Foster and Tuinhof, 2004). According to the world bank assessment of sand dams benefit at Kinud village Kenya (Foster et al., 2012) , the following benefits were reported:
    a) access to drinking water in dry season reduced from 3km (1995) to 1km (2005),
    b) people exposed to droughts reduced from 420 (1995) to zero (2005),
    c) household with irrigated crops increased from 37% (1995) to 68% (2005),
    d) agricultural water consumption increased from 220l/d (1995) to 420l/d (2005)
    e) Household income (US$/a) increased from 180 (1995) to 290 (2005).
- ***Water quality improvement due to MAR is evident from reduction of nitrate and salinity in the aquifer and other contaminant in the recharged water.*** Chemical analysis of nitrate in the aquifer before and after recharge in the Nabeul-Hammamet, case study, Tunisia (Chaieb 2014a) showed significant decrease in nitrate concentration from (234-335 mg/l) to 50 mg/l. In the Soukra case study, Tunisia, the percolation of significant amount of irrigation water into the aquifer results in reduction in salinity for about 2/3 of the total area. According to the Ben Sergao, case study, Morocco (Bennani et al., 1992), wastewater infiltration using dune sands totally removed the suspended matter, reduce the chemical oxygen demand by 95%, 85% of the nitrogen is oxidized and significant reduction in faecal coliform was observed. Similarly, the Abu Rawash case study, Egypt (El-Fakharany, 2013), observed a reduction in biological and chemical demand by 50-80% in treated wastewater used for recharge.

6. Background on GIS-based Multi-Criteria Decision Analysis for MAR Suitability

Geographic Information System Multi-Criteria Decision Analysis (GIS-MCDA) has been used for years to map irrigation land suitability (Joerin et al., 2001; Malczewski, 2004) and groundwater vulnerability mapping (Babiker et al., 2005; Merchant, 1994; Stempvoort et al., 1993). More recently, this technique have been used for delineation of potential groundwater zones (Magesh et al., 2012) and MAR site suitability assessment (Bonilla Valverde et al., 2016; Daher et al., 2011; Ghayoumian et al., 2005; Ghayoumian et al., 2007; Rahman et al., 2012; Russo et al., 2015). According to Dodgson et al. (2009)

GIS-MCDA can be used for many purposes such as to identify the most preferred option, to rank different options, to screen and short-list a number of options for subsequent detail analysis or to distinguish feasible from non-feasible alternatives. In the context of MAR, GIS-MCDA can be used to find best location for MAR application. This will assist improved assessment of the potential of MAR.

6.1 GIS-based Multi-Criteria Decision Analysis Procedures

Multi-Criteria Evaluation is a method of combining information from several criteria to form a single index of evaluation. In the case of Boolean criteria (constraints), logical OR and AND are used. However, for continuous factors, a **Weighted Linear Combination (WLC)** (Eqn. 1) is the most commonly used method.

$$S = \sum wi\ xi \qquad (1)$$

Where S= suitability, wi= weight for factor i and xi= criterion score of factor i

Sutiablity mapping using GIS-MCDA inovlves several steps (Bonilla Valverde et al., 2016; Rahman et al., 2012), as presented below.

Problem definition The problem definition consists of defining and characterizing the problem and the required datasets, which include identifying the appropriate MAR technique, the purpose of MAR application (water quality improvement vs aquifer recharge), the water source, and identifying the available dataset that can be used as criteria.

Constraint mapping: Constraint mapping or screening comparises of excluding part of the area that are not feasible for MAR application. The main reason could be proximity of the water source, protected areas such as nature reserve and parks, land that belong to privae owners etc. This can be perfomed by using Boolen logic opertors such as “ AND” and “ OR”. Using boolen, areas could be assinged a value of 0 or 1, where areas with zero values are those areas which are excluded/ rejected from further sutiablity assesment.

Choice of criteria: Choice of criteria involves selecting relevant surface, subsurface and catchment characteristics. Every selected criteria has to be measurable and non-redundant or correlated (Bonilla Valverde et al., 2016; Dodgson et al., 2009; Malczewski, 2000).

Standardization of criteria: Standardization involves describing each criteria in a common scale. Usually each layer of the map is classified into a common scale value between 0 and 1 (the higher the value is the best). The step-wise and linear functions are the most common standardization methods (Bonilla Valverde et al., 2016).

Assigning relative weights: Assigning relative weight is one of the most important step that used to assign different weight for each criteria based on their importance to the process. Several methods are used to assign weight to the criteria. These methods include the rating methods, ranking method, pairwise comparison, and Multi-Influencing Factor (MIF) Method. Rating methods involves assigning weight based on expert knowledge and by comparison with previous studies. The ranking method on the other hand, involves ranking of criteria according to their rank order from the most important to the least. Then the weights are calculated by $((N-r+1)/\sum(N-r+1))$, where N is total number of criteria, and r is rank order. The Analytic Hierarchy Process (AHP) (Saaty, 2008) is one of the most common method of assigning weight based on pairwise comparisons. This method heavily depend on the experts judgment to assign a scale how much one element dominates another with respect to a given attributes. The MIF method (Magesh et al., 2012; Shaban et al., 2006; Yeh et al., 2009) is another method that involves graphical representation of cause and effect relationship among the criteria used for the suitability mapping. For instance if criteria one has major influence on criteria two the effect of criteria one on criteria two would be denoted by solid continuous line indicating Major effect and would have a score of 1.0. On the other hand, if criteria 1 has minor effect on another criteria that would be represented by broken line and would have a score of 0.5. Finally, all major and minor effects for each individual criteria are summed and divided by the total score to determine the relative weights.

6.2 GIS-based Multi-Criteria Decision Analysis for Recharge and MAR suitability mapping in karst Aquifers

Some of the actual MAR case studies implemented or at experimental stages were presented in Box 1 above. In this section, we review case studies that applied the GIS-Multi-Criteria Decision Analysis for assessing aquifer recharge potential and MAR suitability. Eight case studies related to aquifer recharge and one case study on vulnerability mapping on karst aquifers are reviewed. Criteria used and associated weights are presented.

1. Damour, Lebanon Daher et al. (2011) developed a method named ARAK (Aquifer Rechargeability Assessment in Karst) for MAR suitability mapping and applied this to the Damour-Lebanon case study on the Mediterranean coast. The ARAK methodology considers four criteria for controlling recharge process through the spreading system. These include: 1) Epikarst including the epikarst and its soil cover (all surface karst landforms), 2) aquifer rock type, 3) infiltration potential, and 4) the degree of Karstification of the entire system. Field observations associated with aerial photographs were used for Epikrast identification. Topographic slope was used as proxy for infiltration potential. According to the authors epikarst is one of the most important criteria for MAR application using infiltration method and it received higher weightage. The weightage assigned to the four selected criteria were 60% for Epikarst, 20% for rock type, 10 % for infiltration potential and 10% for degree of karstification.

2. Algarve Region Portugal Rahman et al. (2012) developed a new spatial multi-criteria decision analysis (SMCDA) software tool for selecting sties for MAR. Five criteria were used for suitability mapping. These include soil infiltration rate, groundwater depth, aquifer thickness, groundwater quality (chloride and nitrate) and residence time. Pairwise comparison was used to assign weights for each criteria. The criteria weights used in the study were, slope (10%), soil infiltration rate (30%), aquifer thickness (5%), depth to groundwater (20%), residence time (25%), chloride (5%) and nitrate (5%).

