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Assessing the Site Suitability of Managed Aquifer Recharge (MAR) Projects in Karst Aquifers in Lebanon

A Multi Criteria Analysis

Lukas Rolf
5684269
l.rolf@students.uu.nl
Bosboom Toussaintstraat 3
3532 VK Utrecht

Supervisor at Utrecht University:
prof. dr. ir. Marc Bierkens
M.F.P.Bierkens@uu.nl
Heidelberglaan 2
3584 CS Utrecht

Supervisor at Acacia Water (internship organization):
dr. Koos Groen
Koos.groen@acaciawater.com
Van Hogendorpplein 4
2805 BM Gouda

Content

Abstract

Groundwater overexploitation in Lebanon has led to severely decreased groundwater reserves and enhanced seawater intrusion at the coast. To improve freshwater availability much attention has recently been given to Managed Aquifer Recharge (MAR), a groundwater management technique that employs artificial replenishment of aquifers. In Lebanon the potential of a MAR scheme lies in storing excess winter runoff underground and recovering it during the dry summer. In coastal aquifers infiltrating surface water would also counteract the increasing salinity. While numerous authors have discussed potential MAR schemes in Lebanon no successful project has been implemented yet. This is certainly related to the complicated geology in Lebanon, where 70% of the aquifers are karstic.

Globally, various designs of MAR schemes have successfully been implemented in unconsolidated aquifers, but there is little experience with artificially recharging karstic aquifers even though karst shows considerable potential for MAR. Karstified aquifers often feature high well productivity and are less prone to clogging. However, the high heterogeneity of karst aquifers with high transmissivity values along conduits and a generally low purification potential make them a challenging medium for successful MAR schemes.

In this research a 2-step framework for assessing the suitability of potential MAR sites in karstic aquifers is presented. The core of this approach is a criteria catalogue that guides the assessment of each potential MAR site with regards to physical, social, and economical aspects. The criteria were developed based on an extensive literature and expert interviews. The criteria catalogue helps to structure collected data and gives a good overview of possible proxies that indicate suitable conditions. The alternative sites are compared and ranked in a comprehensive multi criteria analysis.

The methodology is demonstrated for Lebanon. Based on a pre-selection carried out in a previous research by UNDP (2014) nine potential MAR sites are compared. Sufficient data was collected to score 38 of 141 developed criteria. Focus lies on assessing the site-specific physical properties of the aquifers. Monte Carlo Simulations to account for score and weight uncertainties reveal that the ranking is relatively robust, especially the first and last positions.

1 Introduction

Groundwater resources throughout Lebanon are under increasing stress. The small country on the eastern Mediterranean coast is densely populated and has recently become the destination of more than one million Syrian refugees (UNHCR, 2016). In addition, climate change might alter precipitation patterns and make natural aquifer recharge more volatile: A 2°C global temperature increase is expected to result in a 15 – 30 days longer dry period and a 12 – 16 % reduction in water resources (MoE, 2014). Already now the groundwater tables are lowered by over-exploitation, in some regions at alarming rates. In the karstic coastal aquifers, abstracted volumes of groundwater have been replaced by seawater; in some places sweater intrusion extends kilometers land inwards (de Gooijer et al., 2009). To combat water scarcity, much potential is seen in artificially replenishing the groundwater resources by infiltrating surface water, a method known as Managed Aquifer Recharge (MAR). This research aims at evaluating the potential of MAR in Lebanon and developing a framework for assessing site suitability for MAR in karst regions.

1.1 Regional Context

1.1.1 Water Resources of Lebanon

Precipitation in Lebanon is controlled by eastward winds that cause precipitation of up to 2000 mm/year in the coastal mountain regions and as little as 200 mm/year in the inland Daqaa region bordering Syria (see Figure 1). Most of the runoff is generated during the rainy winter between December and March/April.

Lebanon is not a dry country per se. It receives relatively large sums of precipitation and is, unlike most countries in the region, not dependent on inflow from other countries (Klingbeil, 2017). Advantageous is also that snow constitutes a considerable part of the precipitation, which prolongs the natural runoff into the dry summer. Lebanon has renewable water resources of around 900 m³/cap/year, which places it slightly below the water scarcity threshold of 1,000 m³/cap/year (MoEW, 2010).

The country's challenge in water supply is that most water flows rapidly the short distance from the mountains into the sea during the rainy and melting season without being used, while many rivers run dry during the summer when demand for irrigation water is highest. Of Lebanon's 40 streams more than half are seasonal. Thirteen rivers with an average length of <60 km flow from the high Lebanese coastal range directly into the ocean (see Figure 2) (El-Fadel, Zeinati, & Jamali, 2000). Utilizing their winter discharge to recharge groundwater reservoirs is a promising method of improving the water supply during the dry summer. Lebanon's water balance, summarized in Table 1, shows that surface flow, i.e. river discharge into the ocean, has a good potential to strengthen the water supply.

Table 1: Lebanon's water balance for an average year (adapted from MoEW (2010))

	BCM/year
Total rainfall and snow	8,6
Evapotranspiration	-4,5
Outflow across borders	-1,0
Groundwater flow to sea	-0,4
Groundwater recharge	-0,5
Surface flow	-2,2

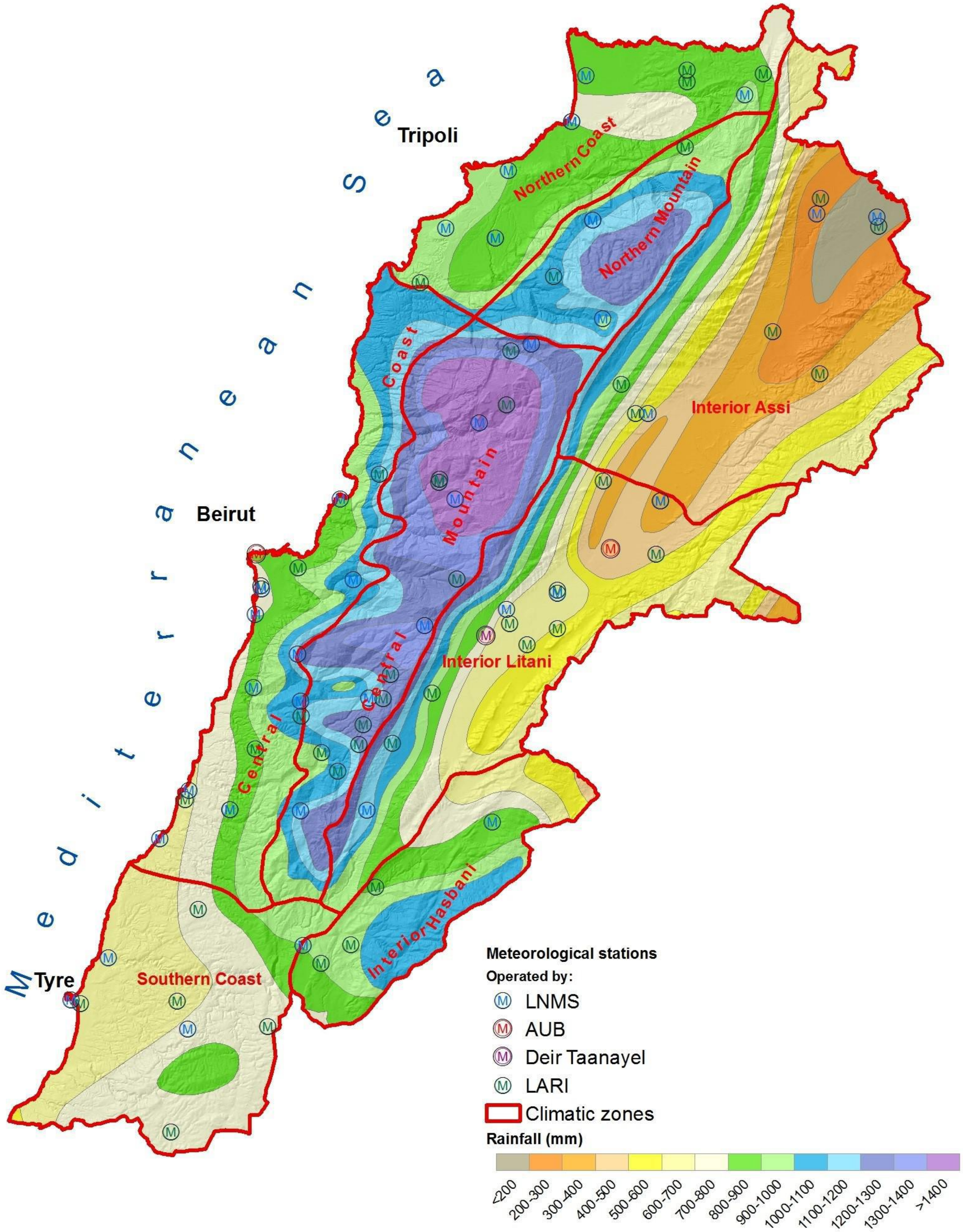

Figure 1: Precipitation distribution of Lebanon (CNRS, 2016)

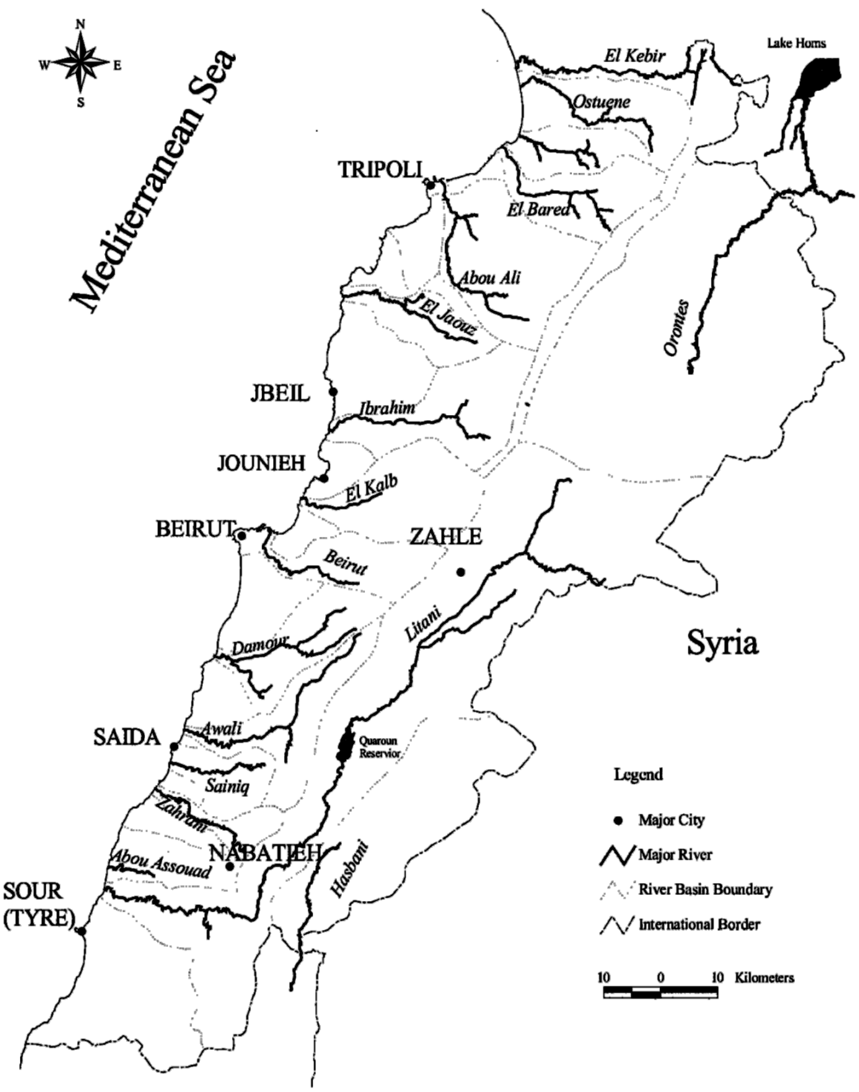

Figure 2: Major river basins of Lebanon (El-Fadel et al., 2000)

Suitable sites for building dams to ensure a year-round water supply are scarce, as Lebanon is a very densely populated country. Furthermore, high sedimentation loads of Lebanese rivers might cause rapid filling-up of the reservoirs and the porous underground is likely to induce significant leakage. Several unconventional water sources have been identified to address Lebanon's water crisis: Desalinated seawater, treated waste water for reuse, and submarine groundwater discharge (karst submarine springs). Projects tapping these sources are either unpromising regarding yield and water quality or they have not been implemented for practical and economic reasons (El-Hajj, 2008; van Beynen, 2011).

1.1.2 Water Demand in Lebanon

Lebanon's water demand is estimated at 1,5 BCM/year, while current supply is merely 1,2 BCM/year (MoEW, 2010). The already existent water shortage is expected to exacerbate over the next decade, especially during the summer months (Metini, El-Fadel, Sadek, Kayal, & Lichaa El Khoury, 2004).

Around 60% of the water withdrawals can be attributed to the agricultural sector. Municipal water use accounts for 29% and industry for 11% (Frenken, 2009). The agricultural area under irrigation is projected to increase from currently 90,000 ha to 150,000 ha in 2035. Groundwater is the source for over half of all used water and around 60% of pumped groundwater is abstracted by private wells (MoEW, 2010).

The often unregulated and poorly monitored exploitation of groundwater resources by unlicensed wells makes it difficult to pinpoint the hotspots of groundwater stress. However, overall declining water tables and local seawater intrusion speak a clear language. Frequent water shortages and an unreliable public water distribution system lead to relatively high costs for water consumers (Frenken, 2009).

1.2 MAR Techniques

To tackle the problem of groundwater over-exploitation Managed Aquifer Recharge (MAR) currently receives much attention as a high-potential mitigation technique. MAR essentially comprises various techniques by which the groundwater is artificially replenished (see Figure 3). Some of the most widely used methods for infiltrating surface water are: The use of percolation basins, inducing infiltration from existing surface water bodies by lowering the natural groundwater level (river bank filtration), facilitate sedimentation to form an artificial aquifer (sand dam), and the direct infiltration through wells. This research focuses on MAR schemes with deep well infiltration.

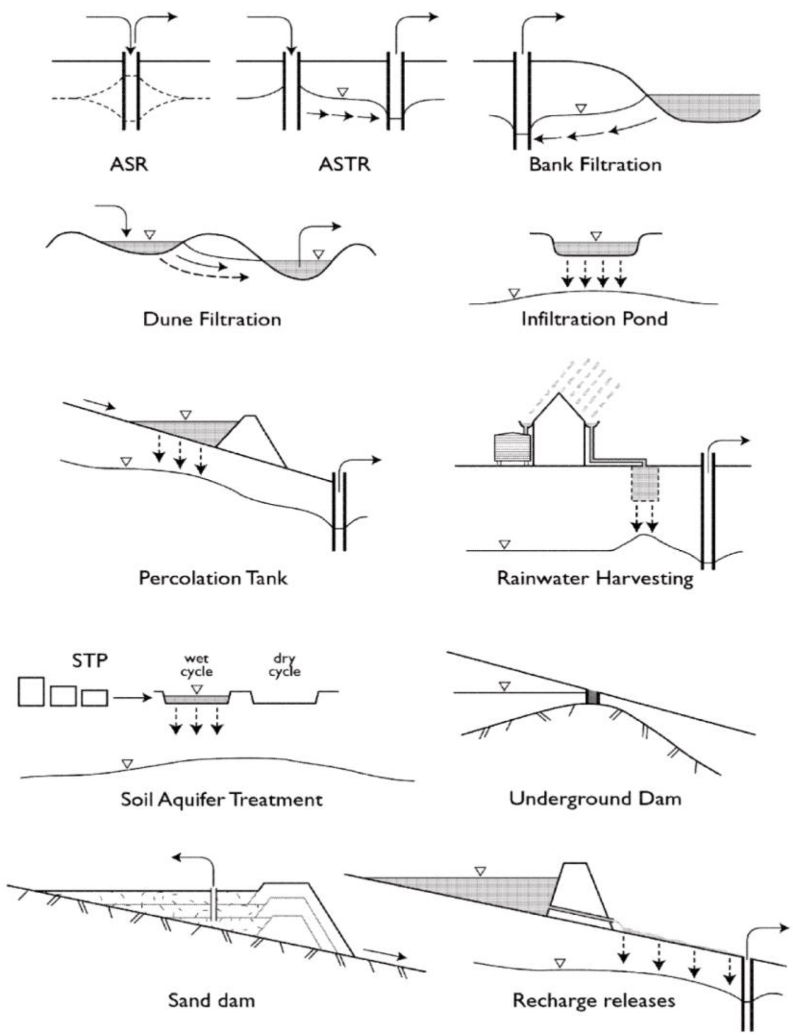

Figure 3: Schematic types on managed aquifer recharge (Dillon, 2005)

While simple MAR techniques, such as sand dams, recharge release dams, or infiltration ponds have the advantage of relatively low implementation costs and simple maintenance, they are only useful for replenishing shallow phreatic aquifers. Furthermore, they occupy a considerable area of land and show high evaporation losses (IGRAC & Acacia Institute, 2007). In Lebanon, the important aquifers are quite thick and often overlain by aquitards so that in many places only well infiltration will yield sufficiently high injection rates. Furthermore, recharge via wells does not require much land – an important factor in a densely populated country such as Lebanon.

Deep well infiltration MAR comprises two different methods (IGRAC & Acacia Institute, 2007):

- Aquifer storage and recovery (ASR): Water is injected and abstracted through the same well.
- Aquifer storage, transmission, and recovery (ASTR): Water is injected through a dedicated recharge well, migrates through the aquifer, and is recovered at some distance through an abstraction well.

The objective of MAR projects considered in this research is to provide a reliable water supply by storing water underground, but MAR projects can also be implemented for other reasons. In coastal areas infiltrated water can create a positive hydraulic barrier to prevent seawater intrusion. Often, MAR projects aim at improving the water quality by making use of natural purification processes as the water passes through porous media (e.g. dune filtration and riverbank filtration).

Sources of infiltration water can be harvested rainfall (e.g. from rooftops), discharges from springs or rivers, or even the effluent of wastewater treatment plants. It will become apparent in this research that source water quality is a determining factor in designing a MAR scheme, especially when water is injected directly into a karstic aquifer.

1.3 Karst aquifers

In Lebanon, almost 70% of the aquifers are karstic (UNDP, 2014). This complicates the implementation of a MAR project because groundwater flow in karst can be rapid and unpredictable. Large features like sinkholes (Figure 4) illustrate the complex hydrogeology of karst. While this implies many difficulties for a MAR scheme, there are also a number of advantages: High hydraulic conductivities of the conduits system allow large quantities of surface water to be infiltrated and stored, if the aquifer is sufficiently confined (van Beynen, 2011). Karst aquifers are also less susceptible to clogging, which reduces the water quality requirements of the source water with respect to turbidity and suspended solids (Stuyfzand, 2017).

Figure 4: Seasonal stream water swallowed into karst sinkhole in Lebanon (Metini et al., 2004)

1.4 Previous Research

A thorough literature review suggested that the global experience with MAR systems in karstic aquifers is rather scarce. A selection of noteworthy case studies is presented in Section 2.2.4. In Lebanon, no successful full-scale pilot project has been implemented until now. Daoud (1973) documents a MAR trial carried out near Beirut before the civil war in the 1970's (see Section 2.2.4).

However, MAR as a potential mitigation measure in Lebanon has been discussed by various authors theoretically. UNDP (2014) provides a comprehensive assessment of Lebanon's groundwater resources and analyses the potential of MAR. The authors identify 30 potential locations for MAR schemes, 20 of which would use river or spring discharge for infiltration and 10 would use sewage treatment plant effluent. Feasibility studies of MAR facilities at four of the proposed sites were conducted (BTD, 2016a, 2016b, 2016c). The proposed projects are of rather large scale and require considerable investments (US$ 3 – 18 mio.).

Daher (2011) developed a conceptual methodology for assessing the rechargeability of karst and demonstrated it for a region in Lebanon. The method, referred to as ARAK, utilizes four physical parameters to develop a map of MAR potential.

Several studies propose MAR schemes of different kind in the Damour area, where public wells for Beirut's water supply cause an aquifer over-exploitation of 13,5 MCM/year (Khadra, Stuyfzand, & Khadra, 2017). Daher, Pistre, Kneppers, Bakalowicz, and Najem (2011), for example, draft a MAR scheme of horizontal tunnels drilled into the side of the Damour River valley to recharge the karstic aquifers. Khadra et al. (2017) propose "fresh-keeper wells" to protect inland groundwater from seawater intrusion and produce fresh water by desalinating brackish groundwater.

1.5 Objective & Research Question

This research aims at determining the most promising circumstances for a MAR scheme in karst. Two major problems to be resolved in designing a MAR pilot project are (van Beynen 2011):

- selection of a suitable infiltration site, and
- selection of the MAR technique.

From reviewing the few efforts to implement MAR in Lebanon it has become apparent that the focus has been on suitable hydrogeological conditions and the technical specifications of the MAR scheme. Successfully implementing a MAR scheme is neither merely an issue of hydrogeology nor technology, even though these domains are important for tackling the problem. Social, economic, environmental, hydrological, and policy concerns also have to be taken into account. A broad approach for assessing the conditions for a MAR project is needed.

ASR and ASTR schemes using well infiltration have been determined as a promising MAR technique in Lebanon, so that this research addresses the question:

How can the site suitability of a Managed Aquifer Recharge project in karstic aquifers be assessed?

2 Theory

2.1 The Multi Criteria Analysis

The objective of planning MAR projects in Lebanon is to replenish aquifers and combat seawater intrusion, thereby making fresh water supply more resilient to climate change, population growth, and inter-seasonal variabilities of water availability. A comprehensive site suitability assessment will have to also focus on social and governance aspects as well as on cost-benefit ratios. The aim of this research is to develop a tool that takes many of these criteria into account to aid decision makers in selecting MAR project sites. Prominent tools for this task are multi criteria analyses (MCA) and cost benefit analyses (CBA).

2.1.1 MCA and CBA

Multi criteria analyses and cost benefit analyses are ex-ante assessments of decisions and both construct a common metric for comparing options (Eijgenraam, Koopmans, Tang, & Verster, 2000). A CBA compares monetizable aspects of different options and is aimed at maximizing economic benefit. A MCA incorporates also qualitative data that cannot necessarily be monetized. It is aimed at effectiveness rather than at economic efficiency. While both methods share common conceptual roots and a similar methodological procedure, the MCA is more accommodating of scientific uncertainty (Kompas & Liu, 2013). The outcome of a CBA is often expressed in absolute (usually monetary) terms and therefore suggests absolute benefit of one option over the other. In a MCA the scoring of options is relative, not absolute. By stressing the qualitative aspects of the assessment more, the MCA transports rating uncertainties of the different criteria to the decision maker in a more transparent way. Since a MCA can incorporate a more diverse range of information and is in some methodological aspects more flexible than a CBA, a MCA is the chosen methodology of this research.

2.1.2 The decision making process

A sustainable water resources management requires many stakeholders to cooperate and to make fair decisions on how to exploit, distribute, and protect the resource. Key roles play governmental institutions which need to balance out societal needs, economic costs, and environmental impacts of the water supply system.

Figure 5 schematizes the decision making process as a 2-step model. It comprises a preliminary phase that focuses on finding a number of plausible options and a second “decision making phase” with a CBA – or in this case MCA – as its core.

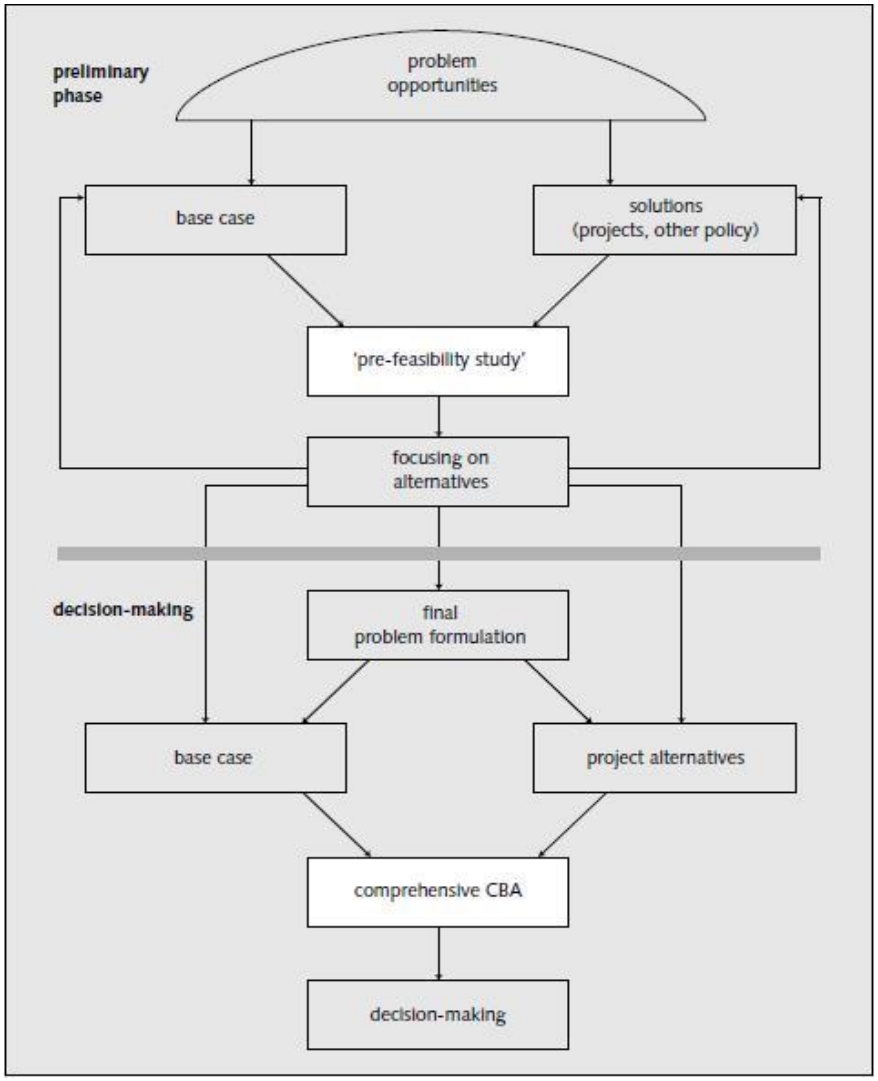

Figure 5: structure of decision-making process (Eijgenraam et al., 2000, p. 9)

Translated to this case study, the problems are decreasing groundwater reserves and seawater intrusion. The base case is "business as usual", thus continuing over-exploitation of aquifers and not taking significant mitigation measures. Solutions to the problems are manifold and include policy instruments to improve water conservation, demand management, or projects to tap non-conventional freshwater sources. The most promising solution is chosen to undergo a pre-feasibility study where the expected performance of the solution is compared with the option of "business as usual". Eijgenraam et al. (2000) stress that the selection of the general solution is a crucial step and attention should be paid to recognize all possible options. Infrastructure projects and engineering works tend to be favoured at this early stage of the decision making process, even though "soft" measures like policy adaptation might pose a better solution. Several alternatives of the proposed solution are developed to then undergo a thorough comparison in the decision-making phase.

In this research, a possible solution to the problem of groundwater over-exploitation is presumed to be MAR systems. The alternatives on which the decision-making needs to focus are the different plausible project sites where a pilot system could be implemented. A pre-feasibility study needs to be carried out to select a range of sites where MAR is plausible. The alternative options derived from the pre-feasibility study are then further assessed in the second step of the process. Requirements which the sites have to fulfil in order to effectively solve the problem will be formulated. The alternatives need to be compared to the base case of business as usual. Finally, a MCA will allow a comprehensive comparison of alternatives and thereby facilitate decision-making towards finding the most promising site for a MAR project.

2.1.3 Objectives and Criteria

To assess the site suitability of alternative locations for a MAR project a set of criteria have to be developed that allow rating the alternatives. The criteria are derived from objectives which a good MAR site should fulfil. Criteria are often grouped into different categories or themes that assess the alternative's performance with respect to different objectives (Janssen, 2001).

A MAR pilot project should, for example, provide safe drinking water without having a negative impact on the ecosystem. This objective can be translated into several criteria belonging different categories. The quality of the injected water is one category that corresponds to the objective of safe drinking water. It can be further differentiated into physically measurable water quality criteria, such as coliform concentrations or salinity content. The topic of environmental impact might not be as easily translated to criteria. Proxies to quantify the environmental impact could be the footprint of the planned MAR facilities on ecologically valuable land or a qualitative assessment by an expert on ecological impact.

Choosing the right criteria can be done by asking stakeholders about their objective, values, and general ideas on the project. This early participation of stakeholders will often also facilitate the implementation of the project (DCLG, 2009). It is important to derive criteria for all themes the objectives of the project addresses. A framework of different themes can help guiding through the mass of different issues that might influence the decision. Absence of a consistent framework for selecting criteria might lead to missing criteria, double-counting of criteria, or confusion between means and ends in the criteria (Janssen, 2001). An important part of this research is the development of a comprehensive set of criteria to guide future MCAs on site suitability for MAR projects in karstic aquifers.

The selected criteria have to meet some requirements. Every criterion must be assessable on the basis of available data for all alternatives. To avoid duplications the description of the individual criteria should be precise and understood by the decision maker selecting the criteria. Furthermore, the criteria should be independent of each other. No characteristic of the proposed solution should be assessed from two sources. In practice this principle is hard to fulfil because some characteristics of an alternative have implicit correlations (Daher, 2011; Daher et al., 2011).

2.1.4 Scales and standardization

The criteria are used to quantify the performance of the different alternatives. Different criteria may have different units of measurements. While coliform concentrations can be measured in colony forming units per 100 ml (CFU/100ml) salinity can be approximated by the value of electrical conductivity (µS/cm). Both criteria are scored on a ratio scale. They have a non-arbitrary zero point and allow comparison such as: The bacterial contamination of 100 CFU/100ml at A is twice as bad as the measured value of 50 CFU/100ml at B. In contrast:

Temperature measured in °C has an arbitrary zero point and is an example of an interval scale where comparisons are more difficult (4°C is not twice as warm as 2°C). Often, a criterion cannot be measured in physical units because it is based on expert judgment or involves stakeholder preferences. Such criteria are scored on ordinal scales which allow for a comparative ranking of alternatives but not for quantifying the degree of difference between them. An example of an ordinal scale is a descriptive assessment of a proposed MAR project on the local ecosystem ("---/+++" or "beneficial / less beneficial / destructive"). A special form is the binary scale that allows only yes/no (or true/false) assessments (Janssen & van Herwijnen, 1994).

The use of different units and scales makes it necessary to standardize the scores of the categories. Standardization translates the observed performances into a common score: the standardized effect, with values ranging from 0 to 1. For ratio and interval scales the user of the MCA must indicate whether it is a cost or benefit criterion. Bacterial contamination, for example, is a cost criterion because higher values mean lower site suitability.

Three different types of linear standardization are commonly used in a MCA (Janssen & van Herwijnen, 1994):

- **Maximum standardization**
  This most often used standardization technique places the scores of the alternatives on a linear function connecting the origin and setting the highest values equal to 1, in case of a benefit criteria. In case of a cost criterion the highest score is translated to 0 and a straight line is fitted to 1 on the y-axis. In maximum standardization the highest scores always translate to a standardized effect of 0 or 1 while the other scores are converted as follows:

  Benefit criteria: $standardized\ effect = \frac{score}{highest\ score}$

  Cost criteria: $standardized\ effect = -\frac{score}{highest\ score} + 1$

  The benefit of this standardization technique is that the proportionality to original scores is kept and no distortion of the standardized effect to the original score occurs. A disadvantage is that small variations in scores might diminish in the standardized effect. Criteria using a ---/+++ scale are usually also standardized using this function (Janssen, 2001).

- **Interval standardization**
  If a criterion is quantified on a scale that does not have a defined 0 point interval standardization may be used. It can also be employed if a criterion is used only comparatively among the different alternatives. The range of the standardized effect is stretched linearly from the lowest to the highest score.

  Benefit criteria: $standardized\ effect = \frac{score - lowest\ score}{highest\ score - lowest\ score}$

  Cost criteria: $standardized\ effect = -\frac{score - lowest\ score}{highest\ score - lowest\ score} + 1$

While it is an advantage that relative scales can be standardized using this method, the danger of distorting the performance of the different alternatives is significant. Interval standardization stretches the range of scores from 0 to 1 even if the differences in the original scores are minor. Thereby it induces an involuntary weighting of the criterion. Interval standardization is therefore used only seldom (Groen, 2017).

- **Goal standardization**

  If there are thresholds for best or worst performances of a criterion these can be manually applied with goal standardization. Electric conductivity (EC), for example, is a good proxy for salinity. It is widely accepted that values below 0,8 mS/cm indicate fresh water and even water with values up to 2 mS/cm is still potable. Applying maximum standardization for this cost criterion might not be constructive because no natural surface water has an EC value of 0 mS/cm. However, only this value would translate to a best-performance standardized effect of 1. Applying goal standardization allows the user to set minimum and maximum values. In this example, a minimum goal of 0,8 mS/cm and a maximum goal of 2 mS/cm would be applied. Water samples of <0,8 mS/cm would all perform equally well (1) while water samples of >2 mS/cm are all scored as unsuitable (0). EC values in-between the goals are translated with a linear function.

2.1.5 Weighting of categories

After standardizing the criteria scores the alternatives could already be compared with each other by simply adding all standardized effects. However, this implies that all criteria are of the same importance to the overall assessment of the alternatives. As this is rarely the case the criteria have to be weighted.

Most MCAs use the method of “swing weighting” which is based on comparison of differences: How does the importance of the swing from 0 to 1 of one criterion compare to the 0 to 1 swing of another criterion (DCLG, 2009)?

Weights can be directly assigned to all criteria by the assessor carrying out the MCA. Weighting can also be done indirectly by further adjusting the weights during the analysis. While there are a number of commonly used methods for indirect weighting (expected value method, random weight method, and extreme weight method (Janssen & van Herwijnen, 1994)) the method deemed most appropriate in the context of this research is pairwise comparison. Two criteria are compared at a time and weighted by the assessor (e.g. “A is 1,5 times as important as B” or “A is slightly less important than B”). Weighting of five criteria with pairwise comparison results in: 4 + 3 + 2 + 1 = 10 necessary comparisons. To keep the number of comparisons manageable and to structure the set of criteria thematically they are grouped in lower-level categories (e.g. water quality, water availability) and higher-level themes (e.g. source water, environmental impact). This structure leads to three levels of pairwise comparisons: The criteria of each category, the categories of each theme, and the themes themselves are compared and weighted.

The actual MCA is then carried out using weighted summation, the most commonly applied MCA method (Janssen, 2001). After the scores of the various criteria have been standardized using linear functions the final performance of each alternative is calculated as the weighted sum of the standardized scores.

2.1.6 Sensitivity analysis

The alternatives are ranked according to the weighted sum of the scores so that a “winner” can be determined. However, a thorough evaluation of the results is important. In a sensitivity analysis the robustness of the ranking is assessed by answering the question: How much change in scores and weights is necessary to bring about a change in ranking (Janssen & van Herwijnen, 1994)?

In a sensitivity analysis it is evaluated which criteria have the greatest effect on the ranking at the given set of weights, or if, on the contrary, the ranking is perhaps insensitive to some criteria. Furthermore, it can be determined at which combination of weights an alternative would score best or worst.

2.1.7 Incorporating Uncertainty

In a MCA two sorts of uncertainties should be accounted for: Score uncertainty and weight uncertainty. The former refers to uncertainties that stem from the data used to estimate the scores of the alternatives while the latter quantifies the uncertainty associated with the importance that is given to the different criteria (Janssen & van Herwijnen, 1994).

Uncertainty can be integrated in the process of the MCA by applying percentage values for score and weight uncertainty of each criterion. Ideally, the score uncertainty is derived from a detailed data quality analysis that quantifies measurement errors and employs error propagation. Often, the researcher will have only limited information about the quality of the data used in the MCA. Using different data sources can help estimating the reliability of the data. Weight uncertainty can be based on inconsistency of weights assigned by different assessors (e.g. stakeholders, experts, or decision makers). Their disagreement on how to weight a certain criterion can be translated into an uncertainty value. In the end, the user will have to make an educated estimation for most score and weight uncertainties.

2.2 Karstic Aquifers

2.2.1 Karst Hydrology

Karst springs and wells drilled in karstic aquifers are the water source for 20-25% of the world’s population (Daher et al., 2011). The term karst originated in former Yugoslavia where karst dominates the geology of the Dalmatian coast. The word combines the Slavic “kar” and the Italian “carso”, both meaning “rock”. It formed into the Germanized version “karst” to describe the special geomorphological features of the region (Singhal & Gupta, 2010).

Karst landscapes typically form in carbonate rock formations of limestones or dolomites. The dissolution process that generates the typical karst features of caves, dolines, karrens, sinkholes, and underground conduits is called karstification. The formation of voids in loess, clay, lava deposits, and effusive rocks is caused by physical erosion rather than by the chemical dissolution. The term karst should not be misused for these formations (Milanovic, 2004). Karstification is governed by the solution of calcium carbonate in acidic water (Singhal & Gupta, 2010):

$$2H_2O + CaCO_3 + CO_2 \Leftrightarrow H_2O + Ca^{2+} + 2HCO^-_3$$

Rainwater dissolves carbon dioxide (CO_2) from the atmosphere and, to a much larger extent, from soil that covers the carbonate rock to form a weak acidic solution (H_2CO_3). Calcium carbonate ($CaCO_3$) is dissolved by this infiltrating rainwater and only later precipitates when the CO_2 levels of the water decrease again, usually when it gets in contact with the atmosphere.

Factors controlling the degree of karstification are manifold and include the amount of rainfall, runoff ratio, and infiltration rate. The solutional capacity of the infiltrating water is controlled by its pH value and strongly determines the rate at which dissolution takes place (Maliva, 2016), as shown in Figure 6. Next to acidity, the flow regime determines the rate at which the carbonate material is dissolved. Turbulent flow increases dissolution significantly compared to laminar flow. Another important factor for the dissolution process is the water temperature. Cold water at 0°C can dissolve four times more limestone than water at 30°C (Milanovic, 2004).

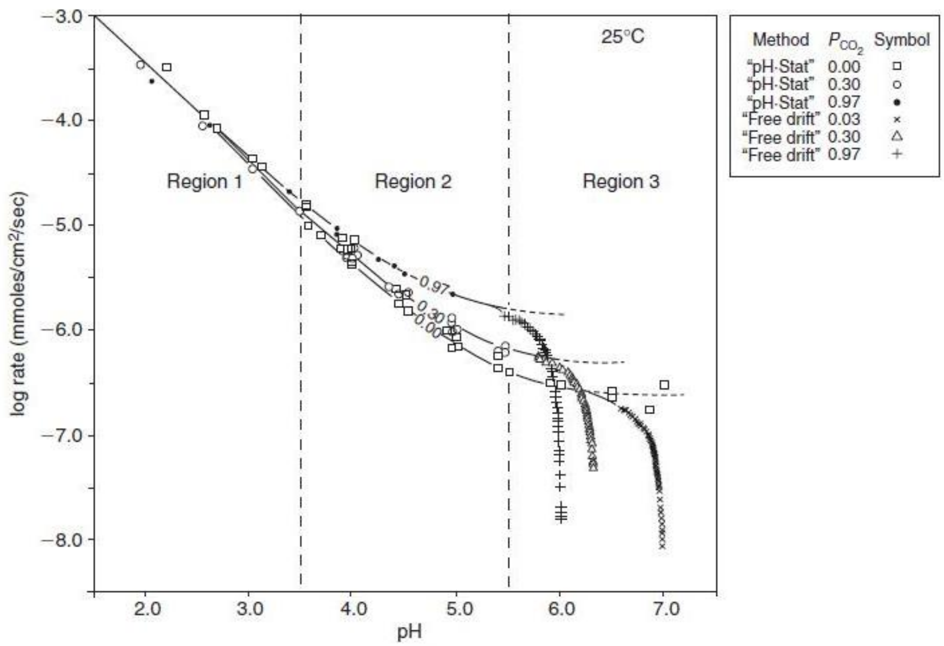

Figure 6: Dissolution rates of calcite as a function of pH (Appelo & Postma, 2004)

Groundwater flow in karst takes place in fissures, fractures, and conduits. A fissured or fractured carbonate aquifer is usually much less productive than a karstic aquifer where voids and joints have been subject to karstification developing them into conduits (Stevanović, 2015). Karstification develops a network of conduits along geological discontinuities and positive feedback of surface water infiltrating along the conduits eventually develops a well-connected karst system (Bakalowicz, 2005).

Next to the pipe-like conduits created by solution, water is transported and stored in fine fissures and intergranular voids of the rock matrix. This is called the primary porosity, as opposed to the secondary porosity of the conduits system (Singhal & Gupta, 2010). The difference in hydraulic conductivity between first and secondary porosity can be as high as 5 – 7 orders of magnitude. Consequently, most of the groundwater flow occurs in the conduits network while the matrix plays a larger role in the storage of groundwater (Maliva, 2016). The pronounced heterogeneity and anisotropy makes it difficult to apply the concept of a Representative Elementary Volume

(REV) to karst aquifers, as it is done for e.g. alluvial aquifers. Observations made at one point by conventional hydrogeology tools such as pumping tests or surface and borehole geophysics cannot be extrapolated to the entire aquifer. The complexity of karst systems makes it very challenging to model groundwater processes numerically (Daher et al., 2011). Furthermore, difficulties commonly arise in determining the boundaries of a karstic aquifer, as they seldom coincide with surface water basins and cannot easily be derived from potentiometric maps (Bakalowicz, 2005).

2.2.2 Hydrogeology of Lebanon

Lebanon's karst is considered to be among the most complex in the world due to the superimposition of several consecutive karstification periods with dissolution occurring at different base levels (Bakalowicz, El Hakim, & El-Hajj, 2008). Figure 7 gives a simplified overview of the country's stratigraphy and lists the hydrostratigraphical character of each layer. The two most important aquifers are the Cretaceous C4-C5 karstic aquifer and the highly karstified Jurassic J4 aquifer. Other karstic aquifers of considerable importance are the Miocene mL aquifer and the Eocene e2b aquifer. Porous medium aquifers have developed in alluvial fans along the coast and in quaternary deposits in the Bekaa Valley.

Formation Period / Age	Code	Thickness (m)	Lithology	Hydrostratigraphy	
Quaternary	Q	<100	Sand, deterial limestone, conglomerates, volcanic or alluvial deposits	Aquiclude or porous medium semi-aquifer	Low permeability, high porosity
Tertiary / Miocene	mL	300 – 400	Reef, marly limestone, continental conglomerates, sequences of thick fractured limestone	Karstic aquifer	High permeability, medium porosity, possibly leaking from upper or into lower aquifer
Tertiary / Eocene	e2b	200 – 600	Marly, chalky, cherty limestone	Karstic aquifer	High permeability, medium porosity
Cretaceous / Maastrichtian – Coniacian	C6	100 – 500	White and marly chalks with phosphate & chert bands	Aquitard	Low permeability, medium porosity
Cretaceous / Turonian	C5	200 – 300	Massive to thin-bedded white-grey limestone and marlstones	Aquifer	Medium permeability, medium porosity
Cretaceous / Cenomanian	C4	500 – 600	Fractured fine and thin-bedded limestone and marly limestone with geodes and chert	Excellent karstic aquifer	Very high permeability, medium porosity
Cretaceous / Albian – Valanginian	C3 – C1	300 – 900	Marls, basalts, limestones, sandstones	Aquitard or semi-aquifer	Low permeability, medium – high porosity
Jurassic / Tithonian – Oxfordian	J7 – J5	100 – 400	Limestone, marls, shale, basalt, chert	Aquiclude or semi-aquifer	Medium permeability, medium porosity
Jurassic / middle	J4	1000 – 1500	Fractured limestone and dolostone with local chert, marls, volcanics	Excellent karstic aquifer	Very high permeability, medium porosity
Triassic		350 – 400	Marly limestone, shale and possibly anhydrite	Possibly semi-aquifer	Not exposed and not studied in Lebanon

Figure 7: Stratigraphy of Lebanon (simplified after Cadham, Thomas, Khawlie, and Shaban (2007; UNDP)

The hydrogeology of coastal Lebanon is controlled by steeply sloping terrain: The surface runoff is high and surface water velocities are relatively high at 3,5 – 4 km/h. Groundwater occasionally flows rapidly at 1,5 – 2 km/h along conduits (Khawlie, Awad, Shaban, Bou Kheir, & Abdallah, 2002). Residence times of groundwater in the aquifers are relatively short. In one of the few comprehensive tracer tests carried out in Lebanon groundwater ages ranging 0,07 – 23,59 years were obtained in the catchment of the Jeita spring (Doummar & Hamdan, 2016).

Many of Lebanon's aquifers show high heterogeneity. In the Cretaceous C4 aquifer at Damour, for example, transmissivity values ranging 105 - 13,220 m²/day were measured (Daher, 2011).

Metini et al. (2004) carried out a groundwater vulnerability assessment in Lebanon using the DRASTIC framework to map the potential of groundwater contamination based on aquifer characteristics and topography. Figure 8 shows that the groundwater vulnerability is especially high in the coastal mountain range of Mount Lebanon and in the inland mountains of Anti Lebanon and Hermon. Regions of high vulnerability correspond roughly to regions of high potential recharge, delineated by Shaban, Khawlie, and Abdallah (2006). In the high altitude regions outcrops of the carbonate aquifers show high karstification (visible as sinkholes, karrens, and dolines) which leads to intensive infiltration with only little surface runoff.

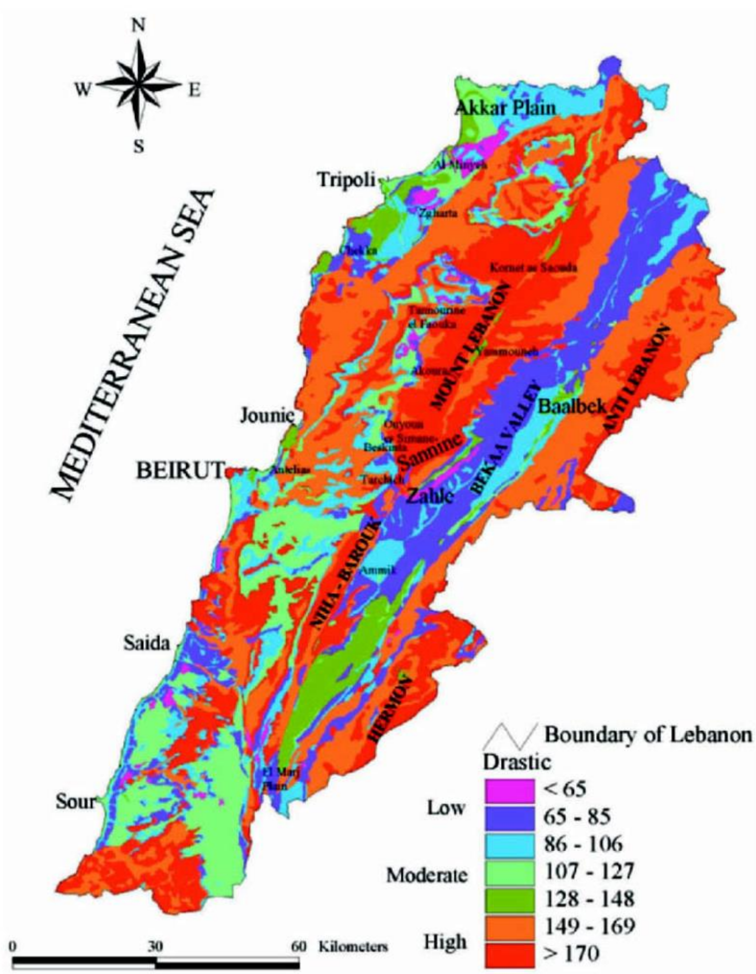

Figure 8: Groundwater vulnerability map of Lebanon (Metini et al., 2004)

2.2.3 MAR in Karstic Aquifers

Managed Aquifer Recharge has been applied in various settings all across the world. In karst, however, there is not much experience with artificial aquifer recharge, especially if the injected water is to be recovered later, as it is the case with ASR and ASTR schemes.

One of the main problems a MAR system in karst faces is the fact that due to the extreme heterogeneity of karst flow patterns of the injected water are difficult to predict. Only a trial infiltration test or an elaborate tracer test will give adequate insight into groundwater flow at the targeted location (Klingbeil, 2017). The recoverability of the infiltrated water – and therefore the success of the MAR scheme – is largely dependent on how fast and far infiltrated water disperses in the aquifer. While conduits might lead to unsuitably high flow rates, the solid rock matrix of limestone is likely to have insufficient permeability for infiltration.

Another important physical factor is the quality of the source water (Klingbeil, 2017). In the Lebanese context rivers that might act as sources for infiltration water often show high bacterial contamination. Stuyfzand (2017) stresses the necessity of treating infiltration water to drinking water standards before directly injecting it into the phreatic zone through sinkholes or wells.

Rapidly infiltrating surface water into a karstic aquifer can disrupt the chemical balance of the ambient groundwater and the aquifer. A high redox potential of the infiltration water can potentially mobilize pyrite and lead to a contamination by arsenic (Stuyfzand, 2017) (see criterion 1.10.1 in Appendix II). In the past, geochemical issues have led to the closure of ASR projects in the USA and England (Brown, 2005). Hydrochemical modelling should therefore be part of planning any MAR scheme (Klingbeil, 2017).

Daher et al. (2011) express their concern about artificially recharging karstic aquifers directly through infiltration wells or sinkholes because of potential contamination and rapid transport through conduits to springs. The authors suggest that MAR projects should focus on slow infiltration through the epikarst. The advantage is that there is some deactivation of pathogens while the water seeps through the epikarst. Furthermore, it is spread out in the epikarst and infiltrates via natural flow paths. The infiltration is delayed but the surface water will eventually be transmitted to the voids system of the phreatic layer, while an infiltration well does not necessarily hit this conductive system of the karst.

Despite the numerous difficulties associated with planning a MAR scheme in karst there are strong advantages, too. Compared with alluvial aquifers karstic aquifers are much less prone to clogging as slightly acidic injection water constantly dissolves some $CaCO_3$ (Gale, 2005). Therefore, direct infiltration into carbonate aquifers might need less pre-treatment, especially with regards to removing suspended solids (NRC, 2008). Even though karstic aquifers do not have good water purification properties the carbonates can still have a positive effect on water quality: As acidic infiltration water dissolves $CaCO_3$ it becomes harder, i.e. the pH increases. This might be desirable if the water is later recovered and transmitted through a pipe system where the increased pH decreases the corrosion potential (Stuyfzand, 2017).

2.2.4 Case Studies of MAR in Karst

In Lebanon, there seems to have been only one documented trial of artificial aquifer replenishment, carried out over four decades ago. Daoud (1973) describes experiments that used existing but non-operational wells for gravity infiltration of surface water. Injection rates of 135 – 174 l/s were achieved in experiments with durations of 10 days to 7 months. Even though the scope of monitoring was rather limited, a noticeable decrease of salinity and a rise of the groundwater table of 1.2 m were observed at 450 m distance of the infiltration well. At a distance of 5.5 km no change in the groundwater table was observed.

In karstic aquifers ASTR schemes are usually designed over longer distances, i.e. with a larger spacing between infiltration and abstraction than would be the case for e.g. dune filtration ASTR. This is done to overcome the difficulty of accounting for small-scale hydraulic transport characteristics of the aquifer (BTD, 2016c). An example is the MAR scheme in a wadi in Jordan that recharges the Hidan wellfield, described by Xanke et al. (2015). A dammed reservoir and infiltration wells are used to recharge the partially karstified aquifer. Total infiltration is 74 MCM per year. Since continuous sedimentation decreases the infiltration capacity of the reservoir the infiltration wells become more important. The infiltrated water is abstracted some 5 km downstream. The advantage of this MAR scheme is that the runoff created by the few but high-intensity rain events can be stored in the wadi reservoir to be later infiltrated. However, the reservoir occupies much land and the existing water system is severely disrupted by the MAR scheme. In a densely populated country like Lebanon this design would certainly face much opposition from land owners and water users.

Wang, Page, Zhou, Vanderzalm, and Dillon (2015) describe MAR in an unconfined limestone aquifer by infiltrating rainwater harvested on a rooftop. A first flush removal device is used to improve the water quality. This MAR scheme is designed as a pilot project with the objective to discharge rainwater without impeding the groundwater quality. Recovery of the infiltrated water is not planned. In Lebanon, using storm water from rooftops is a promising component of improving the drinking water availability. However, instead of recharging the groundwater it would be more efficient to store the water in tanks that most households already have (GIZ, 2015).

Escalante et al. (2016) describe a successful MAR scheme in Ciudad Real (Spain) where surface water is infiltrated through 25 wells of 60 – 100 m depth. The wells are operated under gravity infiltration. A simple pre-treatment by a metal grid, gravel filter, and sand filter is sufficient to improve the quality of the water provided by an irrigation channel. The authors describe a similar ASTR scheme in Menashe (Israel) where a 10 – 20 % reduction in transmissivity of the karstic aquifer has been observed due to clogging by sand and bacteria. Sufficient pre-treatment (especially turbidity) and a large enough diameter of the infiltration well were found to be key factors of the MAR project’s success.

In Nardo (Italy) declining groundwater levels led to seawater intrusion into the karstic coastal aquifer. Kazner, Wintgens, and Dillon (2012) describe a pilot MAR scheme that uses surface runoff and waste water treatment plant effluent to recharge the Mesozoic carbonate aquifer through a natural sinkhole. The high transmissivity of 1.000 – 10.000 m^2/day allows for large volumes to be infiltrated at a single point. Salinity levels of the groundwater significantly decreased after recharge began. Nitrate and organic compound concentrations improved as well. However, E.coli counts in the observation wells often were above legal standards because the source water contained elevated pathogen levels. Adding a membrane bioreactor to the wastewater treatment plant would sufficiently improve the quality of the effluent (pathogens and turbidity) to upscale the MAR project.

Comparing numerous ASR schemes in saline coastal aquifers Brown (2005) concludes that the recovery of freshwater was lower in limestone aquifers as compared to sandstone aquifers. Some of the largest MAR schemes in karstic aquifer have been implemented in Florida. Mobilization of pyrite by infiltration water with a high oxidation potential and the following groundwater contamination with arsenic have led to the closure of some MAR systems there (Stuyfzand, 2017).

2.2.5 Proposed Infiltration Technique

The framework for assessing site suitability for karst MAR projects presented in this paper focuses on ASR and ASTR schemes that employ deep well injection. Injection through sinkholes could also be considered if detailed knowledge of underground flow paths exists. The infiltration water is assumed to be abstracted from rivers or springs. In Lebanon treated wastewater is not (yet) an option, as there are currently no reliably functional sewage treatment plants (El-Fadel et al., 2000).

A major difficulty in exploiting karst aquifers lies in finding an appropriate location for a productive well that taps an aquifer zone of sufficient permeability to result in satisfactory yields (Daher et al., 2011). In Lebanon, Shaban, El-Baz, and Khawlie (2007) observed a significant correlation between water wells productivity and their proximity to faults (Figure 9). 97% of the wells with a productivity of >10 l/s are located <650 m from a fault line. Wells located near faults or fractures are also more consistent in their yields (Singhal & Gupta, 2010)

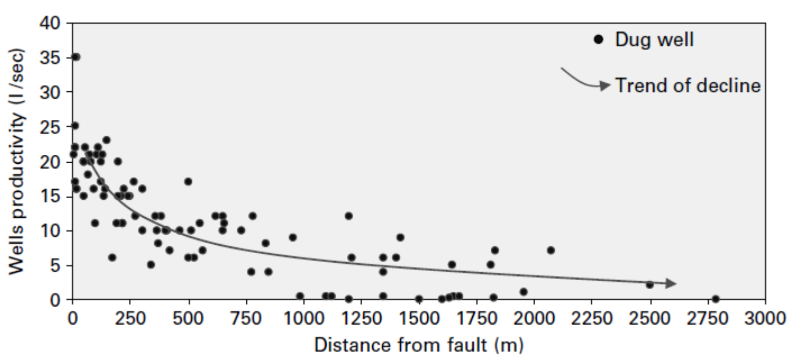

Figure 9: The relationship between water wells productivity and their distance to faults (Shaban et al., 2007)

A resource-saving approach for developing a new MAR system could be to take advantage of already existing wells that have been successfully tapping the groundwater. Productive wells with an appropriate discharge capacity could be employed as designated extraction points of an ASTR scheme. Taking this existing infrastructure as a starting point, a suitable location for infiltration can be searched upstream in the direction of groundwater flow. Injection could be done through existing wells that have fallen dry or that are no longer in use, as demonstrated in Lebanon before (Daoud, 1973).

3 Methodology

To determine the most promising location for a MAR project in Lebanon an assessment framework was developed. Its core is a broad catalogue of criteria that can be useful in comparing alternative MAR sites. The research is based on an extensive literature review and on expert interviews (transcriptions in Appendix VI).

3.1 Interview Partners

As an expert on MAR and geochemistry prof Pieter Stuyfzand (2017) provided valuable considerations regarding technical aspects of ASR schemes and the importance of geochemical reactions. Dr Ralf Klingbeil (2017) is an expert on water resources management in the Middle East who provided diverse input regarding the implementation of MAR projects in the regional context. As a geologist dr Ane Wiersma (2017) offered valuable knowledge on the characteristics of karst and in the general analysis of Lebanon's geology. Throughout the entire research process Acacia Water senior hydrogeologist dr Koos Groen (2017) provided important expertise and guidance regarding the methodology.

3.2 Site Suitability Assessment Framework

The framework for assessing the site suitability with regards to MAR in karst follows the 2-step concept of decision making outlined in Section 2.1.2. A MCA is the core of the framework but a pre-feasibility study is also necessary to determine a number of plausible alternatives (i.e. potential MAR sites). The methodology is therefore divided into two steps, as shown in Figure 10.

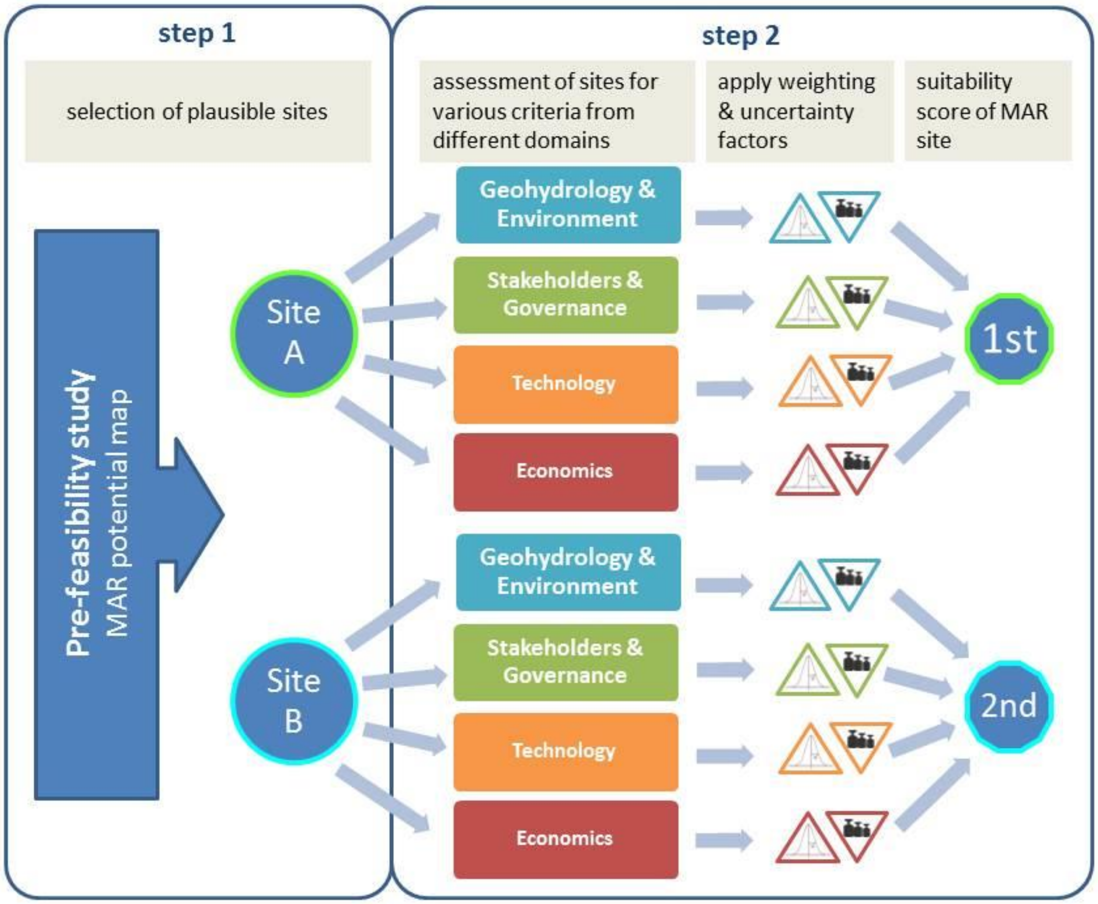

Figure 10: Flow chart of the site suitability assessment framework consisting of a pre-feasibility study (step 1) and the MCA (step 2)

3.2.1 Selection of Plausible MAR Sites

The Multi Criteria Analysis for selecting the most suitable site for a MAR project requires a short-listing of plausible sites, as data gathering can be very time-consuming. Often, this is done by mapping a number of important factors (such as level of aquifer stress or transmissivity values) and overlaying them. This overlay planning methodology results in a map of MAR potential from which potential MAR sites can be selected. It is well suited for feasibility studies on artificial recharge (Brown, 2005). However, a selection could also be made on other grounds. A number of possible sites might be short-listed for political reasons or practical circumstances that cannot be easily mapped.

As constructing a MAR potential map of Lebanon would have gone beyond the scope of this research, a selection of nine plausible MAR sites was made based on the UNDP (2014) report assessing Lebanon's groundwater resources. As the report finds artificial recharge to be a key measure towards resilience of water supply in Lebanon, it proposes 20 potential sites for MAR supplied by river water. Sites were selected based on six preliminary criteria:

- The aquifer needs to be under stress of over-exploitation and/or seawater intrusion
- Hydraulic characteristics of the aquifer provide for a large enough recharge capacity
- Depth to groundwater is rather large to avoid negative effects from groundwater bulging

- Average flow rates of the river providing the infiltration water of >5 m³/s during rainy season
- A road should exist between the abstraction point at the river and injection point
- The distance between abstraction point and recharge point should be <500 m

The 20 sites selected by UNDP (2014) are a valuable pre-selection based on local knowledge (the research was carried out by the Lebanese consultancy “Elard”) rather than a mere GIS analysis. To show-case the developed MCA framework the selection was further narrowed down to nine sites (see Table 2), as to gather as much diverse data as possible within the available time. The selection was made with the aim of retaining a large variety of different physical conditions. The nine sites are situated in eight different groundwater basins and four different geological layers form the respective karst aquifers. Seven sites are spread out in the Lebanese coastal regions while two sites are located in the Bekaa Valley (see Figure 11). The sites are located along seven different rivers and cover a wide range of different elevations, from coastal plains at 40 m asl to high mountain valleys at 1000 m asl. Three sites (A10, A14, A22) were selected because they were further explored in technical feasibility studies carried out by UNICEF (BTD, 2016a, 2016b, 2016c). The potential sites are presented as sections of rivers deemed suitable for a MAR project. Table 2 gives an overview of the nine sites and some site characteristics as determined by UNDP (2014). The initial site names and numbering of the groundwater basins have been kept.

Table 2: Selection of potential MAR sites in Lebanon

Site name	Geolo-gical layer	Ground-water basin	River	Average Winter discharge (m³/s)	Elevation (m asl)	Region
A1	J4	16	Abou Ali	12,14	990-1284	North Lebanon, Bcharre
A3	J4	16	Beirut	5,68	236-317	Mount Lebanon, Baabda
A7	C4-C5	18	El Bared	8	290-400	North Lebanon, El Minieh-Dennie & Akkar
A9	C4-C5	21	Ibrahim	26,9	40-115	Mount Lebanon, Kesrwane & Jbeil
A10	C4-C5	3	Berdouni	3,3	1025-1120	Bekaa, Zahle
A14	C4-C5	19b	Damour	17,47	300-350	Mount Lebanon, Chouf
A16	C4-C5	19a	Litani	20,9	40-115	South Lebanon, Sour & El Nabatieh
A19	e2b	4	Litani	18,13	540-610	Bekaa, West Bekaa
A22	mL	23d	Abou Ali	12,14	41-53	North Lebanon, Tripoli & Zgharta

Site descriptions in Appendix III lay out the characteristics of each short-listed MAR site in more detail. The site descriptions include information about the geological setting, the source water, and the design of the planned MAR scheme.

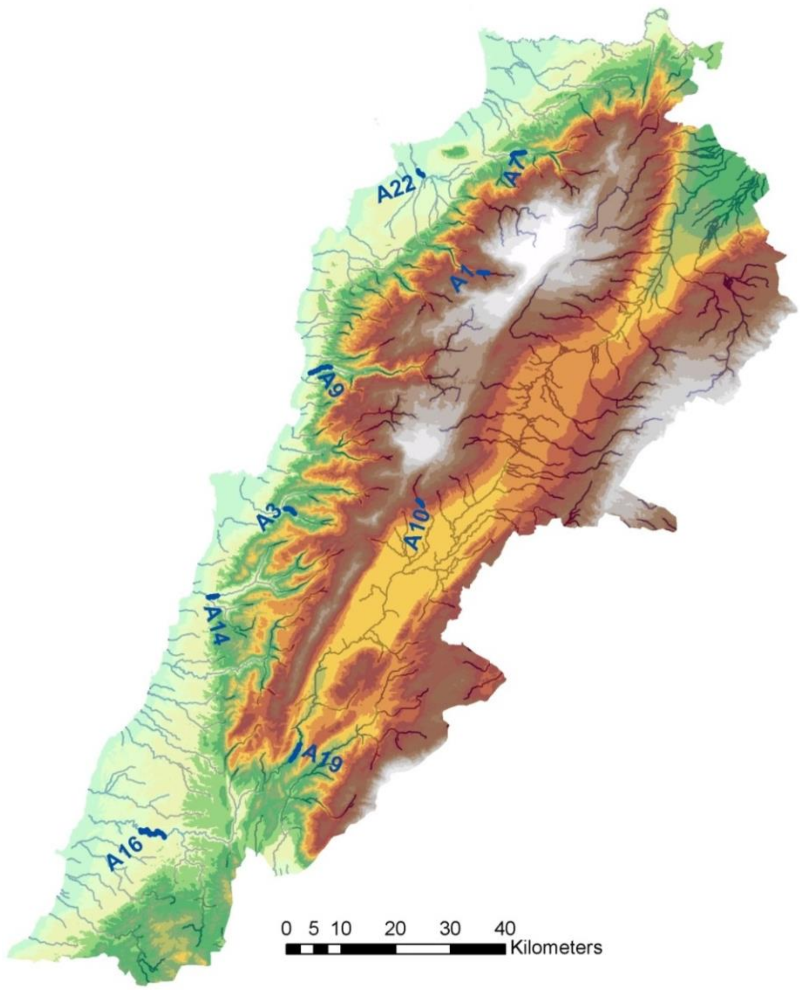

Figure 11: Locations of the potential MAR sites on an elevation map of Lebanon

3.3 Criteria catalogue

The central part of the site suitability assessment framework is the multi criteria analysis. Its core is a criteria catalogue that was developed based on literature review, expert interviews, and discussions with project team members. It provides a wide range of aspects that the plausible MAR sites can be compared in. Depending on the objective of the MAR project and the focus of the decision-making process, criteria from different domains can be chosen. Data availability will also affect the selection of criteria from the catalogue.

The criteria catalogue is divided into eight themes which contain a total of 52 categories (see Figure 12). Each category consists of one or more criteria. The entire criteria catalogue comprises of 141 criteria that are described in detail in Appendix II. The table of criteria in Appendix I lists for each criterion on what scale (unit) it should be scored and what type of standardization should be applied in the MCA. Often, a comment on the objective function of the standardization is given, e.g. water quality standards for standardizing measured values. Some of the criteria of one category overlap thematically and are mainly provided to give the assessor a choice of option depending on the type or scope of the available data.

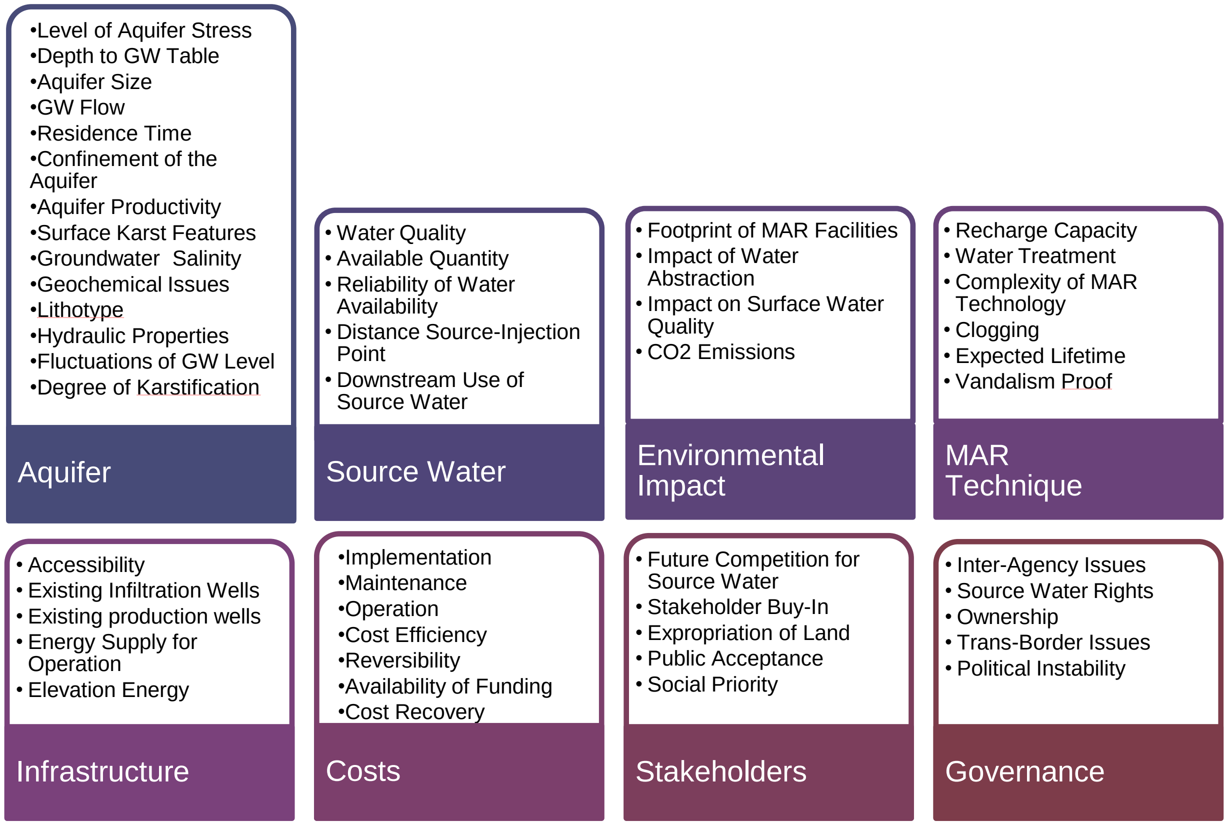

Figure 12: Themes and categories of the criteria catalogue

3.3.1 Aquifer

The first theme comprises of 45 criteria grouped into 14 categories that can be used to assess the site suitability with regards to the groundwater situation and the physical characteristics of the aquifer. This topic has been given the most attention throughout the research process because the complicated hydrogeology of karst controls the recoverability of infiltrated water and therefore has a large impact on the success of a MAR scheme.

Criteria include the assessment of groundwater stress, the estimated size of the groundwater basin as a proxy for sufficient storage, and the groundwater level. Based on the findings of Chowdhury, Jha, and Chowdary (2010) and Steinel, Schelkes, Subah, and Himmelsbach (2016) the depth to the groundwater table should ideally be in the range of 6 – 50 m bgl. Further categories compile information that indicate the site suitability with regards to groundwater flow and residence times.

Horizontal and vertical confinement of the aquifer is an indicator of the probability that the infiltrated water will stay within the boundaries of MAR scheme. Karstic aquifers can be excellent groundwater storages when groundwater flow is constrained (Gale, 2005). Geological layers (aquitards and aquicludes) can provide for vertical confinement and decrease the contamination risk from anthropogenic pollution. Lateral confinement can be provided by vertical barriers. These can be constructed of faults that are filled with low-permeability material such as marl

(Wiersma, 2017) or by uplifting of an underlying aquiclude which then blocks groundwater flow in the lower parts of the aquifer (Singhal & Gupta, 2010). The hydraulic conductivity in karst is usually highest parallel to the extent of the layer, in longitudinal direction (Stevanović, 2015), so that an inclination of the aquifer leads to a preferred flow direction that is oriented downward, instead of horizontally. While a slightly dipping aquifer might be problematic because it facilitates quick flow away from the MAR site, steeply, almost vertically inclined aquifers might have a good potential for providing an underground water storage (BTD, 2016c).

Another criterion addresses the productivity of the aquifer approximated by the installed capacity of groundwater production wells.

The salinity of the groundwater can be a constraining factor, as mixing of infiltrated freshwater and brackish/saline ambient groundwater will occur to some extent. If the resulting salinity of the recovered water is too high the MAR project might fail (Stuyfzand, 2017). Furthermore, geochemical reactions of the infiltration water and the aquifer might deteriorate the groundwater quality. The concentrations of pyrite and gypsum in the aquifer should be analysed (Stuyfzand, 2017).

The hydraulic properties like aquifer conductivity and transmissivity determine infiltration capacity and recoverability. Values obtained at one point in the aquifer will most likely not be valid for the entire aquifer. Nevertheless, transmissivity values measured in the targeted aquifer can be a useful additional indicator for the aquifer's suitability for MAR. Alternatively, the theoretical injection rate estimated using Logan's (1964) approximation derived from transmissivity and groundwater depth can be employed. The aquifer lithology characterized by the relation of carbonates to clay can provide another proxy for hydraulic conductivity, as higher clay contents (marls and mudstones) are associated with a lower hydraulic conductivity and an increased clogging risk when compared to limestone (Milanovic, 2004).

A core criteria category of the MCA is the assessment of the degree of karstification. A diverse set of 17 criteria was collected to give the researcher the possibility of classifying the karst aquifers with respect to their general hydrogeological character depending on the available data. The criteria aim at rating the aquifer as an entity, at the scale of the groundwater basin, and are thus not specific to the MAR site. Several approaches of classifying karst aquifers have been developed by numerous researchers and a selection of these was incorporated in the criteria of this category.

3.3.2 Source water

The MAR projects considered in the Lebanon MCA are planned to use river or spring discharge as infiltration water. The criteria to assess the site suitability with regard to the available source water were developed in this context. However, they are equally valid for alternative water sources, such as sewage treatment plant effluent and harvested rainwater.

Eight of the fifteen criteria that belong to this theme were grouped under the category of water quality. Turbidity and organic material of the source water might be particularly important where the risk of clogging is high due to a low conductivity of the aquifer (Brown, 2005; Escalante et al., 2016; Massoud, 2012). Bacterial contamination, for which E.coli counts are a reliable proxy, is often the most problematic water quality issue as pathogen concentrations in many surface waters exceed drinking water standards significantly and little purification takes place in karstic aquifers (Steinel et al., 2016; Stuyfzand, 2017). The high vulnerability of groundwater in karstic aquifers requires also that chemical contamination of the source water (heavy metals, pesticides, fertilizers, pharmaceuticals, etc.) complies with the standards for the intended use of the recharged water. The inherent peculiarity of carbonate limestones is that they can be dissolved by acidic water. In regions with very instable karst the pH as an indicator for the dissolution capacity of the source water can be taken into account to assess whether recharge might lead to instability of the infiltration well.

Next to quality, the quantity of the available source water will often be an important property of the potential MAR site. Assessment can be done with respect to the duration for which sufficient source water is available for injection or in terms of cumulative annual discharges. The reliability of source water availability can be taken into account by assessing the impact of climate change and anticipated changes of anthropogenic water use.

Other categories of this theme concern the distance between the water source and the injection point as well as the impact water abstraction would have on downstream water uses, including ecosystem services.

3.3.3 Environmental impact

As with any infrastructure project of considerable size a comprehensive environmental impact assessment should be carried out. While this is beyond the scope of a MCA it is important to take environmental concerns into account at an early stage of the site selection. Depending on the geographical and legal context the environmental impact of a MAR scheme can be a constraining factor.

Suggested criteria are the footprint of the planned MAR facilities, the impact of source water abstraction on aquatic fauna, and the impact on the water quality of the water source by potential discharges from water treatment facilities of the MAR scheme. Furthermore, attempts should be made to quantify the CO2 emissions associated with construction and operation of the MAR scheme. For this, fairly detailed designs of the MAR facilities at the different sites are necessary.

3.3.4 MAR technique

The technical aspects of the different MAR schemes are assessed in the theme MAR technique. An important factor for comparing the alternatives is the recharge capacity, i.e. the volume of water that is planned to be infiltrated annually. Another criterion addresses the complexity of the required purification which may comprise of primary treatment (sedimentation, sand filtration), chlorination, secondary treatment (biological purification), or even more complex techniques like reverse osmosis. Furthermore, the complexity of the MAR technology as a whole should be assessed. This refers to the complexity of constructing the MAR facilities (water abstraction structure, transmission pipelines, water treatment facilities, and infiltration wells) and whether local contractors have the capacity to implement them. The complexity of operation and maintenance can also be considered. A simpler design is always preferable.

The MAR scheme's susceptibility to clogging and its expected lifetime should also be part of the comparison. Depending on the socio-economic context, the prospect that the MAR facilities will be destroyed by vandalism or theft can be rated.

3.3.5 Infrastructure

Under the theme infrastructure all those criteria are grouped which refer to the convenience of the location for operating and constructing the MAR scheme. Existing wells usable for infiltration and abstraction are a valuable asset of a potential MAR site. Reusing existing wells for infiltration or abstraction is beneficial in two ways: It significantly decreases the investment costs. Additionally, making use of a productive abstraction well, or one that used to be productive but has fallen dry due to over-exploitation, guarantees that there is a connection to the network of fractures and conduits (Escalante et al., 2015). A newly drilled well could by mischance miss the voids that transport the groundwater and run dead in the solid matrix of the carbonate layer, leading to low well productivity.

The accessibility for heavy machinery is another important aspect. If energy is needed for operation, e.g. for water pumps or for the operation of purification facilities, existing electricity supply can be rated. Furthermore, it is beneficial for the targeted abstraction point to lie at a higher elevation than the point of water use. In Lebanon, for example, a MAR scheme located in one of the steep coastal valleys would imply high pumping costs for lifting the water to the settlements on the plateaus (Klingbeil, 2017).

3.3.6 Costs

It may be difficult or impossible to estimate the implementation costs of a MAR scheme at an early stage of the project process when the MCA is carried out. However, as the affordability of the project is a very substantial aspect of any public infrastructure project, attempts should be made to at least estimate costs in a comparative approach.

Costs are divided into implementation costs (consisting of costs for land, construction, as well as drilling) and annual costs for maintenance and operation. As MAR schemes have a limited lifetime – duration of operation is estimated to be 20 – 30 years (BTD, 2016a; Daher et al., 2011) – it might be possible to estimate an overall cost efficiency of total running and implementation costs per total infiltration capacity. This should also include deconstruction and well-sealing costs.

Means of financing are another aspect under which MAR projects can be assessed. Funding for specific regional development, for certain ethnical or socio-economic contexts, for research, or funding by the water users themselves can differ depending on the location and design of the MAR system. Klingbeil (2017) points out that currently there are substantial funds available for climate change adaptation measures by international organizations and MAR schemes might qualify for this.

3.3.7 Stakeholders

To assess the influence of the planned MAR scheme on various stakeholders – and inversely, the stakeholders' influence on the implementation of the MAR scheme – detailed knowledge of local social structures is necessary. It can be difficult to comprehensively assess the various stakeholder criteria by means of a desk study, as was found during the Lebanon MCA.

Under this theme the influence of future competition for the source water due to planned water projects or demographic development can be judged. Different groups of stakeholders should be identified and their support for the MAR project assessed. Special attention should be given to current users of the source water. In any case it is of great importance to involve key stakeholders in the project at an early stage (Klingbeil, 2017).

Another aspect for comparing the alternatives might address social priority. Projects could be preferred that benefit the largest number of people. Specific priority groups of water users could also be identified, for example farmers, urban residents, industry, or refugees.

3.3.8 Governance

The governance theme accounts for aspects related to the legal and administrative context of the project. If the potential MAR sites all lie within the same administrative region the scores of some criteria might be the same for all alternatives. In this case they can be left out, as the MCA would be insensitive to them.

A MAR project will most likely be implemented by governmental organizations. Unclear responsibilities and division of tasks might lead to inter-agency issues hampering the project (NRC, 2008). Official or customary water rights to the source water might also be an issue (UNDP, 2014). Often, there will be legislation restricting the artificial recharge of aquifers (Stephan, 2007). If the targeted aquifer is shared with bordering nations it might be necessary to cooperate internationally for the MAR project.

Important for the success of a MAR scheme is the question of ownership. The authority in charge of operating the MAR scheme must have the capacity to do so and there should be transparency in their accountability. In case of a private commercial operation the profitability and the owner’s long-term commitment should be assessed. Any owner should be acknowledged and supported by local stakeholders to prevent a boycott of the project.

A certain level of political stability is a pre-requisite for implementing a MAR project. Even though this aspect might be difficult to quantify, a comparative rating of the sites might be possible. In the case of Lebanon some MAR locations could not be visited because the area was under control of Hezbollah. Corruption is another threat for a project’s implementation. Klingbeil (2017) drafts a scenario where high-rank officials could profit from insights of the planning process by privately buying land at the locations assessed to be most suitable for MAR to later demand high expropriation prices, paid for from the project budget.

3.4 Data Collection

Data collection to score the site suitability of the nine pre-selected sites in Lebanon (outlined in Section 3.2.1) was done as a desk study. Unfortunately, a field visit to confirm and to complement the data was not possible within the time frame of this research.

Data sources are scientific articles, reports by national and international organizations, thematic maps, information provided by the Lebanese government and feasibility studies of proposed MAR schemes. A detailed score matrix of the collected data including the individual sources can be found as a spread sheet in the digital attachment to this thesis (see Appendix VII).

3.5 Demonstration of the MCA

The MCA for comparing the nine plausible MAR sites in Lebanon was carried out using the DEFINITE software (Janssen & van Herwijnen, 1994). The sites' performances for a total of 38 criteria were scored. An emphasis was laid on the theme "aquifer" which comprises 13 criteria while the theme "governance" had to be left out entirely due to a lack of reliable data. The criteria which were retained for the MCA are indicated in the table of criteria in Appendix I and an overview table of the site performances of all criteria is given in Appendix IV.

Weighting of the criteria is done by pairwise comparison (as outlined in Section 2.1.5). Ideally, experts, decision makers, and stakeholders would have been involved in the weighting process. While the weighting of lower-level criteria and categories should be done by experts of the subject, the importance of the different themes can be weighted by stakeholders and decision makers. Unfortunately, a field trip to Lebanon was not possible during this research, so that weighting was done exclusively with the expertise of Acacia Water hydrogeologist Koos Groen (2017). Estimation of score uncertainty was also done based on his experience. Following an approach suggested by Janssen and van Herwijnen (1994) a uniform weight uncertainty value of 20% was applied to all criteria. The DEFINITE software carries out a Monte Carlo Analysis that randomly varies the scores and weights within the ranges of the assigned uncertainty values (Janssen & van Herwijnen, 1994). The outcome of 2000 MCA runs with different Monte Carlo weight sets is an important part of the sensitivity analysis. The method used to carry out the MCA is weighted summation of standardized scores (see Section 2.1.5).

4 Results

4.1 Ranking of Alternatives

Site A10 on the Berdouni River in the Bekaa Valley scores best in the multi criteria analysis (see Figure 13). The site-performances in the seven different themes are illustrated in Figure 14. This overview shows, for example, that the best-performing site A10 scores particularly well in 'infrastructure' while it scores among the last in 'MAR technique'. However, both themes contribute relatively little to the overall score, as the distribution of weights in the pie chart of Figure 14 shows. The themes 'source water', 'stakeholders', and 'aquifer' were considered to be more important.