3. Lebanon Rolf (2017) evaluated the suitability of MAR using the injection method in Karstic aquifer. Eight criteria that include: 1) Aquifer, 2) source water, 3) Environmental impact, 4) MAR Technique, 5) Infrastructure, 6) costs, 7) stakeholders and 8) Governance were considered in the two stage MAR suitability assessment framework consisting of a prefeasibility study (step 1) and Multi-criteria decision analysis mapping (step 2). A uniform weight uncertainty value of 20% was used to all criteria.

4. Betic Cordillera, southern Spain Andreo et al. (2008).The aim of the study was to develop method. The study used a method called APLIS to estimate rate of recharge and its spatial distribution into the carbonate aquifer. APLIS is a Spanish acronym for the five parameters used for estimating recharge from precipitation (A=altitude, P=slope, L=lithology, I=Infiltration landforms, S= soil type). Recharge rate is determined using the relation ($R = (A + P + 3L + 2I + S)/0.9$). The weight assigned to each variable used to represent the importance of the criteria for recharge estimation. As shown in the formula lithology has three times more importance than altitude, slope and soil type, while preferential infiltration has twice the importance. This relation was derived by comparing the recharge estimate with previously calculated recharge using conventional techniques.

5. Tirnavos, Greece. Oikonomidis et al. (2015) used eight criteria to map the ground water potential in the Karstic aquifer. These criteria include rainfall, potential recharge, lithology, lineament density, slope, drainage density and depth to groundwater. Potential recharge is calculated as a difference between annual rainfall and actual evapotranspiration both expressed in cubic meter per annum. Pairwise comparison was used for assigning weight. The assigned weights to each criteria were rainfall (30%), lithology (30%), slope (15%), lineament density (4%), drainage density (4%) and depth to groundwater (4%).

6. Burdur, Turkey Sener et al. (2005) used seven criteria to map groundwater potential in karstic aquifer using remote sensing and GIS methods. These include lithology, lineament density, drainage density, topography elevation, slope, land use and annual rainfall. The weighted linear combination was used assuming equal weight for all criteria.

7. Saldoran region, Western Iran Karami et al. (2016) used seven criteria recharge zones of major karstic springs. The criteria and weight used were: Karstic domain (30%), precipitation (15%), drainage (5%), fracture density (13%), slope (17%) and lithology (10%). Karstic domain received the highest weight of all. Karstic domains were determined based on geologic and topographic map and filed investigations. The study identified four kind of surface karstic features which are 1) areas with developed sinkholes, 2) areas with distinct polje, 3) areas with developed karst features such as karren other surface dissolution features and 4)areas with non-apparent karst, which are covered by thick soil accumulations.

8. Maknassy basin, southern central Atlas of Tunisia Chenini et al.(2010) mapped groundwater recharges zones in the karstic aquifer settings using eight criteria. 1) Watershed limit, (2) drainage, (3) drainage density, (4) lithology, (5) fractured outcrops, (6) lineament, (7) permeability, and (8) piezometry. In the first step, each two layers were combined to produce four maps. The final four thematic map layers were aggregated using a weighted aggregation method. In the sense that, the four maps were summed without any weight or assumed equal importance (20%, each). According to the authors, the motivation for including sub-basin area as criteria was because it directly related to water source for the MAR. Areas with high drainage density values were favoured because they indicate high surface runoff for harvesting excessive runoff. This is in contrary to other studies that attribute high drainage density to more surface runoff and less infiltration. This underscore that the same criteria may be used in different study with different context (e.g. promote natural infiltration, or runoff harvesting).

9. Banyas catchment West Syria Kattaa et al. (2010) evaluated aquifer vulnerability using the RISKE model. The RISKE model uses five criteria (Rock of Aquifer media, Infiltration, Soil media, Karst, and Epikarst) to map aquifer vulnerability. Weights used for the final vulnerability mapping were 10% (Aquifer rock type), 50% (infiltration, slope as proxy), 10% (soil media), 20% (Karstification) and 20% (Epikarst)).

7. MAR Suitability Mapping for the Ramotswa Transboundary Aquifer Area

Objective and Scale of Focus The primary objective of this section is to determine MAR suitability in the RTBAA. Given some uncertainty associated with the precise boundary of the RTBAA and interest in understanding MAR potential in the adjacent areas in which the RTBAA sits, however, this section focuses on assessing MAR suitability in the Ramotswa Aquifer Flight Area. This report builds on Sajad (2017) MSc Thesis.

Spreading method for MAR. The present study assumes that the preferred method of MAR in the RTBAA is the spreadign method, for at least four reasons. First, the spreadign method islow cost and practically simple to apply. Second, data is easily available for suitability assessment according to this method. Third, spreading methods are a preferred method for MAR in karstic aquifer as they allow spreading of recharge water through slow and diffuse infiltration. Finally the spreading method allows a natural treatment process (Daher et al., 2011). The suitability assessment through the spreading method is applicable for all kinds of measure that enhance natural recharge (e.g. infiltration basins, controlled flooding etc.). Annex 1 provides summary of suitable MAR methods that can be applied in Karstic and semi-arid regions.

7.1 Methods

7.1.1 Criteria selection and data sources

The selection of criteria were based on literature review study conducted for the karstic and arid and semi-arid regions (see annex 2, and 3). For the current study four criteria – namely slope, lithology, soil and land use/land cover – were used. Lineament density and drainage densities used in Sajad (2017) were excluded in this study to reduce the uncertainty. Sajad (2017) used dykes to calculate lineament density. Lineament density which represent fractures should have been considered instead of dykes. However, data is not available that clearly distinct dykes from lineament related to fractures. Hence, including this criterion only adds uncertainty. Sajad (2017) also calculated drainage density per grid. Drainage density should have been calculated based on the watershed. As indicated in the previous reviews, the role of drainage density criteria differs from study to study. Some study attributed high drainage density with more runoff and low infiltration and classified it as low; some others classified high drainage density as high because high drainage density results more runoff that can be captured for MAR applications. For the present study, this parameter was not included to reduce the uncertainty.

Depth to groundwater was not included due to lack of spatially distributed data. Rainfall intensity also plays an important role in recharge generation. Generally, higher rainfall intensities are indication of less infiltration and more runoff, vice versa with lower rainfall intensity (Kresic, 2006). However, given the small area of the flight zone, no significant difference in rainfall would be expected. Proximity to water bodies was not used as this is more related to source of water. For instance, if treated wastewater is considered as source of water, distance to wastewater treatment plant is more important than distance to other water bodies. Table 10 presents the four selected criteria used in the analysis and data sources.

Table 10: Source of data for the four criteria thematic maps and resolutions

Thematic layers	Source	Link	Resolution
Slope	SRTM 1ARC-Second Global	https://earthexplorer.usgs.gov/	30 x 30 m
Soil	Harmonized World Soil Database v 1.2	FAO soil portal http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/	1 km
	Soil Atlas Africa	https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa	Vector file

Land use/Land cover	GLOBCOVER 2009	http://due.esrin.esa.int/page_globcover.php	300 x 300 m
Lithology	Simplified geology map for Flight zone	https://apps.geodan.nl/igrac/ggis-viewer/viewer/ramotswa/public/default	Vector file

7.1.2 Reclassification and standardization

Criteria 1: Slope

There is an inverse relationship between topographic slope and soil infiltrations. Steep slopes will result in more runoff, which will affect the amount of infiltration. Less infiltration will occur on slope and hills than on flat areas and depression where runoff is slow, accumulates in depressions, and has more time for infiltration to occur. In contrast, gentle slope will have less impact on the infiltration process due to decreased runoff. The slope in the study area ranges from 0-130 percent. Based on slope suitability for MAR using the spreading method the slope is normalized to a scale from [0 – 1]. Areas with a slope to 5% (flat to gentle slope) obtain a value '1' (very suitable). For the areas with a slope between 5 and 30%, a continuous criteria as shown in Figure 17 was used with the following linear function: y= - 0.04 x+1.2. Areas with a slope > 30% are unsuitable and assigned a value '0'. Figure 18 presents the standardized slope suitability map for MAR.

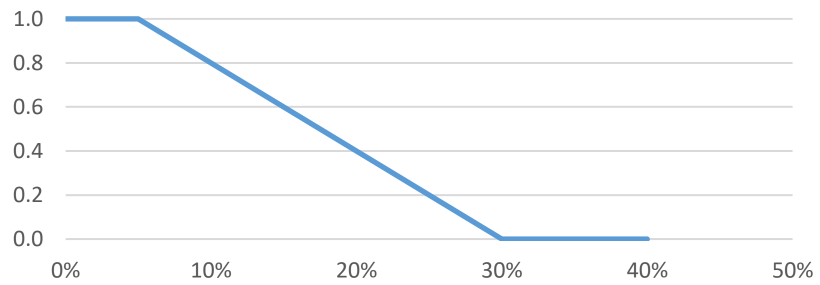

Figure 17: Slope classification based on MAR suitability

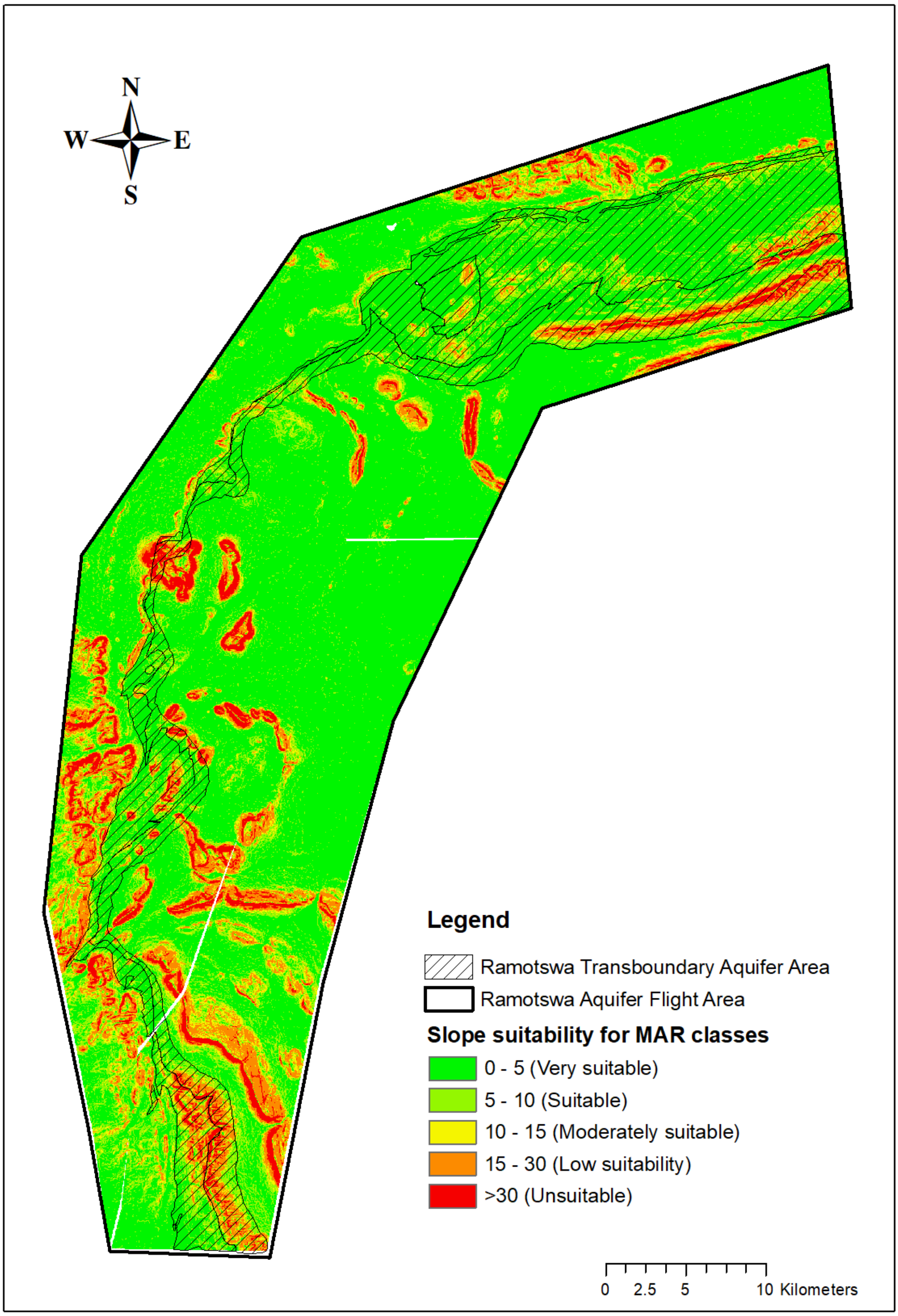

Figure 18: Slope suitability for MAR, Ramotswa Aquifer Flight Area

Criteria 2: Lithology

Lithological and tectonic characteristics of the bedrock play a dominant role in aquifer recharge particularly when soil covers is thin or absent (Kresic, 2006). Fractured bedrocks surface greatly increase infiltration rates, whereas layers of un fractured bedrock sloping at the same angle as the land surface may reduce infiltration (Kresic, 2006). On the other hand, mature karst areas, where rock porosity is greatly increased by dissolution, generally have the highest infiltration capacity of all geologic media (Kresic, 2006). Aquifer permeability and storage are the two main factors that play vital role in determining suitable site for MAR. Aquifers, with high permeability are preferred as they can accept high rates of recharge to store large volume of water (Dillon and Pavelic, 1996). Sedimentary formations (carbonate, gravel and sand) with various degree of consolidation are usually targeted for MAR (Dillon and Pavelic, 1996).The unconsolidated (loosely arranged) sand and gravel, alluvium have a large volume of interconnected pore space for water storage. Sand stones and conglomerates are rocks that have been formed by cementing sand gravel in the process of lithification., and the cementing material is mostly where the grain touch, leaving the space between the grains open. Therefore, the rocks is generally porous and well connected, so it can store and transmit significant volume of water (Coakley et al., 2017). Shales on the other hand impends groundwater flow and restrict its movement.

Geological map developed using airborne electromagnetic survey was used for the present analysis. Professor Tamiru Abiye, University of Wits, South Africa and Dr. Modrick Gomo, University of Free State, South Africa provided help for lithological classification and standardization. Table 11 present the lithological classes and standardized values for the Ramotswa Aquifer Flight Area. Figure 19 show lithological suitability map for MAR.