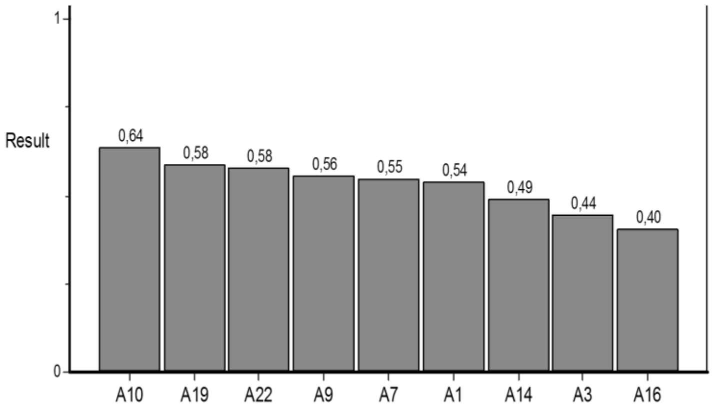

Figure 13: Results of the MCA: weighted summation of scores

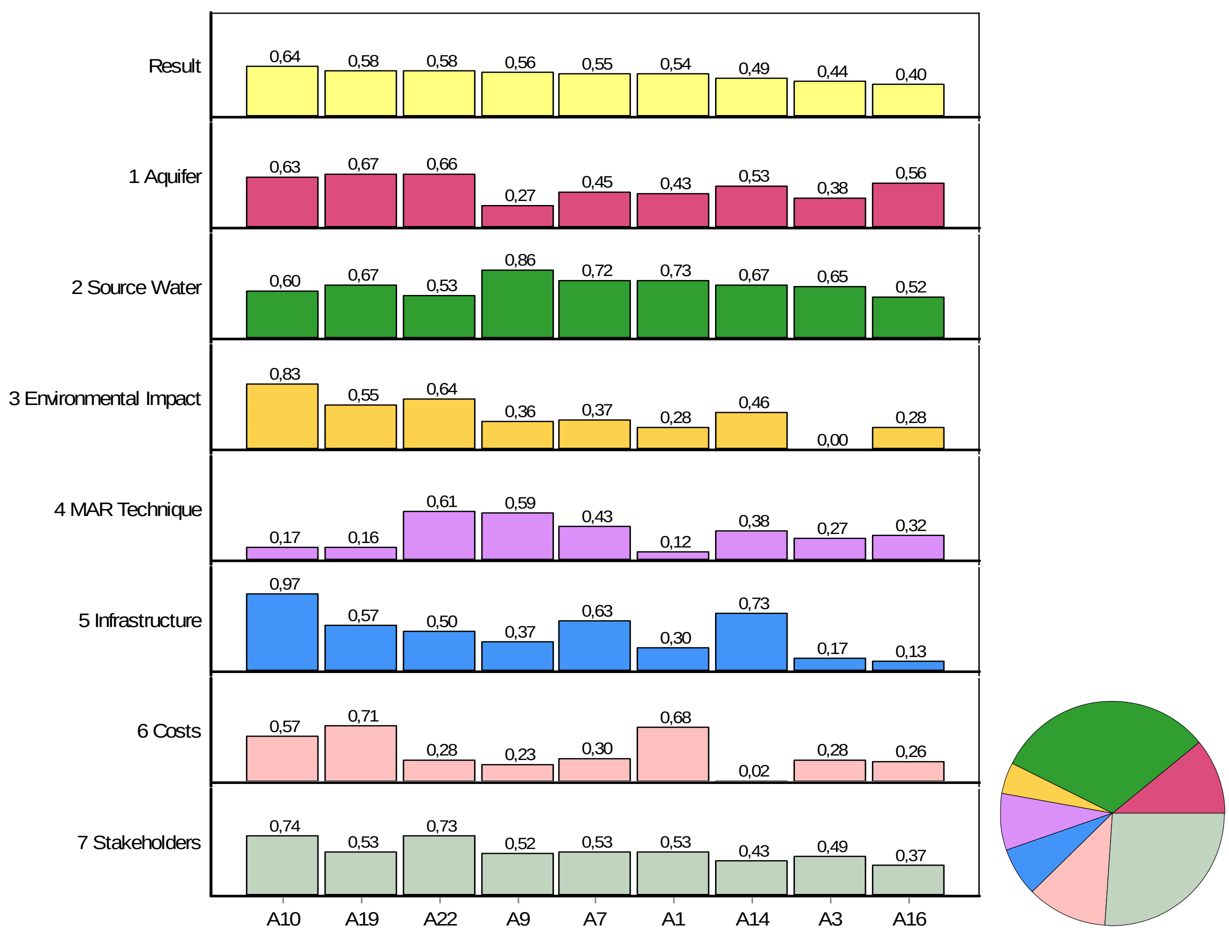

Figure 14: Site scores of the different themes and weighted contribution of themes

The best-performing alternative A10 scores average or high in all themes but MAR technique. The geology of the site is such that some confinement of the targeted aquifer is expected and preferential flow along faults is improbable. However, karstification is pronounced in the aquifer as indicated by the spring hydrograph analysis and the amount of karst features in the area. This leads to an above-average rating of the site's MAR suitability regarding the aquifer characteristics. For a detailed description of the site's hydrogeology see Appendix III.

The theme 'source water', as single most influential group of criteria, is scored slightly below average because of high bacterial contamination and a relatively low water availability with sufficient river flow of only four months. It is suspected that the score of this theme would have been even lower if it had been possible to obtain turbidity values for all rivers and include this as an extra criterion in the MCA. The turbidity concentrations at site A10 can exceed the Lebanese standard of 5 NTU significantly and peak up to 465 NTU (BTD, 2016c).

The 'environmental impact' consists of three criteria and has the least effect on the total outcome of the MCA. Site A10 scores particularly well in this theme because the MAR scheme is proposed to use the effluent of an existing hydropower plant, which makes it avoidable to build a new water abstraction dam that would impede fish migration. The design also results in a relatively little footprint of the MAR facilities and construction would take place on already developed or agricultural land of relatively low ecological value.

In the aspect of 'MAR technique' alternative A10 does not score well. The infiltration capacity would be comparatively small at 2 MCM/year, infiltrated through 5 – 6 dual purpose wells at 250 l/s over four months. The proposed ASR scheme is relatively complex in its construction and operation because deep dual purpose wells would be employed. Furthermore, full treatment of the river water is necessary including large sedimentation basins, rapid sand filtration, and chlorination.

As the MAR scheme is to be constructed close to an existing hydropower plant and in a well-developed valley, site A10 is easily accessible and most likely has an easy-to-access electricity supply for operating the water treatment plant. This results in the high rating for infrastructure.

At US$ 2,8 million implementation costs, as estimated by BTD (2016c), the project is among the three least expensive options. However, one should keep in mind that it is also designed to infiltrate only a fourth of the volume that the largest project (A9) aims at. Maintenance and operating costs are consequently also lower than most of the other alternatives, resulting in a good score for the 'costs' theme.

The project at site A10 would benefit the city of Zahle which lies only a few kilometres downstream in the Bekaa Valley. It is a growing city which plans new groundwater abstraction wells with roughly the same capacity that the proposed ASR scheme would provide. Different groups of stakeholders in Zahle and its surroundings would profit from the project. This leads to a good score in the theme 'stakeholder', further outlined in the following.

4.2 Evaluation

4.2.1 Scenarios of Different Social Priority

The theme ‘stakeholders’ is made up of three categories: The expropriation of land and the probability of strong future competition for the source water both consist of only one criterion. The third category regards the social priority of the project and is scored exemplary by three criteria for different groups of water users: Agriculture, local water users, and Syrian refugees who live in small camps spread out throughout the country. It is scored to which extent the different MAR sites cater these three stakeholder groups.

The MAR scheme at site A10, for example, would benefit the local population in the city of Zahle, but also the surrounding agriculture. The Bekaa Valley is the region with the highest density of irrigated crop fields in Lebanon. Using the karst aquifers at the valley’s sides for MAR would decrease the competition for the groundwater in the alluvial sediments of the valley plain. Furthermore, Zahle and the entire Bekaa Valley have become the temporary home for many Syrian refugees (UNHCR, 2016). They live in small camps, often depend on water supply from private tanker trucks and would profit from a more reliable public water supply. The three criteria categorized under ‘social priority’ – the large population of Zahle to profit from the MAR scheme, the large area under irrigation in the vicinity of the site, and the high density of Syrian refugee camps – lead to a good score of the ‘stakeholder’ theme of alternative A10.

Different institutions implementing or financing the MAR scheme might have different emphases on who should profit from the project. To simulate this, four different sets of weights were created to rank the alternatives: One in which all groups (local residents, irrigation agriculture, and Syrian refugees) have the same social priority, and three in which each group is weighted “extremely more important” than the remaining two. Furthermore, in these three “social priority scenarios” the categories expropriation and future competition for source water are weighted less important as in the neutral scenario. The weighting of the other criteria as well as of the seven themes was retained from the expert assessment.

It should be noted that the scores of the three criteria mentioned under social priority were obtained from different map material and could not be validated in the field. The weights are varied only to demonstrate preference biases: Different assessors prioritizing different stakeholders might come to different overall outcomes of the MCA.

When prioritizing the benefit for irrigation agriculture, instead of attributing equal weights to all three water user groups, the ranking of the alternatives changes slightly (see Figure 15). While the first three rankings remain in the same order, changes occur in the middle of the ranking and the last two positions are reversed. A16, initially scored least suitable, is located in a rural stretch of the lower Litani River surrounded by some irrigation agriculture and has changed positions with site A3 which is affected by the urban sprawl of Beirut, thus would not benefit agriculture there.

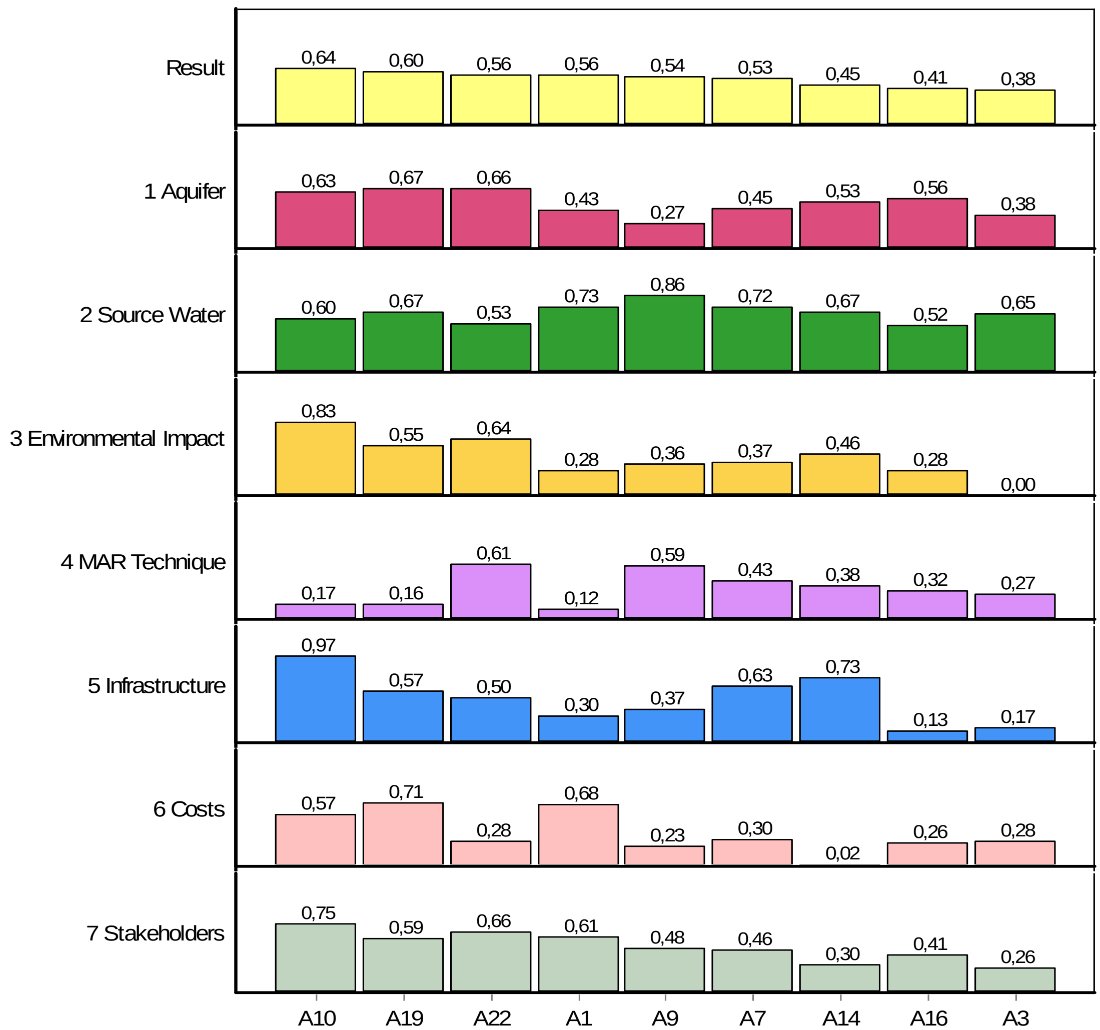

Figure 15: Site scores of a MCA with an altered weight set to prioritize agricultural water use

Comparing the impact of all four scenarios shows that A10 would always score highest (see Figure 16). The remaining order of ranks can be subject to change, depending on the scenario. Alternative A19, for example, falls from the second to the sixth rank if priority is given to supplying Syrian refugee camps (scenario 2 in Figure 16). It is located in a remote area where no refugee camps are mapped.

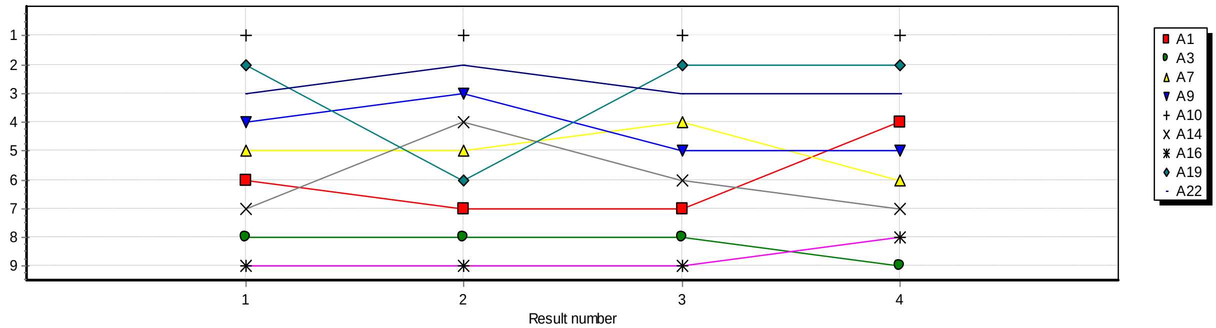

Figure 16: Comparison of rank numbers under different scenarios of social priority: 1 = equal social priority, 2 = priority for local residents, 3 = priority for Syrian refugees, 4 = priority for agriculture

Altering weights to express preferences for certain criteria might easily lead to a changed outcome of the MCA. Note that in the above presented scenarios three weights of the third and second level were altered in a MCA of 38 criteria, yet the ranking is changed. This sensitivity underlines the importance of thoroughly evaluating the MCA.

4.2.2 Sensitivity Analysis

In a sensitivity analysis the influence of changing weights and scores is evaluated systematically. In Figure 17 the influence of changed first-level weights of the theme ‘aquifer’ is visualized. While site A10 remains on the first position, changes of the other rankings occur depending on the overall weight. Site A9, for example, scores better when the hydrogeological aspects of the aquifer play only a minor role. The aquifer is directly connected to the sea, is subject to pronounced karstification, and does not provide for any confinement of the infiltrated water. It is therefore rather unsuitable for MAR from a hydrogeological perspective. The site has otherwise preferable conditions with large amounts of available infiltration water of relatively good quality, proximity of many stakeholders who would profit from the MAR scheme, and it is estimated to have a good cost efficiency.

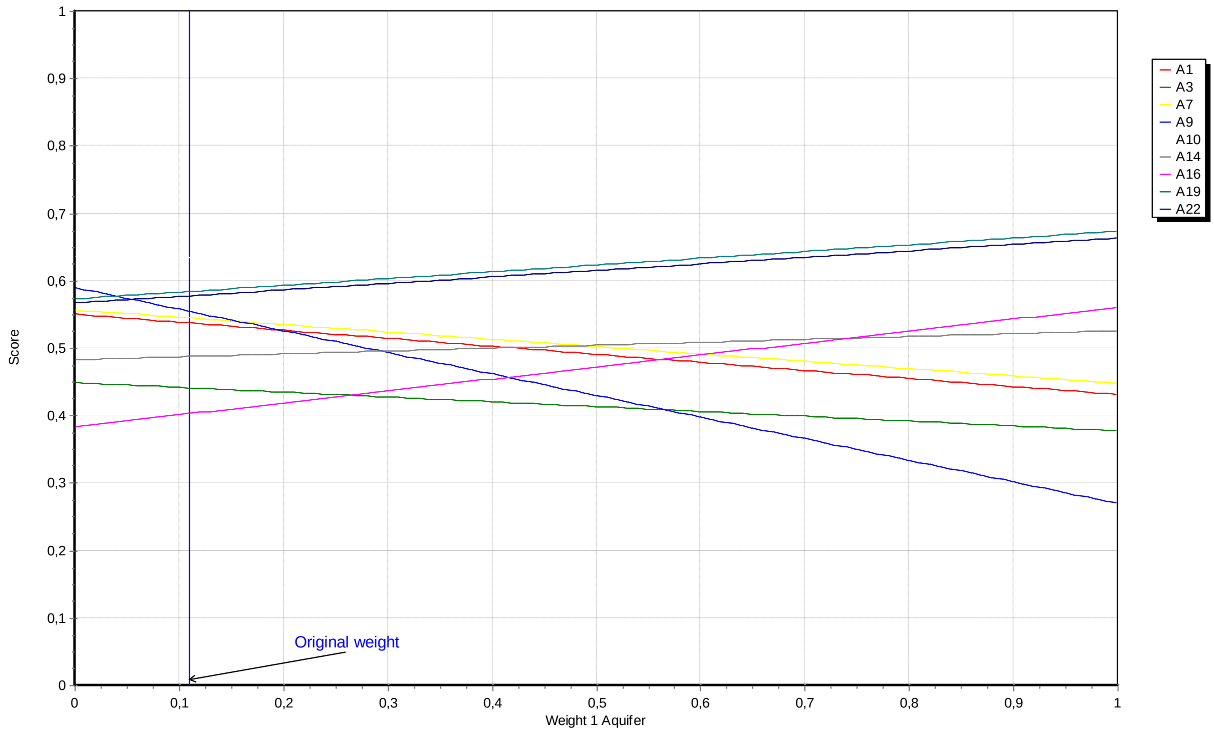

Figure 17: Sensitivity of the MCA ranking to changes in weights of the theme 'aquifer'

The DEFINITE software also allows to determine the set of weights that would lead to a specific ranking of alternatives. In order for alternative A10 to loose the first position, the themes ‘MAR technique’ and ‘aquifer’ would need to be weighted more important. The themes ‘infrastructure’, ‘environmental impact’, and ‘source water’ would need to decrease in importance.

Site A22, just as A14, was short-listed by UNICEF for a more thorough feasibility study of a MAR scheme. The project would benefit the metropolitan region of Tripoli in the north of the country. For the sensitivity analysis a set of weights was determined to put A22 at the head of the ranking (see Table 3). While alternative A22 features a more favorable Miocene limestone aquifer that is moderately karstified, it lies along the lower reaches of the polluted Abou Ali river, so that the weighting for ‘aquifer’ is increased and the weighting for ‘source water’ is decreased in order for A22 to score better than A10. Other significant changes in weights occur in ‘infrastructure’, because A22 is not as easily accessible. A22 scores better in ‘MAR technique’ as it requires less profound treatment and is designed to utilize simple gravity infiltration wells (ASTR scheme). An interesting observation is that this set of weights produces an only slightly better overall score for site A22 of 0,59 (original

Table 3: Sets of weights of original MCA and a perspective that puts A22 to first position

Theme	Weights of original MCA	Weights of “A22 to first position”
1 Aquifer	0,110	0,146
2 Source Water	0,316	0,283
3 Environmental Impact	0,046	0,030
4 MAR Technique	0,081	0,141
5 Infrastructure	0,070	0,023
6 Costs	0,116	0,107
7 Stakeholders	0,262	0,270

score: 0,58), while all other alternatives score worse than in the original MCA. The score of alternative A10 dropped from 0,64 in the original MCA to 0,58 in the scenario that forces alternative A22 to first position.

Alternative A14 on the Damour River is the most prominent in research publications discussing MAR in Lebanon. However, in this MCA there was no combination of weights found that would grant A14 the highest ranking.

4.2.3 Impact of Uncertainty

The quality of the data on which the MCA is based was accounted for by assigning score uncertainty values to the different criteria. Score uncertainties range from 10% to 30% (see Appendix V). Preference uncertainty was accounted for by applying a uniform uncertainty value of 20% to all weights. A Monte Carlo simulation resulted in the following outcome.

Figure 18 shows that the overall ranking is relatively insensitive to weight uncertainty. While there is a slight chance that some positions in the middle of the ranking change, the first and the last three positions are simulated to be always occupied by the same alternatives. There is a 36% probability of alternatives A19 and A22 swapping positions 2 and 3.

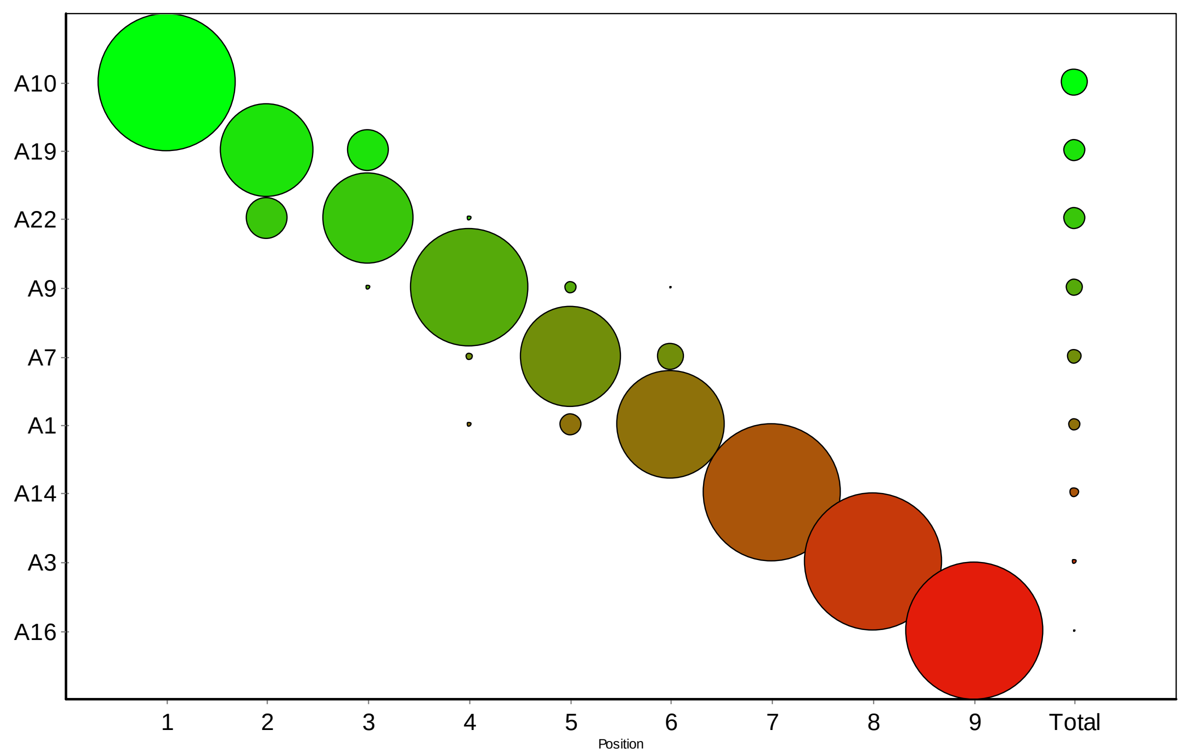

Figure 18: Influence of 20% weight uncertainty on the overall ranking of alternatives

The Monte Carlo simulations for the assigned score uncertainties result in more heterogeneous rankings. Especially positions 4, 5, and 6 are associated with some uncertainty regarding the ranking. Alternative A9, for example, was initially ranked 4th but achieves this position in only 42% of all simulations while it is ranked 5th in 45% of all simulations. This irregularity is due to the random drawing of scores from a normal distribution within the limits assigned by the uncertainty estimations.

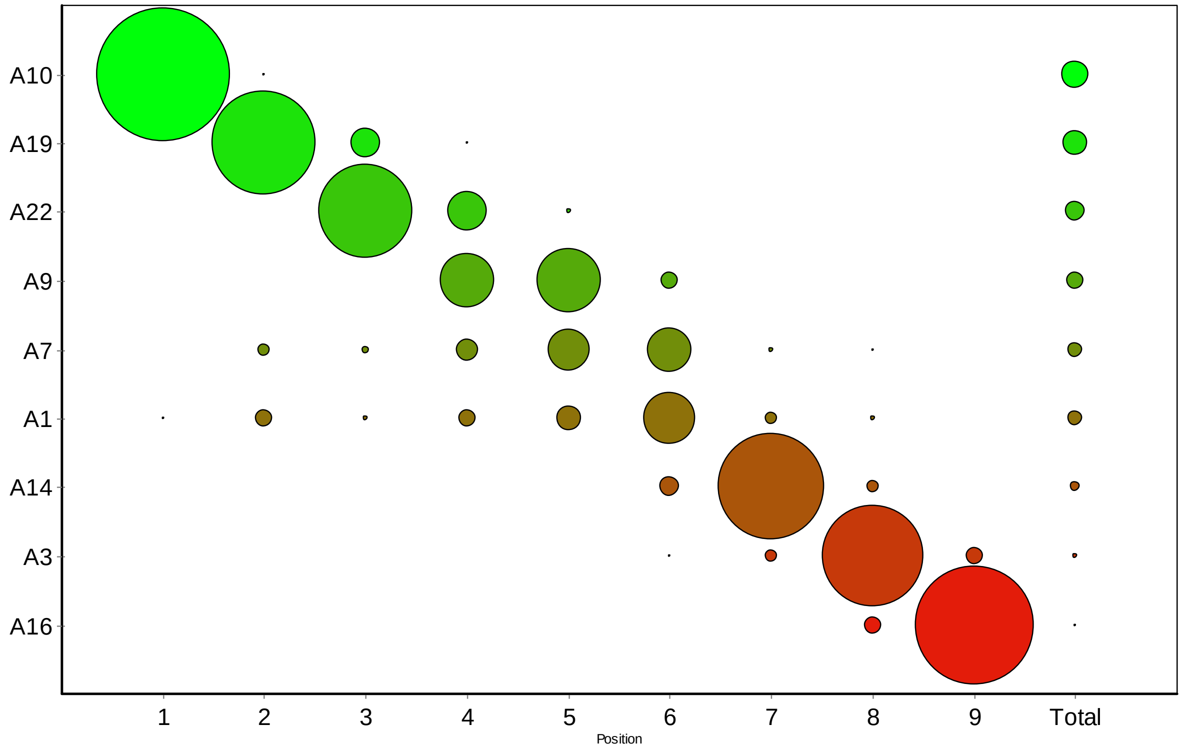

Figure 19: Influence of score uncertainty on the overall ranking of alternatives

The results of the Monte Carlo analysis show that it is crucial to not simply rely on the final rating of a MCA for decision making, but to account for data uncertainty and preference uncertainty. In this example the first and last positions are relatively insensitive to changed weights and scores in the range of the assigned uncertainty values. Alternatives in the middle of the ranking, however, show similar overall scores (see Figure 13) and are therefore more susceptible to position changes.

5 Discussion

The application of the developed framework in the Lebanese context shows its strength in systematically assessing site suitability of potential MAR sites. The criteria catalogue helps to structure the gathering of data and carrying out the multi criteria analysis proves valuable in creating an overview of the alternative sites, their strengths and weaknesses. However, some challenges of the method should be discussed.

5.1 Data Uncertainty

The easy-to-use interface of the DEFINITE software allows for thorough comparisons of the alternatives and produces informative visualizations. In this, however, there lies a certain danger of taking the entered scores at face value. The process inherently separates the data collection from the data analysis, but uncertainties noticed during data collection need to be passed on through the entire MCA process to be incorporated in the analysis of results. The perhaps most noteworthy issue of the presented framework is thus that it depends on data that it can help to disguise unreliable data as true facts, if applied incautiously. Score uncertainty should always be accounted for in the uncertainty assessment. The software allows the user to assign uncertainty values for each effect, but unfortunately not for individual scores. However, since the scores of the different sites in one criterion were derived from miscellaneous data sources, different uncertainties apply in theory. In the final MCA one combining score uncertainty value per criterion was engaged.

5.2 Limited Data Availability

In many regions of Lebanon data on groundwater is scarce and uniform nationwide data is limited to a few summarizing reports. Access to governmental groundwater databases was unfortunately not possible. Many of the developed criteria could thus not be incorporated into the final assessment (all collected data can be found in the score matrix of the digital appendix). Even criteria for which data for most of the alternatives were found could not be used, as the method requires scores for all alternatives of all incorporated criteria. The theme ‘stakeholders’ consists of only three categories, even though it is weighted as relatively important, and for the theme ‘governance’ not enough data could be collected to allow any scoring of criteria. It is suggested to focus in a next step on data collection by in-situ research and interviews with local experts.

Several authors agree that data availability is a serious dilemma in Lebanon (Metini et al., 2004; Mohammad, 2016). Especially site-specific hydrogeological data is difficult to find and some spatial extrapolation is often inevitable, which further adds to data uncertainty (Steinel et al., 2016).

5.3 Expert Estimation of Weights and Uncertainties

Criteria weighting can have a significant effect on the overall outcome of a MCA, as was outlined in Section 4.2.2. In the presented MCA weighting was based on a single expert judgement. Ideally, decision makers and stakeholders would have been involved in the assigning of weights as well. They might have priorities that differ from the scientist’s view but that will be determining in the implementation process of the MAR project.

Uncertainty values are likewise based on expert judgement. Ideally, the incorporated uncertainties would have been derived by a systematic uncertainty estimation including error propagation. This was not possible because all data were obtained from secondary sources. The inflexibility of the MCA software to account for uncertainties of individual criteria posed another challenge. However, even when assuming relatively large uncertainty margins the ranking of alternatives proved to be robust, except of some possible changes of the middle ranks.

5.4 Inherent Disadvantages of Karst for MAR

MAR seems to currently be a very popular measure for addressing water supply problems. This research was initiated from a project that aims at implementing a MAR system in Lebanon, where most aquifers are karstic. However, one should keep in mind that there is not much experience with MAR in karst and that there are inherent disadvantages of karst rooted in its pronounced heterogeneity and anisotropy. Especially with limited funds, it might be more promising to target non-karstic, alluvial aquifers for a MAR pilot in Lebanon (Groen, 2017; Klingbeil, 2017; Stuyfzand, 2017; Wiersma, 2017).

Integrated Water Resources Management should consider a wide range of measures beyond MAR to address water problems. In the case of Lebanon this could include protection of areas with high groundwater recharge potential, more surface water storages (see for example http://www.greenplan.gov.lb/), rainwater harvesting at household level, demand management, and more efficient water infrastructure (GIZ, 2016; IWMI, 2017).

5.5 Further Research

When deciding for a MAR project in karst, more data is needed for the actual design of the scheme than is gathered for the here presented method.

5.5.1 Artificial Tracer Tests

The precise flow path of the injected water is difficult to determine. However, it is essential for estimating the recoverability of the infiltrated water. Artificial tracer tests can reveal detailed insight into travel times and pathways. In Lebanon, a number of tracer tests have been carried out at different locations (an overview of the studies is given in UNDP (2014)). In these studies a tracer is injected into a surface karst feature, such as a sinkhole, with the aim to find connections with natural springs and to determine the fastest velocity. This allows determining vulnerable areas of groundwater catchments (Doummar & Hamdan, 2016). For designing a MAR scheme it is more important to find out what portion of the infiltrated water travels at slow velocities and whether this is dependent on the infiltration rate or groundwater level. It is also of interest where the infiltrated water migrates to underground, and where, consequently, a good location for abstraction would be. Carrying out tracer tests at the targeted MAR site with the objective of finding slow flow pathways and determining the portion of infiltrated water that flows at sufficiently low velocities could be valuable in assessing the project’s feasibility.

5.5.2 Radon Analysis

Radon measurements as a method to quantify the responsiveness of karst was considered during the research but then omitted due to resources and time limitations. Radon is a radioactive noble gas that occurs in the environment. As radon in water does not react with other gases and does not sorb onto soil grains it is fairly stable, except from its radioactive decay with a half-life time of 3,8 days. The fact that concentrations of radon in soil are much higher than in limestone could be used to determine when the analyzed groundwater has infiltrated into the aquifer (Baskaran, 2016). Savoy, Surbeck, and Hunkeler (2011) were able to determine whether groundwater in a cave infiltrated within the past 25 days or whether it had been in the karst for longer. A similar study was carried out by Falcone et al. (2008). Analyzing radon concentrations of karst springs in Lebanon could be a valuable method for quantitatively comparing the responsive characters of different groundwater basins.

5.5.3 Effect of Acidic Infiltration Water

Infiltrating slightly acidic water into carbonate aquifers will result in some solution of CaCO3. In the scope of this research it could not be concluded whether infiltrating considerable amounts of surface water over a 20 – 30 year period would cause dangerous instability of the underground. It would be interesting to carry out comprehensive hydrochemical modelling and determine whether the dissolution process would have consequences for engineering.

6 Conclusion

The presented framework proved to be a valuable tool for comparing locations in karst regions with respect to their suitability for MAR. The criteria catalogue, developed on the basis of a thorough literature review and valuable expert interviews, facilitated the collection of data by focussing the research on subjects deemed most important while making it simple to organizing data of various formats.

The framework was applied to compare nine pre-selected potential project sites in Lebanon with regards to their suitability for MAR. Site A10 on the Berdouni River in the Bekaa Valley scored best. Its advantages are: An indication of some hydrogeological confinement, acceptable source water conditions, good infrastructure, relatively low costs, and a wide range of stakeholders to potentially profit from the project. To demonstrate preference biases, weights of three criteria were changed to simulate different social priorities. The ranking's sensitivity to the changed weights was analysed. Uncertainty in the ranking of alternatives was assessed systematically by applying uncertainty values to scores and weights. Monte Carlo simulations for weights and scores within the uncertainty margins support the robustness of the overall ranking.

This research focuses on MAR with deep well infiltration, as this technique promises high recharge rates while having a relatively small footprint, which is favorable in a densely populated country like Lebanon. Using existing wells should be considered for carrying out a MAR pilot, as this saves drilling costs and ensures connection the water-bearing system of voids. Nevertheless, other techniques, especially small-scale, should also be considered in the Lebanese context.

Managed Aquifer Recharge in karstic aquifers faces many challenges. Limited storage capacity, pronounced heterogeneity, and high transmissivity along conduits imply considerable uncertainty regarding the recoverability of infiltrated water. The large voids that make up the groundwater storage space in karst have little purification potential. Infiltration water must therefore be of good quality, especially if the later abstracted water is intended for drinking water use. In the example of Lebanon, rivers and springs were considered as recharge water sources. In all considered cases pre-treatment would be necessary, especially to reduce bacterial contamination and turbidity. While the hydrogeological circumstances in Lebanon pose significant challenges for implementing a MAR project, even bigger problems could be issues of governance and financing. MAR is an unfamiliar technique in Lebanon and large dams are still seen as the primary solution to the country’s water problems. The fact that in Lebanon there is no pilot MAR scheme to showcase its potential makes funding difficult. Corruption might impede implementation and some potential MAR sites have to be suspended because of political instability.

Given the numerous challenges which large-scale MAR projects are likely to encounter in Lebanon it might seem promising to focus on other water management interventions. However, the reality is that large volumes of water flow unused into the ocean during the winter and that storing a fraction of these discharges has great potential for improving the country’s water supply. To quantify this potential, and to contribute to the global experience with MAR in karst, a well-designed MAR pilot project in Lebanon would be desirable. The presented site suitability assessment framework could be valuable in the planning process.

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Appendices

Appendix I: Table of Criteria

Category	Applies to	Number	Criterion	Unit or scale	Standardization	Comment on Objective	Lebanon MCA
1 Aquifer							
1.1 Level of aquifer stress	ASR, ASTR	1.1.1	Anthropogenic abstraction	mm/a	max - bc	Annually abstracted water volume per groundwater basin area	✓
		1.1.2	Abstraction-infiltration ratio	- (mm/mm)	max - bc	Anthropogenic abstraction / natural recharge of aquifer	✓
		1.1.3	Groundwater budget	mm/a	max - cc	If the recharge of a groundwater basin is smaller than the discharge from it, there is water stress	
		1.1.4	Decrease of gw levels	m/a	max - bc	Decrease of observed mean gw levels in wells across the entire aquifer	
		1.1.5	Increase of salinity	g/l/a or mS/cm/a	max - bc	Average annual increase of salt concentrations in gw	
1.2 Depth to GW table	ASR, ASTR	1.2.1	Piezometric head	m bgl	goal; max - bc	With a minimum of 6 m and a ceiling at 50 m bgl	
		1.2.2	Depth to bottom of aquifer	m bgl	goal; max - bc	In case piezometric head data is not available	
1.3 Aquifer size	ASR, ASTR	1.3.1	Aquifer storage capacity	km^3	goal; max - bc	Area x thickness x effective porosity	✓
1.4 GW flow	ASR, ASTR	1.4.1	Groundwater gradient	-	max - cc	Should be as little as possible, with a maximum of 0.005 for ASR	
		1.4.2	Groundwater flow velocity	m/day	max - cc	Velocities estimated in tracer tests represent quick flow	✓
		1.4.3	General direction of GW flow	° of deviation	max - cc	The regional orientation of groundwater flow should be from injection towards abstraction point	

		1.4.4	Preferential flow paths along faults	ordinal		Potential influence of primary and secondary faults. Differentiate between filled and opened faults, if possible.	✓
1.5 Retention times	ASTR	1.5.1	Travel time to abstraction point	days	goal; max - bc	Groundwater velocity / injection-abstraction distance. Longer storage is better, but legal min residence times should be respected	
1.6 Confinement of the aquifer	ASR, ASTR	1.6.1	Overlaying aquitard	ordinal		In densely populated areas an overlying aquitard can decrease the contamination risk	
		1.6.2	Lateral confinement	ordinal		Confinement by vertical geological barriers	✓
		1.6.3	Inclination of the aquifer	ordinal		Horizontal orientation is usually preferred. However, extreme inclination might create an underground reservoir	
	ASR	1.6.4	Connection to sea	ordinal		Estimated probability that injected water is lost to the sea	✓
1.7 Aquifer productivity	ASR, ASTR	1.7.1	Achieved abstraction capacity	well count or total productio n rate	max - bc	To be estimated as pumped volumes or productive wells in the vicinity of the site	
1.8 Surface karst features	ASTR	1.8.1	Possibility of infiltration without wells	ordinal		Suitability of karst feature (sinkhole or large fissure) that could be used as injection hole instead of well	
1.9 Groundwate r salinity	ASR, ASTR	1.9.1	Salt concentrations of ambient gw	mgCl/L or mS/cm	goal; max - cc	Upper threshold, depending on mixing within the aquifer, water use, and source water salinity	

		1.9.2	Samples exceeding the salinity standard	%	max - cc	Percentage of sampled wells in a aquifer that show salt concentrations beyond drinking water standards	
1.10 Geochemical issues	ASR, ASTR	1.10.1	Pyrite concentrations in the aquifer	%	goal; max - cc	A constraining threshold value should be determined	
		1.10.2	Gypsum concentrations in the aquifer	%	goal; max - cc	Less is better, especially if intended for drinking water	
1.11 Lithotype	ASR, ASTR	1.11.1	Clay content	%	max - cc	should be <35% (marlstone), closer to 5% (limestone)	
1.12 Hydraulic properties	ASR, ASTR	1.12.1	Aquifer Transmissivity	ordinal or m^2/day	max - bc / max - cc	should be >100 m^2/day, ideally 1000 - 4000 m^2/day but not >4000 m^2/day	
		1.12.2	Theoretical injection rate	m^3/day	max - bc	Transmissivity value and piezometric head are needed (Logan's approximation). 50 l/s = 4300 m^3/d per well deemed feasible by various authors	✓
1.13 Fluctuations of gw levels	ASR, ASTR	1.13.1	Intra-seasonal fluctuations	- or ordinal	max - cc		
		1.13.2	Correlation with tides in coastal aquifers	ordinal			
1.14 Degree of karstification	ASR, ASTR	**General Karstification Analysis**					
		1.14.1	Local expert assessment	ordinal		Assessment of hydrogeologists with in-depth knowledge of the local karst system	
		1.14.2	Geological description	ordinal		Expert assessment of the karstification of the aquifer and its suitability for MAR based on the geological description of the stratigraphy. Assessment per geological layer.	✓

		1.14.3	Karst age	ordinal		If karst age can be associated with period of karstification and degree of karstification	
		1.14.4	Platform vs. Geosyncline karst	ordinal		ASR more promising in platform karst, in geosyncline karst ASTR is more preferred	
		1.14.5	Influence of tectonic faults	ordinal		Exaggerated karstification in the area of primary faults can be expected. Assess on regional level.	
		Karst Feature Assessment					
		1.14.6	Density of surface karst features	features/ km² or ordinal	max - cc	High karst exposure (sign of unsuitability for MAR), moderate karst exposure (more favorable), and restricted karst exposure (favorable if at least some dissolution has taken place)	✓
		1.14.7	Number of springs	-	max - cc	Presence of numerous springs in the vicinity of the planned MAR scheme and that discharge from the targeted aquifer indicate unsuitable hydrogeological conditions	✓
		1.14.8	Presence of caves	ordinal		2D or 3D cave network: confined flow (least suitable); small, rare, irregular caves: Diffuse flow (most suitable)	✓
		Fracture Properties					
		1.14.9	Fracture porosity	- (m/m)	goal; max - bc	Product of fracture frequency and aperture. Small apertures are preferred while the overall fracture porosity should not be too small.	