Table 11: Lithological classification based on MAR suitability for the Ramotswa Aquifer Flight Area

Specific geological name	**Lithology**	**Standardized values**
Unconsolidated surface deposits	Alluvium	1
Dolomite	Mote Christo formation, chert rich dolomite, good aquifer	1
	Eccles formation, chert-rich dolomite, good aquifer	1
	Frisco formation, chert-free dolomite	0.8
	Littleton formation, chert-poor dolomite	0.8
	Oaktree formation, chert-free dolomite	0.8
	Magopane formation, massive stromatolitic and ferruginous cherts	0.8
	Maholobota formation, Intimately interlayered stromatolitic cherts and massive dolomites	0.8
	Ramotswa dolomite formation, massive dolomites with chert and limestone lenses and layers	0.8
	Malmani formation, dolomite subordinate chert minor carbonaceous shale limestone and quartzite	0.8
Deutschland Formation	Carbonaceous mudrocks, limestone and dolomite	0.8
Pre-Transvaal formations	Clastic sediments and volcanics	0.8
Igneous dikes and sills	Dolerite, sills and dikes	0.0

Woodlands formations	Sandstones, shale and volcanics	0.6
Silverton formation	Shale and volcanics	0.6
Rooihoogte formation	Conglomerate and shale/siltstone	0.6
BlackReef quartzite	Quartzite	0.4
Waterberg Supergroup	Conglomerate, sandstone, shale and siltstone	0.4
Magaliesberg formation	Sandstone/quartzite	0.4
Ditlojana quartzite	Shale/siltstone and sandstone	0.4
Ditlojana volcanics	Andesite	0.4
Ditlojana Shale	Shale/siltstone, sandstone and conglomerate	0.4
Timeball Hill formation	Shale/siltstone and sandstone	0.4
Penge formation	Banded Iron Formation and Shale	0.0
Bushveld igneous complex	Granite, gabbro, norite	0.0

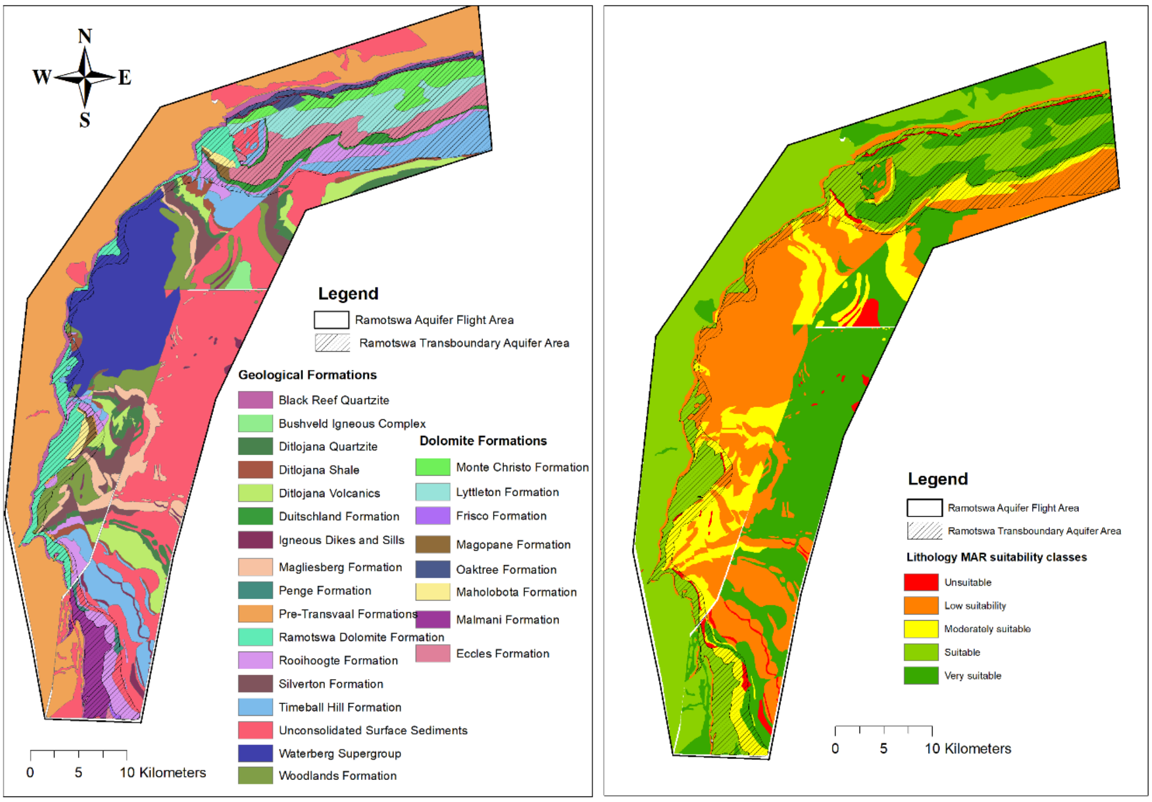

Figure 19: Lithology and lithological suitability map of the Ramotswa Aquifer Flight Area

Criteria 3: Soil texture

Soil properties are the most significant factors affecting infiltration rate. The rate at which water enters into the soil cannot exceed the infiltration capacity of the soil. In general, soil infiltration rate decreases with increasing clay content in the soil. Runoff conditions on low-permeable soils develop much sooner and more often than sands and gravels, which have infiltration rates higher than most rainfall intensities (Kresic, 2006). In the present study, Harmonized World Soil Database (HWSD) (Nachtergaele et al., 2008) and Soil Atlas of Africa (Dewitte et al., 2013) were used to classify and standardize soil classes. HWSD contain information for top and sub-soil layers. The top soil ranges from 0-30 cm and the sub-soil 30-100 cm. For all soils with restricted reference soil depth in the HWSD the soil parameters are provided for top soil only.

In general, sandy soils have the highest infiltration capacity (value '1'), followed by loamy sands (value '0.75'), silt/loams (value '0.5') and clay (light) (value '0.25'). Soils that consist of heavy clay are unsuitable for spreading methods and have a value '0'. Discrete function shown in Figure 20 was used for the standardization. Figure 21 shows the standardize soil map based on the above classifications. The Soil Atlas Africa soil Map was used to define the extent of each soil type as shown in Figure 21. It is important to mention that, soils in the eastern part of the Ramotswa dolomite has only top soil layer. The soil depth is may be limited by occurrence of impermeable layers and hence, classified as low suitability.

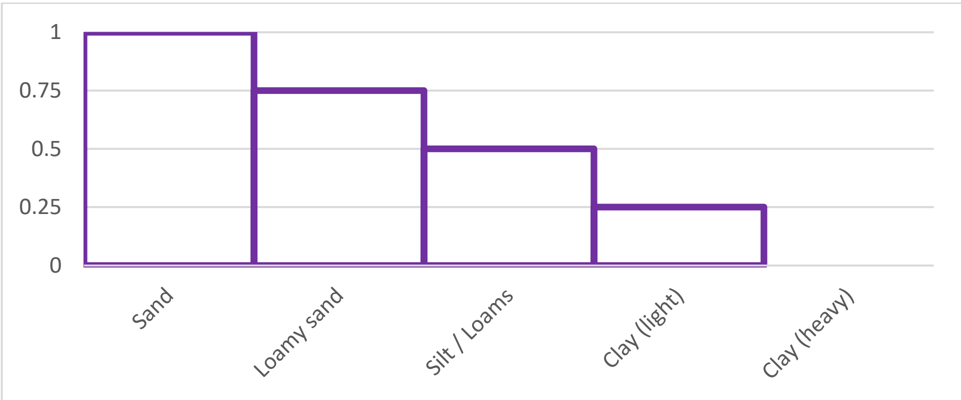

Figure 20: Soil classification based on their relative suitability for MAR

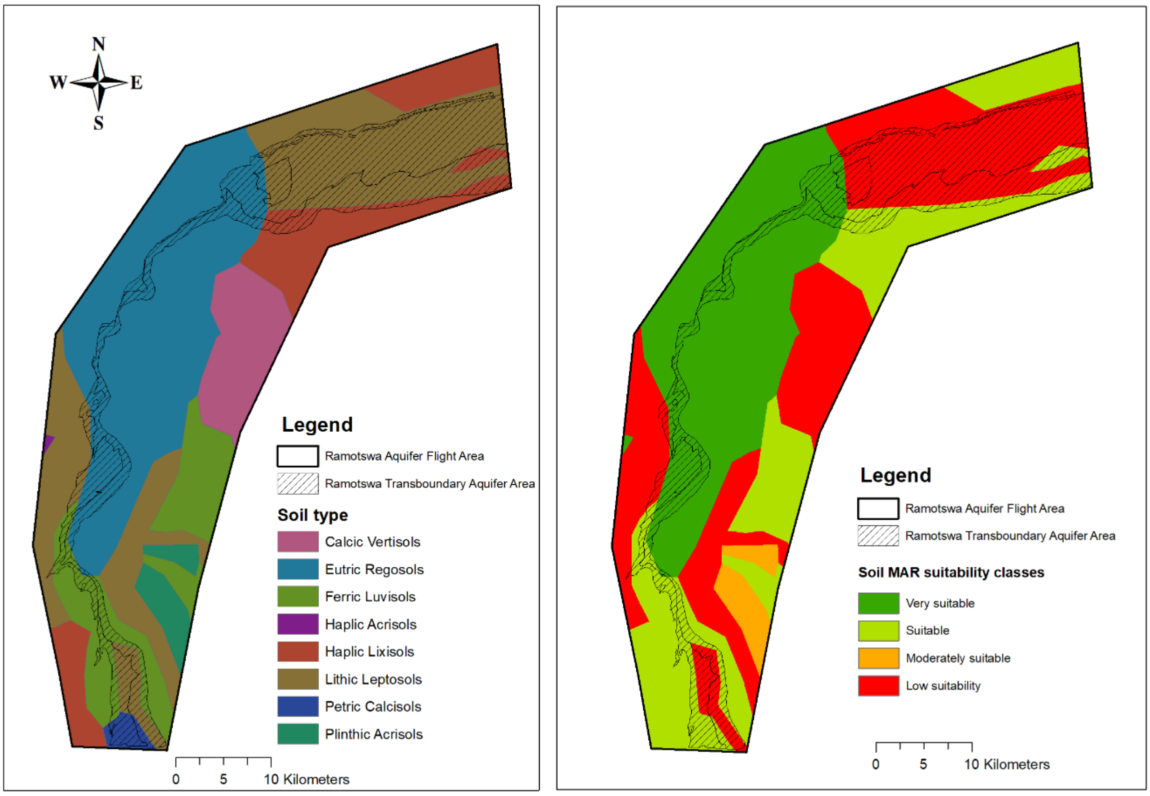

Figure 21: Soil type from Soil Atlas Africa and soil suitability map for MAR of the Ramotswa Aquifer Flight Area

Criteria 4: Land use and Land cover

Vegetation in arid and semi-arid regions are sparse because of limited rain and often occur in geomorphic and surface drainage zones with a high moisture content (Adams et al., 2003). Presence of vegetation protects the soil surface from the impact of rainfall. Root systems of vegetation tend to enhance soil porosity and permeability. Organic matter greatly increase pore sizes and pore size distribution. Urban areas and development generally decrease infiltration rates and increase surface runoff because of the increasing presence of various impervious surfaces. Degradation of vegetation cover leads to increased surface runoff and erosion. Soils compacted by grazing in rangelands and pastures will exhibit lower infiltration rates. Measured macro porosities for forest soils were five times higher than pasture (Osman, 2013). The high average infiltration capacities measured for soils under forest suggest that very high rainfall intensities are required to generate surface runoff (Osman, 2013). According to Adams et al. (2003) and reference cited there in, vegetation increase infiltration by three mechanisms: by retarding surface water movement, by reducing rain drop compaction, and by increasing organic matter content, bulk density and surface horizon depth. Increase in natural recharge due to vegetation is evident from the above reference. However, land use and land cover classification for MAR in this study is based on the context of land clearing and land preparation requirement for MAR using the spreading method. Hence, areas with high vegetation are less preferred.

The land use and land cover classification was carried out based on the GLOBCOVER 2009 land use and land cover classes (Bontemps et al., 2011) (see annex 4). GLOBCOVER 2009 land use and land cover consists of 22 land use classes; however; only nine classes were identified for Ramotswa Aquifer Area. Sparse vegetation and Bare areas regarded as very suitable (value ‘1’), followed by Grassland

and Cropland (value '0.75'), Forest (15-40%), (value '0.5') and Forest (>40%) (Value '0.25'). Water bodies and urban areas are considered as unsuitable and have a value '0'. See annex 4 for detail descriptions of the land use and land cover classifications. Figure 22 presents the GLOBCOVER 2009 land use and land cover classes and standardized MAR suitability map based on the above classifications.

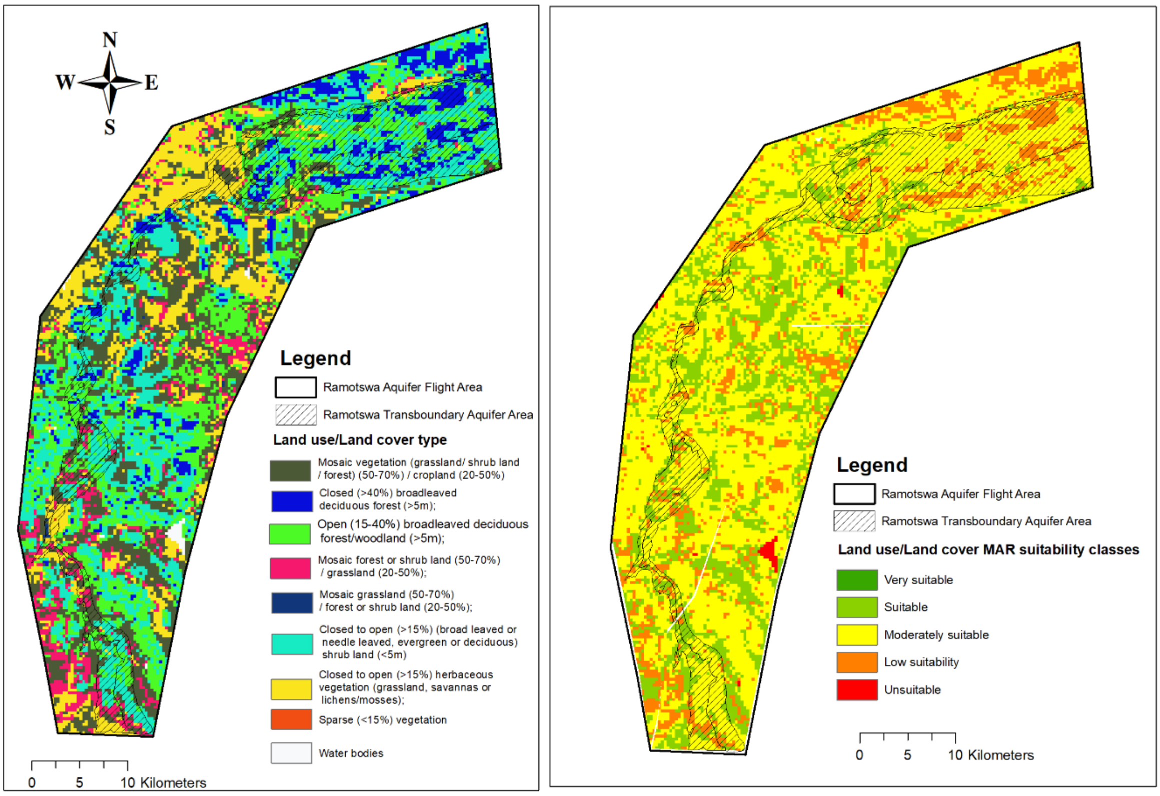

Figure 22: Land use/ land cover from GLOBCOVER 2009 and land use/ land cover suitability map for MAR of the Ramotswa Aquifer Flight Area