		1.14.10	Fracture persistence	ordinal		Interconnectivity of fractures should be moderate to strong	
		Spring Hydrograph Analysis					
		1.14.11	Degree of Karstification (d.o.k.)	d.o.k.	goal; max - bc	D.o.k. estimated according to Malík and Vojtková (2012). Based on recession coefficients. Least suitable: d.o.k. = 0,5 & 10, most suitable: d.o.k. = 5	
		1.14.12	Summed recession coefficients	-	max - cc	Regression coefficients of quick flow (a1) and base flow (a2), summed	✓
		1.14.13	Ratio of base flow to total flow	-	max - bc	flat graph more suitable than pointy graph	✓
		1.14.14	Hydrograph shape categories	ordinal		A long memory effect, represented by a flatter hydrograph, is preferred	
		1.14.15	Chemigraphy Analysis	ordinal		No mixing (less suitable) vs full mixing (suitable)	
		Catchment Drainage Analysis					
		1.14.16	Drainage density	km/km²	max - cc	Best suitability between 1 and 3 km/km²	✓
		1.14.17	Lag time of storm runoff	days	max - bc	Longer lag time indicates slower hydrogeological processes (if rivers have similar length and slopes) which is favorable for MAR	
2 Source Water							
2.1 Water quality	ASR, ASTR	2.1.1	Turbidity	NTU or TSS (mg/l)	goal; max - cc	Nephelometric Turbidity Unit (NTU) roughly equivalent to Formazin turbidity unit (FTU) and Jackson turbidity unit (JTU)) or concentration of Total Suspended Solids (TSS)	
		2.1.2	Organic material	TOC (mg/l) or BOD5 (mg/l)	goal; max - cc	Concentration of total organic carbon (TOC) or biochemical oxygen demand (BOD5)	✓

		2.1.3	Bacterial contamination	MPN or CFU	goal; max - cc	Bacterial contamination approximated by E.coli or total coliforms counted as colony forming units (CFU) or	✓
		2.1.4	Salinity	mS/cm or mgCl/l	goal; max - cc		✓
		2.1.5	Nitrate Concentration	mg/l	goal; max - cc	To be measured during infiltration season. Values of <50 mg/l are unproblematic	✓
		2.1.6	Acidity	pH	goal; max - cc	Potential of hydrogen (pH) should be basic (around 7) to not dissolve too much CaCO3 or to cause precipitation due to degassing	✓
		2.1.7	Chemical Contamination	ordinal		Presence of chemical contamination (heavy metals, industrial waste, pesticides, …) beyond drinking water standards	
		2.1.8	Potential contamination point sources	ordinal		Estimated impact of potential contamination point sources upstream of water in-take	
2.2 Available quantity	ASR, ASTR	2.2.1	Duration of sufficient discharge	e.g. months	max - bc	If source water is abstracted from river months with avg Q of >5 m^3/s is suggested by UNDP (2014)	✓
		2.2.2	Available infiltration volume	MCM/a	max - bc	Annual discharge of the water source (e.g. cumulative river discharge)	✓
2.3 Reliability of water availability	ASR, ASTR	2.3.1	Development of source water discharges	-	max - bc	Ratio of past observed source water discharge to present rates. Values of >1 indicate an increase	✓

		2.3.2	Impact of climate change	ordinal		Comparison of anticipated available water quantity under climate change scenario to currently available quantity	
2.4 Distance source – injection point	ASR, ASTR	2.4.1	Distance from water source to injection point	m or ordinal	max - cc	Transmission above ground is costly	
		2.4.2	Elevation difference to injection point	m or ordinal	max - cc	Pumping is to be avoided	
2.5 Downstream use of source water	ASR, ASTR	2.5.1	Impact of water abstraction on downstream uses	ordinal		Comparative assessment. Impact can be positive if flood risk is reduced by MAR and negative if ecosystems are negatively affected by the abstraction.	
3 Environmental Impact							
3.1 Footprint of MAR facilities	ASR, ASTR	3.1.1	Dimensions of facilities to be constructed	ordinal			✓
		3.1.2	Footprint on ecologically valuable land	m²	max - cc		
		3.1.3	Footprint on undeveloped land	m²	max - cc		
		3.1.4	Footprint on developed land	m²	max - cc		
3.2 Impact of water abstraction	ASR, ASTR	3.2.1	Fish passability	ordinal		Only if the river is a natural fish habitat	✓
		3.2.2	Endangered Species	yes/no	max - cc	Presence of endangered species in the source water?	
		3.2.3	Flexible abstraction rate	yes/no	max - bc	Abstraction rate dependent on actual river discharge?	
3.3 Impact on surface water quality	ASR, ASTR	3.3.1	Discharge of treatment plant effluent	yes/no	max - cc	Discharge of contaminated treatment plant effluent back into the river?	✓
3.4 CO_2 emissions	ASR, ASTR	3.4.1	Amount of concrete to be used	tons	max - cc		
		3.4.2	Energy required for drilling	Joules or hours of drilling	max - cc		
		3.4.3	Fuel-intensive	ordinal	max - cc		

			transportation				
		3.4.4	Energy requirement for operation	Joules, kWh/a, or L diesel/h	max - cc		
4 MAR Technique							
4.1 Recharge capacity	ASR, ASTR	4.1.1	Recharge volume	MCM/a	max - bc		✓
		4.1.2	Infiltration rate	l/s	max - bc		
	ASR	4.1.3	Recharge efficiency	- (m^3 abstracted / m^3 injected)	max - bc	Can only be estimated in sufficiently homogeneous aquifers	
4.2 Water treatment	ASR, ASTR	4.2.1	Complexity of required purification	ordinal		no treatment (best), primary treatment (sedimentation, sand filtration), chlorination, secondary treatment (biological), RO (worst)	✓
4.3 Complexity of MAR technology	ASR, ASTR	4.3.1	Capacity of local contractors	ordinal			✓
		4.3.2	Complexity of operation	ordinal			✓
		4.3.3	Complexity of maintenance	ordinal			
4.4 Clogging	ASR, ASTR	4.4.1	Time until physical clogging	years or ordinal	max - bc		
		4.4.2	Biological and chemical clogging	ordinal			
4.5 Expected lifetime	ASR, ASTR	4.5.1	Time until technology failure	years	max - bc		
4.6 Vandalism-proof	ASR, ASTR	4.6.1	Visibility of valuable parts	ordinal		only if socio-economic context gives reason to account for vandalism or theft	
		4.6.2	Surveillance	ordinal			
		4.6.3	Sturdiness of MAR facilities	ordinal			
5 Infrastructure							
5.1 Accessibility	ASR, ASTR	5.1.1	Accessibility for heavy machinery	ordinal			✓
5.2 Existing infiltration wells	ASR, ASTR	5.2.1	Presence of usable injection borehole	m or ordinal	max - cc	Existing dry wells or low-yield wells that used to be productive should be used for infiltration.	
5.3 Existing production wells	ASTR	5.3.1	Capacity of Public Abstraction Wells	m^3/s or ordinal	max - bc	Existing public groundwater production wells at a suitable distance from the infiltration point are favorable	
5.4 Energy supply for	ASR, ASTR	5.4.1	Proximity to electricity lines	m	max - cc	Applies only if energy is needed for operation	✓

operation		5.4.2	Reliability of power supply	ordinal		(water treatment or pumping)	
5.5 Elevation energy	ASR, ASTR	5.5.1	Elevation difference from abstraction point to consumers	m	max - cc	MAR schemes should be constructed close to the water consumers to minimize pumping costs	
		5.5.2	Required pumping energy	kWh/m³	max - cc		
6 Costs							
6.1 Implementation costs	ASR, ASTR	6.1.1	Land for MAR facilities	US$	max - cc		✓
		6.1.2	Construction	US$	max - cc		
		6.1.3	Drilling	US$	max - cc		
6.2 Maintenance costs	ASR, ASTR	6.2.1	Spare parts	US$/year	max - cc		✓
		6.2.2	Maintenance personnel	US$/year	max - cc		
		6.2.3	Anti-clogging measures	US$/year	max - cc		
6.3 Operating costs	ASR, ASTR	6.3.1	Pumping costs	US$/year	max - cc		✓
		6.3.2	Treatment operations	US$/year	max - cc		
		6.3.3	Monitoring and administration	US$/year	max - cc		
6.4 Cost-efficiency	ASR, ASTR	6.4.1	Ratio of total cost to total infiltration capacity	US$/m³	max - cc		
6.5 Reversibility	ASR, ASTR	6.5.1	Cost of deconstruction and well-sealing	US$	max - cc		
6.6 Availability of funding	ASR, ASTR	6.6.1	Funding for regional development	ordinal or US$	max - bc		
		6.6.2	Ethnical or socio-economic support	ordinal or US$	max - bc		
		6.6.3	Climate change mitigation funds	ordinal or US$	max - bc		
		6.6.4	Research funds	ordinal or US$	max - bc		
6.7 Cost recovery	ASR, ASTR	6.7.1	Financing by water users	ordinal or US$	max - bc		
7 Stakeholders							
7.1 Future competition for source water	ASR, ASTR	7.1.1	Planned water infrastructure projects	ordinal			✓
7.2 Stakeholder buy-in	ASR, ASTR	7.2.1	Holders of water rights	ordinal			
		7.2.2	Stakeholders upstream	ordinal			
		7.2.3	Stakeholders downstream	ordinal			
		7.2.4	Landowners	ordinal			
		7.2.5	Facility owners	ordinal			

		7.2.6	Environmental Protection Organizations	ordinal			
7.3 Expropriation	ASR, ASTR	7.3.1	Area of land to be expropriated	m²	max - cc		✓
7.4 Public acceptance	ASR, ASTR	7.4.1	Public perception of the project	ordinal			
		7.4.2	Public understanding of local GW stress	ordinal			
		7.4.3	Perception of current water supply	ordinal			
		7.4.4	Acceptance of infrastructure/water projects	ordinal			
		7.4.5	Stigma of water source	ordinal			
7.5 Social priority	ASR, ASTR	7.5.1	Number of people to directly profit from the MAR project	-	max - bc		
		7.5.2	Allocation for priority water users	ordinal		Rate how much the MAR will profit the targeted water users (e.g. agriculture, urban residents, industry, refugees)	✓
8 Governance							
8.1 Inter-agency issues	ASR, ASTR	8.1.1	Involved authorities	-	max - cc	Number of authorities involved in the project	
		8.1.2	Local vs national authorities	ordinal		Potential of conflict arising from local vs national authorities	
		8.1.3	Water authorities vs other authorities	ordinal		Potential of conflict arising from involved water authorities vs other authorities	
8.2 Source water rights	ASR, ASTR	8.2.1	Existing water abstraction rights	- or ordinal	max - cc	Number of abstraction permits, permitted abstraction rate, or qualitative assessment	
8.3 Ownership	ASR, ASTR	8.3.1	Reliability of profit	ordinal		In case of commercial operation	
		8.3.2	Strength of accountability / public control	ordinal			
		8.3.3	Owner's ability to do maintenance	ordinal			
		8.3.4	Acceptance of owner by local stakeholders	ordinal			

8.4 Trans-border issues	ASR, ASTR	8.4.1	Flow across borders	yes/no	binary (max) - cc		
		8.4.2	Issues with downstream countries	ordinal		Is the abstraction from water source likely to cause problems with downstream nations?	
8.5 Political instability	ASR, ASTR	8.5.1	Regional conflicts	ordinal			
		8.5.2	Local ethnical conflicts	ordinal			
		8.5.3	Corruption	ordinal			

Appendix II: Criteria Catalogue

1 Aquifer

The following criteria refer to the geological and hydrogeological characteristics of the karstic aquifer which is to be recharged as well as to groundwater conditions. Criteria are grouped into categories (1.1 – 1.14).

1.1 Level of Aquifer Stress

As a MAR project usually aims at mitigating groundwater shortages a project site should be chosen where the positive effect on the groundwater situation is relatively large. Therefore, aquifers that are under stress should be prioritized. Aquifer stress is characterized by decreasing groundwater levels and/or increasing salinity. The criteria are formulated as benefit criteria, indicating that higher levels of aquifer stress increase the suitability of the corresponding site for a MAR project.

1.1.1 Anthropogenic Abstraction

The annual volume of groundwater abstracted by humans divided by the area of the groundwater basin yields the anthropogenic abstraction depth. Data on the abstracted volumes can be obtained from monitored wells or approximated by estimated water consumption of the population, agriculture, and industry that is supplied by the aquifer.

1.1.2 Abstraction-Infiltration Ratio

The anthropogenic abstraction depth (criterion 1.1.1) is divided by the estimated natural recharge of the aquifer. This approach recognizes the fact that high abstraction rates not necessarily lead to depletion of an aquifer if the natural replenishment of the groundwater is sufficient. Estimating natural recharge rates can be require much data, but often studies are available that already have quantified recharge for a region, different land-use types, or specific aquifers. (For Lebanon see for example (Daher, 2011; Khawlie et al., 2002; Metini et al., 2004). However, as natural discharge from the aquifer is not taken into account, this criterion has limited significance for estimating the actual aquifer stress. An aquifer that gets much recharge but also discharges a large portion of it to other aquifers might be over-exploited rather quickly. The criterion should therefore be used in combination with other aquifer stress criteria to rank the alternatives with respect to aquifer stress.

1.1.3 Groundwater Budget

The groundwater budget is calculated by subtracting an groundwater basins' discharge (groundwater usage for irrigation, domestic, industrial and tourist use, losses to the sea or other aquifers, and natural discharge of springs) from its recharge (infiltration from rainfall, snowmelt, irrigation return flows, water supply networks, and leaky sewage systems, as well as gains from other aquifers) (UNDP, 2014). A negative groundwater balance indicates an over-abstraction of the aquifer. Even though this is a relatively holistic approach to assessing aquifer stress it often shows little practicality as many of the required variables are difficult to measure. The groundwater balances estimated for the groundwater basins of Lebanon are associated with too large uncertainty to include in the MCA.

1.1.4 Decrease of Groundwater Levels

A sound way to approximate the level of aquifer stress is to analyse the development of groundwater levels observed in wells all over the aquifer. For each well the change in groundwater level over time can be calculated and an average increase or decrease can be expressed in meter change per year. Sufficient groundwater level records over a significant period (>10 years) must be available.

1.1.5 Increase of Salinity

Increasing salt concentration threaten groundwater supplies especially in coastal regions where abstracted volumes of fresh groundwater are replaced by seawater. Here, groundwater levels might not actually fall because even if drastic over-exploitation occurs. In these cases a good criterion for the increase of aquifer stress is the change in salt concentrations measured in the aquifer over a number of years. The increase of salinity levels can be express in grams per litre per year (g/l/a) or as change of electric conductivity per year (mS/cm/a).

1.2 Depth to Groundwater Table

1.2.1 Piezometric Head

Measured as the distance between the ground surface and the piezomatric head in a well at or close to the MAR site this criterion is important for possible infiltration rates, prevention of surface flooding due to a too short well shaft for the built-up of infiltration water, and an indicator for sites that would cause high pumping costs in case of a ASR scheme. The groundwater level should be determined as the highest observed piezometric head during the planned infiltration season (wet season). Based on the findings of Chowdhury et al. (2010) and Steinel et al. (2016) it is suggested as a benefit criterion with a minimum of 6 m and a maximum ceiling of 50 m: Sites with groundwater depths of less than 6 m are scored least suitable while sites with 50 m groundwater depth are scored most suitable. Particularly deep groundwater table (>150 m) should be excluded if an ASR scheme is planned.

1.2.2 Depth to Bottom of Aquifer

If data on piezometric heads are not available, the depth to the bottom of an aquifer might be a viable surrogate criterion. Often, karstification is strongest in the lower parts of a geological layer which suggests that most of the aquifer's water is stored here. A MAR scheme should always target to replenish an aquifer in the lower water-bearing parts in order to not activate previously dry regions as this might lead to unforeseen groundwater flows (BTD, 2016c).

1.3 Aquifer Size

1.3.1 Aquifer Storage Capacity

The volume of an aquifer, together with its porosity, determines its total storage capacity. This criterion is used to make sure that no aquifers are selected that cannot store the planned recharge volumes. Usually, the storage capacity is not an issue since the selected aquifers are over-exploited. Therefore, a rough-and-ready calculation of the aquifer volume is sufficient to ensure the aquifer size is large enough. The estimated surface area of the aquifer can be multiplied with its average thickness and with the approximate effective porosity (km^2*km* %).

Milanovic (2004) calculated the effective porosity of carbonate karst to be in the range of 1,4 – 3,5%. Even though the actual range of effective porosity might be larger (Singhal & Gupta, 2010), it is practical to assume an effective porosity of 1 % for this criterion.

For Lebanon, infiltration rates of 50 l/s per well are deemed feasible and often a recharge period of four months is assumed (BTD, 2016a). The annual infiltration volume for one well is thus around 0,5 MCM. To accommodate this volume an aquifer volume of 0,05 km³ with a porosity of 1% would be necessary. To be on the safe side, a minimum aquifer volume of 1 km³ is proposed and linear benefit standardization is applied with a maximum at 50 km³. The aquifers considered in the Lebanon MCA are all larger than 30 km³.

1.4 Groundwater Flow

1.4.1 Groundwater Gradient

The slope of the groundwater table, or the groundwater gradient, can be an easily obtainable proxy for estimating how quick groundwater flows. It can be derived from groundwater levels observed in wells in the area of the planned MAR project. In his decision framework for planning ASR project Brown (2005) suggests a maximum gradient of 0,0005 for ASR schemes, to ensure limited mixing with ambient groundwater and a high enough recovery efficiency. However, the heterogeneity of karst and the often large influence of conduits lead to the observation that variations in piezometric heads tend to be small while variations in velocities and travel times tend to be large (Maliva, 2016). This criterion should therefore be carefully interpreted and weighted correspondingly.

1.4.2 Groundwater Flow Velocity

Velocities of groundwater flow tend to be very variable in karst and it is generally difficult to quantify this. Often, artificial tracer tests in region or even in the targeted aquifer have been carried out (for an overview of studies done in Lebanon see UNDP (2014)). These tests usually aim at finding connections of two surface points (e.g. a sinkhole and a spring) by underground passages. The estimated travel time is that of quick flow through conduits distinctive for the specific research site and cannot easily be extrapolated to the entire aquifer (Katsanou, Lambrakis, D'Alessandro, & Siavalas, 2016). However, tracer tests carried out in different aquifers can provide valuable insight into the functioning of the groundwater system and they highlight differences in extreme values of the groundwater basins. For the Lebanon MCA averaged quick flow velocities observed during tracer tests carried out in different groundwater basins were used to compare the plausible MAR sites. Groundwater flow velocity is a cost criterion; lower values are preferred.

1.4.3 General Direction of Groundwater Flow

Often, the regional pattern of groundwater flow is known. The general flow direction, the direction to which the groundwater gradient is oriented, can serve as a rough proxy for whether the infiltrated water will end up at the abstraction point or whether the deviation towards another direction is rather large. Since the regional behaviour of groundwater does not necessarily correspond to the local groundwater flow at the MAR site this criterion should not be given too much weight, but it can help in the overall assessment. Scoring can be done on an ordinal scale or quantified as ° deviation from the targeted direction.

1.4.4 Preferential Flow Path along Faults

In highly karstified aquifers much of the groundwater flows along preferential pathways, through conduits that have developed through the solution of calcium carbonate. Conduits often develop in a positive feedback process along primary or secondary faults where surface water can infiltrate easily. These geological discontinuities are often mapped. In a comparative method the potential influence of secondary faults that are located in the area of the proposed MAR projects can be assessed on an ordinal scale. The assessment should be done with respect to the number of faults thought to possibly influence the MAR project, their lengths, and orientation.

However, faults not necessarily have to be preferential pathways. On the contrary, they can develop into aquicludes if they are smeared with e.g. marls (Wiersma, 2017). If the information is available, the differentiation between open and filled faults should be made.

1.5 Residence Time

1.5.1 Travel Time to Abstraction Point

If the MAR site has been thoroughly researched reliable information about travel velocities of infiltration water might be available. The velocity can be set to relation of the distance from injection to abstraction site to yield the travel time, or retention time. This is an important measure for assessing the feasibility of an ASTR scheme. The objective function for rating the site-suitability with respect to this criterion needs to be fit to the local context. In Lebanon, the objective of a MAR project is to store surface water in the winter for use in the dry summer. The aquifer should therefore be able to retain the infiltration water for at least half a year. In other circumstances this objective might be different. Often a legal minimum of residence time (e.g. 60 days) applies. An ASTR scheme should be designed in such a way that the legal minimum is guaranteed by spacing infiltration and abstraction point far enough.

While this criterion might seem like a crucial prerequisite for designing any MAR system, it is very difficult to reliably quantify in karst. The complicated hydrogeology of karst aquifers will always imply some uncertainty, especially in overall groundwater velocities. If, however, comprehensive tracer tests at the planned injection site have been carried out and reliable travel times to the abstraction point were determined this criterion may be very important to the MCA and should be weighted accordingly.

1.6 Confinement of the Aquifer

1.6.1 Overlaying Aquitard

Groundwater contamination by anthropogenic pollution that seeps from the ground surface down to the aquifer is a problem which is particularly pronounced in karst regions, as the high infiltration rates provide for very little natural attenuation of the contamination (Bakalowicz et al., 2008). In areas with high population density, or where groundwater contamination is expected due to industry or intensive agriculture, it might therefore be preferable to choose aquifers for a MAR project that are protected by an overlaying aquitard (or aquiclude). This criterion should then be rated with respect to the extent of the aquitard compared to the aquifer and its retarding effect (vertical conductivity).

1.6.2 Lateral Confinement

Lateral confinement can be essential for a successful MAR project in high-permeability karst. Vertical barriers can have a positive effect by blocking off groundwater flow or steering it towards the targeted abstraction point. Natural geological barriers can be formed by faults or fissures that are filled (smeared) with marl or other low-permeability material (Wiersma, 2017). Faults can also create barriers by uplifting of an underlying aquiclude which then blocks groundwater flow in the lower parts of the aquifer (Singhal & Gupta, 2010). In Figure 20 examples (a) and (b) show displaced aquifers that are in consequence truncated at the fault line. Truncation of an aquifer may also lead to seepage or creation of springs along the fault (c). Intensive erosion of the uplifted block may also lead to the aggregation of erosion material that can form a good unconfined aquifer (d).

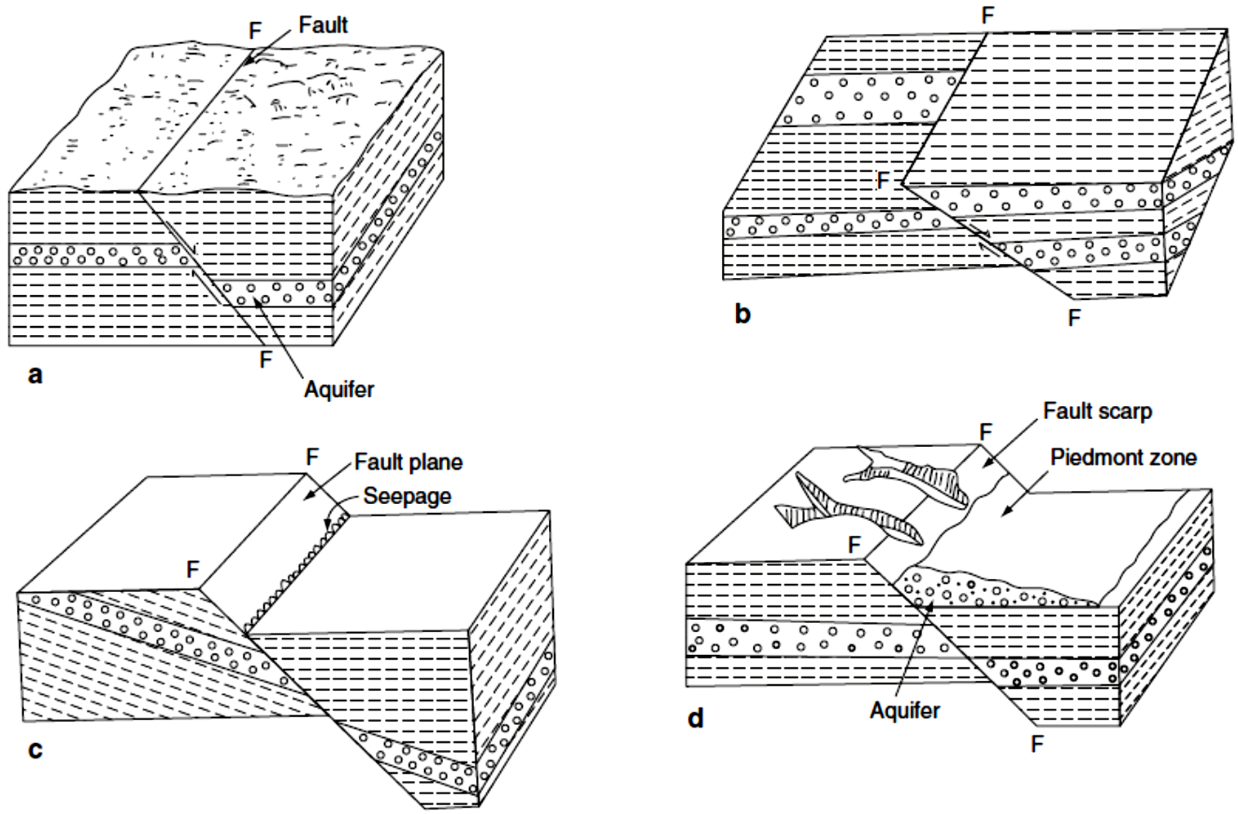


Figure 20: Effects of faults on aquifers (selection) (Singhal & Gupta, 2010)

Rating of this criterion should be done on an ordinal scale and a good geological understanding of the studied sites is needed to sufficiently take into account all factors. Sketches of cross sections of the regions stratigraphy as well as geological maps showing faults, outcropping layers, and springs can form the basis of this assessment. The lateral confinement of a targeted aquifer by truncation by faults is to be rated positively only if the aquifer is confined. Then, the characteristics of the faults should be carefully analysed: The orientation of the fault should be beneficial to the design of the MAR scheme; ideally it should of block off groundwater flow (orientation perpendicular to groundwater flow). The ratio of the throw (vertical uplifting of the aquiclude) to the thickness of the aquifer should be as large as possible. Ideally, the uplifted aquiclude blocks of the entire aquifer. Furthermore, the length of the fault plane should be taken into account.

1.6.3 Inclination of the Aquifer

Geological dips cause the aquifer to be inclined, which has an impact on groundwater flow in the vertical direction. The hydraulic conductivity in karst is usually highest parallel to the extent of the layer, in longitudinal direction (Stevanović, 2015). When the aquifer is inclined this leads to a preferred flow direction that is oriented downward, instead of horizontally. While a slightly dipping aquifer might be problematic because it facilitates quick flow away from the MAR site, steeply, almost vertically inclined aquifers might have a good potential for ASR: If the largest hydraulic conductivity is oriented downward, the horizontal movement of groundwater will be hindered by the lower conductivity and the aquicludes covering the aquifer. If the percolation to deep groundwater is limited (by aquicludes or geological discontinuities), steeply dipping strata might provide promising hydrogeological conditions for an ASR scheme, as for example planned at site A10 in Lebanon (BTD, 2016c).

Information on the inclination of the aquifer can be obtained from geological studies, cross sections of the stratigraphy, or from fieldwork. The criterion's influence should be scored with respect to the possible MAR technique (ASR or ASTR) on an ordinal scale. A horizontal orientation (no inclination) is usually preferred, but in certain circumstances a steeply inclined aquifer can construct a vertical reservoir.

1.6.4 Connection to the Sea

A good confinement of the aquifer is also important for protection against seawater intrusion and loss of infiltrated water through quick flow into the ocean. Coastal karst aquifers often have a direct connection to the sea and thus show increasing salinity levels when they are exploited as freshwater is replaced by seawater. A MAR project that aims at storing drinking water underground should not be planned in an aquifer that is directly connected to the sea, as the possibility of direct outflow of infiltrated water exists and mixing of the infiltrated freshwater with saltwater might make it undrinkable. Indicators for how well an aquifer is connected to the sea are increased salinity levels of the groundwater, faults that run perpendicular to the coastline and "connect" the aquifer with the sea, as well as karst submarine springs. Assessment of this criterion should be done comparatively on an ordinal scale.

In some cases MAR projects are designed to combat seawater intrusion, and not just store drinking water. In these instances this criterion should be omitted from the MCA. Examples of successful MAR projects in karstic aquifers that are to some degree connected to the sea can be found in Florida (Brown, 2005) and in Italy (Kazner et al., 2012). A number of studies have presented designs for combating seawater intrusion in Lebanon, using positive hydraulic barriers (Masciopinto, 2013) or so-called fresh-keeper wells (Khadra et al., 2017).

1.7 Productive Wells

1.7.1 Installed Production Capacity

The aquifer productivity at the different MAR sites can be assessed by comparing the abstraction through existing wells at the considered sites. Instead of quantifying aquifer characteristics such as storativity, transmissivity, or specific yield this criterion approximates an aquifer's suitability by simply comparing how successful groundwater exploitation is at the different sites. Scoring can be done by counting the number of productive wells in a defined area around the MAR sites or by comparing the total production rates of all wells at the different sites. Wells located on or close to fractures or lineaments usually have a significantly higher and more constant yield than those wells which are placed away from fracture traces (Singhal & Gupta, 2010).

For this criterion, a comprehensive inventory of the existing wells must be available. In Lebanon, most of the existing wells were drilled privately and without a license (UNDP, 2014). Estimates of total well numbers and abstraction rates are rather unreliable.

There certainly is some uncertainty involved in this criterion. An aquifer whose water is used for a large agricultural area under irrigation may be tapped by many wells while a more productive aquifer in a sparsely populated region might not have any productive wells at all. However, as limited data availability often is an issue for assessing the productivity of karstic aquifer this criterion might pose a valuable addition to the MCA.

1.8 Surface Karst Features

1.8.1 Possibility of Infiltration without Wells

The MAR schemes considered in this research would infiltrate surface water directly into the aquifer via deep wells. This is associated with considerable costs for drilling and equipping the well. Karst features, such as sinkholes or large, unfilled fissures that provide a direct connection from the surface to the aquifer could be used for infiltration, as shown in a case study in Italy described by Kazner et al. (2012). Infiltration rates in sinkholes can be very large and should be determined by field experiments before designing the MAR scheme. An advantage of using existing karst features for infiltration is that tracer tests can be carried out to determine the response time of the aquifer and fine potential connections to springs (Klingbeil, 2017). The karst feature considered as infiltration point should be easily accessible and within close proximity of the water source (distances of <500 m are suggested), as transmitting pipelines and pumping costs might decrease the design's benefit over a drilled well. The criterion should be assessed on an ordinal scale based on the individual features size or infiltration capacity and its location.

1.9 Groundwater Salinity

Infiltrated water will to some extent always mix with the ambient groundwater, even if the hydrogeological conditions are perfect. The salinity of the ambient groundwater can be determining for the success of a MAR project as to high salt concentrations might make the abstracted water useless. Less salinity is preferable and a threshold value for salt concentrations should be determined for the specific MAR project (Stuyfzand, 2017). The tolerable value is dependent on the amount of mixing that occurs in the aquifers, on the salt concentrations of the infiltration water, and on the intended use of the abstracted water (tolerable salt concentrations in drinking water are much lower than in irrigation water). MAR in brackish aquifers is possible while hyper-saline aquifers should be avoided (Brown, 2005; Stuyfzand, 2017).

1.9.1 Salt Concentrations of Ambient Groundwater

Salinity of ambient groundwater can be measured as the concentration of chlorine in mg/l or approximated by the electric conductivity, measured in mS/cm. The Lebanese standard for drinking water is 200 mg/l (UNDP, 2014).

1.9.2 Samples Exceeding the Standard

Another approach to comparing the site-suitability regarding groundwater salinity is to rate the aquifers according to the percentage of wells where water samples exceeded the drinking water standard for salinity. In the case of Lebanon it was found that these data were more complete and reliable than measured salt concentrations.

1.10 Geochemical Issues

An aquifer and its natural groundwater are in a hydrochemical balance that might be altered when surface water of a different chemical composition is infiltrated. Klingbeil (2017) therefore suggest to always carry out hydrochemical modelling of ambient groundwater and injection water as part of planning a MAR scheme. Indeed, geochemical issues have led to the closure of some MAR projects in Florida (Brown, 2005). Stuyfzand (2017) points out that the presence of pyrite (criterion 1.10.1) in the aquifer might lead to the problematic mobilization of arsenic and that gypsum (criterion 1.10.2) can have negative effects on the total hardness of the recharged water.

1.10.1 Concentration of Pyrite in the Aquifer

Pyrite (FeS_2) can be present in limestone aquifers. Infiltration water is likely to have a high oxidizing potential from fertilizers, chlorination, and natural oxygen concentrations. The pyrite is oxidized by the newly infiltrated oxidants and forms iron hydroxide, which in turn can mobilize arsenic that is potentially present in the aquifer (Stuyfzand, 2017). While this was not an issue for drinking water production with the ambient groundwater, the newly infiltrated surface water might contaminate the water.

This criterion should be rated on a quantitative scale (% pyrite of the aquifer material) and cautious thresholds should be applied. Determining thresholds for tolerable pyrite concentrations is beyond the scope of this research, therefore this criterion was applied as a constraint: The selected aquifers are to not contain any pyrite.

1.10.2 Concentration of Gypsum in the Aquifer

Limestone aquifers are often interbedded with gypsum layers. This can cause a problem to the water quality because gypsum results in high sulphate and a high total hardness due to calcium (Stuyfzand, 2017). This is not desirable in drinking water. The amount of gypsum in the targeted aquifer should be such that drinking water standards for sulphate and total hardness are not exceeded. Unfortunately, thresholds could not be determined as part of this research.

1.11 Lithotype

1.11.1 Clay Content

The ratio of carbonates to clay content determines the lithology of karst aquifers (see Figure 21). Pure limestones contain more than 90% carbonates while marl contains 65 – 35 % carbonates (Milanovic, 2004). Higher clay contents are associated with a lower hydraulic conductivity and a higher risk of clogging. It is therefore recommended to target aquifers for MAR that contain >65 % carbonates (calcareous marlstone, argillaceous limestone, and limestone).

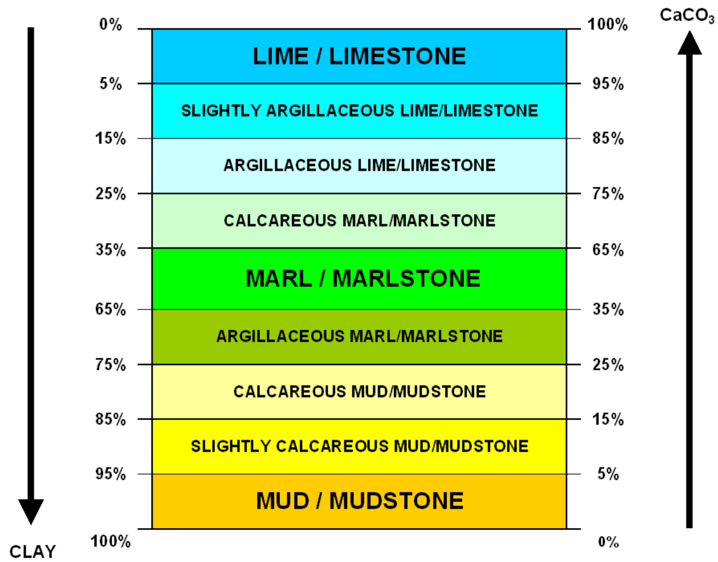


Figure 21: Lithotypes depend on the content of clay and carbonates

1.12 Hydraulic Properties

1.12.1 Transmissivity

Transmissivity is also called the kD-value of an aquifer, because it is the product of the aquifer's hydraulic conductivity (k) and its saturated thickness (D). Transmissivity is usually measured by packer pumping tests, single-well pumping tests or multiple-well pumping tests (Maliva, 2016). Values for successful ASR and ASTR schemes with sufficiently high yields should be above 100 m^2/day and ideally 1000 – 4000 m^2/day (Groen, 2017). While higher values indicate even higher possible infiltration rates (and equally high abstraction rates), a transmissivity of >4000 m^2/day should make the planners suspicious as they are can be associated with very fast groundwater flows that are unfavourable for MAR.

Transmissivity also determines the aquifer's ability to inactivate pathogens: A lower transmissivity results in better water treatment as the groundwater flows through the aquifers (Kazner et al., 2012).

The heterogeneity of karst makes an interpolation of transmissivity values obtained at one point to the entire aquifer more an educated guess than sound quantification of real hydraulic properties. The criterion should therefore not be given too much weight, but it can be useful in comparing the aquifers. It is suggested to score the alternatives on an ordinal scale, instead of deriving scores analogue to the available transmissivity values. Aquifers where many pumping tests indicate the transmissivity to be in the range of 1000 – 4000 m^2/day should be scored most suitable.

1.12.2 Theoretical Injection Rate

While transmissivity refers to the rate at which groundwater can be transported horizontally through an aquifer expressed in unit width the theoretical injection rate is given as a volumetric rate. It may therefore be more useful for designing MAR schemes. The theoretical injection rate is calculated analogue to Logan's (1964) approximation for well discharge as a function of transmissivity and drawdown.

Transmissivity (T) can be estimated by pumping tests where the abstraction rate (Q), the drawdown (s_w), the radius of influence (r_e), and the well radius (r_w) are known (Misstear, Banks, & Clark, 2006):

$$T = \frac{Q}{2\pi\, s_w} \ln \frac{r_e}{r_w}$$

Logan (1964) proposed a fixed value of 7,65 for the ln-term because even though the ratio r_e/r_w can vary significantly the long term is relatively insensitive to these variations. This approximation allows estimating the well discharge as a function of drawdown and transmissivity:

$$Q = \frac{T\, s_w}{1{,}22}$$

The major advantage of using this approximation is that during the pumping test no observation wells are necessary because the drawdown in the abstraction well together with one other variable is sufficient to determine the third.

The drawdown is the difference in piezometric heads observed in the well under normal and under pumping conditions. If water is infiltrated in the well by gravity the difference in piezometric heads of the undisturbed groundwater table and the pressure head is equal to the groundwater depth, i.e. the difference in elevation between the groundwater table and the surface (Groen, 2017). The well discharge (Q) then corresponds to the theoretical injection rate, i.e. the maximum rate at water could be infiltrated into the aquifer in one well. This criterion thus combines estimated values for transmissivity and depth to the groundwater table. BTD (2016a) estimates feasible injection rates of 50 l/s per well, which corresponds to an injection rate of 4300 m³/day. It is suggested that sites with a theoretical injection rate of 4300 m³/day are rated with the best suitability score. This criterion might be of greater value for the planner than the transmissivity alone but it is associated with larger data uncertainty, as it is derived from transmissivity and groundwater depth.

1.13 Fluctuation of Groundwater Levels

1.13.1 Intra-Seasonal Fluctuations

A high variability of the groundwater table might indicate a connection to surface waterbodies and a strong influence by these, or extremely high conductivities. Either is deemed unsuitable for MAR because infiltrated water is likely to disappear quickly. A measure for estimating this is the ratio of highest to lowest groundwater level at the infiltration site during the infiltration period (usually rainy season). The higher this ratio, the more variable are groundwater conditions and associated uncertainties can be high. Especially sharp peaks in groundwater levels immediately after rain events can be a sign of alarm, because the groundwater level might be governed by a river (BTD, 2016c). The criterion can be rated on an ordinal scale or on a scale of ratio values.

1.13.2 Correlation with Tides in Coastal Aquifers

In coastal aquifers records of groundwater levels might indicate a correlation to tides of the ocean. This should be interpreted as a sign of alarm, as it suggests a direct connection of the aquifer to the sea (see also criterion 1.6.4). A correlation of groundwater level and tides does not mean that mixing of salt and freshwater has to occur, but it makes it more likely. Scoring should be done on an ordinal scale and take into account the level of correlation.

1.14 Degree of Karstification

A diverse set of criteria was collected to give the researcher the possibility of classifying the karst aquifers with respect to their general hydrogeological character depending on the data availability*.* Several approaches of classifying karst aquifers have been developed by numerous researchers. Classification of karst is often subjective, as it is usually done based on morphological features, structural factors, geographical position, and depositional environment (Milanovic, 2004). Here, a number of methods have been collected that allow appraisal of the aquifer's hydrogeological character and how suitable it is for MAR. The criteria of the degree-of-karstifiaction category are to be assessed for the aquifer as an entity and not specific to the MAR site.

Conceptual Karst Classification

Atkinson (1985) developed a conceptual classification of karst aquifers. The flow regime (Darcian or turbulent flow) is related to the structure and size of voids in the carbonate rock. Flow can be controlled by conduit flow, diffuse flow through the matrix, or by flow through the fissure network. A karst aquifer can be classified on this three end-member spectrum (Figure 22) and from this the prevailing flow regime can be derived (Figure 23). In a karst aquifer most suitable for MAR, flow would mainly occur in the fissure network and in the matrix, possibly as a mixed flow regime. While this framework is useful for comparing the behaviour of different karst aquifers, it is purely conceptual and has very limited practicality because the methods to measure the different end-members are missing (Atkinson, 1985).

The criteria (1.14.1 – 1.14.17) developed in this research make as much as possible use of observable qualities to allow for a characterization of the aquifer with regards to its suitability for MAR. In a generalizing karstification analysis the different groundwater basins can be compared based on geological description, age, karst form, and greater geological setting. The assessment of karst features such as dolines, sinkholes, springs, and caves in the area of the planned MAR project can also be helpful. A more small-scale approach focuses on fracture properties which allow conclusions to be drawn about groundwater flow regimes. Discharge data of karst springs can reveal important characteristics of the supplying aquifer. Five suggested criteria are based on spring hydrograph analyses.

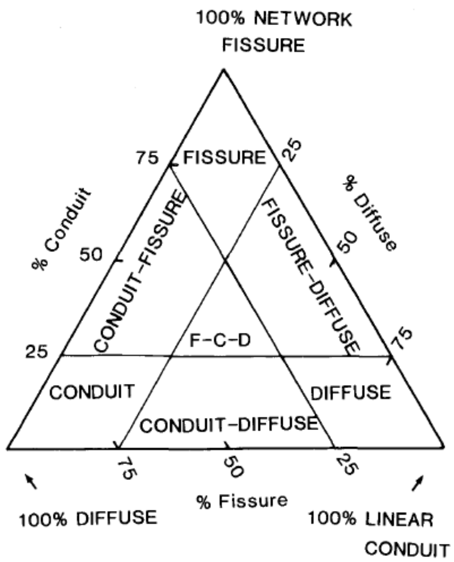


Figure 22: Conceptual classification of karst aquifers (Atkinson, 1985)

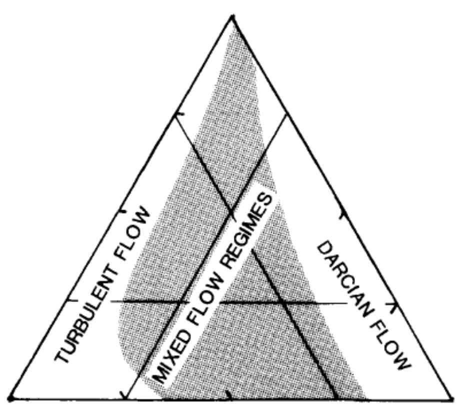


Figure 23: Presumed relationship to predominant flow regime (Atkinson, 1985)

General Karstification Analyses

1.14.1 Local Expert Assessment

Experts on the geology of a karst region could integrate their experience from field visits and research to come to a comparative (albeit somewhat subjective) assessment of the general degree of karstification of different areas of the karst system. Daher et al. (2011) classified the Lebanese karst into five classes regarding their suitability for MAR based on various information, such as spring hydrographs, data from hydraulic and tracing tests, geophysical surveys, geochemical data, as well as speleological and field observations. The karst with the most functionality (conduit flow type, binary karst, high flow velocities in tracer tests of >100 m/h) is given the least suitable rating. Less developed karst systems characterized by diffuse flow (fractures and fissures control flow) are rated most suitable for MAR.

If a qualified expert opinion is available for the study area it can provide a valuable proxy for comparing entire karstic groundwater basins on an ordinal scale.

1.14.2 Geological Description

Descriptions of the geological stratigraphy of the research area can contain valuable qualitative information of the hydrogeological properties of an aquifer. Often, generations of geologists have researched the different geological layers and described them in a generalizing manner. For a MAR project the characterizations of the different strata which form the aquifers of the plausible project sites can be interpreted by a hydrogeologist without local expertise. The assessment of the aquifers' suitability for MAR is then comparative, as it is not based on quantified parameters but on general description.

Geological descriptions of a region's stratigraphy include classification into aquifer, semi-aquifer, aquitard, and aquiclude. Often the degree of karstification is described qualitatively and information is given about the composition of a layer. The age of the carbonate layer and the duration for which it has been subject to solution processes can be an important indicator for the degree of karstification. For this study descriptions of Lebanon's geology from three different sources were analysed (BTD, 2016a; Daher, 2011; UNDP, 2014) and the four different karst aquifers of the potential MAR sites were compared on a -/+ scale.

1.14.3 Karst Age

If a detailed description of the geological strata is not available a karst assessment could at least take into account the karst age. The longer the carbonate strata have been subject to solution processes the more developed their karst features are. Older aquifers, therefore, tend to be more karstified than younger strata of the same region. However, built-up of overlaying aquicludes over time can stop karstification processes of a geological layer, permanently or for a period of time. The duration of active dissolution is therefore more significant and when using karst age as an indicator for the degree of karstification one has to keep this in mind (Wiersma, 2017).

Maliva (2016) mention that Cenozoic limestones which have never been buried usually show relatively high porosities and hydraulic conductivities while still providing good matrix storage. Mesozoic and Paleozoic limestones have lower porosities, lower matrix storage and much groundwater flow through secondary porosity which leads to "flashiness" of the aquifer. Therefore, in a rough-and-ready approach the younger (Cenozoic) limestones would be assessed more suitable for MAR than the older (Paleozoic) strata.

1.14.4 Platform vs Geosyncline Karst

Milanovic (2004) points out that the general form of a larger karst entity has influence on its hydrogeological characteristics. Platform karst consists of horizontal or slightly sloping strata. The carbonate rocks in platform reliefs often show a higher percentage of marly material which hinders karstification. The absence of differential tectonic movements means that no pre-defined flow paths exist where concentrated dissolution could occur. Dissolution of calcium carbonate is more spread out within the entire aquifer. This leads to lower hydraulic conductivity and lower heterogeneity. Platform karst, compared with geosyncline karst, is therefore more suitable for ASR (Stevanović, 2015).

Geosyncline often is subject to more intense karstification processes. The strata are folded and frequently show ruptures and faults. Along these structural discontinuities infiltration water is concentrated and dissolution processes lead to preferential flow paths. This leads to a more complex hydrogeology with higher but also more heterogeneous flow velocities. Geosynclines vary significantly in size. U-shaped synclines of a dozen meter in diameter as well as large regional synclines exist. The strata of the Bekaa Valley in Lebanon for example dip towards a syncline that is N-S oriented. Outcrops of the strata dip in the Mount Lebanon region in the west to surface some 20 km further to the east. Because of the inclination such geosynclines are less suitable for ASR schemes but might be present quite favourable conditions for ASTR schemes. Water could be infiltrated in the outcrops of the dipping karst layers and abstracted at the lowest point of the syncline. In the case of the Bekaa Valley, however, this seems to be unfeasible as the aquifers' lowest points lie at 1000 – 2000 m too deep below the surface of the valley. Attention should be paid that the longitudinal inclination along the axis of the syncline is not too large as otherwise the infiltrated water will not stay at the abstraction point (Wiersma, 2017).

Just as the karst age criterion, the geosyncline vs platform criterion is a qualitative comparison and significant expert knowledge is needed to translate the rather broad, descriptive information into a rating of site-suitability for MAR. In a region with platform as well as geosyncline karst this criterion could help to decide on where to implement which MAR technique, ASR or ASTR.

1.14.5 Influence of Tectonic Faults

Tectonic activity can cause faults which may lead to complex fractures and secondary faults. Along these discontinuities exaggerated karstification can be expected. Depending on the scope of the tectonic movement and the complexity of the resulting fracture system karstic areas along the fault might be rated unsuitable for MAR because of the high influence of conduit flow. This criterion should be assessed qualitatively and comparatively on a larger, regional scale as tectonic fault systems can have far-reaching impact.

For the analysis of MAR site-suitability in Lebanon this criterion was omitted. The geology of this rather small country is controlled by the Dead Sea Transform Fault, a tectonic plate boundary that runs through the entire length of the country parallel to the coast (UNDP, 2014). It has led to complex karst formations in the entire country. Local differences in karstification could not be related to this criterion.

Karst Feature Assessment

1.14.6 Density of Surface Karst Features

The density of surface karst features of the outcropping area of an aquifer or groundwater basin can hint at the degree of karstification. Analysing the density of surface karst features, experts can comparatively assess the suitability of different aquifers for MAR. Surface karst features include dolines, sinkholes, vertical shafts, as well as clints and grikes of karrens. UNDP (2014) classify geological outcrops into “high karst exposure”, “moderate karst exposure”, “restricted karst exposure”, and “covered karst”. While a high density of karst features (or high karst exposure) might indicate too much solution activity for a successful MAR project no or very few karst features can be a sign of very solid carbonates that will not be able to store much water. The criterion can be assessed on an ordinal scale or quantitatively in karst features per km². Identification of karst features can be done from topographic maps, field observations and remote sensing (aerial photos or radar data), as demonstrated for Lebanon by Shaban et al. (2006).

1.14.7 Number of Springs

The number of springs situated in an aquifer in proximity to the planned MAR site is an easy indicator for the aquifer's suitability for artificial recharge. The presence of many springs is a sign of high karstification or unfavourable geology, such as shallow aquitards or dips of the water-storing strata. The advantage of this criterion is its simplicity: Location of springs can be easily obtained from thematic maps or various databases. If detailed information about the region's geology is known the analyst can determine from which aquifer a spring discharges. Only springs should be counted that are in the vicinity of the planned MAR project and discharge from the same aquifer that is proposed for the artificial recharge. One should keep in mind that merely counting the springs does not reveal any details about the discharge rates from the aquifer. The criterion, thus, has limited informative value.

1.14.8 Presence of Caves

In highly karstified strata positive feedback of carbonate dissolution leads to a few major conduits or caves that then have very little storage and retention potential. The presence of caves at the MAR site or downstream of it in but in the targeted aquifer allows some conclusions about the aquifer's suitability for MAR. Maliva (2016) relates three types of caves to prevailing flow regimes: In less soluble or less karstified rock where diffuse flow is dominant caves are rare, small, and irregular. These aquifers seem most suitable for a MAR project. In aquifers where free flow is dominant groundwater flow is localized to form well-integrated cave systems. Even larger cave networks which extend along two or three dimensions indicate confined flow. This category of aquifers is deemed least suitable for MAR.

Assessment of this criterion should be done comparatively and on an ordinal scale based on the judgement of experts who are familiar with the local caves. Speleological associations can provide valuable information.

Fracture Properties

Fractures are cracks and fissures of different size that cut through a geological layer. In limestone, detailed characterization of fractures can be important for estimating the direction of groundwater flow, hydraulic conductivity, and degree of karstification (Singhal & Gupta, 2010). Characterization of fracture properties should be done at the outcrops of the carbonate aquifer to then allow an assessment of the entire aquifer with respect to MAR suitability. Assessing fracture properties includes extensive fieldwork where no previous assessment is available.

1.14.9 Fracture porosity

Singhal and Gupta (2010) suggest to estimate fracture porosity (ηf) with the scan line method: Along a straight line across the outcropping area the number of intersections with fractures are counted and the aperture (crack width) of the fractures is measured. The fracture porosity is given by ηf = Fa, where "F" is the number of intersections per unit distance and "a" is the mean aperture of fractures. It is unit-less (m/m). Aperture is related to transmissivity by cubic law: Tf ∝ a3.

Highly fractured limestones will very often have high hydraulic conductivities unsuitable for MAR projects (Khadra et al., 2017). However, too low fracture porosity values can be a sign of insufficient storage capacity of the aquifer. Preferable are fractures with relatively small apertures (a < 0,5 cm) that are well-connected. Compared with the aperture the fracture frequency (F) has much less influence on the hydraulic conductivity. For example, the hydraulic conductivity of an aquifer with a fracture frequency of F = 1/m at an average aperture of a = 0,5 cm is the same as the hydraulic conductivity of an aquifer with F = 100/m and a = 0,1 cm (Singhal & Gupta, 2010). Further research is needed to find an optimal range of fracture porosity for a MAR scheme.

1.14.10 Fracture Persistence

Fracture persistence describes the length of the fractures and how well they are interconnected. Figure 24 shows the schematic categorization of fracture patterns. Fracture persistence is described qualitatively and should be scored with respect to suitability for MAR on an ordinal scale. Moderate to strong fracture persistence is believed to be most promising for a MAR project. It is important though that the fracture aperture is sufficiently small.

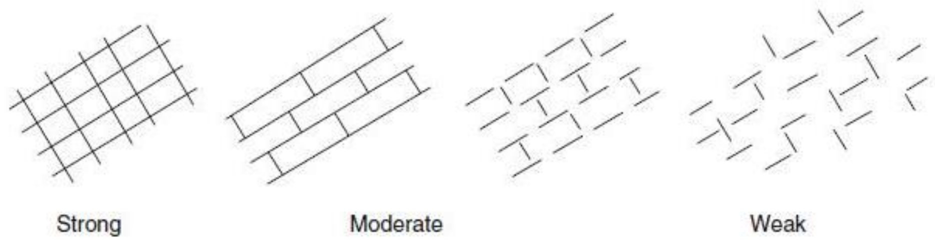


Figure 24: Influence of persistence of discontinuity on the degree of fracturing and interconnectivity (Singhal & Gupta, 2010, p. 27)

Spring Hydrograph Analyses

Discharge data of karst springs can reveal important characteristics of the supplying aquifer. Hydrographs of springs draining the aquifer of the potential MAR site can be analysed using different methods to determine how much retardation effect the karst has on infiltrated surface water. The shape of the hydrograph is dependent on the general geometry of the aquifer but also on the relationship of quick flow through the conduit system to base flow through porous media and small fractures (Maliva, 2016). Figure 25 shows the response of a karst spring to recharge of the aquifer. The steep slope of the hydrograph just after the recharge event is caused by large volumes of discharge being quickly transported through the conduit system while the fissure network where flow is dominantly diffuse has a retarding effect that leads to a slower decrease of discharge as time progresses.

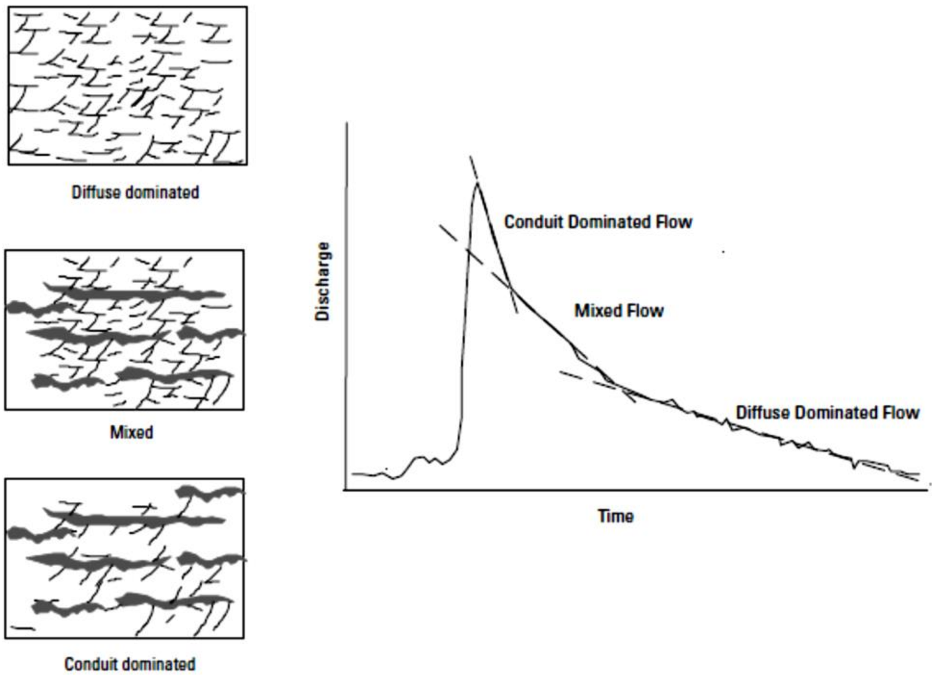


Figure 25: Conceptual spring hydrograph showing changes in slope and dominant flow regime (conduit, mixed, diffuse) due to differing hydraulic responses (Taylor & Greene, 2008)

The proportion and shape of the different flow components of karst spring discharges are a good indicator for the degree of karstification. Flatter parts of the hydrograph result from slow groundwater drainage and are linked to flow through pores and micro fissures. The recession of a flow component can often be described by an exponential function controlled by different exponents, the so-called recession coefficients. Smaller recession coefficients represent flatter parts of the hydrograph which usually corresponds to slower flow components. Enhanced karstification leading to fast flow through widened joints and conduits causes steep slopes of the hydrograph that are best described by one or more linear equations (Stevanović, 2015). Exponential recession curve equations are in the form of

$Q_t = Q_o \cdot e^{-\alpha \cdot t}$ and

$\alpha = (\ln Q_0 - \ln Q_t)/t$

where α is the recession coefficient, Q_t the flow observed at time t in m³/s and Q_0 the flow observed at the beginning of the recession in m³/s.

1.14.11 Degree of Karstification

Malík and Vojtková (2012) present a method to assess the degree of karstification (d.o.k.) on a scale from 0 to 10 based on a recession curve analysis of spring hydrographs. Recharge areas with no or very little karstification (d.o.k. <2.3) have a single exponential flow component with a low recession coefficient of α <0.007. D.o.k. values of 2.3 – 4 are characterized by two or more exponential flow components with recession coefficients of α1: <0.0024 – 0.018 and α2: <0.033 – 0.16. D.o.k. values of 4 – 5.5 are described by one linear model flow component and two or more exponential components. The linear recession is relatively little in time and volume of discharge compared to the exponential flow components. The authors give values for the exponential recession coefficients of α1 >0.018 and α2 >0.16. The linear relationship of the first response of the recession curve is given by

$$Q_t = Q_0 \cdot (1 - \beta \cdot t)$$

with the recession coefficient β >0. Karstification of this class is characterized by a dense network of open fissures and a minor influence of the conduit system (causing small values of β). Higher degrees of karstification (d.o.k. >5.5) would result in more complex regimes described by several exponential and linear recession coefficients which are not further quantified by the authors. Spring hydrographs of the highest degree of karstification (10) are described by three linear flow components, resulting in only perennial flows.

Based on these properties d.o.k. degrees values of around 5 on the scale presented by Malík and Vojtková (2012) are estimated to be most suitable for a potential MAR project. Least suitable are d.o.k. values around 0 because the associated carbonate aquifer is likely to have a very low transmissivity. Furthermore, the opposite site of the spectrum with d.o.k. values of 10 is also seen as unsuitable because of high flow velocities and large heterogeneity.

1.14.12 Summed Recession Coefficients

While the above mentioned method allows for a rather detailed classification of the degree of karstification it requires discharge data of reliable quality at a high temporal resolution to properly separate the recession curve into exponential or linear segments and to determine the recession coefficients precisely enough. If data of the spring discharge is limited a simplified or more descriptive approach might be useful.

UNDP (2014) derived a standard of two recession coefficients (α1 and α2) for every of the 14 evaluated springs in Lebanon. The falling limb of the annual hydrograph was separated into a quick response and a slow response approximated by exponential functions (see Figure 26). A simple comparative hydrograph assessment is the summation of the two recession coefficients. Larger values for this summed recession coefficient indicate a steeper recession of the quick flow (conduit flow), diffuse flow, or both. Lower values would therefore be more preferable as they indicate larger retention times and slower releases of groundwater. Even though this criterion does not allow for an absolute classification of the karst aquifer it offers an easy and transparent method to rank karst aquifers based on crude spring discharge data. For this comparative assessment the different aquifers should receive similar amounts of precipitation recharge. In the case of Lebanon a mere two recession coefficients for the entire hydrological year are sufficient as recharge is restricted to four months in winter. In regions with two rainy seasons or constant year-round precipitation this approach might not be applicable.

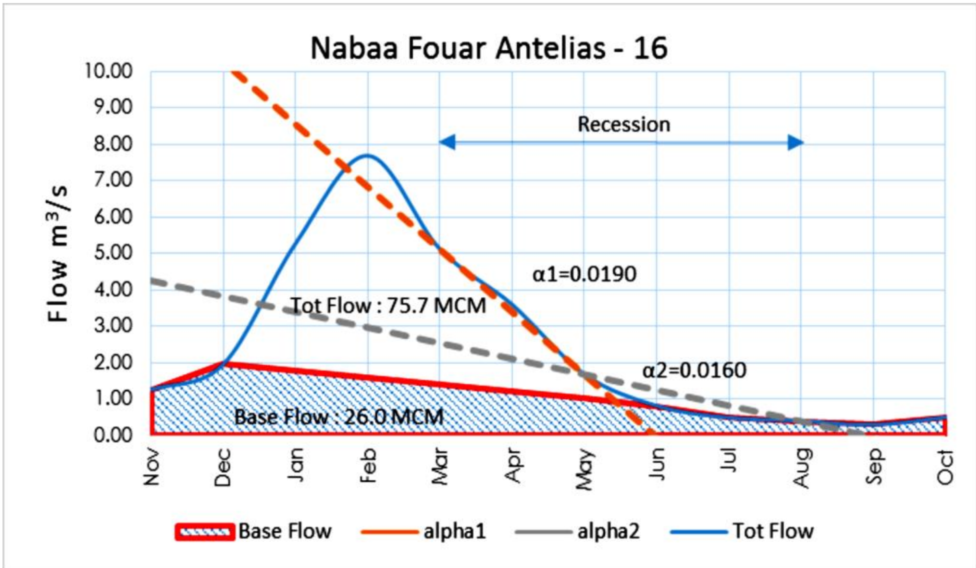


Figure 26: Hydrograph of Nabaa Fouar Antelias (2002-2010) in the Kesrouan Jurassic Basin (Basin 16). (UNDP, 2014)

1.14.13 Ratio of Base Flow to Total Flow

The spring hydrograph depicted in Figure 26 allows for another simple assessment: The ratio of base flow to total flow characterizes how much discharge happens quickly after precipitation input occurred compared to discharge that is retained by slow flow (Maliva, 2016). The higher this ratio the more preferable the aquifer would be for MAR as the retardation effect is larger and fraction of water quickly lost through conduit flow is smaller. This proxy, too, is suited for a comparative assessment of the suitability for MAR of karst aquifers of the same region rather than a sound classification of the karst aquifer itself. This method is not restricted to climates with one defined rainy season as long as the annual hydrograph is properly separated into base flow and quick flow.

1.14.14 Hydrograph Shape Categories

If the available data does not allow for a quantitative analysis of the spring discharge but the general form of the hydrograph of a single rain event exists a more qualitative approach can be chosen. Mangin (1984) empirically classified four different karstic springs and quantified the “memory effect” (prolongation of recharge on hydrograph shape). A reduced memory effect of 5 days forms a sharp peak on the hydrograph while a significantly longer memory effect of 70 days results in a much flatter hydrograph (see Figure 27). Comparing spring hydrographs after one or more rain events to these schematized graphs is another method for approximating MAR suitability of a karst aquifer from spring discharges. Flatter graphs are preferred over sharp peaks with little memory effect. Ranking is done on an ordinal scale.

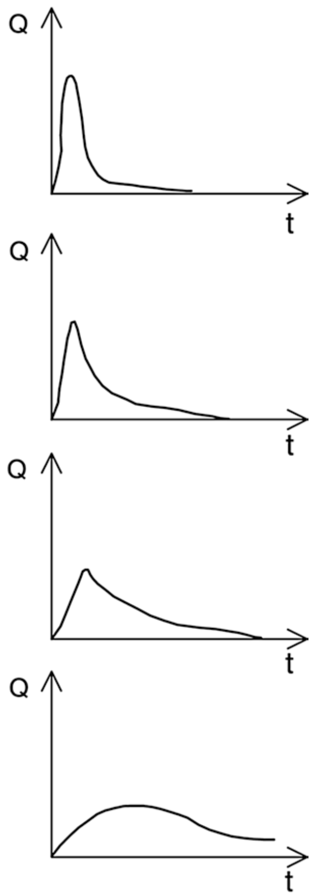


Figure 27: Mangin's typical single hydrographs of four tested springs proposed as etalons. From the top Aliou (memory effect: reduced, up to 5 days); Baget (memo: moderate, 10–15 days); Fontestorbes (memo: large, 50–60 days); and Torcal (memo: significant, 70 day

1.14.15 Chemograph Analysis

In aquifers with predominant diffuse flow springs are small and mixing of the groundwater takes place. Consequently, chemical characteristics of spring discharge do not vary much in between seasons or after storm events. In highly karstified aquifers, where conduit flow is predominant, mixing between ambient groundwater and infiltrating storm water is hindered. This reflects in varying chemical traits of the spring water after heavy storms and inter-seasonally (Shuster & White, 1971). By analysing the development of chemical concentrations in the spring discharge over the course of a year the supplying aquifers can be compared with respect to their ability to mix water from different sources. Full mixing (no variation in chemical concentrations) are rated more suitable for MAR than aquifers that show little mixing.

Catchment Drainage Analysis

In some cases the analysis of drainage networks and discharge data of the surface of an aquifer allows for some interpretation of the underlying hydrogeological processes. To characterize a karst aquifer using data related to the drainage observed at the surface one needs to be certain that the extent of the surface area corresponds to the extent of the aquifer, or that the conclusions can safely be extrapolated.

1.14.16 Drainage Density

The network of streams and rivers on the surface of an aquifer can be set in relation to its surface area. The drainage density expressed in stream lengths per area (km/km²) allows some conclusion of the aquifers ability to infiltrate water. A very solid and impermeable geology will lead to a denser drainage network while higher infiltration capacities imply that not as many streams form to drain the catchment. Therefore, lower drainage densities are preferable for MAR project. Chowdhury et al. (2010) suggest that aquifers with good infiltration capacities have a drainage density of <3 km/km². Very low drainage densities, however, could indicate excessive karstification with very high infiltration rates and hydraulic conductivities. Best ratings should therefore be given to values of 1 – 3 km/km². This criterion is of course a rather rough approach to assess the degree of karstification and it should not be given too much weight in the MCA. However, it is a quantitative criterion that can be derived from easily available data. Aquifers that are compared using this criterion should be situated in a similar relief (similar inclinations) as steep-sloping surfaces naturally have lower drainage densities.

1.14.17 Lag Time of Storm Runoff

The lag time that passes between a rainfall event and the peak outflow from a catchment is controlled by the size of the catchment, the slopes of the stream network, but also by the underlying hydrogeological processes. Longer lag times indicate slower hydrogeological processes (Shaban, Robinson, & El-Baz, 2009) – which are in karstic regions generally more favorable for MAR projects. This criterion, too, might not be a very strong indicator for the degree of karstification of the aquifer underlying the catchment. It may, however, allow some qualitative comparisons of aquifers where the overlying stream networks used for the analysis have similar sizes and slopes.

2 Source Water

Criteria under this theme refer to the characteristics of the source water. For the Lebanon MCA only rivers were considered as sources for infiltration water.

2.1 Water Quality

2.1.1 Turbidity

Turbidity and Total Suspended Solids (TSS) play a major role in clogging of an aquifer by physically plugging its pores. Direct infiltration in karstic aquifers may be possible with much higher sediment loads than infiltration in alluvial aquifers where clogging due to suspended solids is a much larger issue (NRC, 2008). Turbidity can be measured in Nephelometric Turbidity Units (NTU) (which is roughly equivalent to Formazine Turbidity Unit) or it can be measured in the concentration of TSS in mg/l. Lebanese drinking water standards demand a turbidity of <5 NTU. Brown (2005) suggests maximum TSS concentrations for MAR projects of 5 mg/l for ASTR schemes and 10 mg/l for ASR wells. The higher value of ASR wells results from the fact that regular pumping of the infiltration well backwashes the aquifer and the well screen, thereby removing some of the clogging material.

Removing suspended solids from the source water can be costly, as large sedimentation tanks have to be built. A cost efficient measure can be intake management depending on the source water's turbidity: Especially fast-flowing rivers carry much sediment after heavy rainfalls. Omitting this turbidity peak by pausing the abstraction from the water source until normal conditions prevail again can be a good management option that can make pre-treatment of the infiltration water unnecessary (BTD, 2016c).

2.1.2 Organic Material

Next to physical clogging due to solids suspended in the infiltration water, biological clogging, as an effect of organic material that is infiltrated into the aquifer, can be an issue for MAR schemes (Stuyfzand, 2017). The load of organic material in the source water can be measured as the concentration of Total Organic Carbon (TOC) in mg/l or as the biochemical oxygen demand, expressed as the amount of oxygen consumed per liter of sample during 5 days incubation at 20 °C. Due to the large transmissivity of karst biological clogging is estimated to not pose a serious threat to MAR projects in karstic aquifers (UNDP, 2014).

Lebanese guidelines for the quality of surface water state a BOD5 of <3 mg/l (Massoud, 2012). Guidelines for TOC concentrations give a range of acceptable values which average to around 10 mg/l (Escalante et al., 2016). It is suggested to use these values as lower thresholds and standardize higher scores according to maximum standardization.

2.1.3 Bacterial Contamination

In karst, disinfection of the water as it flows through the aquifer is not to be expected. Stuyfzand (2017) is of the opinion that recharge water should therefore be treated to meet drinking water standards before infiltration. In Lebanon a high population density together with a low standard of wastewater treatment results in high bacterial concentrations in surface waters. Water related diseases like diarrhea are still a leading cause for child mortality (Frenken, 2009). The recharge water should be treated to drinking water standards before being infiltrated into the karst aquifer (Stuyfzand, 2017). This can be done by filtration (slow and fast sand filtration) and disinfection through chlorination, ozone treatment or even reverse osmosis.

Bacterial contamination can be approximated by counting E.coli bacteria, fecal coliforms, total coliforms, or Enterococcus bacteria (a type of fecal streptococci) in a water sample. Units of measurement often are Colony Forming Units per 100 ml (CFU/100ml) or Most Probable Number (MPN/100ml). Steinel et al. (2016) suggest values of 10 MPN/100ml. Considering that there will be some breakdown of bacterial contamination during the residence time in the aquifer it is suggested to score contamination values of <10 MPN/100ml best and >100 MPN/100ml worst, with linear standardization in-between.

2.1.4 Salinity

Salt concentrations of the source water might not be crucial for the overall site assessment unless very elevated values are observed. Tolerable levels are dependent on the salinity of the ambient groundwater and on the intended use of the later abstracted water. While salinity values in drinking water should not exceed 0,1 ppt irrigation water can contain salt up to 2 ppt. Salinity can further be measured in mgCl/l or approximated by electric conductivity (EC) in mS/cm. It is suggested that scoring is done with a minimum threshold of 1 mS/cm for the case that salinity values of the ambient groundwater are not elevated.

2.1.5 Nitrate Concentration

Surface waters are likely to be contaminated by pesticides and fertilizers which are washed out from neighboring fields or livestock farms. Since purification of the infiltrated water in the karstic aquifer is not to be expected the initial concentrations of agrochemicals should be as low as possible (Stuyfzand, 2017). Nitrate is an important chemical in this context. Tolerable concentrations in drinking water are at 50 mg/l relatively high, but higher values should be a cause for alarm as nitrate itself can be toxic but also is an indicator for dangerously high concentrations of other chemicals (Steinel et al., 2016). It is suggested to score this criterion on a scale of concentration (mg/l) and use a maximum standardization with a maximum goal of 100 mg/l.

In Lebanon, nitrate contamination is not a big issue. During the planned infiltration period (winter) not much fertilizer is applied to the fields and the nitrate concentrations in the rivers, which then carry much water, are relatively low (Massoud, 2012).

2.1.6 Acidity

Acidity, determined as the potential of hydrogen (pH), controls the dissolution of $CaCO_3$ in limestone and dolomites and is thereby the driving factor of karstification. Acidic water (low pH) usually results from CO_2 enrichment, especially as the water passes through soil where much biodegradation occurs. Next to acidity, the water temperature is an important factor for the dissolution process as cold water at 0°C can dissolve four times more than water at 30°C. Furthermore, turbulent flow increases dissolution significantly compared to laminar flow (Milanovic, 2004).

For a MAR scheme acidity of infiltration water might pose a problem if the well stability is threatened as a result of enhanced solution rates. Water saturated with calcium carbonate might precipitate the material when degassing of CO_2 occurs, potentially leading to clogging of the infiltration well or the water treatment facilities where the water will get in contact with the atmosphere and have the possibility to degas. Thus, the $CaCO_3$ content in combination with the pH of the source water should be considered. In cases of a very instable karstic underground hydrochemical modelling of the dissolution process might be necessary to assess the threat of well instability due to low-pH infiltration water. In most cases, however, the present karst will be too massive and the dissolution processes during the lifetime of the MAR scheme too slow to cause any well instability (Wiersma, 2017).

Here, it is suggested to apply simple maximum standardization with an upper goal of pH 7 for rating this criterion. Only if unusually acidic surface water ($pH < 5,5$) or water with high $CaCO_3$ contents is to be infiltrated a more comprehensive analysis should be undertaken.

2.1.7 Chemical Contamination

Contamination of groundwater by infiltrating chemically polluted surface water is an acute threat in karst where no attenuation can be expected and flow velocities are large, shortening response and warning times in case of a disaster. Chemical contamination includes heavy metals, pesticides, pharmaceuticals, salts, and toxins produced by bacteria. Concentrations of chemicals that are relevant for human health should be carefully analyzed and compared to drinking water standards. Rating of the site-suitability regarding this criterion should be done on an ordinal scale.

2.1.8 Potential Contamination Point Sources

Often, reliable measurements of concentrations of hazardous elements in the source water are not available. Even if water samples have been tested negatively for contamination this is no proof that infiltration water will always be safe. Anthropogenic pollution from point sources such as factories, gas stations, sewer overflows, and farms upstream of the water in-take for the MAR scheme can occur as event discharges causing contamination peaks which are not observed during random sampling. An inventory of sites from which potential contamination could come about can help to assess the safety of the infiltration water at the considered MAR site. The rating of this criterion should be done on an ordinal scale.

2.2 Available Quantity

2.2.1 Duration of Sufficient Discharge

To make a MAR scheme most efficient, recharge should take place during as long a period as possible per year. If water is abstracted from rivers or springs this period could be determined by the time of prevailing water use for irrigation etc., or by a minimum discharge rate to ensure that ecosystem services are not impeded and downstream users still receive enough water. In the case of Lebanon, rivers and springs will serve as water sources and UNDP (2014) suggests that a minimum discharge of 5 m^3/s should be observed during times of recharge. The actual abstraction should be limited to 10 % of the river discharge. As many rivers fall (almost) dry during the dry summer, and water abstraction for irrigation reaches a peak during this time, the duration of recharge would be limited to 4 – 8 months, depending on the river.

An intriguing idea is the use of wastewater treatment plant effluent for recharge, as it is available at a close-to constant rate throughout the entire year and is usually not used otherwise. As the treatment process usually does not improve the wastewater quality to drinking water standards much attention has to be paid to overall contamination concentrations in the groundwater. A pilot project has been carried out in Italy (Kazner et al., 2012).

2.2.2 Available Infiltration Volume

Similar to criterion 2.2.1 the available infiltration volume can help to compare the considered MAR sites with regards to efficiency. The criterion quantifies the volume of source water theoretically available for infiltration each year and does not refer to the actual infiltration capacity which is dependent on the design of the MAR scheme. If the quality of the data is sufficient the sites could be scored with respect to the annually available water after all restrictions concerning duration of infiltration and percentage of allowable abstraction from total discharge. If only discharge quantities are known this will suffice for comparing the sites. Discharge volumes are usually given in million cubic meters per year (MCM/a).

2.3 Reliability of Water Availability

2.3.1 Development of Source Water Discharges

The development of discharges of the water source (e.g. annual river discharges) can be a good indicator for whether the MAR project is likely to encounter future problems due to decreasing source water availability. Anthropogenic land-cover change, increased abstraction rates, augmented river courses, or changed precipitation patterns can all be causes for a long-term change of the observed discharges. Extrapolating this trend to the lifetime of the MAR scheme can be a useful criterion for assessing the project's long-term success. The criterion can be quantified as the ratio of discharge rates averaged over a certain period in the past to the average discharge rate presently observed over a period of the same length. Values of >1 thus indicate an increase in discharge.

For the Lebanon MCA discharges of seven rivers from 1975-1979 were set in relation to the discharges from 2005-2009 (MoE, 2014). Many rivers show significant increases in discharges with a maximum increase of 70% for the Beirut River. It is assumed that this is due to a pronounced development of the catchment: The urban sprawl along the popular coast has led to a higher percentage of sealed surfaces and consequently higher runoff rates. Discharges of the rural Litani River on the other hand decreased in the same period by over 20%, which is likely due to higher abstraction for human consumption and irrigation.

2.3.2 Impact of Climate Change

Even though climate change is a longer term phenomenon it is likely to have some impact on the water availability within the lifespan of a MAR project of 20 – 30 years. Different climate scenarios model regionally variable changes in temperature and precipitation. As the presented framework focuses on assessing potential MAR sites that are usually located close to each other changes in temperature or precipitation are not expected to vary between sites within the same climate change scenario. However, the catchments providing the infiltration water for the different sites may respond differently to a changed climate. Many factors need to be taken into account, such as change in annual precipitation, extreme rainfall events, evapotranspiration, snow and snow melt. Assessment of the site-suitability with regards to the anticipated impact of climate change on the available quantity of source water should therefore be done comparatively and on an ordinal scale.

In Lebanon, climate change is expected to lead to an increase in temperature, a decrease in annual precipitation, and an increase in extreme rainfall events (Mohammad, 2016). This might lead to more problematic hydrological conditions, as more water will flow unused the short distance from the mountains into the ocean during heavy rainfall events and less water will be stored as snow on the mountain peaks. This might be especially problematic for MAR schemes that are planned in small snow-fed catchments of the coastal mountain range, as the duration with sufficient river discharge might decrease significantly. Larger river catchments such as the Litani catchment might be able to store and retard the rainfall better flattening out the increasing volatile discharge peaks.

2.4 Distance to Water Source

2.4.1 Distance from Water Source to Injection Point

The water source (e.g. spring, river, reservoir) should not be far from the targeted injection point, as transmitting water over long distances will increase monetary and environmental costs. To come to an accurate assessment the exact location of the planned infiltration well and the abstraction site have to be known. However, based on the topography and the existing infrastructure distances over which infiltration water would need to be transmitted above ground can be estimated to assess the site-suitability comparatively. Both, an assessment according to absolute distances (m) as well as an assessment on an ordinal scale is possible.

2.4.2 Elevation Difference to Injection Point

Infiltration should ideally happen under gravity conditions, thus without pumping to artificially increase the pressure head. Pumping for transmitting the water from the abstraction point to the injection well should also be avoided. If transmission pumping is necessary the elevation difference that needs to be overcome should be as small as possible, as pumping costs increase with the elevation difference. Rating of this criterion can be done quantitatively (in m) or qualitatively, i.e. on an ordinal scale.

2.5 Downstream Use of Source Water

2.5.1 Impact of Water Abstraction on Downstream Uses

Already in the short-listing process for selecting the plausible MAR sites an effort should be made to exclude cases where the water planned for infiltration is diverted from more promising uses. A MAR scheme should compete as little as possible with direct water users and it should not be considered if a more efficient technique of storing or using the source water is available. Often, this is not easily determined. Criterion 2.5.1 is meant to compare the physical impact of abstracting the infiltration water from its source on the downstream reaches of the river. Socio-economic impacts should be assessed separately under the theme ‘stakeholders’ of the MCA.

The impact of a MAR scheme on the riverine ecosystem downstream of the abstraction point can be negative if too much of the natural river discharge is used for infiltration. UNDP (2014) suggest a threshold of 10%, more water should not be abstracted in order to reduce the impact on downstream ecosystems. However, abstraction could have a positive impact for the downstream reaches of a river, too, if it contributes to decreasing flood risk. The actual impact of the water abstraction will depend on the abstraction rate and the existing downstream water uses. This criterion might not be assessed easily and should be scored on an ordinal scale.

3 Environmental Impact

3.1 Footprint of the MAR Facilities

3.1.1 Dimensions of the facilities

Due to the high vulnerability of groundwater in karst aquifers a MAR scheme in karst will often need large water treatment installations if surface water is used for infiltration. As these should be built close to the water source – often a river – it is possible that a considerable area of valuable riverine ecosystems, such as flood plains, will be developed in the course of the project. The environmental impact might be significant. It is therefore suggested to account for the footprint of the MAR facilities by assessing how much land would be used for building abstraction structures, transmission pipelines, water treatment facilities, wells, and servicing roads. Necessary levelling and landscaping should be accounted for as well. A differentiation should be made depending on whether the land to be used is already developed, undeveloped but of lower ecological value (e.g. agricultural lands), or ecologically valuable land (e.g. flood plains, nature reserves). The assessment can then be done either qualitatively (criterion 3.1.1) or quantitatively by determining the footprint on each of the three land-use classes (criteria 3.1.2 – 3.1.4). The latter option makes it possible to weight the criteria differently depending on how important the impact in the different classes is perceived to be.

3.2 Impact of Water Abstraction

3.2.1 Fish Passability

When infiltration water is abstracted from a river it might be necessary to build an intake structure, such as a small dam. The impact of this structure on fish migration should be assessed. It is dependent on the design of the structure (height) and on whether fish naturally migrate in the targeted river stretch. If possible, existing intake structures (such as weirs, irrigation channels, or outlets from hydropower plants) should be used for abstraction.

3.2.2 Endangered Species

The presence of endangered species in the source water could be a constraint for developing a MAR project if environmental protection is regarded as very important. The impact of a MAR project by damming the river and abstracting considerable amounts of discharge could seriously threaten the survival of small fish and invertebrates. It is suggested to rate the presence of endangered species in the intake area on a binary scale (yes/no).

3.2.3 Flexible Abstraction Rate

To ensure the functioning of downstream ecosystems it can be useful to limit the abstraction to a certain percentage of the natural river discharge. A flexible abstraction rate dependent on the actual river discharge could help to minimize the impact of water abstraction.

3.3 Impact on Surface Water Quality

3.3.1 Discharge of Treatment Plant Effluent

As most surface waters are too contaminated to be infiltrated into the karst aquifer directly pre-treatment will often be a necessary part of the MAR scheme. If the effluent from the water treatment facilities is discharged back into the river this might significantly increase the concentration of pollutants downstream. A more environmentally friendly solution would be to dispose of the residues of the treatment process in the local waste water system. If the flow rates which of the river are large enough to sufficiently dilute the effluent plume this criterion might not be an issue.

3.4 CO2 Emissions

Carbon dioxide emission result can result from construction, operation, and transportation associated with the MAR scheme and should be minimized in order to reduce the climate impact of the project.

3.4.1 Amount of Concrete

The production of concrete causes a significant portion of global CO2 emissions. The amount of concrete used in the construction of a MAR scheme can be a valuable proxy for the emitted CO2.

3.4.2 Energy Required for Drilling

Drilling, especially through hard rocks, can be very energy-intensive. As drilling machinery is usually fuel-powered CO2 emissions correlate with the energy required for drilling the infiltration or abstraction wells. This would ideally be expressed in Joules but could also be approximated by the net drilling time estimated by the contractor carrying out the operation.

3.4.3 Fuel-intensive Transportation

Not only drilling the wells consumes much energy, constructing of a MAR scheme requires the use of various heavy machinery. If a MAR site in a remote location needs to be accessed by fuel-intensive trucks over many runs this can lead to significant CO2 emissions during the construction phase. A more easily accessible site or a site where less landscaping and therefore less truck runs are required should be preferred from an emission reduction perspective. It is proposed to assess this criterion on an ordinal scale based on estimations about the distance heavy machinery needs to travel to reach the site and the number of runs required.

3.4.4 Energy Requirement for Operation

There are two likely sources for continuous energy consumption during the operation of the MAR scheme: Pumping from the source to the injection point and treatment of the source water. Ideally, electricity should be used as continuous power supply as it can potentially be produced from renewable energy sources. In remote locations it might be necessary to utilize diesel pumps or employ generators to provide energy for the treatment process. Energy consumption in the form of estimated kWh per year or fuel per hour of operation can be used as a proxy for comparing the CO2 emissions of the MAR schemes.

4 MAR Technique

4.1 Recharge Capacity

4.1.1 Recharge Volume

The recharge capacity, expressed as volume of infiltrated water per year, is one of the most important technical properties of a MAR project. A MAR scheme with infiltration through deep wells and possibly with large water treatment facilities is an expensive endeavor. Large recharge volumes will lead to a better cost efficiency, expressed in costs per m³, if the retrievable groundwater is proportional to the infiltrated volumes.

4.1.2 Infiltration Rate

The infiltration rate of a MAR scheme is closely related to the recharge volume and yet different as it quantifies how much water the MAR scheme is designed to infiltrate maximally during operation. It is expressed in l/s and is determined by the amount of available source water, by the number of infiltration wells, and by the possible injection rate per well (see criterion 1.12.2). While the recharge volume (criterion 4.1.1) is more meaningful for the overall efficiency of the MAR scheme, the infiltration rate can be useful in case the annual recharge rate cannot be determined or if the objective is to infiltrate large quantities over a short period of time (e.g. as flood mitigation). Due to issues of interdependency this criterion should not be included if criterion 1.12.2 or criterion 4.1.1 are used in the MCA.

4.1.3 Recharge Efficiency

If the MAR project is designed as an ASR scheme it might be possible to determine the recharge efficiency depending on aquifer properties. The recharge efficiency is the ratio of the infiltration quantity to the abstracted quantity. Usually, water is lost during storage or mixes with ambient groundwater of unsuitable quality so that the recharge efficiency drops well below 1. Zuurbier, Bakker, Zaadnoordijk, and Stuyfzand (2013) propose a method for determining the recharge efficiency of an ASR scheme in a brackish coastal aquifer. The approach requires detailed knowledge of the hydraulic properties of the aquifer (required are: horizontal hydraulic conductivity, hydraulic gradient, duration of storage, porosity, longitudinal dispersivity, vertical hydraulic conductivity, density difference ratio (fresh-salt water), pumping rate, aquifer thickness). Furthermore, the aquifer has to be sufficiently homogeneous, thus behave similar to a granular medium aquifer. It is considered improbable to reliably estimate the recharge efficiency of an MAR project in karst.