7.1.3 Assigning relative weights

For weight assignment, the ranking method was compared to the MIF method. The MIF method used by Sajad (2017) was re-adjusted to four criteria instead of six, and based on this configuration weights are calculated. However, the method gives more weight to land use and land cover (30%) than soil (20%), which is unrealistic. Therefore, the weights calculated based on ranking method are preferred over the MIF. The criteria weight based on the ranking method are presented in Table 12.

Table 12 Criteria weight based on the ranking method

Criteria	Rank (r)	N-r+1	Weight
Slope	3	2 (4-3+1)	0.2 (2/10)
Lithology	1	4 (4-1+1)	0.40 (4/10)
Soil	2	3 (4-2+1)	0.30 (3/10)
Landcover	4	1 (4-4+1)	0.10 (1/10)
Σ		**10**	**1**

7.2 Results

MAR suitability assessment results for the Ramotswa Aquifer Flight Area is presented in Figure 23. Following Bonilla Valverde et al.'s (2016) approach the final suitability map was classified into six classes and area in each suitability classes is calculated. Table 13 presents the percentage area of each MAR suitability classes calculated based on their respective total area. As it is shown in Table 13, the suitable area covers about 52% percent of the Ramotswa Aquifer Flight Area, while, for the RTBAA the suitable areas account for about 63%. About 26% of the Ramotswa Aquifer Flight Area and 16% of the RTBAA are very suitable for MAR.

Table 13: Calculated percentage area of each suitability classes for the Ramotsa Aquifer Flight Area and RTBAA

Map values	**Suitability classes**	**Percent area of the Ramotswa Aquifer Flight Area**	**Percentage area of the RTBAA**
0	Unsuitable	6.7	5.9
0 – 0.2	Very low suitability	0.0	0.0
0.2 – 0.4	Low suitability	2.2	2.6
0.4 – 0.6	Moderately suitable	13.1	12.6
0.6 – 0.8	Suitable	52.3	62.6
0.8 – 1.0	Very suitable	25.8	16.2

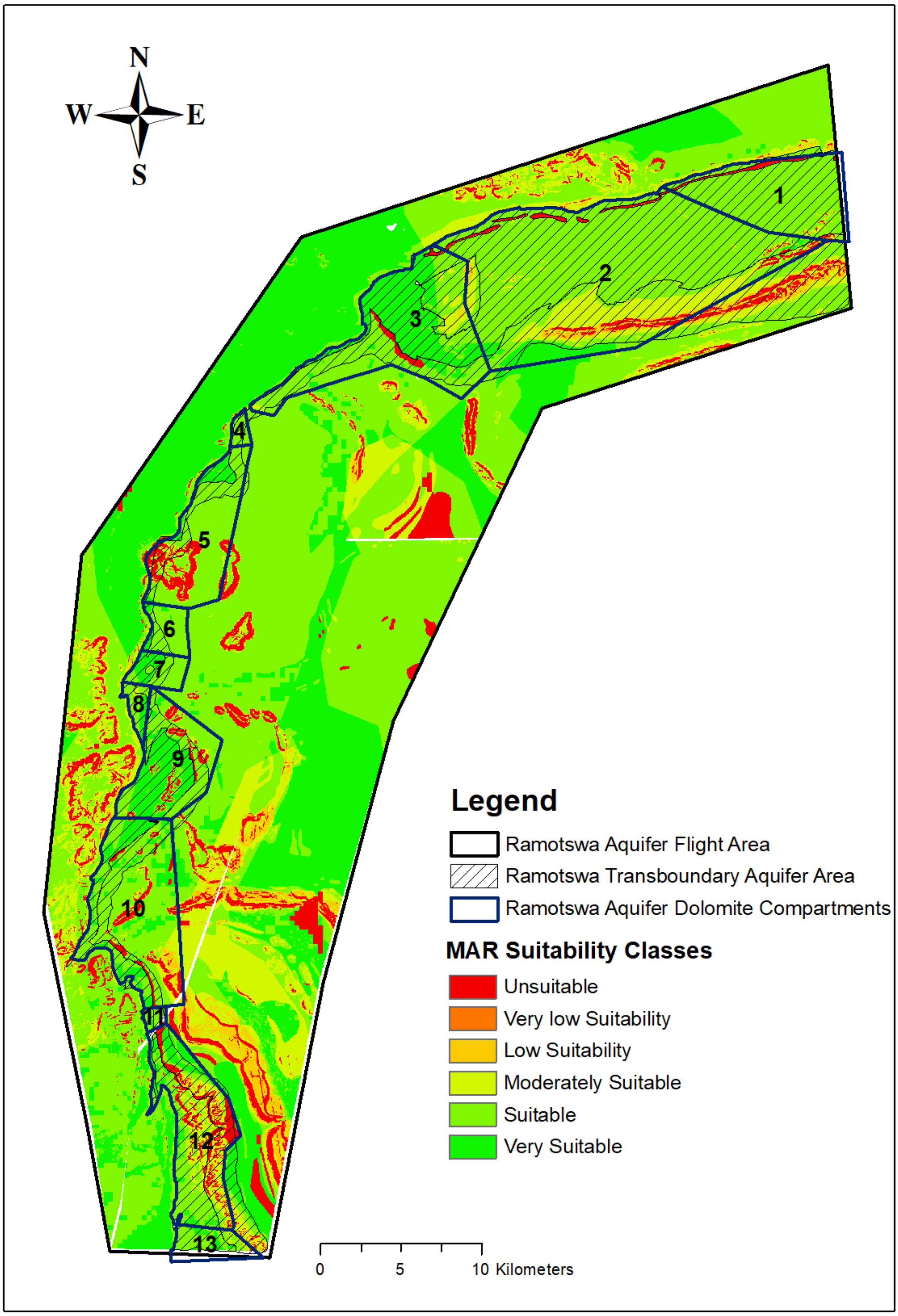

Figure 23: MAR suitability map for the Ramotswa Aquifer Flight Area

8. Conclusions and Next Steps

While further work must be done, there is substantial potential for MAR in the Ramotswa Aquifer. About 52% of the Ramotswa Aquifer Flight Area was mapped as suitable area for MAR application using spreading method. About 26% of the Ramotswa Aquifer Flight Area falls in a very suitable class. Similarly, about 63% of the RTBAA belongs to the suitable class, while 16% is very suitable. This shows the presence of good recharge sites in the area.

Caveats The suitability map produced in this report represents the intrinsic suitability, purely based on the intrinsic characteristics of the biophysical parameters. Water source, demand and water quality issues are not considered. Depth to groundwater was not included due to lack of data. Therefore, caution is needed in interpreting the MAR suitability map. Results from the suitability mapping should be updated as new data become available, and need to be validated against field data.

Assessment of water source availability. The main source of water for MAR for the Ramotswa Transboundary is the the Ngotwane/Notwane ephemeral River. The period between November-March has good rainfall (above 50 mm/month) hence may provide good runoff that can used for MAR. However, there are concerns about diversion of the Ngotowane River flow for aquifer recharge that may reduce water now available for storage downstream in the Gaborone dam. The Kharkams, case study South Africa, provide a good example where empheral flow is diverted using intake structure and used for MAR via injection wells. Other potential sources of water for recharge include wastewater from the Ramotswa village. The advantage of considering wastewater as a source is its availability throughout the year irrespective of the rainy season. The downside is that it required extensive pre-post-treatment and it would be very costly. Investigation of water source and its availability is required going forward.

MAR feasiblity assessment, determing aquifer storage potential. Suitable sites for MAR will now be examined for specific dolomite compartments, with special focus on compartment 3 (Figure 23). Focused hydrogeological modelling is expected to be conducted on this compartment, to inform placement of proposed MAR schemes for senario analsyis. Compartment 3 was selected for hydrogeological modelling because of: i) data avalibility for model calibration, and ii) the reality that is one of the largest transboundary compartments. The main challenge is that, most of the aquifer area in compartment 3 is located close to Ngotwane/Notwane River and this area is flooded during rainy season and the water level is approximately 1-2 meter below the ground surface, thereby 'filling' potential storage capacity. This may in turn necessitate aquifer recharge to take place in compartment 2. For this reason, the hydrogeological model will be extended to cover part of compartment 2. However, due to lack of data the depth to groundwater level in compartment 2 is unknown but expected to have relatively greater storage space as it is far from the river. Further investigation with hydrogeological model scenario analysis will help us to:

1. evaluate how the aquifer system reacts to the induced recharge , increase in groundwater level, and change in flow pattern
2. quantify the volume of water that can be added to the storage
3. clarify the length of period that recharged water remain in storage, determine the recovery efficiency

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Annex

Annex 1: Suitable MAR techniques in case of karstic and semi-arid region

Source Sajad (2017)

<table>
<tr><th>Number of importance</th><th>MAR main type</th><th colspan="4">Specific Mar type</th><th>Reason</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">Well, shaft and borehole recharge</td><td colspan="2">Deep well injection</td><td colspan="2" rowspan="2">Dug well/ shaft/ pit injection</td><td rowspan="2">• Allowing to induced deep injection (Escalante et al. 2016)
• Minimal evaporation losses and therefore lowest evaporation potential (Escalante et al. 2016)
• Experienced enough in other case studies for karstic region
• No need large lands
• Favourable for deep aquifers (Gale 2005)
• Can works in high and moderate slope, less-related to topography (Escalante et al. 2016)
• Can works in complex geology such as impermeable rocks (Gale 2005)
• Can solve water issues such as shortage, increasing recharge rate
• Improving water quality
• Strong Socio-economic effects
• Capacity range from small to medium
• High potential for karstic region</td></tr>
<tr><td>ASTR</td><td>ASR</td></tr>
<tr><td>2</td><td>In channel modification</td><td>Recharge dam</td><td>Subsurface dam</td><td>Sand dam</td><td>Channel spreading</td><td>• Minimal evaporation losses and therefore lowest evaporation potential (Escalante et al. 2016)
• Favourable for both deep + shallow aquifers (Gale 2005)
• Suitable for high slope areas (embedded valley) (Escalante et al. 2016)
• Allowance to supply for small town with filtration (Escalante et al. 2016)
• Ability to resolve geotechnical problems in urban areas (Escalante et al. 2016)
• Erosion control (Knoop et al. 2012)
• Improving groundwater quality
• Possibility of protection of evaporation tank by structures (Escalante et al. 2016)
• Capacity range from small to medium
• For sand dam is not expensive version and for subsurface dam ranging from cheap to expensive depends on geological characteristics.
• Comparing with spreading method needs less area for implementation
• Good enough potential for karstic region</td></tr>
</table>

3	**Spreading method**	**Infiltration pond**	**Flooding**	**Induced bank infiltration**	• Low construction cost and maintenance, • Improve water quality during infiltration process • Long life systems and facilities • Easy monitoring infiltration rate • Reuse available structures such as abandoned mines, or quarries • Simple-anti clogging measure for systems of infiltration • Increase the infiltration rate • SAT Increase the infiltration rate specially in flat bottoms • Accumulation of sediments during flooding process make profitable land for agricultural uses (Escalante et al. 2016) • Improving soil fertility in case of flooding • Located as last possible option due to high possible evaporation rate which leads to loss too much water in spreading method • Reduce flood risk and therefore reduce flood damage • RBF is Suitable for cities which are close to rivers and streams, as supply resources (Escalante et al. 2016) • RBF Providing high water quality uses (Escalante et al. 2016) • In several case of RBF (river bank filtration) named as one of the largest capacity of MAR techniques (Jeude 2016) • Can use close to urbanized so that other needed parameters satisfy such as existing water bodies (Jeude 2016) in case of RBF

Annex 2 Review of application of GIS and geophysics techniques for assessing Managed Aquifer Recharge (MAR) suitability map with respect to karst and different climates

Source Sajad (2017)

Number	References	Location	Karst	Climate	Methodology																											
	Classifications				GIS/Remote sensing											Field Observation Data																
					Surface analysis												Subsurface analysis															
					Landscape (geological/hydrological and hydrogeological)characteristics																						Karst specific criteria					
																											ARAK[1], RISKE[2], APLIS[3], ERIK[4]					
	Thematic layers				Slope (DEM)	Land use/Land Cover	Geology	Geomorphology	Lithology	Soil	Lineaments density	Drainage density	Proximity to Surface Water Bodies	Precipitation	Karst Domain	Preferential Infiltration	Aquifer thickness	Static water table	Depth to GW	Transmissivity	Regolith thickness	Permeability	Pizometric Map	Geophysics techniques	Net recharge	Others	*Altitude*	*Epikarst*	*Rock type*	*Infiltration*	*Karstification*	*Soil*
1	(Karami et al. 2016)	Western Iran	Yes	Semi-arid	x				x		x	x		x	x											x						
2	(Chenini et al. 2010)	Central Tunisia	Yes	Mediterranean Climate					x		x	x										x	x									
3	(Andreo et al. 2008)	Southern Spain	Yes	Mediterranean Climate	x				x					APLIS													x			x		x
4	(Oikonomidis et al. 2015)	Central Greece	Yes	Mediterranean Climate	x				x		x	x		x					x						x							
5	(Rahman et al. 2012)	Algarve, Portugal	Yes	Mediterranean Climate	x											x	x		x							x						
6	(Ioannidou 2016)	Crete, Greece	Yes	Mediterranean Climate	x	x	x						x					x														
7	(Kattaa et al. 2010)	Syrian	Yes	Mediterranean Climate										RISKE														x	x	x	x	x
8	(Sener et al. 2005a)	Turkey	Yes	Mediterranean Climate	x	x			x		x	x		x													x					