4.2 Water Treatment

4.2.1 Complexity of Required Purification

Injection of surface water through deep wells directly into a karstic aquifer requires good-quality source water, as almost no purification can be expected in the aquifer (Stuyfzand, 2017). When water is infiltrated into a sinkhole pre-treatment to remove pathogens is usually needed as well (Kazner et al., 2012). Rainwater collected from relatively clean surfaces such as roofs is usually of sufficient quality for direct infiltration after the first flush of a rain event is discarded (Stuyfzand, 2017).

Sedimentation tanks and filtration should be employed to remove suspended solids. These clarification techniques should also remove any hydrocarbons, if present in the source water. Furthermore, it was found that 95 – 99 % of average heavy metal concentrations can be removed in this basic purification process. The infiltration basin could be filled with sand and gravels on a geomembrane. If calcium-carbonate rich water is used for infiltration (e.g. from a karstic spring) degassing prior to infiltration should be kept at a minimum. Degassing will lead to lowered CO2-levels and consequently facilitate the precipitation of the dissolved calcium carbonate. If this happens in the infiltration well it can cause clogging and precipitation in the water treatment installations can increase maintenance costs (Daher, 2011).

The quality of the source water determines the type of treatment that is necessary prior to infiltration. While spring water from well protected areas might be pure enough for infiltration without treatment, most surface water requires some sort of purification. High turbidity needs to be removed in large and expensive sedimentation basins as it might eventually lead to clogging. Furthermore, slow or rapid sand filtration might be necessary to remove suspended solids sufficiently. Pathogens can be deactivated by disinfection techniques such as chlorination. If the residence time of the infiltration water in the transmission pipelines between abstraction and infiltration point are long enough, chlorine can be dosed at the beginning of the pipeline. If the mixing period in the pipes is too short chlorination basins might need to be built, increasing the costs and complexity of the MAR scheme (BTD, 2016c). In cases of very high contamination more profound treatment techniques like reverse osmosis might be necessary. This would further increase the complexity of the MAR scheme.

Rating should be done on an ordinal scale: No treatment is considered most suitable, primary treatment (sedimentation, sand filtration) less suitable, followed by chlorination, secondary treatment (biological purification), and reverse osmosis (least suitable).

4.3 Complexity of MAR Technology

4.3.1 Capacity of Local Contractors

MAR schemes utilizing deep wells can require very sophistication construction techniques and planning might not match the capacity of local contractors. The unpredictable nature of karstic aquifers (large voids, fissures, instability) can pose a challenge in drilling and construction of the well. In case of high static groundwater levels drilling a well with sufficient productivity might be a difficult challenge that goes beyond the experience of the local drilling industry (BTD, 2016a). Furthermore, the size of planned MAR facilities and the available space might increase the complexity of the construction.

This criterion should be scored on an ordinal scale by answering the question: Does the capacity of local contractors match the complexity of constructing the MAR scheme?

4.3.2 Complexity of Operation

It is assumed that simple structures are more reliable in their operation than complex ones. An ASTR scheme is probably easier to operate than an ASR scheme using dual-purpose wells. Fixed source water intake structures need no or little monitoring while quantity- or quality dependent water intake requires reliable monitoring and management. The complexity of the water treatment facilities is another important component. These sorts of particularities of operation of the MAR scheme should be accounted for in this criterion.

4.3.3 Complexity of Maintenance

Maintenance involves keeping the intake structure clean, assuring an unobstructed functioning of the treatment process, and maintaining the infiltration well including anti-clogging measures. An overview of well development and anti-clogging measures is given in Figure 28. The complexity of maintenance comprises of the required knowledge to carry out the maintenance work and the estimated time that would be required for maintenance each year. The local availability of spare parts should also be accounted for. Depending on the social context and the ownership of the MAR scheme it might be a possibility that maintenance is done through the local community. This should be encouraged if the MAR scheme can be designed simple enough.

Method	Action	Variations
Overpumping	Well is pumped at a greater than operational rate.	Well pump
		Air lift
Surging	Repeated reversals in flow	Air lift
		Well pump
		Surge block or swab
		Isolation/interval development
Mechanical	Direct contact methods used to dislodge material on inner surface of casing and screen	Brushing
		Scraping
Jetting	High pressure water flow clears screens, disrupts mudcake, and agitates and rearranges particles	Water jetting
		Water jetting combined with air lift.
Acidification	Dissolution of carbonate minerals	Hydrochloric acid
		Sulfamic acid
		Carbonic acid
Dispersants	Chemicals are added to disperse clays, which facilitates their removal by over pumping and surging	Sodium acid pyrophosphate
		Tetrasodium pyrophosphate
		Sodium tripolyphosphate
		Sodium hexametaphosphate

Figure 28: Well development and anti-clogging measures (Maliva, 2016)

4.4 Clogging

In general, clogging of karstic aquifers is not to be expected if the infiltration water shows low turbidity. The secondary porosity of karst is usually large enough and dissolution of CaCO3 removes the clogging film frequently (Gale, 2005; Stuyfzand, 2017). However, if large concentrations of suspended solids are present in the source water, or if storage in the targeted aquifer is predominantly in the primary porosity of fissures and micro fractures, clogging can become a problem in the course of the project.

4.4.1 Time until Physical Clogging

Physical clogging of the aquifer voids by the particles which are suspended in the injection water can decrease the infiltration capacity considerably and eventually lead to the failure of the MAR scheme (Brown, 2005). Some attempts have been made to estimate the time until physical clogging depending on aquifer characteristics and injection water quality. Masciopinto (2013) estimates the time until clogging (95% loss of fractured aquifer conductivity) as a function of flow rate through fractures, density of the colloids, initial concentration of colloids or suspended solids, number of parallel fractures of the medium, average aperture of the parallel fractures, plane surface area of a single fracture, and hydraulic conductivity. If it is not possible to estimate an absolute time of clogging it might still be possible to qualitatively compare the danger of project failure due to clogging at the different MAR sites based on this approach.

4.4.2 Biological and Chemical Clogging
Biological and Chemical Clogging are not to be expected in karstic aquifers (Stuyfzand, 2017). However, if the aquifer permeability is very low (i.e. groundwater flow is controlled by low primary porosity) biological clogging might be an issue. This is dependent on content of organic material in the infiltration water.

4.5 Expected Lifetime

4.5.1 Time until Technology Failure
The expected lifetime of the entire MAR scheme is of great importance for the overall cost efficiency of the project. Water managers should carefully consider for how long they can rely on the MAR scheme for local water supply and plan new schemes or develop alternative sources in time. Daher (2011) estimates the lifetime of a MAR scheme to be around 20 years while BTD (2016b) considers 30 years.

4.6 Vandalism Proof
If the socio-economic context gives reason to account for project failure due to vandalism or theft, these are some criteria that might be helpful in addressing site suitability.

4.6.1 Visibility of Valuable Parts
Does the MAR scheme have any visible technical parts that would be valuable to looters (in the socio-economic context)?

4.6.2 Surveillance
This criterion scores the surveillance of the MAR facilities by local authorities, operators, or the local community, if ownership includes the community. The assessment should also be done with regards to the remoteness of a site.

4.6.3 Sturdiness of MAR Facilities
The physical sturdiness of the MAR facilities is possibly the most determining factor in the category of vandalism proof. In this assessment it should also be considered how well the facilities are protected from intruders by fences etc.

5 Infrastructure

5.1 Accessibility

5.1.1 Accessibility for Heavy Machinery
A potential MAR site might show very favorable physical properties, but that is of no use if it cannot be reached. This might especially be the case if the site selection is derived from a map of MAR potential. MAR schemes that use deep well infiltration will usually be designed at a larger scale to achieve a reasonable ratio of recharge capacity to investment costs. Heavy machinery will certainly be necessary to construct MAR components of sufficient size. The sites should be rated as to how easily they can be assessed by machinery for construction and by personnel later for operation. Often, the construction of some service road might be necessary but the dimension of the access infrastructure that is needed further complicate the project on different levels, including cost increase, worsening of the environmental impact, and possibly more issues with stakeholders such as land owners.

5.2 Existing Infiltration Wells

5.2.1 Presence of Usable Injection Borehole

“Do not close a well, reuse it.” Escalante et al. (2015) point out in a review of MAR solutions. Reusing existing wells or boreholes for infiltration is beneficial in two ways: It significantly decreases the investment costs of the project because drilling deep wells can be quite expensive. Additionally, making use of a productive abstraction well, or one that used to be productive but has fallen dry due to over-exploitation of the aquifer, guarantees that there is a connection to the network of fractures and conduits. A newly drilled well could by mischance miss the voids that transport the groundwater and run dead in the solid matrix of the carbonate layer. Consequently, the realizable infiltration rate would be very low.

The criterion can be scored on an ordinal scale or measured as the distance between the point of water abstraction and the location of the potential infiltration well. Dry wells or low-yield wells should be preferred.

5.3 Existing Production Wells

5.3.1 Capacity of Public Abstraction Wells

In case of an ASTR scheme, the existence of operating public groundwater production wells downstream of the injection site is beneficial. If the capacity of these wells matches the infiltration rate, or if it can be easily increased, then no new abstraction wells have to be drilled. The wells should be at an appropriate distance to the injection well as to achieve residence times that correspond to the project’s objective and meet potential legal minimums. Existing production wells can be used as a starting point for designing an ASTR scheme, so that infiltration is planned at an appropriate location upstreamt.

5.4 Energy Supply for Operation

Energy might be needed for the operation of the water treatment facilities or potential pumping costs. A MAR scheme that does not require constant energy input would be preferable though.

5.4.1 Proximity to Electricity Lines

The access to the national power grid can be assessed as distance to the nearest electricity line, or on an ordinal scale.

5.4.2 Reliability of Energy Supply

As the presence of a power grid does not necessarily imply constant energy supply, the reliability of the supply can be assessed separately. There might be regional differences in the reliability of energy supply. Sites with regular disruptions of the electricity supply should be omitted, as alternative power supply by generators would make the operation very costly.

5.5 Elevation Energy

If possible, MAR schemes should be constructed in close proximity to the targeted water users. Transportation distances should be minimized and especially elevation differences are critical as lifting water is associated with high costs (Klingbeil, 2017).

5.5.1 Elevation Difference from Abstraction Point to Consumers

As a rough-and-ready approximation for determining the energy required for lifting the abstracted water to its destination the difference in elevation from the abstraction point to the consumer can be estimated.

5.5.2 Required Pumping Energy

If the planned technical details permit it, the energy required to pump the abstraction water to the consumers can be quantified and used to compare the sites.

6 Costs

6.1 Implementation Costs

It may be difficult or impossible to estimate the implementation costs of a MAR scheme at an early stage of the project process when the MCA is carried out. However, as the affordability of the project is a very substantial criterion for any public infrastructure project attempts should be made to estimate costs at least to allow for comparison of the alternatives.

In the Lebanon MCA technical feasibility studies including cost estimates for three of the nine sites were available (Brown, 2005; BTD, 2016a, 2016b, 2016c). Using the costs for the different components proposed in the feasibility studies as a reference, imaginary MAR schemes for the remaining six sides were developed, including rough cost estimates.

6.1.1 Land for MAR Facilities

In a densely populated country like Lebanon, land prizes are high and can contribute significantly to the overall project costs.

6.1.2 Construction

Costs for the construction of the abstraction structure, pipeline system, treatment plant, well and monitoring equipment are summarized in this criterion. The size of the different components depends to some extent on the infiltration capacity of the entire system, which, in turn, is controlled by the quantity of available source water.

6.1.3 Drilling

Drilling costs are depth-dependent, but are also associated with the complexity of the karst; whether there are many voids, difficult geological entrapments, hard overlying layers, or problematic groundwater levels.

6.2 Maintenance Costs

Maintenance costs are annual costs that are necessary for ensuring the proper working of the MAR scheme but they are somewhat different from operating costs.

6.2.1 Spare Parts

The anticipated annual costs of spare parts are largely dependent on the complexity of the water treatment facility.

6.2.2 Maintenance Personnel

The costs for maintenance personnel include wages of technicians employed by the MAR operator as well as costs for sub-contractors tasked with maintenance of the facilities.

6.2.3 Anti-Clogging Measures

Even in karstic aquifers, anti-clogging measures of the infiltration well might sometimes need to be carried out on a regular basis. If the conductivity of the aquifer is high enough and if the source water is clean enough this might not be necessary. Anti-clogging measures include reverse pumping or jetting of the infiltration borehole.

6.3 Operating Costs

The operating costs should be estimated per year and can be subdivided into three criteria.

6.3.1 Pumping Costs

If applicable, pumping costs should be accounted for. MAR schemes that are purely gravity-driven have an obvious advantage.

6.3.2 Treatment Operations

If the quality of the source water makes purification necessary there will be some costs associated with the operation of the treatment facilities. Disinfection materials such as chlorine are constantly consumed and tasks such as cleaning of the sand filter (back-flushing) create costs on a regular basis as well.

6.3.3 Monitoring and Administration

The many uncertainties associated with the complicated geohydrology of karst make close monitoring an essential part of any MAR scheme. Several observation wells might be necessary to monitor the influence of the artificial recharge on the groundwater level in the area. Furthermore, regular groundwater samples should be taken to analyze the quality and detect potential contamination by the infiltration water as soon as possible. The associated costs, together with the costs for administration, should be quantified in this criterion.

6.4 Cost Efficiency

6.4.1 Ratio of Total Cost to Total Infiltration Capacity

In theory, the cost efficiency of a MAR scheme over its entire lifespan can be calculated as the ratio of total costs, including implementation and running costs, to the total amount of infiltrated water. Costs for dismantling the MAR facilities and sealing the injection well after operation is stalled should be included in the total costs. As this criterion represents a combination of recharge capacity, lifespan, and costs it should only be used instead of the three composing criteria, not in addition to them. This would result in double counting, artificially adding weight to these criteria.

6.5 Reversibility

6.5.1 Costs of Deconstruction

In case of a failure of the MAR scheme, or in case of stalled operation after the planned lifetime, the MAR facilities need to be deconstructed. Furthermore, the infiltration wells need to be sealed properly, to protect the groundwater from contamination. These costs should be included in the overall project costs.

6.6 Availability of Funding

The possibilities of (co-)financing the MAR scheme with loans or funds for specific objectives can be manifold. National and international organizations can provide money for the project, but the financing is usually aimed at a certain goal. Fulfilling the donor's requirements is dependent on the specific MAR project.

6.6.1 Funding for Regional Development

Financial support for development in specific regions (e.g. rural areas) could be a source of funding. MAR sites in (semi) urban areas would score less good in this example.

6.6.2 Ethnical or Socio-economic Support

Conceivable could also be funds targeted at improving the livelihoods of specific ethnical or socio-economic groups. If it can be argued that the project's location serves this goal this could be a means of financing the MAR scheme.

6.6.3 Climate Change Mitigation Funds

Recently, large climate change mitigation funds are available, often from international organizations. As precipitation patterns are likely to be altered due to climate change MAR schemes are valid measures to mitigate its effect on drinking water supply. A number of countries already have good experiences with financing alternative water supply projects through global climate funds. Often, these funds address especially large projects (Klingbeil, 2017).

6.6.4 Research Funds

MAR schemes that are properly monitored can have a great value for research. As outlined before, there is not much experience with MAR in karst globally. Promising MAR designs might be implemented as pilot projects and could perhaps be (co-)financed by research initiatives.

6.7 Cost Recovery

6.7.1 Financing by Water Users

Recovering the implementation and running costs of the MAR scheme directly from the water users is a sound method to ensure the financing of the project. If the project is designed to generate a profit, private investors can be found to cover the initial costs. Possibly, public private partnerships can be set up. However, a number of conditions have to be met to allow re-financing by passing on costs to water users. The price for the abstracted water has to be competitive and affordable for the consumers. Water consumption has to be metered, which is often not the case in developing countries. Charging water consumers for the costs of the MAR scheme will increase its bureaucratic complexity. It requires a strong, uncorrupt water authority that can enforce the pricing. The possibility that re-financing the project costs should be rated on an ordinal scale and in a comparative manner.

7 Stakeholders

7.1 Future Competition for Source Water

7.1.1 Planned Water Infrastructure Projects

This criterion is to assess the probability that the source water availability will be impeded by possibly implemented water projects that would utilize the same source water. In an ideal setting, of course, water management is done holistically by a uniform water authority and with long-term planning. However, water management is often political and infrastructure projects might be implemented regardless of the current situation. On the other hand, planned projects might never be implemented because circumstances change or funding does not become available. While it might be difficult to make assumptions about the effect of possible future projects on the planned MAR scheme, this criterion can be used to do so in a comparative, qualitative assessment.

7.2 Stakeholder Buy-In

Different groups of stakeholders should be identified and their support for the MAR project assessed. It is of great importance to involve key stakeholders in the project at an early stage (Klingbeil, 2017). A comprehensive stakeholder analysis can be very time consuming. The following criteria represent possible groups of stakeholders that should be identified with the knowledge of local experts.

7.2.1 Holders of Water Rights

Criterion for assessing possible issues arising from conflicts with holders of legal or customary water rights. In Lebanon, most springs have water use rights and cooperation with the water right holders needs to be established.

7.2.2 Upstream Stakeholders

Buy-in of stakeholders situated upstream of the MAR site, such as industries that might need to install waste water treatment schemes owing to the MAR project.

7.2.3 Downstream Stakeholders

Buy-in of stakeholders downstream of the abstraction point. Their approval of the project is important as unannounced reduction of the water source might have serious implications on the livelihoods of downstream water users.

7.2.4 Landowners

Buy-in of landowners that would be affected by the MAR project; acceptance of those who would have to permit construction of MAR facilities on their land or be willing to sell it.

7.2.5 Facility Owners

Buy-in of property owners that would be affected by the MAR project or that would need to cooperate, such as owners of irrigation channels used for water supply or operators of wells to be used for infiltration/abstraction.

7.2.6 Environmental Protection Organizations

The influence of environmental organizations and their approval of the project can be determining for the success of a MAR project. If NGO's are included early on in the project they can be a valuable multiplier for promoting acceptance of the MAR scheme. While there is some environmental impact associated with any MAR project, environmental organizations might be convinced of the project if the entire water problem is made understood and the impact of alternatives, such as storage dams, is laid out.

7.3 Expropriation

7.3.1 Area of Land to be expropriated

Especially in densely populated areas land might need to be expropriated from individuals to construct the MAR facilities. The project management should always include landowners at an early stage and possibly aim for ownership of the facilities by the landowner. If it is not possible at the stage of carrying out the MCA to determine the particular landowners and assess their buy-in of the project a suitable proxy is the area of land that would need to be expropriated for the project.

7.4 Public Acceptance

Additional to the buy-in of different groups of stakeholders the support by of the project by the general public can be important. This category aims at assessing the acceptance of a certain project in the general public debate, if there is any.

7.4.1 Public Perception of the Project

It might be possible to assess qualitatively if the general public and especially the local community affected by the project are in favor of the particular MAR scheme at the planned site.

7.4.2 Public Understanding of local Groundwater Stress

If the public understands the concept of groundwater stress and knows about the local groundwater situation the measure is more likely to receive public support. Especially where groundwater stress has not yet affected the water supply the general understanding of the issue is important. If groundwater levels are generally falling or salinity values are increased but wells have not yet fallen dry and groundwater can still be used for its designated use the public might be reluctant to the project as problems are not yet apparent.

7.4.3 Perception of Current Water Supply

As groundwater and the concept of groundwater stress are somewhat abstract and often not known to the public an alternative criterion could be to assess the public perception of the current water supply. If this is already insufficient it is safe to assume that people would be in favor of a project that strengthens the public water supply.

7.4.4 Acceptance of Infrastructure or Water Projects

Civil engineering works carried out by the government might face principal opposition, regardless of its goal. This criterion can be used to assess the public’s general attitude to infrastructure or water projects in the particular region.

7.4.5. Stigma of Water Source

While groundwater is widely used as a source for water supply there might be local stigmata associated with the groundwater or the water source used for infiltration. These could be spiritual or based on bad experiences with either water. Education, public debate, and demonstrations of water use from the stigmatized water source could help to overcome the issue.

7.5 Social Priority

7.5.1 Number of People to directly profit

A simple proxy to compare the proposed MAR schemes with regards which site would serve the most people would be to count how many people or households would directly profit from the MAR scheme. If the recovered water is pumped into an existing supply or irrigation network, all households connected to this network would profit from the MAR scheme.

Note that this criterion does not evaluate the need for water of the people to profit from the project, nor does it assess the economic benefit of it.

7.5.2 Allocation for Priority Water Use

Different decision makers, donors, or implementing authorities could have varying objectives regarding who should profit from the MAR project. This research was carried out embedded in a project that was initiated with the objective to support Syrian refugees in Lebanon. Other projects might aim at improving irrigation agriculture or foster urban water supply.

If a priority water use has been identified by the project management it should be assessed to which extend the proposed MAR schemes would benefit this use. Consequently, the alternatives can be compared regarding their performance in fulfilling the donor’s objective of providing water supply for a specific purpose. Comparison should be based on a qualitative rating and often a rather large estimation uncertainty needs to be accounted for.

8 Governance

The governance theme accounts for aspects related to the legal and administrative context of the project. If the potential MAR sites all lie within the same region the scores of some criteria might be the same for all alternatives. In this case they can be left out, as the MCA would be insensitive to them.

8.1 Inter-Agency Issues

8.1.1 Involved Authorities

The number of authorities involved in the MAR project can be a simple proxy for assessing potential complications in the field of governance. The underlying assumption: The more agencies need to cooperate, the more complicated the implementation of the project gets.

8.1.2 Local vs. National Authorities

Decentralized projects, i.e. projects carried out by local or regional institutions, are usually preferable to those implemented by a central authority (Klingbeil, 2017). However, regional water authorities can also create complicated interagency issues: For example can have national, centralized authorities a broad agenda that is very different from that of the involved local agency. Conflicts might especially arise if the agencies have different objectives because one authority is publically elected while the other is centrally appointed (NRC, 2008).

The focus and structure (local vs. national) of the involved authorities and the arising conflict potential should be assessed on an ordinal scale.

8.1.3 Water Authorities vs. Other Authorities

Several authorities of similar importance might be involved in a MAR project and the purpose of the different authorities will determine to which extent they are supportive of the project. Environmental protection agencies might oppose a MAR scheme if it negatively impacts the water source and energy agencies might disapprove the storage of river water that could potentially be used for energy production.

8.2 Source Water Rights

8.2.1 Existing Water Abstraction Rights

Often, the targeted water source will already be used and possibly legal or customary water abstraction rights are granted to specific individuals or communities. In Lebanon, almost all springs have existing water abstraction rights and a future MAR project will have to take this into account (UNDP, 2014). It should be assessed to what extend existing water abstraction rights would impede the source water availability. As recharge should only be done when surplus water is available (e.g. during the rainy season) there might not be an issue with existing water rights, but the cooperation of water right holders is still necessary.

Assessment could be done by comparing the granted abstraction permits or the total permitted abstraction rate for each source. If these data are not available or are not informative the rating should be done qualitatively, i.e. on an ordinal scale.

8.3 Ownership

8.3.1 Reliability of Profit

In case the MAR scheme is owned and operated by a private institution or as a private-public-partnership the reliability of profit is one important factor for the success of the project. If the owner is hindered to make a profit of operating the MAR scheme, e.g. by inefficient revenue collection system, corruption, or unlawful use of the abstraction water without payment (water theft), it can be assumed that the involvement of the owner will phase out. If the project is operated as “for profit” then the institutional setting must be such that the owner can reliably profit from his investment, otherwise maintenance and operation of the MAR scheme are jeopardized. The institutional setting and the socio-economic environment can differ from site to site and should be assessed qualitatively.

8.3.2 Strength of Accountability or Public Control

If the MAR scheme is operated by an owner to serve the common good or other water users besides themselves, accountability mechanisms should be in place to assure that the owner fulfills maintenance and operation standards. A MAR scheme owned by a regional water authority which is democratically controlled (e.g. by an elected board) is associated with a strong accountability. Accountability and public control can also stem from media coverage of the project or deep involvement of well-connected stakeholders.

8.3.3 Owner’s Ability to do Maintenance

The owner should have the financial and structural properties to carry out reliable maintenance of the MAR scheme. The simpler the technology, the better. A MAR scheme owned and operated by a community with the means to also carry out the necessary maintenance has great advantages over larger projects implemented with one-time donor investment and then handed over to weak institutions that have difficulties with the maintenance. The knowledge and capacity of local contractors or maintenance personnel of the owner need to match the complexity of the MAR scheme (see category 4.3).

8.3.4 Acceptance of Owner by Local Stakeholders

Local stakeholders, especially owner of land the MAR scheme is built on, holders of source water rights, users of the recharge water, and influential groups/individuals should be supportive of the owner of the MAR scheme. If there exists strong resentment against the future owner by the local community friction, problems, or a boycott might occur during implementation of the project.

8.4 Trans-Border Issues

8.4.1 Flow across Borders

There are numerous examples for transnational water conflicts. In the case of MAR, two potential conflict sources were identified. The first criterion is meant to assess the conflict potential of infiltration water that crosses the country's borders. While generally it can be assumed that everyone would be supportive of increased groundwater resources, governance would be complicated by the necessary cooperation of two nations. Without involvement of the neighboring country there might arise disagreement over the quality and quantity of the injected water. If the groundwater level is raised so much that it damages buildings or crops liability issues arise. It is assumed that a MAR project on the territory of only one country has a greater chance of success than a transnational project.

8.4.2 Issues with Downstream Countries

Tapping rivers for infiltration water might significantly decrease the water available to downstream countries. It should be assessed if this could lead to problems and if the approval of the neighboring country is necessary. Possibly a joined river management institution is in place or can be set up. The project could then be implemented with input of this international institution. If necessary, the abstraction rate for the MAR project should be adjusted to balance out the water needs of the upstream and downstream country.

8.5 Political Instability

Safety and political stability are important prerequisites for any infrastructure projects. At the same time not all types of conflicts would hinder the implementation of a MAR scheme and often the demand for improved water supply is especially big in conflict regions.

8.5.1 Regional Conflicts

Under this criterion the safety situation with regards to regional, both national and international, conflicts should be assessed. In Lebanon, for example, the war in Syria jeopardizes the security situation in the border regions. In the south, Hezbollah controls large parts of the country.

8.5.2 Local or Ethnical Conflicts

Religious or ethnical tensions can be very local and difficult to foresee for outsiders. Consultation with local experts and members of the community should take place before field work is started, especially if the experts to carry out the field work come from a different ethnical group. Water supply can be a sensitive topic and it is sometimes organized along hierarchical structures of the local community which are reluctant to any change in the system. Previous or present local conflicts that are related to water or that could impede the implementation of the project should be assessed.

8.5.3 Corruption

Corruption is another threat for a project's implementation. Klingbeil (2017) drafts a scenario where high-rank officials could profit from insights of the planning process by privately buying land at the locations assessed to be most suitable for MAR to later demand high expropriation prices, paid for from the project budget.

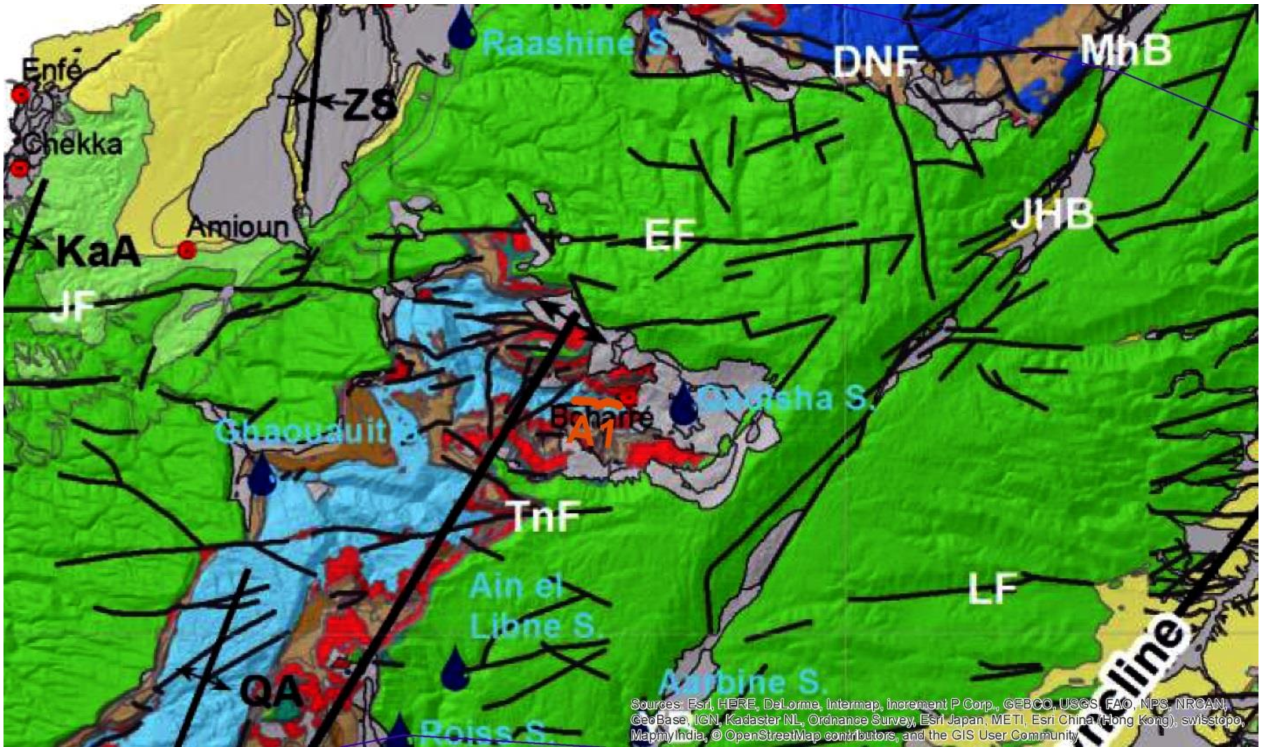
Like most of the criteria of the theme 'governance' it might be rather difficult to quantify the extent to which corruption might endanger a MAR scheme at a certain site but a qualitative comparison might be possible. Differences in the extent to which corruption might threaten the project could be different water authorities, different forms of ownership, the structure of the local water supply system, but also the social control of the local community.

Appendix III: Site Description

A1

Situated along the upper course of the Abou Ali River, a potential MAR project at the A1 location would infiltrate water into the Jurassic J4 aquifer in a relatively steep river valley in the high mountains. As the topography slopes significantly towards the Mediterranean in this area, a rather large groundwater gradient or high flow velocities are to be expected. UNDP (2014) only provides data for the Abou Ali River as an entity so that the stated discharge of 12 m³/s is likely to be over-estimated. The MAR project would recharge the northern part of groundwater basin no. 16, which extends far into the south along the Lebanese coast.

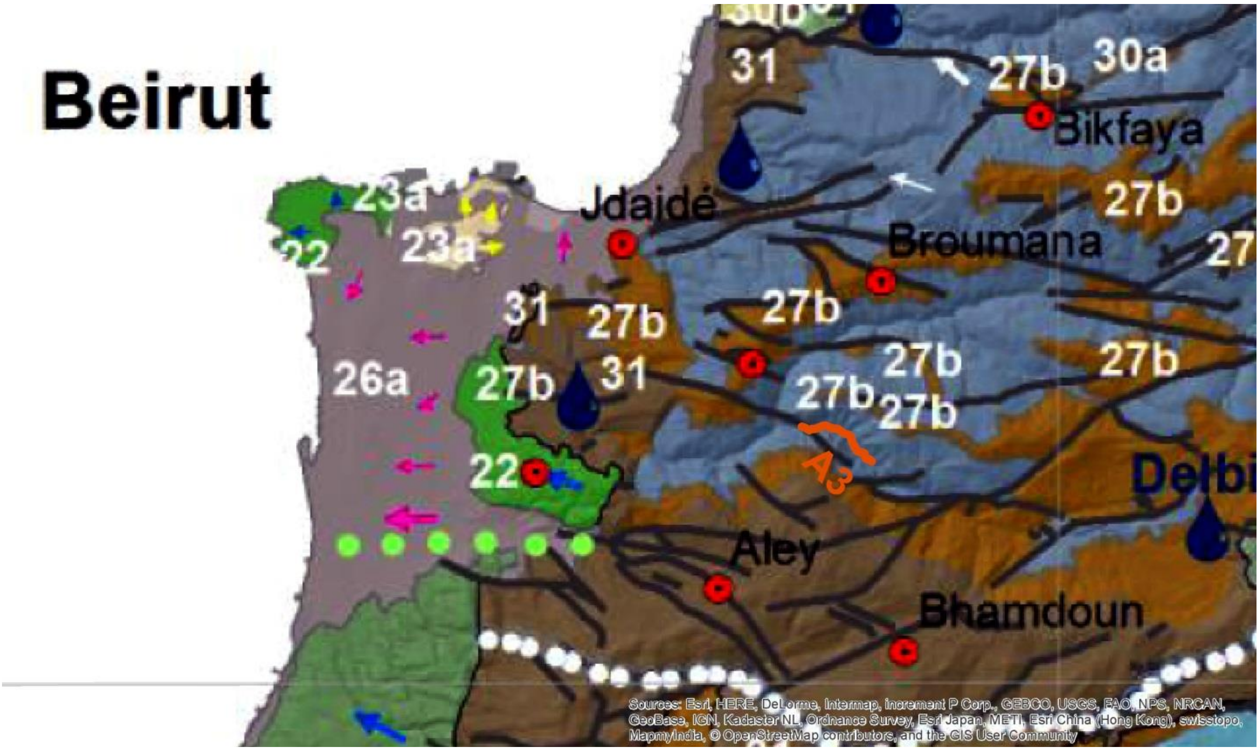
Figure *next map* shows the complicated geological setting of site A1. It is located just on the outcrops of the Jurassic layer (light blue). Infiltration into surrounding groundwater basins of other geologies is likely, as Margane (2012) found an interaction of groundwater basin 16 with cretaceous aquifers in the recharge area of the Jeita spring, located in the south of the groundwater basin. Quadisha Spring around 2.5 km upstream of the proposed MAR site is the source of the Abou Ali River. There are three short secondary faults intersecting the recharge zone. Around two kilometres downstream the North Mound Lebanon Anticline (NMLA) almost perpendicular intersects the river and the general direction of groundwater flow. This could be advantageous for a MAR project. Uplifting of the Western part of the layer along the anticline raised the underlying Triassic aquitard with respect to the Eastern part above the level of the lower part of the Jurassic aquifer. Potentially, this might act as a natural vertical barrier of the groundwater flow and could help to store water that was infiltrated upstream of the anticline. Tracer tests would be able to indicate if the water injected in wells along the proposed stretch of the river would end up and stay at the geological barrier or if flow paths and retention times are less suitable for a MAR scheme. The difficult geology, the mountainous topography suggesting quick groundwater flows and the large number of springs in the area might indicate difficulties for MAR. However, river water quality is likely to be superior to those sites situated further downstream of springs. Another benefit of the location is, in fact, its elevation and the resulting energy savings when groundwater is used to supply consumer in lower-lying regions.



A3

This MAR site lies at the southern end of the Jurassic groundwater basin no. 16, just west of Beirut (see figure *next map*). It is situated in the lower parts of the valley created by El Maten River, just before its confluence with Beirut River, from which the infiltration water is to be diverted.

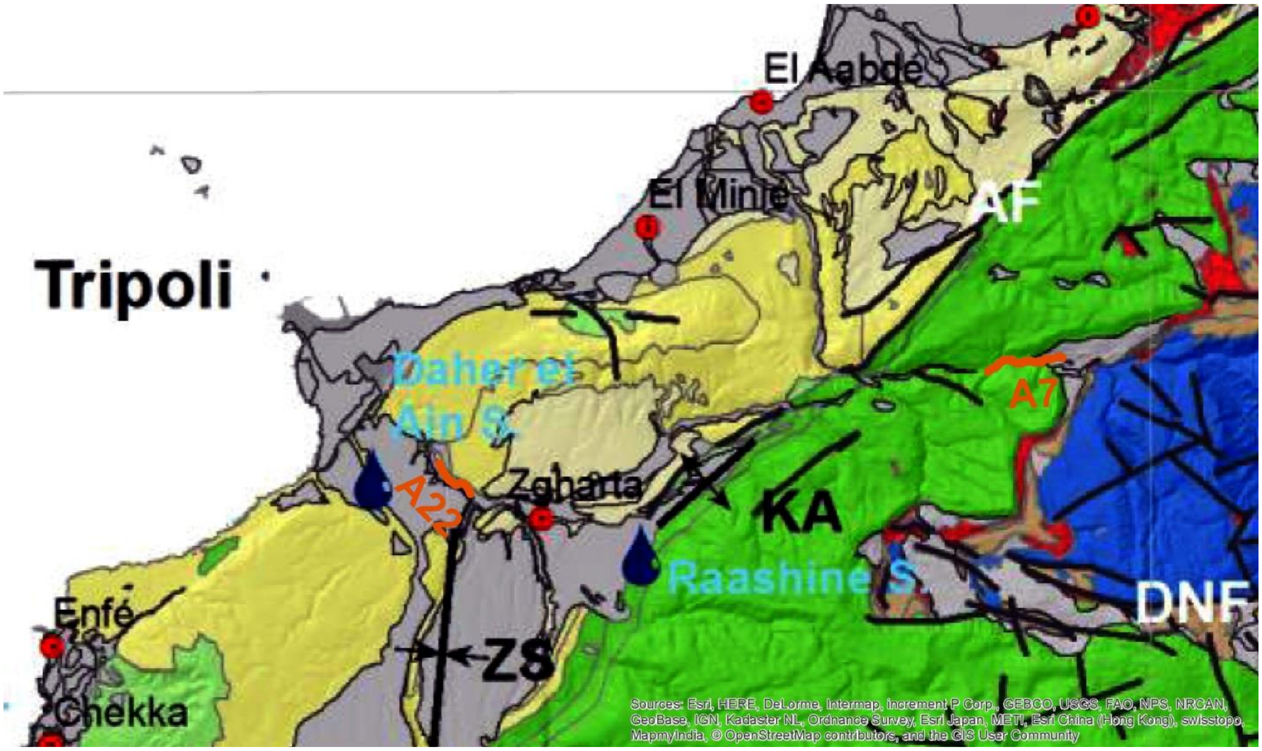
Tracer tests in the valley along Beirut River found travel velocities of 4 cm/s and 2.3 cm/s (UNDP, 2014). Other tracer tests of the aquifer carried out 10 km further north found that not all of the tracer could be retrieved, possibly indicating deep percolation or storage in fissures and karst pockets (Margane, 2012). A secondary fault transects the MAR area in WNW-ESE direction and extents at least 5 km in the approximate direction of groundwater flow in this region. If the fault is not filled or smeared it could have caused increased infiltration and consequently enhanced $CaCO_3$ dissolution, possibly developing preferential pathways. A MAR project would have to make sure to determine flow paths along this fault. If the there is indeed a conduit system along the fault retention times might not be suitable for MAR. In this case a MAR project at this site would have to keep a certain distance to the fault with infiltration preferably taking place downstream of the fault. However, the fault depicted in the geological map provided by UNDP (2014) does not necessarily impede a MAR project. Factors that are believed to complicate a MAR scheme at this location are insufficient river water quality and land availability.



A7

The MAR site is situated in the highly over-exploited Cretaceous groundwater basin no. 18 near the city Tripoli in northern Lebanon. The proposed location stretches along the lower part of the El Bared River valley, that is at 2% slope still relatively steep. The general direction of groundwater flow is oriented SW and this might be enhanced by two secondary faults oriented in the same direction (see figure *next map*). The Akkar Flexure (AF) with a similar orientation might act as a hydraulic barrier in NW direction (*speculation*).

A MAR project at this site would require more tracer tests or a well-monitored pilot scheme (possibly using existing wells), as data that would hint at flow paths or travel velocities are missing. A benefit of this site would be the relative reliability in water supply by the El Bared River which discharges >5 m^3/s during 10 months per year.

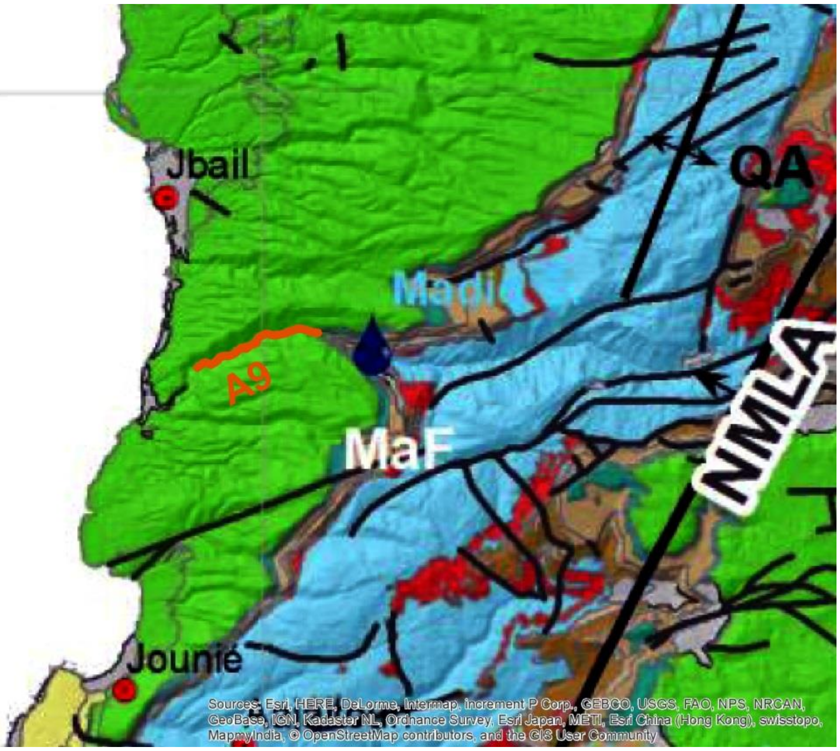


A9

This proposed MAR site lies close to the coast in a region where the Cretaceous C4-C5 aquifer outcrops parallel to the coastline, limited by the surfacing Jurassic layer in the East (see figure *next map*). The geological layers are thus inclined towards the Mediterranean Sea so that the Cretaceous groundwater basin no. 21 is in direct contact with the ocean which leads to considerable saltwater intrusion.

At the interface of two geological layers, just upstream of the MAR site, the Madiq Spring is located. It might be a potential source of clean infiltration water (*speculation*).

A submarine spring was mapped just north of the river’s mouth off the coast. This could indicate conduit flow through the aquifer into the ocean. A MAR project would have to be carefully designed to not recharge one of these preferential flow paths. Perhaps it would be more promising to recharge the underlying J4 aquifer which is unlikely to be directly connected to the sea.



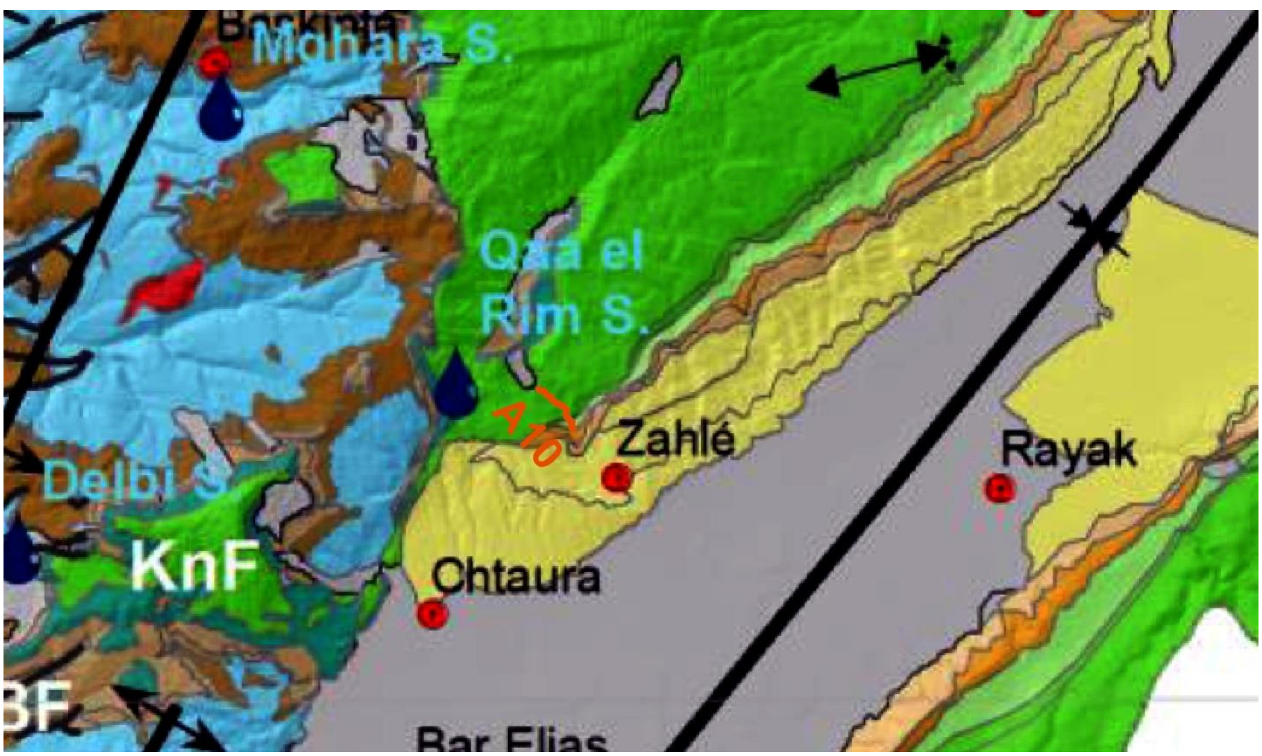
A10

As one of two selected sites in the Bekaa Valley, A10 is situated along a reach of Berdouni River, a tributary to Litani River. The proposed MAR scheme would recharge the southern part of the large Cretaceous groundwater basin no. 3. The geological layers are inclined (roughly due east) towards the syncline of the Bekaa Valley. At the site the Berdouni River slope is rather steep at around 5%. The river is fed by a number of springs that occur along the Yammouneh fault where aquicludes are uplifted and block off the important C4c aquifer, generating the Qaar el Rim spring and others.

A10 is one of the three sites for which a comprehensive technical feasibility study is available, carried out by BTD (2016c). The authors suggest implementing an ASR scheme using 5 - 6 dual-purpose wells that would inject river water during January – April and produce groundwater when it is needed during the summer period. An estimated 2 MCM would be recharged over four months, corresponding to a recharge rate of 250 l/s. The recharge volume roughly equals the planned increase in production of public wells to supply the city of Zahle, which the MAR scheme would serve.

The river water is of insufficient quality, due to untreated wastewater discharges of upstream factories (including a paper factory) and settlements. The turbidity is usually below the Lebanese standard of 5 NTU but can peak to 465 NTU after heavy rain events. Consequently, extensive pre-treatment is proposed, including coarse screening, sedimentation, rapid sand filtration, and disinfection by chlorination. Two design alternatives are proposed, with estimated costs of US$ 2.8 million for either design. An estimated US$ 0.9 million could be saved by an advanced management option, where river water would only be abstracted when turbidity is low enough (thus not after heavy rainfalls). Chlorination alone would then be sufficient treatment so that large sedimentation as well as filtration basins would need to be built. This option would require sound monitoring and reduce the total infiltrated water by an estimated 25%.

The geology of the MAR sites led the authors to propose an ASR instead of an ASTR scheme, which intuitively would seem like the option of choice for MAR in a mountainous karst aquifer. The C4-C5 aquifer outcrops only over a short stretch of the river (see figure *next map*). The geological layers are steeply inclined, so that the aquifer is blocked off by the aquicludes underlying the quaternary deposits of the Bekaa valley in the general SE direction of groundwater flow. An ASR scheme would profit from this sort of confinement. However, as a consequence of the inclination, the longitudinal hydraulic conductivity (kx) of the aquifer is oriented downwards towards the Bekaa syncline. There is uncertainty about whether water flows through the C4-C5 layer to its deepest part around 2000 m under the surface of the Bekaa Valley, where it would be lost for conventional water supply. The number of productive wells in the area suggests, however, that much groundwater is retained in the lower parts of the aquifer at the A10 site. The inclination of the aquifer might pose another problem: As kx is usually the highest conductivity in an aquifer, the recharge plume is likely to migrate along this direction downward – and upward, if lateral dispersing is little (low ky values). This could cause flooding, if the recharge rates are too high. However, pumping tests in an existing well close to the MAR site have revealed transmissivity values of almost 4000 m²/d, a large (but not too large) value, suggesting high possible recharge rates. The wells are proposed to recharge the lower parts of the C4c and C5b aquifers where karstification is relatively pronounced, at depths of 400 m and 350 m respectively.



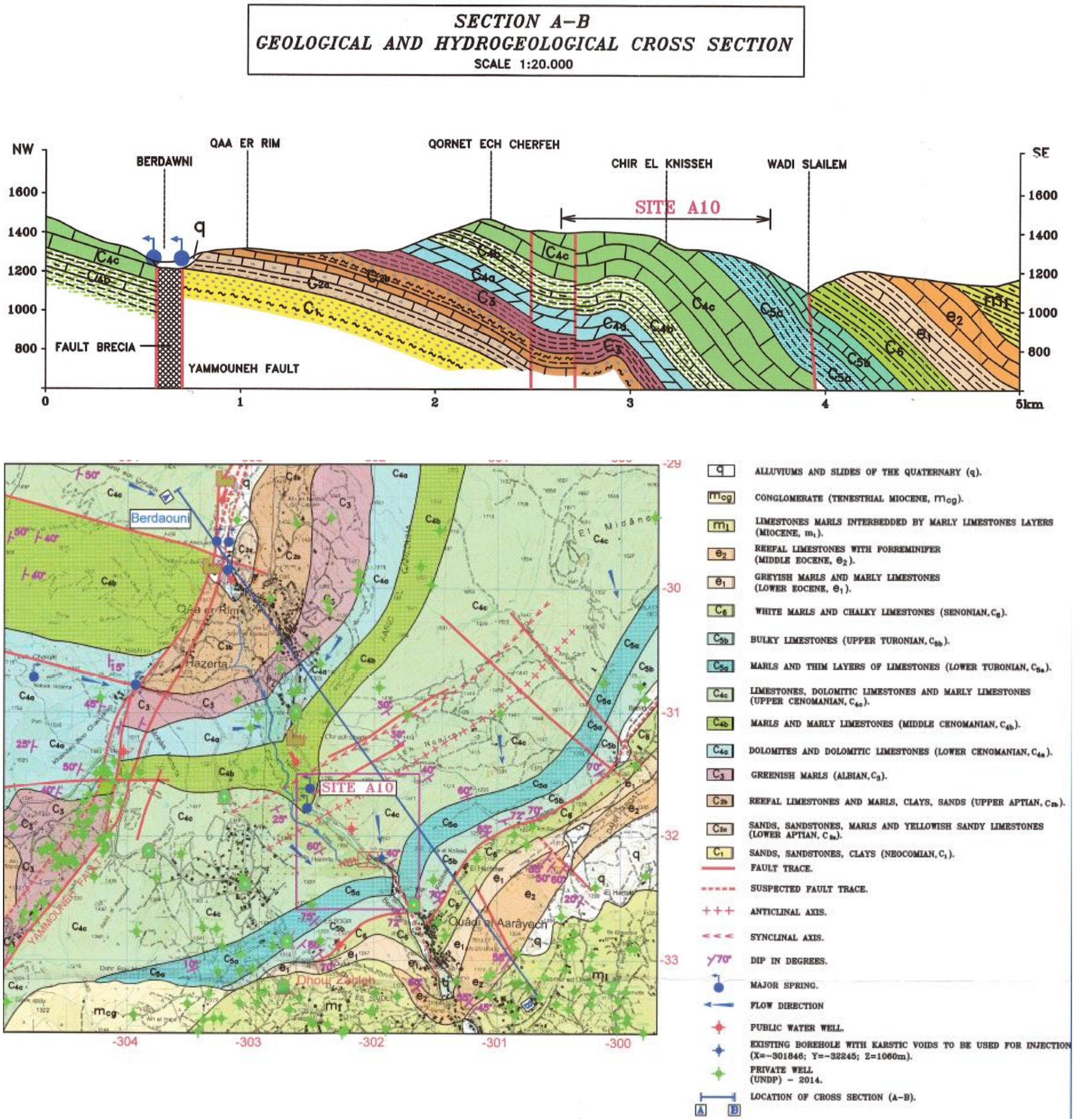


Figure x: Geological and hydrogeological map of Wadi El Aarayesh Berdawni River site A10 (BTD, 2016c) *maybe put in appendix*

A14

This site has been proposed for a MAR project in several studies before the recent UNDP report (Daher et al., 2011), possibly because the groundwater of the area plays an important role in Beirut's water supply and has been subject to seawater intrusion due to over-exploitation since the 1960's. BTD (2016a) carried out a technical feasibility study for the MAR project.

Injection water would be abstracted from the Damour River which has a reliable water supply thanks to its relatively large catchment with considerable runoff originating from snow melt. The

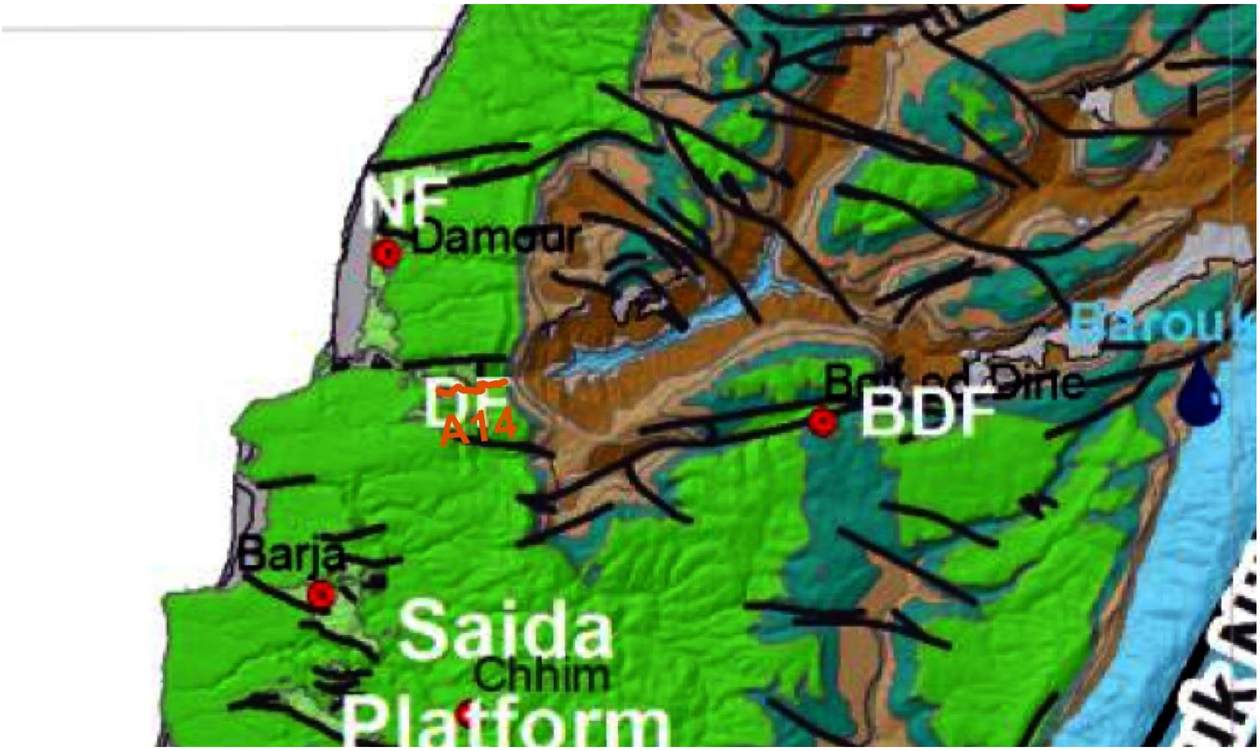
MAR project is proposed to recharge two Cretaceous aquifers: The shallower C5b aquifer which is brackish due to seawater intrusion and the lower-lying C4c aquifer which is still fresh but shows rising salinity levels (possibly due to perforation of the aquiclude by the large number of illegally drilled wells). The geological layers are inclined by approximately 20° and slope towards the west, “dropping” into the Mediterranean Sea. The proximity to the Damour Fault (DF, see figure *next map*) might threaten a recharge project at this site as there is a chance of preferential flow pathways along the fault transporting recharged water into the sea.

Two different MAR scheme designs are discussed by BTD (2016a). As well as earlier studies drafting MAR projects in the area, they suggest infiltration but in two galleries that are to be dug perpendicular to the river on the right side of the valley instead of infiltration through wells. However, the well option, being much cheaper, is also briefly presented in the feasibility study.

The galleries would be oriented parallel to the coast line and one tunnel would extent horizontally 1100 m into the C4c aquifer while the other would extent 1300 m into the C5b aquifer. This design would spread out recharge to benefit most public wells of the Beirut water supply which are located around the town of Mechref, to the north of the river. At the same time this design would counteract seawater intrusion. Since the geological layers are significantly inclined and overlain by aquitards they are somewhat confined and direct flow into the sea is unlikely, except from flow through large conduits along e.g. the Damour Fault. Any large voids detected in the galleries would be cemented to foster infiltration into the fissure system instead of the conduit system.

There are a number of advantages of this MAR design over well infiltration: Recharge is spread out more homogeneously and chances of obtaining high infiltration rates into the fissure system while avoiding fast-flowing conduit systems are higher. To create a hydraulic barrier against seawater intrusion an elongated recharge design is more effective than point recharge. The public wells to benefit from the project are situated on the plateau to the north of the river, more than 200 m above the river. Since the openings of the galleries are almost at the elevation of the river no pumps are required to lift the water to the point of recharge, as would be the case if recharge was to be done by wells drilled upstream of the public wells.

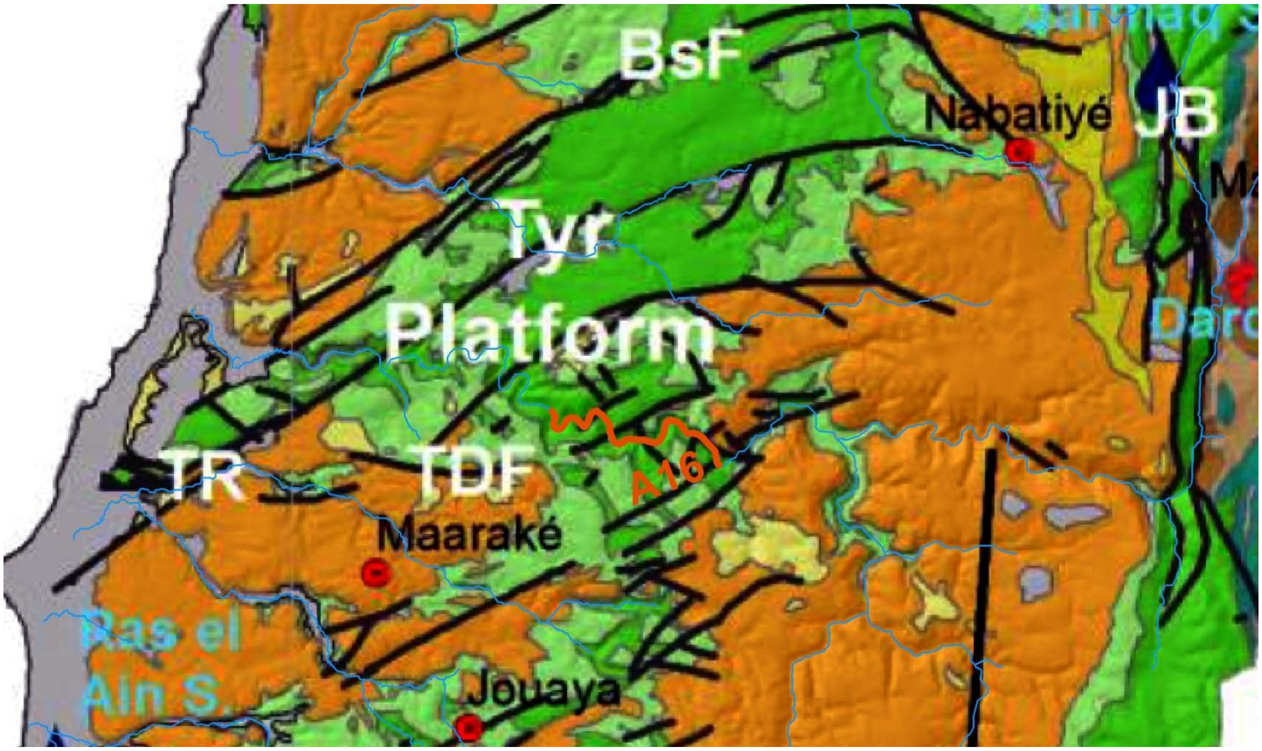
However, there is no experience with this design of a MAR scheme. The estimated costs are at US$ 18 million considerably large for a project of “experimental character”. The authors mention that a cheaper alternative could be to drill infiltration wells next to the Damour River. High static groundwater levels might jeopardize this option though, as sufficient recharge rates would be more difficult to realize and local drilling industry would have significant problems with these circumstances. To achieve the infiltration rate of 600 l/s BTD (2016a) proposes six wells to recharge the C5b aquifer over its entire extent (125 m deep) and six wells to recharge the C4c aquifer at depth of up to 250 m. Even though several authors favour the tunnel option at site A14, in the multi criteria analysis (*section MCA*) well recharge will be assumed to make A14 comparable to other sites.



A16

This proposed MAR site lies in the south of Lebanon where the coastal mountain range is less high. It is located in the lower reaches of Lebanon's longest stream, the Litani River. At the site the southern parts of the Cretaceous groundwater basin no. 19b outcrop in-between Ecocene Marls, depicted in orange in figure *next map*. The relatively long section for the proposed MAR site is crossed by five secondary faults with lengths of 0.5 – 4 km oriented in SW direction, which is also the general direction of groundwater flow. The aquifer does not show increasing salinity levels, but it is stressed by over-abstraction (UNDP, 2014). An estimated 500 private, unlicensed wells can be found in the area (Daher et al., 2011).

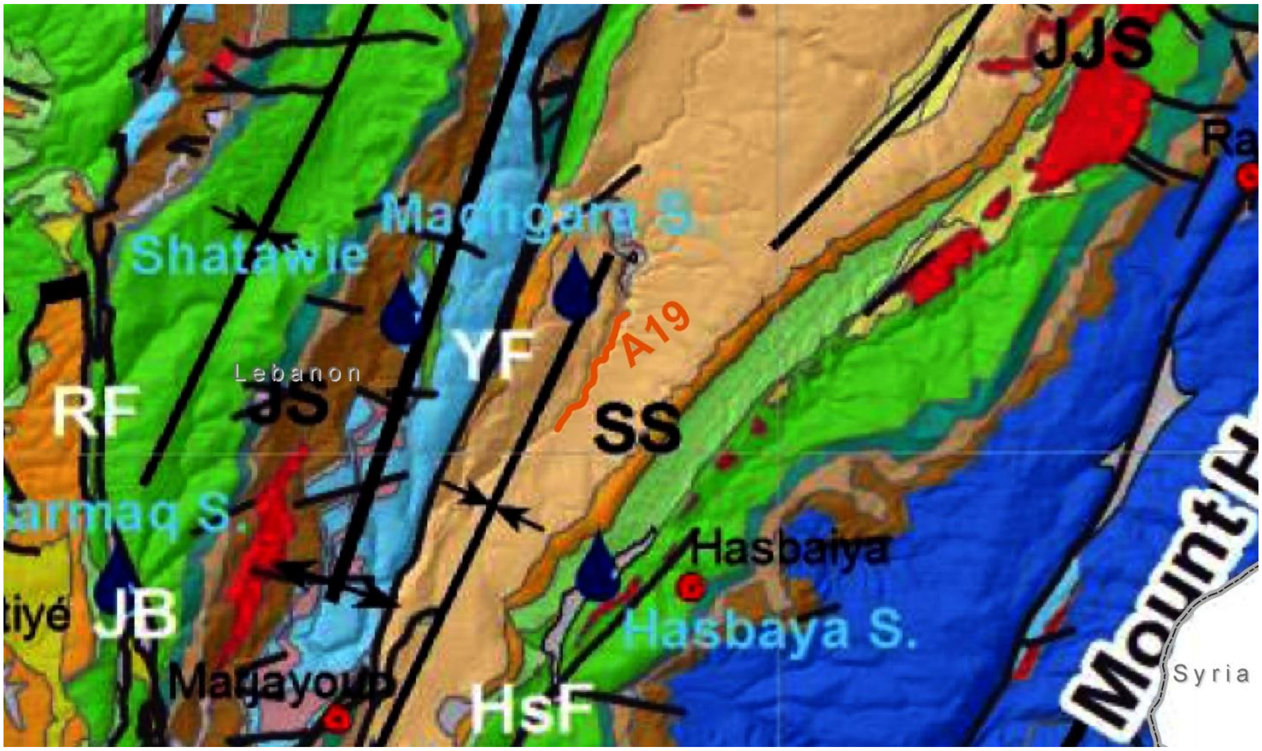
There are no karst features like dolines or caves in the vicinity of the site, which indicates that the aquifer might be less karstified than other Cretaceous aquifers of the Lebanese mountain range to the north. The site extends over 6.5 km along the mostly uninhibited valley of the Litani that is cut into the hills of the coastal plain. The general topography slopes only mildly in this region and the gradient of the river bed is at 0.6 % relatively small. Possibly, the aquifer, too, shows rather small inclination and a horizontal orientation of the longitudinal hydraulic conductivity. Together with the fact that there are no apparent signs of strong karstification this could be interpreted as favourable circumstances for a MAR project. However, there seem to be fewer hydrogeological data available for this part of the country (e.g. cross sections of the geology, tracer tests, pumping tests etc.), so that more field work is essential for adequately assessing the site and comparing it to others. A challenge would be the insufficient water quality with elevated faecal coliform values (Cadham et al., 2007).



A19

The proposed MAR project is to recharge the Ecocence limestone aquifer e2b of groundwater basin no. 4 in the south of the Bekaa Valley. It is situated parallel to the Sohor syncline (SS) that crosses Litani River downstream of the MAR site (see figure *next map*). The A19 site lies around 12 km downstream of the Qaraan reservoir. Much of the water downstream of the reservoir is diverted into a tunnel to be used for electricity production on the other side of the Lebanese mountain range. For this reason the Litani River falls partially dry upstream of the MAR site. A number of springs along the Sohor syncline feed the river but it should be validated that there is enough discharge at the section proposed for the MAR project to infiltrate sufficient quantities. The water quality is better than at the A16 MAR site but faecal coliform values are well above drinking water standards (Cadham et al., 2007). The general direction of groundwater flow in the area follows the orientation of the river due SSW and the river bed slopes gently at 0.6 %.

Pumping tests carried out in the Ecocene aquifers in the Bekaa Valley (though not at the proposed MAR site) determined transmissivity values ranging from 0.34 m²/d to 440 m²/d with the well closest to site A19 showing a transmissivity of 3.4 m²/d (USAID, 2014). The large range is not unusual for karstic aquifers, however the values are considerably lower than the desirable 1000 – 4000 m²/d. This might indicate a lower degree of karstification as compared with Cretaceous aquifers that are older and have been subject to dissolution processes for longer. One needs to keep in mind that the heterogeneity of karst principally does not allow to extrapolate hydraulic properties derived at one point to the entire aquifer, so these transmissivity values are only indicative.



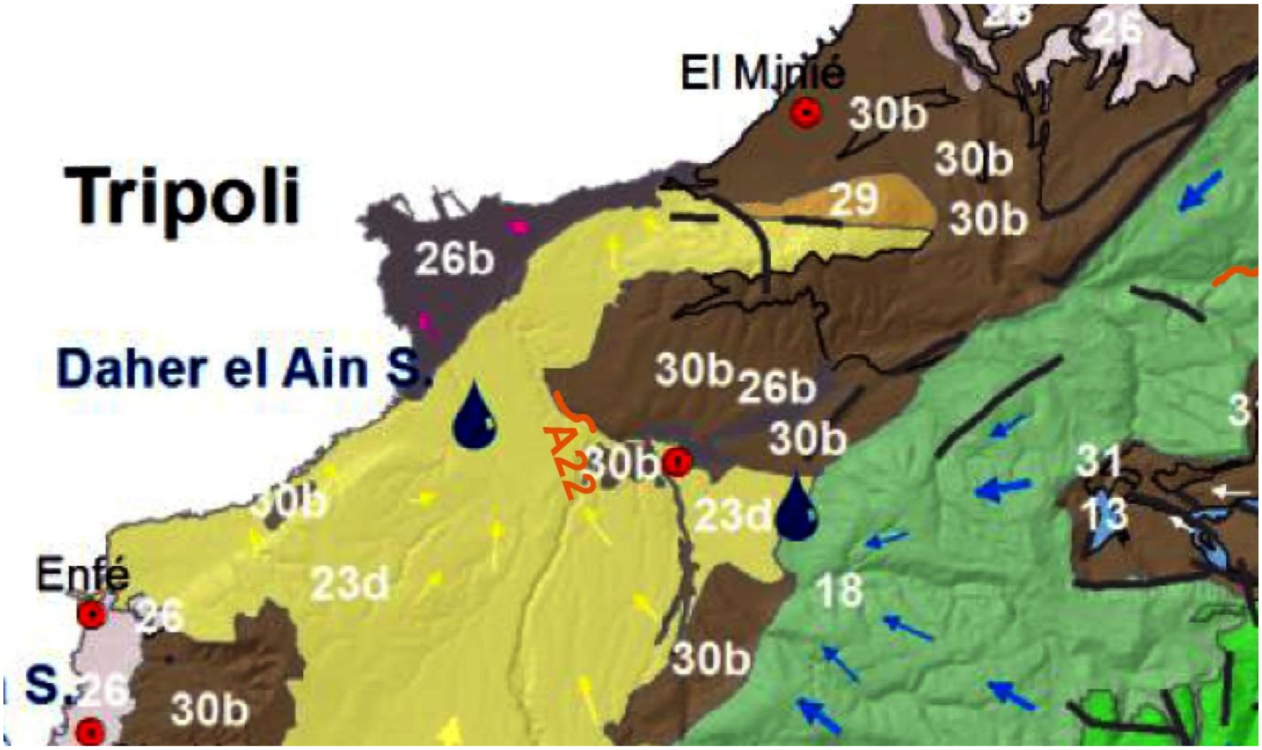
A22

This proposed MAR site is situated in the north of Lebanon just east of the city of Tripoli. It is situated along the lower reaches of the Abou Ali River in rather flat terrain with a river bed slope of 0.5 %. The Miocene limestone groundwater basin no. 23d is to be recharged. It is highly over-exploited, showing decreasing groundwater levels and increasing salinity levels. The aquifer is described to be highly karstified (BTD, 2016b). A fault in NE-SW direction lifted up the Eocene formation on which Tripoli lies, depicted as groundwater basin 26b in figure *next map*. Since this Eocene layer is impermeable the fault constructs a hydrological barrier perpendicular to the direction of groundwater flow of the aquifer to be recharged. It also hinders seawater intrusion.

BTD (2016b) carried out a technical feasibility study for a MAR scheme at site A22 and suggest to infiltrate water along the course of the river at three locations in two wells each by gravity method. The total recharge rate off 600 l/s (100 l/s per well) would approximately match the rate at which the aquifer is estimated to be over-exploited. However, recharge would be possible only during four months per year yielding 6 MCM/year while over abstraction totals 22 MCM/year.

The river water shows high levels of bacterial contamination and periods of high turbidity. It is therefore suggested to use water from the Rachaaine Spring which discharges into the Rachaaine River, a tributary to the Abou Ali River. During the winter months the spring discharges 1 – 3 m^3/s that are not used for irrigation. It is proposed to transport the water through pipelines up to 10 km to the infiltration sites. A chlorination unit at the head of the pipeline would be sufficient treatment.

Alternative MAR designs featuring infiltration galleries (as proposed for A14) were dismissed due to their high estimated cost of US$ 25 million. The more promising design with six recharge wells was estimated to cost US$ 5.2 million with almost 2/3 of the costs stemming from constructing the conveyor pipelines.



Appendix IV: Effects Table

	Cost / Benefit	Unit	**A1**	**A3**	**A7**	**A9**	**A10**	**A14**	**A16**	**A19**	**A22**
1 Aquifer											
1.1 Aquifer stress											
1.1.1 Anthropogenic abstraction	B	mm/a	222	222	204	75	40	153	194	157	90
1.1.2 Ratio of abstraction to infiltration	B	mm/mm	0,28	0,28	0,33	0,14	0,06	0,34	0,5	0,39	0,38
1.3 Aquifer size	B	km^3	441	441	184	153	451	158	245	36	39
1.4 Groundwater flow											
1.4.2 Preferential flow along faults		---/0	-	-	-	0	0	--	--	0	0
1.6 Aquifer confinement											
1.6.1 Confinement of the aquifer		0/+++	++	0	+	0	++	+	0	0	++
1.6.2 Connection to the sea		---/0	0	0	0	---	0	-	0	0	-
1.12 Pumping tests											
1.12.2 Theoretical injection rate		-/+	-	-	-	-	+	+	+	0	+
1.14 Karstification											
1.14.1 Geological description of karstification		-/+	-	-	-	-	-	-	-	+	0
1.14.2 Surface karst of river catchments	C	-	14	12	9	21	20	9	10	6	17
1.14.3 Number of springs	C	-	48	14	8	9	20	10	0	5	3
1.14.4 Spring hydrology		---/+++	--	--	0	0	--	+	0	++	0
1.14.5 Drainage density	C	km/km^2	4,2	2,5	4	2,4	0,9	3,4	1,1	2	3,4
1.14.6 Presence of caves		---/0	---	--	-	-	0	-	0	-	0
2 Source Water											
2.1 Water quality											
2.5 Organic material (BOD5)	C	mg/L	69,7	69,7	4,7	2,2	10	1,4	79	79	69,7
2.6 Bacterial contamination	C	CFU / 100ml	1000	4000	3500	3700	4000	4700	7400	2000	12000
2.7 Salinity	C	µS/cm	500	400	450	284	735	370	400	400	500
2.8 Nitrate contamination	C	mg/l	2	3	2,6	4	0,5	1,4	10,3	6,8	2
2.9 Acidity	B	pH	8,3	8	9,2	8,4	7,3	7,4	8	8	8,3
2.2 Available water quantity											
2.2.1 Months of sufficient river flow	B	-	4	4	10	8	4	5	5	5	7
2.2.2 Annual river discharge	B	MCM/a	159	110	183	470	45	211	209	209	315

2.3 Development of water availability	B	-	1,39	1,71	0,9	1,58	1	1	0,78	0,78	1,39
3 Environmental Impact											
3.1 Footprint of MAR facilities		---/0	---	---	--	-	0	--	--	-	--
3.2 Fish passability		---/0	0	---	-	---	0	0	--	-	0
3.3 Impact of reducing source water quantity											
3.3.2 Contaminated discharge from MAR scheme	C	binary	yes	yes	yes	yes	yes	yes	yes	yes	no
4 MAR Technique											
4.1 Recharge capacity	B	MCM/y	1	4	6,2	9,3	2	6	4	1	6
4.2 Water pre-treatment		---/0	---	---	---	---	---	---	---	---	-
4.3 Complexity of MAR scheme											
4.3.1 Complexity of construction		---/+++	-	--	-	--	-	---	0	+	-
4.3.2 Complexity of operation		---/+++	-	-	-	-	--	0	-	-	+
5 Infrastructure											
5.1 Accessibility		---/+++	-	---	+	-	+++	++	--	+	0
5.4 Energy supply for operation		---/+++	--	++	0	0	++	-	---	--	0
6 Costs											
6.1 Implementation costs	C	mln US$	1,9	3,9	3,3	4	2,8	5,7	3,6	1,7	5,2
6.2 Maintenance costs	C	tsd US$/a	80	240	240	270	99	271	240	80	10
6.3 Operating costs	C	tsd US$/a	38	100	140	115	37	124	140	38	90
7 Stakeholders											
7.1 Future competition for source water		---/0	0	0	-	0	-	-	-	-	-
7.3 Expropriation of land	C	m²	2500	5200	5200	6500	4200	8500	5400	2500	2000
7.5 Social priority											
7.5.1 People to profit from MAR		0/+++++	+	++++	+++	+++	+++++	+++++	++	+	+++++
7.5.2 Syrian refugees to profit from MAR		0/+++++	0	+	+++	++	++++	++	0	++	+++
7.5.3 Agriculture to profit from MAR		0/+++++	+++	0	++	++	++++	+	++	+++	+++

Appendix V: Weight and Uncertainty Estimation

Weighting and score uncertainty estimation was done by Acacia Water expert Koos Groen.

Weighting by Pairwise Comparison

Pairs of criteria, categories, or themes were compared and given the following weights:

"Is equally important as": 1

"Is moderately more important": 1-3

"Is strongly more important": 3-5

"Is very strongly more important": 5-7

"Is extremely more important": 7-9

For "less important" use inverse: e.g. 1/2,5

In the tables, the columns are compared with the rows. The first cell thus indicates that the theme 'aquifer' is more important than the theme 'source water'.

Weighting of Themes

	1 Aquifer	2 Source Water	3 Environmental Impact	4 MAR Technique	5 Infrastructure	6 Costs
2 Source Water	3					
3 Environmental Impact	1/3	1/7				
4 MAR Technique	1	1/3	3			
5 Infrastructure	1/3	1/5	1	3		
6 Costs	1	1/3	3	1	3	
7 Stakeholders	3	2	3	5	7	2

Weighting of the Criteria of Category "1.14 Karstification"

	1.14.1 Geological description of karstification	1.14.2 Surface karst of river catchments	1.14.3 Number of springs	1.14.4 Spring hydrology	1.14.5 Drainage density
1.14.2 Surface karst of river catchments	1/2				
1.14.3 Number of springs	1/5	1/5			
1.14.4 Spring hydrology	1/2	1	3		
1.14.5 Drainage density	1	1	5	1	
1.14.6 Presence of caves	1/7	1/5	1	1/5	1/7

Weighting of the Criteria of Category "2.1 Source Water Quality"

	2.1.1 Organic material (BOD5)	2.1.2 Bacterial contamination	2.1.3 Salinity	2.1.4 Nitrate contamination
2.1.2 Bacterial contamination	7			
2.1.3 Salinity	3	1/5		
2.1.4 Nitrate contamination	5	1/3	3	
2.1.5 Acidity	1/3	1/9	1/5	1/5

Score Uncertainty Estimation

Criteria			C/B	Unit	Uncertainty [%]
1 Aquifer	1.1 Aquifer stress	1.1.1 Anthropogenic abstraction	B	mm/a	10
		1.1.2 Ratio of abstraction to infiltration	B	mm/mm	20
	1.3 Aquifer size		B	km³	10
	1.4 Groundwater flow	1.4.2 Preferential flow along faults		---/0	30
	1.6 Aquifer confinement	1.6.1 Confinement of the aquifer		0/+++	30
		1.6.2 Connection to the sea		---/0	30
	1.12 Theoretical injection rate			-/+	
	1.14 Karstification	1.14.1 Geological description of karstification		-/+	20
		1.14.2 Surface karst of river catchments	C		20
		1.14.3 Number of springs	C		10
		1.14.4 Spring hydrology		---/+++	20
		1.14.5 Drainage density	C	km/km²	10
		1.14.6 Presence of caves		---/0	10
2 Source Water	2.1 Water quality	2.1.1 Organic material (BOD5)	C	mg/L	10
		2.1.2 Bacterial contamination	C	CFU/100ml	10
		2.1.3 Salinity	C	microS/cm	10
		2.1.4 Nitrate contamination	C	mg/l	10
		2.1.5 Acidity	B	pH	10
	2.2 Available water quantity	2.2.1 Months of sufficient river flow	B		20
		2.2.2 Annual river discharge	B	MCM/a	10
	2.3 Development of water availability		B		20
3 Environmental Impact	3.1 Footpring of MAR facilities			---/0	30
	3.2 Fish passability			---/0	20
	3.3 Contaminated discharge from MAR scheme?		C	binary	10
4 MAR Technique	4.1 Recharge capacity		B	MCM/y	10
	4.2 Water pre-treatment			---/0	20
	4.3 Complexity of MAR scheme	4.3.1 Complexity of construction		---/+++	30
		4.3.2 Complexity of operation		---/+++	30
5 Infrastructure	5.1 Accessibility			---/+++	30
	5.4 Energy supply for operation			---/+++	10

6 Costs	6.1 Implementation costs		C	mln US$	30
	6.2 Maintenance costs		C	tsd US$/a	30
	6.3 Operating costs		C	tsd US$/a	30
7 Stakeholders	7.1 Future competition for source water			---/0	20
	7.3 Expropriation of land		C	m²	10
	7.5 Social priority	7.5.1 People to profit from MAR		0/+++++	20
		7.5.2 Syrian refugees to profit from MAR		0/+++++	20
		7.5.3 Agriculture to profit from MAR		0/+++++	20

Appendix VI: Transcription of Interviews

Interview with prof. dr. Pieter Stuyfzand

On 07-Feb-2017, 16.30h

At KWR Water Cycle Research Institute in Nieuwegein, The Netherlands

Lukas Rolf: Mr Stuyfzand, would you mind if I quote you later on, so that I can actually use the interview for my thesis?

Pieter Stuyfzand: That's okay, no problem.

LR: Thank you. Well, if I understood correctly you work a lot on MAR systems here in the Netherlands?

PS: Yes.

LR: In Lebanon, a lot of the times but not always, the situation is different because there are karstic aquifers.

PS: I dealt with karstic aquifers as well, in Florida for instance. You have a lot of karst over there. There are many ASR wells and I have been working together with David Pyne on the arsenic problem they had in that karstic area in a Floridian aquifer. I've dealt with a karstic aquifer in Adelaide where they have also applied ASR with treated sewage effluent and that's about it, I think.

LR: Okay.

PS: And then in Lebanon of course with Wisam thinking about MAR projects.

LR: … most recently.

PS: Yes, he is dealing with limestone aquifers, dolomitic limestone, a coastal aquifer where he has salinization because of over-pumping and one of the solutions could be Managed Aquifer Recharge. One of the things he has put in a peer-reviewed paper is about brackish water extraction from below the fresh water lens in this salinized aquifer.

LR: The "fresh-keeper" principle...

PS: The fresh-keeper principle, to make through reverse osmosis fresh water from it, which has a high price in Lebanon. I said: Well, you can sell it in two ways: Either through the tap or by bottling the water. But he said, strange enough, even putting it in the transport mains also has a high value.

LR: People are willing to pay for it a lot?

PS: The system seems to be economically feasible, even if you are not bottling it. Of course, even in the Netherlands, you get many Euros per liter, so then everything becomes feasible.

LR: Do you know if there is experience with the fresh-keeper principle in karstic aquifers?

PS: No. This was just a modelling exercise. A feasibility and modelling exercise.

LR: And the karstic aquifer recharge examples you mentioned before, from for example Florida, is that with the intention to store drinking water?

PS: No, many kinds of water. In most cases it is intended for drinking water supply, yes. So they put in treated surface water, to the level of more or less drinking water standards. But they also have the injection of treated sewage water. For instance Miami is doing that. Well, the karst, if you have a well-developed karst system, it is extremely easy to inject water because you have macro pores and as David Pyne says: You can even infiltrate buses, train wagons or whatever, because in Florida you have huge karst systems. It is even a problem with building houses. Houses disappear because of collapsing dolines and that kind of stuff.

LR: Okay. Looking at Lebanon, what do you think what kind of MAR technique - so I'm talking about the injection technique - would be the most feasible there? I thought that the most obvious would be probably wells, deep wells, directly injecting it into the aquifer, possibly would be also recharge through sinkholes, basically the surface outcrops, but maybe also dams where you store water; where you're enhancing natural recharge by retaining it there might be an option. What do you think?

PS: I think all these options are viable, all depending on the whole situation, how the aquitards are situated, what kind of water do you have? Do you also have saline intrusion in the area or not? What about the porosity, the permeability within the aquifer? But yes, you can apply wells, basins, dolines, you can do water harvesting, you can build dams, everything is in principle an option. Because it certainly strongly depends on water availability. You need water to infiltrate. And do you have the sources of water and that could be a problem in Lebanon. Water, also of the right quality. Although that can be treated, you can pre-treat water and normally you should pretreat water before infiltration. But the availability is a crucial point. There is not so much surface water, I think. There is some in the area Wisam Khadra … you have the Damour River to the south of Beirut and it has reasonably much water so you could use that. On the other hand if you use that water too much, is there going to be damage to people downstream? That is also something to think about. Because some of these flows are not so strong, so taking out the water it has an impact on the people downgradient. So water availability should be on your map. It is one of the variables to put in.

LR: Right now we thought about the very obvious source: River water. But most of the time it is available for around four months a year, so a lot of talk has been around WWTP effluent, but none of them are really functional yet in Lebanon, unfortunately. Other sources could be, for example, rooftop harvested rainwater. That could then later be infiltrated. About this rooftop rainwater: I had the idea that maybe this would be of such good quality that it would not need pre-treatment. What's your thought on that?

PS: That depends on the aquifer. If the aquifer is a karstic, holokarstic aquifer with well-developed karst then you could do that. As I said, in Florida you can infiltrate train wagons, so why not rooftop water with a little bit of sediment, because there is always a little bit of sediment.