9	(Daher et al. 2011b)	Lebanon	Yes	Mediterranean Climate										**ARAK, ERIK**														x	x	x	x	
10	(Alraggad & Jasem 2010)	Jordan	No	Desert Climate, Arid	x		x				x		x													x						
11	(Mukherjee et al. 2012)	India	No	Arid	x	x		x	x	x	x	x		x																		
12	(Fenta et al. 2015)	Northern Ethiopia	No	Semi-arid	x	x		x	x		x	x		x																		
13	(Ghayoumian et al. 2007)	Southern Iran	No	Semi-arid	x											x								x		x						
14	(Machiwal et al. 2011)	Western India	No	Semi-arid	x		x	x		x			x												x	x						
15	(Russo et al. 2015)	California, USA	No	Mediterranean Climate			x									x		x		x						x						
16	(Adham et al. 2010)	Bangladesh	No	Subtropical monsoon		x			x		x	x																				
17	(Fashae et al. 2014)	Southern Nigeria	No	Tropical hot climate	x	x	x	x		x	x	x	x	x																		
18	(Forkuor et al. 2013)	Northern Ghana	No	Tropical hot climate														x		x	x				x							
19	(Shahid et al. 2000)	West Bengal	No	Tropical Savannah	x			x	x	x		x	x												x							
20	(Dutta 2015)	Western India	No	Tropical	x	x		x	x			x						x														
21	(Krishnamurthy et al. 1996)	South India	No	Tropical	x	x	x			x	x	x	x																			

1 Aquifer Recharge Assessment in Karst 2 Reservoir rock (R), Infiltration potential (I), Soil (S), Development and behaviour of karst (K), Epikarst (E) 3 Altitude (A). Slope (P), Lithology (L), Infiltration (I), Soil (S) 4 Epikarest(E), Rock type(R), Infiltration (I), Karstification (K)

Annex 3: Weightage (%) used in previous study for assessing Managed Aquifer Recharge (MAR) suitability map with respect to karst and different climatic regions

Source Sajad (2017)

Number	References	Location	Karst	Climate	Methodology																											
	Classifications				GIS/Remote sensing													Field Observation Data														
					Surface analysis														Subsurface analysis													
					Landscape (geological/hydrological and hydrogeological)characteristics																						Karst specific criteria					
																											ARAK[1], RISKE[2], APLIS[3], ERIK[4]					
	Thematic layers				Slope (DEM)	Land use/Land Cover	Geology	Geomorphology	Lithology	Soil	Lineaments density	Drainage density	Proximity to Surface	Precipitation	Karst Domain	Preferential Infiltration	Aquifer thickness	Static water table	Depth to GW	Transmissivity	Regolith thickness	Permeability	Pizometric Map	Geophysics techniques	Net recharge	Others	*Altitude*	*Epikarst*	*Rock type*	*Infiltration*	*Karstification*	*Soil*
1	(Karami et al. 2016)	Western Iran	Yes	Semi-arid	17				10		13	5		15	30											x						
2	(Chenini et al. 2010)	Central Tunisia	Yes	Mediterranean Climate					20		20	20										20	20									
3	(Andreo et al. 2008)	Southern Spain	Yes	Mediterranean Climate	12.5				37.5					APLIS													12.5			25		12.5
4	(Oikonomidis et al. 2015)	Central Greece	Yes	Mediterranean Climate	15				30		4	4		30					4						15							
5	(Rahman et al. 2012)	Algarve, Portugal	Yes	Mediterranean Climate	12.5											37.5	4		16							20						
6	(Ioannidou 2016)	Crete, Greece	Yes	Mediterranean Climate	25	25	25						25					-														

7	(Kattaa et al. 2010)	Syrian	Yes	Mediterranean Climate										RISKE														18.8	9.09	45.45	18.18	9.09
8	(Sener et al. 2005a)	Turkey	Yes	Mediterranean Climate	14.28	14.28			14.28		14.28	14.28		14.28													14.28					
9	(Daher et al. 2011b)	Lebanon	Yes	Mediterranean Climate										ARAK, ERIK														60	20	10	10	
10	(Alraggad & Jasem 2010)	Jordan	No	Desert Climate, Arid	20		20				20		20													20						
11	(Mukherjee et al. 2012)	India	No	Arid	15	5		15	20	10	15	15		5																		
12	(Fenta et al. 2015)	Northern Ethiopia	No	Semi-arid	10	2		16	38		24	6		4																		
13	(Ghayoumian et al. 2007)	Southern Iran	No	Semi-arid	22.2											29.9								19.2		28.7						
14	(Machiwal et al. 2011)	Western India	No	Semi-arid	12.7		14.28	17.46		12.7			6.34												20.63	15.98						
15	(Russo et al. 2015)	California, USA	No	Mediterranean Climate			20									20		20		20						20						
16	(Adham et al. 2010)	Bangladesh	No	Subtropical monsoon		18			47		13	22																				
17	(Fashae et al. 2014)	Southern Nigeria	No	Tropical hot climate	10.2	12.6	17.5	12.8		14.7	8.0	4.8	2.2	17.2																		
18	(Forkuor et al. 2013)	Northern Ghana	No	Tropical hot climate														25		25	25				25							
19	(Shahid et al. 2000)	West Bengal	No	Tropical Savannah	7.14			25	21.4	17.9		10.7	3.6												14.3							

20	(Dutta 2015)	Western India	No	Tropical	x	x		x	x			x						x														
21	(Krishnamurthy et al. 1996)	South India	No	Tropical	17.3	28.6	18.4			20.5	1.1	14.0	1.07																			

1 Aquifer Recharge Assessment in Karst *2* Reservoir rock (R), Infiltration potential (I), Soil (S), Development and behaviour of karst (K), Epikarst (E) *3* Altitude (A). Slope (P), Lithology (L), Infiltration (I), Soil (S) *4* Epikarest(E), Rock type(R), Infiltration (I), Karstification (K)

Annex 4: Land use land cover classification based on MAR suitability

Source Sajad (2017)

MAR Classes	LULC Classes	GLOBCOVER 2009 LULC Classes
Unsuitable (0.0)	*Unfavorable*	No Data
		Water bodies
		Permanent snow and ice
		Artificial surfaces and associated areas (Urban areas >50%)
		Closed (>40%) broadleaved forest or shrub land permanently flooded - Saline or brackish water
Low suitability (0.25)	*Forest (>40%)*	Closed (>40%) broadleaved deciduous forest (>5m)
		Closed (>40%) needle leaved evergreen forest (>5m)
		Mosaic forest or shrub land (50-70%) / grassland (20-50%)
Moderately (0.5)	*Forest (15-40%) And Forest (>15%)*	Closed to open (>15%) mixed broadleaved and needle leaved forest (>5m)
		Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water
		Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
		Closed to open (>15%) (broadleaved or needle leaved, evergreen or deciduous) shrub land (<5m)
		Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
		Mosaic vegetation (grassland/shrub land/forest) (50-70%) / cropland (20-50%)
		Open (15-40%) broadleaved deciduous forest/woodland (>5m)
		Open (15-40%) needle leaved deciduous or evergreen forest (>5m)
Suitable (0.75)	*Grassland and Cropland*	Mosaic grassland (50-70%) / forest or shrub land (20-50%)
		Rain fed croplands

		Post-flooding or irrigated croplands (or aquatic)
		Mosaic cropland (50-70%) / vegetation (grassland/shrub land/forest) (20-50%)
		Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
Very suitable (1.0)	*Sparse vegetation and Bare areas*	Sparse (<15%) vegetation
		Bare areas