However, when you have a clastic aquifer composed of sand then clogging might be an issue. So in that case some rapid or even slow sand filtration could be the cure to prevent suspended solids to clog the well.

LR: Here in the Netherlands, is clogging also mostly due to suspended solids or what are the determinants?

PS: Yes, and also biological clogging. That works together. Chemical clogging of injection wells is not a big issue because the front spreads out at a large distance and it happens also only for a short while. And with ASR you also pump back. But that also depends on whether you really wish to have ASR wells or separated wells. Because if you have a regional gradient you don't get back the bubble you have been infiltrating. So then you have to make your recovery well downgradient and then... Anyhow, I think it will be different from what we do in the Netherlands. In the Netherlands, in the dunes we have ATR systems, Aquifer Transfer Recovery, so you have infiltration, mostly by basins, and simultaneously you have the recovery. So it is not so much the storage which is interesting but it is the whole spread detention times and natural attenuation in the aquifer which is doing a good job while maintaining also the water level of the dune ecosystem. So storage is not the main issue of our system in the dunes. Whereas in Florida, in Australia, and also in Lebanon storage of winter water is the issue. So it is more or less ASR.

LR: And in aquifers, such as in Lebanon, with really high transmissivities, around 10000 m^2/day or something like that - do you think there is any attenuation in the aquifer to be expected at all? Any water quality improvements?

PS: Well, it depends. For instance, if there are pesticides in the water, then I expect very little from it because there is little surface area where bacteria can do their job. There are short transit times. So, no, not so much. However, if you put acid water in a karstic aquifer it will certainly dissolve some of the karstic rock and you will get water hardening. So you will dissolve the calcium carbonate and your pH will go up, which is sometimes desired because acid water is difficult to distribute in a piping system because it will corrode somewhere.

LR: That would actually be one of my next questions. Do you think there would be problems with well stability if you infiltrate normal rainwater and this has, in a bad case, maybe a pH of 6.5 or 6, do you think over a lifetime of let's say 20 years this poses a threat to well stability? Would it dissolve so much karst, so much calcium carbonate?

PS: Well, they had this problem also in Adelaide. The water was also aggressive and the aquifer dissolved a little bit, but it was not a big problem because the rock was solid enough and it helped to prevent or counteract the clogging. Because that was treated sewage effluent so there was some more loading of suspended solids, but because the water was aggressive it dissolved the calcium carbonate. So the suspended material did not form a clogging layer so easily because it moved further into the aquifer and dissipated somehow. So, it can be an advantage, provided you don't have for instance a limestone which is crumbly, which is sandy, marly. Then you might have collapses. So it must be a reasonable solid rock, then I think this would not pose a problem.

LR: In Lebanon the data availability is probably not comparable to Florida and also of course not to the Netherlands and this causes a big problem. Nevertheless, people want to implement those MAR projects; it seems to be a really hot topic at the moment. Do you think there is a way to classify karst into more and less suitable classes for aquifer recharge?

PS: Yes, I think there are two limitations. Perhaps, that are lithology and water quality. Under lithology I would say, yes, it should be permeable enough. That is of course very important. You can have a very dense limestone or dolomite where you have a low transmissivity and then you have problems of many kinds. You don't realize enough storage then within a specific period. Or you need a lot of wells. It is a cost aspect as well. So permeability is a big issue and it may be primary or secondary porosity, that doesn't matter. It should be transmissive. That's one.

Water quality, well, if the aquifer is completely saline and you would apply ASR with fresh water you get into a various problems. You get the buoyancy effect because fresh water wishes to go up. We pay a lot of attention in The Netherlands with multiple partial penetrating wells. You may have heard of it, my colleague Zuurbier did his PhD on it. You know now that if you have density stratification then you should take care and in limestone this would also be a problem. The other thing is that if you have a high salinity and you also have lateral flow then your recovery efficiency might be very low because only a little bit of salt may make the water be completely useless. I calculated this for The Netherlands because we were also interested to do ASR below the huge freshwater lens we have in the dunes. There is space, there is a lot of saline groundwater for hundreds of meters over there, so there we could create a barrier of freshwater, but if you wish to recover that freshwater if you only take, I think, 0.3% of the saline water you are above the drinking water standards. And it is very difficult to get a high recovery efficiency where you don't have this mixing of saline water. There is always a little bit you get from some point.

LR: What is this factor the most dependent on: The water quality of the injected water, the salinity or the groundwater velocity?

PS: This, what I now was saying, is about the salinity of the ambient groundwater. If you just have 0.5% of salinity and you pick it up then you are lost with your approach. But of course in most cases the salinity is much lower, it would be brackish, so in that case you can calculate how much mixing you may have up to which level you can go in order to have drinking water quality. If it is about drinking water quality. With irrigation water there are other standards. So it's dependent on the use and this is an important factor. Can you recover the water you are infiltrating? What is your recovery efficiency? Because water is valuable. If you mix it with saline water you have lost a lot of valuable water you have been putting in. So, I think the native groundwater composition is extremely important. So don't do it in hyper-saline aquifers. You can do it in slightly brackish aquifers, that can still be done.

LR: About the lithology aspect of the aquifer: Do you think there could be a proxy that could be derived from already existing data that would then indicate how well developed the porosity is? Because that is usually not easy to determine and pumping tests in Lebanon are usually missing for aquifers. So for example, would the marly content of a limestone be an indicator?

PS: Yeah, that could help. Of course that makes a difference if you have marl, marly limestone, dolomitic limestone, limestone, dense... There are a lot of classes and it always depends on also the secondary porosity made by bedding planes, made by caves and big macro pores. Even the less desirable limestones could still be good enough, if they have macro porosity. So certainly you could make a kind of classification of this. Then probably there are some well tests in the different types of limestones or lithology. You could extrapolate perhaps, because really the transmissivity is the parameter that's interesting. It also means the transmissivity increases if you make your well screen longer. But if you make it longer you might be more at risk of finding brackish or saline water. This is also an issue. So the transmissivity can be deceiving, in a way, because it is mainly the freshwater transmissivity that's interesting.

LR: Another idea circulating for the MAR projects in Lebanon is to build freshwater barriers to prevent further seawater intrusion but then with the aim of building this positive hydraulic barrier and not so much of infiltrating drinking water. What do you think is determining of the success of something like that?

PS: The success is also determined by the gains of such an enterprise. What do you gain by such a seawater barrier? Well, probably, as in the United States they have such a big one. It protects the water supply of the irrigation in the hinterland. So, if this is the case in Lebanon you have in the hinterland freshwater supplies which otherwise would be managed. This could be a good temporary solution because you have to continue pumping. Because if you stop pumping and the whole system collapses sooner or later - certainly later it arrives inland.

LR: And what do you think then the infiltration rate that is needed to keep the seawater out, what is this infiltration rate dependent on?

PS: It depends on, well, you can think about it yourself nearly. It depends on the permeability, if depends on the hydraulic gradient between the sea and the groundwater table in the hinterland. It also depends on the water availability. I would not so much... Perhaps that's not such a good idea to do this in a small country where the agricultural grounds are perhaps more in the inland.

LR: That is true. Most of the agriculture is actually taking place in the Bekaa Valley.

PS: Yeah, that is behind the mountains, isn't it?

LR: Exactly.

PS: So, there it is not an issue. There are other issues. Probably saline water from evaporating lakes or irrigation return flows, things like that.

LR: Maybe to conclude: From your experience in The States, what are the factors that make a good MAR project in karst and what are maybe not so successful factors? Because in papers you often read about the success stories, not so much about failures.

PS: That's true. Well, for instance the arsenic was a big issue in Florida. The limestones over there contain pyrite and the water they infiltrate contains nitrate and oxygen and they also chlorinate the water. These are all oxidants oxidizing the pyrite and in their typical environment this arsenic became mobilized because of very specific conditions, because the native, the ambient groundwater was brackish, it had very high sulfate contents because of gypsum and then arsenic, which is oxidized also from the pyrite; you have iron hydroxides forming from the pyrite. They are deposited also in the limestone. The arsenic is adsorbed partly to this newly formed iron hydroxide, but then when you pull back the bubble, when you are recovering, this high sulfate and chlorine water more easily desorbs the arsenic. And there are some other reasons. I have written this down in a paper. So, this was really a problem. And they had problems with the authorities because, yeah, arsenic has a drinking water standard of 10 micro grams per liter now, also in the US. This was more or less a reason to abandon the whole ASR systems. Well, then a lot of efforts were spent to say that as happens with ASR with many cycles this problem with arsenic mobilization goes down because the system evolves like it does in subterranean iron removal, that is a similar system. It dies out at a specific moment. And on the other hand they can also treat their water afterwards if you wish. Makes it more expensive but you can do that. So, they can do it. But this was certainly a problem and I don't know how it is in Lebanon, could be the same. This could be a problem. In limestone you could have pyrite. I think the limestones Wisam Khadra has been studying they don't contain pyrite. So there it would not be a problem.

LR: And pyrite is here the only mineral that would be of importance?

PS: Another mineral could be gypsum. Often in limestone units you can have interbedded gypsum layers. They can also be a problem because gypsum gives you a lot of sulfate and a very high total hardness due to calcium. That is not desirable from a drinking water treatment point. You cannot easily remove sulfate. So you get easily above the standards. So gypsum is another enemy.

LR: Maybe coming back to the projects in The States but then looking at the quantity: What about the recovery efficiency over there?

PS: They are usually rather good, I think. There are different definitions of recovery efficiency. You can have the pure recovery efficiency, meaning that the water you put in, you are measuring actually the same molecules in the recovered water. The recovery efficiency is defined by what you take out divided by what you have been putting in. But it should be the same water. However, with recovery you can also have some mixing with the ambient groundwater. So it is still good enough because it is diluted or the quality is not so bad and then you could - with a very good ambient groundwater - you could even have a recovery efficiency higher than 100%. So it depends on how you define it. This is a very important point, I think.

LR: But they didn't have to abandon any ASR projects over there because of bad recovery efficiency?

PS: There must be some sites which were not affordable at the end. You can have up-coning, that is another risk in karstic aquifers, that when you recover the water that you are on a bad position right on top of an artery going vertically down. That could be the case. Normally, it also depends on the recovery rate. If you pump slowly it is different than when you pump at a high pumping rate which could provoke up-coning of saline water. But on average in Florida there have been many success stories. You should read the book of David Pyne. I suppose you have it?

LR: I actually ordered it 1,5 months ago.

PS: Okay, that's one of the books you should read. He has been working in the whole United States and also abroad, but mainly in Florida. There will be many case studies that will be of help.

LR: Yeah, he has been cited a lot. Unfortunately, I haven't found a copy over here yet but the university library has ordered it now.

PS: Acacia Water should also order it. But probably they are a little bit refraining... There is another book of Schlumberger. He has edited another... A very heavy, thick book, not a little one to bring with you to read it on the train. It is a very heavy book but it gives you somehow the details. Both books are good.

Interview with Ane Wiersma

On 27-Feb-2017

At Deltares office in Utrecht, The Netherlands

Lukas Rolf: We already talked a lot about which MAR systems would be possible over there in Lebanon and while the project partners are still busy with thinking in all directions I had to focus my thesis one particular technique, so I thought about ASR and ASTR wells. What they mean by that is that they infiltrate water into drilled wells. With Aquifer Storage and Recovery you basically pump it in and pull it out of the same well and ASTR works with two wells where you have one infiltration well and you recover at a different well. I read one paper which mentioned as a threshold value of the groundwater gradient for ASR to work, so to pull it back out of the same well, would be 0,005, so more or less a stable groundwater table. Not much of a gradient and groundwater velocities of around 0,1 m/day. Do you have experiences with that or thoughts about that? Because I didn't find much more information about that.

Ane Wiersma: About the velocity?

LR: Yes, to come up with some proxies to decide where to implement ASR and where to implement ASTR.

AW: Both are very local...

LR: Well, that depends. Technically you could also infiltrate it kilometers further upstream and recover it with the ASTR, right?

AW: Yes, exactly. I can imagine that these methods only work with classic aquifers. Sedimentary or sandy aquifers. I guess this doesn't work in karst regions. To be honest, I have no clue about the velocities but I can imagine, from what I have seen on the geological map of Lebanon, that this is only possible in the Bekaa valley and it depends on how coarse the sediments there are. I can imagine that it is very gravely, a lot of erosional products as well. In that case I can imagine that the velocities are faster. It all depends on the more local conditions. I guess the Bekaa valley does have a gradient. So I can imagine that it is easier to do, in that case, large systems. So infiltrate upstream and extract downstream.

LR: I still had the hope that it would be possible in karst, also because the big aquifers in Lebanon are karstic aquifers, or at least fractured aquifers. There are some positive examples in Florida, also in Italy and Australia, but the experience is not that great on MAR in karst.

AW: In Italy, is that in the "heel"?

LR: Yes. What they do is that they infiltrate into a sinkhole there.

AW: So they do have problems with bacterial contamination?

LR: Yes. But only with bacterial contamination, I think. They use WWTP effluent, but from the amounts they infiltrate and also from the decreasing salt concentrations which they have problems with it seems pretty promising.

AW: 5000 m^3 per day, something like that.

LR: Huge amounts. So I thought because there are some positive examples, why not make it possible in Lebanon?

AW: You really need to know how the local system works in the bigger system. Clearly some of the aquifers just drain into the Mediterranean and I still wonder how that system works exactly. So, where is the water infiltrated, into what layers? I can imagine that it could work in a local system where you have enough porosity and permeability. Especially if you have covered system.

LR: Yes. The confinement is probably an important thing?

AW: Yes.

LR: My approach was to try to classify karst into more and less suitable karst aquifers for MAR. More suitable would, as you said, be something with a high porosity but then still behaves like a gravel soil, where the matrix flow is dominant and not so much the conduit flow where it just disappears into all areas. So I tried to come up with all kinds of proxies because in Lebanon the data availability is a problem. I've come up with some from literature or from just thinking about the criteria. I just wanted to hear your opinion on that. One of the studies, also addressing Lebanon, said that they classified karst into binary karst with high velocities, very unsuitable. (...) Unary karst with a low functionality but still relatively high velocities, and next the preferred moderately fractured ones, limestone or dolomite, where you have full chemical mixing. Unfortunately, the author doesn't really go into detail on how he determines these classes. (...) How he determines whether a karst is category 1 or 4 I could not figure out. I guess it has a lot to do with field experience.

AW: It is probably a bit subjective. About dolomites: I know that dolomites are like limestones but the calcium is replaced by magnesium and magnesium needs a smaller volume, so in the end you can recognize dolomite in the field by the little cavities. It often looks a bit like sandstone; you also see the separate minerals. But I am not sure if it's permeable. I know it is porous. Do you know if the permeability in dolomite is caused by that process?

LR: It is also subject to karstification but not as much as limestone. I guess because of the magnesium.

AW: Yes, it dissolves less easy.

LR: But you do also have this secondary porosity development through karstification, through the dissolution of calcium carbonate.

AW: But also some primary porosity?

LR: That would be actually interesting to look into.

AW: Because if you would have an almost not karstified dolomite layer, that could behave more like a normal aquifer. The problem with dolomite is that it can be a very local process.

LR: I thought about a couple of other criteria. I read in one paper that the karst form could be a criterion. I though platform karst might be good for ASR but not so good for ASTR as opposed to a geosyncline karst where you basically have a bathtub. You could infiltrate upstream and could place a well in the syncline maybe.

AW: It all depends on the scale. I can imagine that ASR can also work in the geosyncline karst, for sure in the depression. But often the synclines have a gradient themselves in the third dimension. On the large scale that must have influence on the groundwater flow but still I can imagine that the velocities are not very high. It depends on where it goes. If it's a closed-off aquifer and there is almost no flow... It not necessarily has to be like this.

LR: Do you think the karst age might say something about how suitable a karst aquifer is?

AW: I think so. The geological report (of the UNDP 2014 study) was quite dry. (...) I can imagine that different ages have a longer low stand and you need a low stand period to create the karst. Then you get horizontal karst systems and a more or less horizontal groundwater table. The longer the low stand is the bigger your cavities. In Florida you can park a bus in the cavities. I can imagine that there are other periods where you get smaller cavities. I can also imagine that the tectonics make a large difference. If you form one of these synclines you get a lot of fractures and the more fractures you have the more water can flow through and the easier it is to form big karstic systems. So, yes, I can imagine that the age in relation to the tectonics has an influence.

LR: There are many approaches how to classify karst aquifers but they usually set out on one method. Many for example use spring hydrographs and see how that responds to the rainfall, basically.

AW: I can imagine that if your hole would be five meters further down in some systems you get a different spring hydrograph. Transmissivities can be very local.

LR: Just recently Koos Groen had an idea about these karst spring discharges. Our ideal spring would be in an aquifer that retards the water, with a lag, of something like a month at least. Koos had the idea of doing radon analyses and I thought maybe you know something about that?

AW: I really don't know. (...) Have you already done regression analyses of spring hydrographs?

LR: Some springs have been studied quite extensively and some of these do lag behind.

AW: That is an important analysis to do. I think we have to be careful to not focus too much on MAR in karstic systems. We should have that in mind but we should also be open, because we are not the first to come up with these ideas. We have to be careful to not follow the same path and merely come up with a report. That's why I think that it is really important to just do these spring hydrograph analyses. But also to just walk around and see how coarse is the sediment, can we do water harvesting or does the water immediately infiltrate into the soil, what kind of alluvial sediments are there exactly below the river? Is it too coarse or to fine or too shallow? Such analyses are very important.

(Inspecting the map)

I can imagine faults can act as an aquiclude and can act as a funnel.

LR: All these little faults here: Would that be good for MAR or should one stay away from them? I read that some 90% of all productive wells in Lebanon are situated within 500 m of one of those faults. So I thought maybe I would also work the other way around and place an infiltrating well close to the faults so that the large volumes can be infiltrated.

AW: There is a good chance that these faults are integrated into a big karst system. But there are also marls, and aquicludes consisting of marls. Marl is a combination of clay and limestone. Often there are also some salts involved. They can smear into faults in that case you can get a fault that is completely impermeable to water. For instance in the Netherlands you can see the groundwater stepping over it. (...)

LR: So, we can't say we have a fault here and therefore this is very conductive?

AW: Well, I don't know how these faults have developed. I've seen both versions in the field. They could form compartments, vertical barriers, but it could also be that all the water is preferentially flowing through them. If all the productive wells are close to the faults it could mean that the water is stopped by the fault or it could mean that the water is preferentially flowing there. This is something we should have a look at in literature and in the field.

(Further study of the map)

LR: Would you prefer a MAR system in the quaternary aquifers?

AW: I do not prefer anything. I guess it is already being done or people have decided not to do it for a reason. I think especially the water harvesting locally is a very elegant idea for such an idea. I don't know if that's a new Dutch thing, to do these measures locally at a small scale and if you add that up you replenish the aquifer at a larger scale. I don't know if that's a new idea. I am not into MAR. All I am saying is to not focus too much on the MAR option. As soon as you are there in the field things might look completely different. (...) We need a list of potential MAR systems if MAR is the goal of the project but we should go in as open minded as possible with as much knowledge as possible.

LR: Maybe one more karst-specific question: The karstification process, the dissolution of calcium carbonate, do you know how quickly that happens? Do you think that if you infiltrate a lot of water you might run into instability problems of the well?

AW: I cannot imagine that, to be honest. I have seen that it takes at least several millennia. In one of the articles it says that it takes a million years. At high flow rates you might get some physical erosion and an increased rate of chemical erosion that could happen. But to be honest I cannot imagine that with an infiltration well, that is built for several decades at most, that at that scale you could get any problems. Look at soft carbonate sand stone that a building is made of... They are a bit weathered but they are not eaten away, even not by acid rain. I cannot imagine that it has a noticeable effect, unless you infiltrate hydrochloric acid. That is my feeling. We know that it took low stands millions of years to really form the big karstic systems. Did you find any literature on where the big karstic systems are? How deep and how big?

(Continuing of map evaluation)

LR: For a carbonate aquifer to behave like a sand aquifer, would you want to have dolomitization or not?

AW: I think you would want to be in one of those dolomite chunks.

LR: That would require much localized knowledge. Do you think one would be able to detect stuff like that with geophysical methods?

AW: No, I don't expect so.

Interview with dr. Ralf Klingbeil

On 20-Feb-2017, 11 am
Skype video call
Language: German

Dr. Ralf Klingbeil is expert for water resources management in the Middle East at BGR (German Federal Institute for Geoscience and Natural Resources)

Lukas Rolf: Guten Tag Herr Klingbeil. Wenn ich es richtig verstanden habe, haben Sie ziemlich viel Erfahrung mit nachhaltigem Wassermanagement im Mittleren Osten.

Ralf Klingbeil: Ich würde das nicht übertreiben. Es gibt sicherlich Menschen, die praktischer orientier sind. Ich habe relativ viel gesehen, aber ich würde nicht sagen, dass ich die Person bin, die am meisten Erfahrung hat. Da gibt es sehr viele andere auch.

LR: Ich mache ein Praktikum im Rahmen meines Masterstudiums bei einem Grundwasserbetrieb die im Moment ein Projekt machen im Libanon zu Grundwasserwiederauffüllung. Ich bin zwar deutsch, mache mein Studium und meine Arbeit hier aber auf Englisch. Hier nennt man das Managed Aquifer Recharge. Ist dieser Term auch im Deutschen gebräuchlich?

RK: Ich habe eine Kollegin, die auch mit holländischen Kollegen arbeitet, auch zu Managed Aquifer Recharge. Wohl nicht im Libanon, mit einem Herrn Stuyfzand. Ist der auch bei dem Projekt dabei?

LR: Ja, der ist tatsächlich auch bei dem Projekt mit einbezogen und ihn habe ich auch schon interviewt. Er hat MAR viel mehr von der geohydrologischen Seite untersucht. Und ich dachte, dass Sie vielleicht eher praktisch, wie es mit der Umsetzung aussieht von diesen MAR-Projekten im Nahen Osten, das Sie da vielleicht ein paar Tipps an der Hand haben. Herr Stuyfzand hat zwar ziemlich viel Erfahrung mit diesen MAR Projekten, aber nicht so sehr in Entwicklungsländern.

RK: Prinzipiell glaube ich ist es sehr schwer zu verallgemeinern, weil jedes Land seine spezifischen Eigenschaften hat. (Verbindungsprobleme) Libanon hat bestimmte Herausforderungen, die anders sind als andere Länder, von den physischen Gegebenheiten, was Wasserverfügbarkeit angeht, aber auch vom institutionellen mit Wassermanagement anders umzugehen. Da kann man die Länder nicht so über einen Kamm scheren. Erstmal ist es natürlich von der physischen Ressource her das Land, das relativ pro Kopf immer noch am meisten Wasser zur Verfügung hat. Dieses Wasser, was sie haben, hängt eben auch nicht ab von irgendwelchen Oberflägchengewässern, die in das Land hineinfließen, anderes als bspw. Ägypten. Und damit ist der Libanon eigentlich immer etwas gesegnet, wenn man das so religiös ausdrücken möchte, mit den Wassermengen, die er zur Verfügung hätte. Dummerweise fallen diese erstmal auf eine Oberfläche, die relativ porös ist, fallen auch immer dann, wenn man es gerade nicht haben will, nämlich im Winter, fallen als drittes auch als wichtiger Teil als Schnee, was im Nahen Osten relativ selten der Fall ist, vor allem in den Mengen. Damit gibt es dann drei unterschiedliche Voraussetzungen, die anders sind, als in vielen anderen Ländern. Wenn es auf poröses Gestein fällt, was vor allem im Winterhalbjahr stattfindet, fließt es oberflächlich ab und wird relativ wenig abgefangen bevor es ins Meer fließt. Das wird immer wieder moniert im Libanon, dass sie ihr Wasser verlieren. Vieles fließt einfach so angeblich ungenutzt ab. Es hat natürlich auch den Vorteil, dass durch diese Hochwässer im Winter einmal die ganzen Flusstäler wieder gereinigt werden von dem, was die Menschen so reingeworfen haben. Ob das natürlich die ideale Lösung ist, weiß ich nicht... Der andere Punkt ist, dass man im Grunde eine große Menge an Wasser oberflächlich abfließen hat, natürlich versickert und auch nicht richtig genutzt wird. Und da setzen ja viele dieser Ideen an. Einige haben da ja auch schon dran gearbeitet, dass sie gerne die Oberflächenabflüsse aufstauen möchten um die Oberflächenabflüsse dem Grundwasser zukommen lassen zu wollen. Da gibt es auch ganz abstruse Vorstellungen. Wenn man erstmal Wasser aufstaut, muss man erst mal planen, dass es da auch aufgestaut werden kann und nicht da wieder versickert. Und dass man es da versickert wo man es im Nachhinein auch wieder verwenden kann. Und das ist auch eines der großen Mankos von heutigen Staudämmen, die heute gebaut werden, dass vieles im Karst versickert oder es bilden sich Leckagen, mit denen man vorher nicht geplant hatte. Mit richtig großen Staudämmen Wasser aufzustauen und dann umzuleiten ist ein bisschen kritisch. Aber das Ziel, was Ihre Kollegen da auch meistens verfolgen, ist das Grundwasser anzureichen über verschiedene Abflüsse, die man abfängt und dann dem Grundwasser wieder zufügen möchte. Im Prinzip ist das gut, aber ich befürchte, dass die Probleme meiste irgendwo im Abstrom auftreten. Wenn ich Wasser infiltriere, aktiv oder passiv, ist es im Karst relativ schlecht vorherzusagen, wo dieses Wasser wieder genutzt werden kann. Das ist glaube ich eine der Hauptherausforderungen, rein physisch, dass ich in ein relativ komplexes Karstsystem, das ich ja schon natürlich relativ schlecht deterministisch beschreiben kann, Wasser hinzugebe, an Stellen, wo man glaubt, dass man es im Unterstrom wieder nutzen kann. Aber man glaubt es eben nur. Aber das festzustellen ist eigentlich nur möglich, wenn ich es ausprobiere und damit muss ich halt viel in Infrastruktur investieren. Eine andere physische Herausforderung ist die Qualität des Wassers. Unicef hat das vor wohl auch überrascht. (...) Ich weiß nicht, wie transparent Unicef da jetzt war in Gesprächen, aber mein Problem war immer, dass sie etwas durchgeführt haben, meistens über eine Consultingfirma Elard, aber die Berichte meist nicht so offen zugänglich waren, wie sie nach UN-Standard eigentlich sein sollten, weil sie sich da vielleicht eher mit ihrem eigenen Standard nicht so auskennen, was Verfügbarkeit von Berichten angeht. Meistens stehen sie unter Druck von dem Ministerium, dass sie vieles nicht dürfen, aber im Grunde müssten sie nach UN-Standard alles frei zur Verfügung stellen, das tun sie aber leider nicht. Was ich verstanden habe, dass bei deren MAR feasibility Studien an bestimmten Standorten im Grunde das Wasser, was man hätte einspeisen können, aus den Bächen und Flüssen, so stark belastet ist, dass man es erst aufbereiten müsste, bevor man es als Grundwasser wieder injizieren kann. Das ist die zweite physische Herausforderung im Libanon. Das eine ist das Wiedergewinnen von dem, was man injiziert und das zweite ist die Qualität des Wassers, die durch nicht vorhandene Kläranlagen meistens Hausabflüsse beinhaltet, aber auch landwirtschaftliche und Industrieabfälle aus dem Oberlauf beinhalten. Das ist für die Untersuchung wohl etwas überraschend gewesen, wie stark diese Gewässerbelastung eigentlich ist. Das sind rein die physischen Herausforderungen, die schon schwer genug sind. Das andere, was ich sehe, ist das viele von diesen MAR Studien davon ausgehen, dass sie irgendwann ein Volumen gereinigten Wassers zur Verfügung, was sie irgendwo anders injizieren wollen, aktiv verpressen wollen. Damit lässt man dem Wasser natürlich nur relative wenig Zeit sich an das geologische Medium drum herum zu gewöhnen. Das Wasser, was ich injiziere hat selten die gleiche hydrochemische Komposition wie das Wasser aus dem Untergrund. Daraus ergeben sich Situationen, die auch jeder andere Wasseringenieur hat wenn man unterschiedliche Wässer mischt. Entweder kann sich etwas ausfällen oder es kann Korrosion unterstützen, es kann alles Mögliche passieren. Das ist im Grunde auch das, was man in der Region überall bemerkt, wo man aktiv versucht zu verpressen. Die Alternative wäre, das man Wasser möglichst lange bevor es in das Grundwasser versickert möglichst lange mit dem Gestein in Verbindung bringt durch das das ursprüngliche Grundwasser schon geflossen ist, also viel passiver infiltrieren lassen über Drainagen, über alle möglichen Sachen. Inwieweit man das im Libanon bisher von staatlicher Weise sieht weiß ich nicht. Ich glaube das ist ein eher wissenschaftlicher Diskurs bisher.

LR: Richtig. Aber anscheinend ist es auf libanesischer Seite auch so, dass dieses Managed Aquifer Recharge ein sehr beliebtes Thema ist, so dass da jetzt wirklich etwas passieren soll und auch hier im Projekt bei Acacia Water soll wirklich innerhalb der nächsten zwei Jahre ein Pilotprojekt implementiert werden. Die Machbarkeitsstudien, die bisher gemacht wurden, die sind allerdings immer groß und teuer. Da gibt es teilweise Vorstellungen, dass durch Stollen infiltriert werden soll. Es soll nicht verpresst werden, es soll wirklich mit Schwerkraft alleine infiltriert werden. Eine dieser Machbarkeitsstudien sieht wirklich vor, in der Nähe von Beirut an einem Fluss Stollen im Tal Stollen in den Berg zu treiben, kilometerlang, wo das Wasser dann versickert werden soll. Die Kosten dafür sind jetzt mit etwa 18 Mio $ veranschlagt, also ziemlich hoch für ein Projekt, mit dem man noch nicht besonders viel Erfahrung hat. Das ist eine Machbarkeitsstudie im Damourtal, in der Nähe von Beirut. Das ist der Standort, der auch schon am meisten in der Literatur diskutiert wurde. (...) Alle diese Machbarkeitsstudien sind also relativ teuer. Würde Ihnen da, vielleicht aus dem Bauch heraus, noch MAR-Möglichkeiten einfallen, die das Ganze etwas kleiner angehen?

RK: Einmal muss man sich überlegen, in welchem Bereich man denn Grundwasser anreichern möchte. Die Idee, dem Damour Wasser zu entziehen und durch eine Galerie das Wasser infiltrieren zu lassen ist auch schon in dem einen Artikel, den ich Ihnen geschickt habe, schon mal als Idee aufgekommen. Was ich noch nicht geschickt hatte, war eine GIZ-Studie zu seawater intrusion in Hazimieh in Beirut. (...) Im Falle von Damour geht es darum eine Möglichkeit zu finden, die Brunnengalerien (...Verbindungsfehler). Es geht darum, dass man im Oberlauf mehr Wasser ins Gestein versickern lässt um die Salzwasserintrusion zurückzudrängen und mehr Frischwasser zur Verfügung zu haben. Das haben aber schon damals die Franzosen als relativ kritisch betrachtet. Nicht nur aufgrund von der Technik, sondern auch weil man in bestimmten Landstrichen aktiv wird, wo man sich mit verschiedenen Gruppen einig werden müsste über die Landnutzung und dort Probleme schaffen würde. Das steht zwar so nicht in den Artikeln, aber das sind so die kleinen Governanceprobleme im Hintergrund. Im Prinzip ist es eine gute Idee, aber auch da ist die Frage, kann man denn vorhersagen, dass das Wasser denn dann zur Verfügung steht wo man es denn nachher haben will. Eine andere Sache wäre, dass man im größeren Stil kleinere Rückhaltemöglichkeiten und Versickerungsmöglichkeiten in den Bergen schafft und sagt, dadurch dass man diffus dem Grundwasser etwas Gutes tut im Unterlauf. Es wird den Wissenschaftler nie zufrieden stellen, dass man das nicht vernünftig vorhersagen kann. Man kann da wahnsinnig tolle, komplexe Modelle rechnen. Ob das aber dem Bedürfnissen im Libanon gerecht wird... Die Karstmodelle können ja recht umfangreich werden. Die eigentlichen Herausforderungen liegen wahrscheinlich gar nicht in den naturwissenschaftlichen Ungereimtheiten, sondern vielmehr darin, wer denn dann diese Sache vor Ort durchführt, bzw. ob man das Land überhaupt nutzen kann und ob andere Wassernutzungen mitbetroffen sind. Das ist eine Sache, man greift in ein System ein, was sich über viele Jahre entwickelt hat, auch wenn zu viel Wasser im Winter da abfließt, greift man jetzt ein und wird dann entsprechend Wasser aufstauen, wozu ich eine Fläche brauche, die irgendjemandem gehört und die auch heute schon genutzt wird. Ich muss mir immer wieder Gedanken machen, welchen Einfluss ich eigentlich habe auf die vorhandenen Arten der Wasserverteilung. Das wird bei den meisten Studien ein bisschen vernachlässigt, weil im Grunde genommen auch die heutigen Landwirte ein irgendwie ausgeklügeltes Wassernutzungssystem in den Bergen haben, um ihre Felder zu bewässern. Wenn ich jetzt da eingreife und dieses Wasser nicht mehr zur Verfügung steht, hat das für die Nutzer natürlich einen Nachteil. Diese Situation muss man von Standort zu Standort auch beurteilen. Eine andere Option wäre meiner Meinung nach im Küstenbereich zu bleiben, wo man auch schon jetzt größere Versalzungen hat, fast in allen Stadtbereichen der Fall, und dort bewusst versucht küstennah Grundwasser anzureichern. Dort kann man wahrscheinlich in den Küstensedimenten bleiben und man muss nicht unbedingt in den Karst gehen. Man könnte solche Fördermaßnahmen besser monitoren, bspw. auch mit solchen Methoden, wie sie in den Niederlanden eingesetzt werden. Wenn man einen Riesenaufwand treibt und das Wasser nachher nicht dem Förderbrunnen zugutekommt ist es schwieriger. Wo das viel schlauer, sinnvoller und einfacher ist, ist in den Nicht-Karstgebieten. Also in der Bekaa-Ebene stärker darauf zu achten. Dort hätte man auch vernünftigen Boden, der filtert. Der Boden hat natürlich auch eigene Filterfunktionen. Vielleicht nicht für alle Schadstoffe, die da transportiert werden, aber doch für eine ganze Menge mehr, als man allgemein annimmt. Da könnte man mehr machen, meiner Meinung nach. Dass man auch in der Bekaa-Ebene das Grundwasser anreichert. Es gab ja 2013/2014 dieses besonders trockene Winterhalbjahr mit der entsprechend starken Grundwasserabsenkung. Das wäre meiner Ansicht nach schon ein Ansatzpunkt, dass man bewusster auf die Talebenen geht und versucht, da auch im Rand der Tallagen die Abflüsse, die sonst verloren gehen, gezielt da einzuspeisen. Das sind alles sehr dezentrale, kleine Maßnahmen, die sicherlich aufwendiger sind, als die großen, aber auch nicht so viel Schaden anrichten können. Man kann mit vielen kleinen Maßnahmen genau so viel erreichen. Genauso wie beim Staudammbau für Energie. Ich kann auch durchaus Kleinkraftwerke verwenden, aber es ist viel aufwendiger das zu organisieren und auch auszuschreiben und für die Ministerien so etwas zu managen. Es ist immer die gleiche Herausforderung. (Verbindungsfehler). Wo das auch interessanter wäre, wäre im Süden, bei Saida, da sind die Verkarstungen nicht ganz so stark. Dort im Südlibanon gebe es bestimmt auch einige Möglichkeiten. Durch unterschiedliche geologische Gegebenheiten hätte man dort auch Sedimente, keine stark verkarsteten Bereiche, und dort versucht zu erneuern. Aber nicht nur da, es gibt auch im Norden eine Möglichkeit. Dass man also versucht im kleineren Bereich Sachen zu finden, die man unterstützen kann. Diese Projekte könnte man besser beobachten, könnte man auch besser die Grundwasserstände beobachten. Ich rede aber über Studien, die ich nicht gesehen habe und bemerke da nur, dass es Probleme mit der Qualität gibt. Und dann ist da der Kostenfaktor, da muss man sich überlegen, wie man das Wasser aufbereitet oder ob man es schafft, Schutzzonen auszuweisen. Das war auch ein Ansatz bei einem BGR-Projekt zur Jeita-Quelle. Landnutzungsplanung im Libanon ist ja auch irgendwie etwas chaotischer als in anderen Ländern, aber wenn man da gezielt sagt, dass es im Unterstrom eine schützenswerte Quelle gibt und entsprechend muss ich im Oberlauf bestimmte Maßnahmen umsetzen, dann hätte man im Libanon schon viel erreicht. Sie planen ja selten ihre Landnutzung in irgendeiner nachhaltigen Form. Das verlangt eine ganze Menge mehr vorausschauendes Planen auf staatlicher Seite, aber auch ein Miteinbinden der Bürger und das kann man im Libanon nicht einfach so ignorieren. Es gibt dort inzwischen genug Menschen, die sich nicht einfach so bevormunden lassen. Wir haben ja genug Probleme bei der Entnahme von Wasser, also die Umsetzung dieses Grundwassergesetzes, dass man eigentlich eine Genehmigung bräuchte heutzutage für private Brunnen ist nicht unbedingt praxisnah. Viele der Brunnen auch gerade außerhalb der städtischen Bereiche sind weiterhin vom Ministerium als illegale Brunnen bezeichnet, anstatt sie einfach als noch nicht registrierte Brunnen zu bezeichnen. Das klingt ja etwas positiver, als dem Landwirt zu sagen, er hat einen illegalen Brunnen. Man hat ja auch im Rahmen des UNDP Projekts gesehen, dass gerade in der nördlichen Bekaa-Ebene große Bereiche, wo überhaupt keine regulierten oder vom Staat wahrgenommene Brunnen sind. Da ist die Entnahme schon ein Problem. Wenn ich jetzt aber Wasser anreichern möchte, ergibt sich für mich auch eine rechtliche Absicherungsfrage: Wer ist eigentlich zuständig, wenn da etwas schiefläuft. Wenn dann irgendwer, im wahrsten Sinne des Wortes, nasse Füße bekommt, Keller volllaufen, weil plötzlich Wasser da ist, was vorher noch nie da war... Als ich diese rechtlichen Konsequenzen einmal ansprach mit einer Beraterin vom Wasserminister meinte sie nur, dass sei nicht so problematisch. Es sei ja rechtlich gelöst, denn es sei ja das Ministerium für Wasser. Also hat man sich über diese Schadensersatzansprüche überhaupt keine Gedanken gemacht und man ist ja der Staat und damit gibt es auch keine Schadenersatzansprüche. Es gibt wohl durchaus Regeln vom Umweltministerium zum Einspeisen von Wasser. Ich habe die nicht, aber das wäre durchaus auch eine Überlegung, ob das für MAR eine Bedeutung hat. (...) Dieses konsequente Durchdenken von dem, was bei einem Grundwasseranstieg eben auch passieren kann spielt für die staatliche Seite bisher leider überhaupt keine Rolle. Bei diesen fesaibility-Studien konzentriert man sich häufig rein auf die hydrogeologischen Gegebenheiten: Kann man dort Wasser infiltrieren oder wem kommt das Wasser nachher zugute? Ich weiß nicht, ob sie sich schon mit Cost-Benefit-Analyen beschäftigt haben.

LR: Das ist auch einer von meinen Kritikpunkten, dass sich viele von diesen wissenschaftlichen Studien alleine mit der geohydrologischen Seite beschäftigen, oder vielleicht noch mit dem Wasserverbrauch, aber viele andere, vor allem auch institutionelle Faktoren, werden überhaupt nicht berücksichtigt und ein paar von den geohydrologischen Faktoren scheinen mir ein bisschen willkürlich gesetzt. Zum Beispiel ist in dem UNDP Report ein von sechs Kriterien für ihre Standortwahl, dass dort eine Straße zwischen dem Fluss und dem Versickerungspunkt sein muss und dass es maximal 500 m entfernt sein darf. Das scheint mir ziemlich willkürlich, wenn man doch auch Pipelines bauen kann. Letztendlich kam bei diesen Studien auch heraus, dass diese Pipelines tatsächlich die Hälfte der Kosten ausmachen können. Weil die Wasserqualität flussabwärts so schlecht ist muss man im Prinzip bis zur Quelle gehen um dort das Wasser zu entnehmen und dann 10 km weiter flussabwärts zu infiltrieren. Das ist ziemlich teuer.

RK: (Verbindungsfehler) Da ergeben sich natürlich noch weitere Fragen: Darf ich auf dem Land einer anderen Person eine Pipeline verlegen? Wie müssen die rechtlichen Gegebenheiten dafür

sein? Das sind alles Fragen, die meistens etwas kurz kommen in solchen Studien und im Grunde genommen eigentlich einer Vorklärung bedürfen, bevor man sich einzelne Standorte anguckt. Diese Studien sind ja an bestimmten Standorten durchgeführt worden. Auch da hat sich Unicef immer sehr bedeckt gehalten, welche vier Standorte sie sich denn jetzt näher angucken. Es hätte vermutlich politische Konsequenzen, denn in dem Moment wo jedem klar ist, dass dort eventuell eine Planungsmaßnahme des Staates demnächst zukünftig Wasser einspeisen möchte... Ich glaube im Jemen gab es Situationen, wo Leute anfingen, den idealen Grund für städtische Brunnen den man irgendwo haben wollte, schnell zu kaufen, weil sie dann lange Entschädigungsprozesse führen können um viel Geld wieder reinzukriegen. Also spekulativ Land zu kaufen im Vorfeld zu einer staatlichen Investition und sich daran zu bereichern. Das wäre im Libanon eigentlich eine ganz klassische Methode, wie dort diverse Minister sich dort wahrscheinlich selber absichern. Aber genau deswegen ist das direkte klären von Einzelstandortfragen ohne die Rahmenbedingungen geklärt zu haben, etwas unpraktisch. Die Rahmenbedingungen sind für mich, dass solche Dinge im Vorhinein klar sind. Wenn der Staat für die öffentliche Wasserversorgungseinrichtung eine Grundwasseranreicherung plant, dann muss gewährleitstet sein, dass er dieses auch durchsetzen darf. Oder die Kosten für Entschädigung müssen mitberücksichtig werden. Eine Pilotstudie machen ist das eine, aber wenn ich darüber hinaus plane muss ich die gesetzlichen Grundlagen haben. Dass ich jemandem Land wegnehmen darf für den Benefit der Gemeinschaft. Und wie weit das für Grundwassereinspeisungen geklärt ist, ist mir nicht bewusst. Wenn ich für den Straßenbau jemanden enteignen muss, ist das eine Sache. Aber für Grundwasser kann es sein, dass das noch nicht definiert ist. Das muss man erst mal sicherstellen. Aber das sind die allgemeinen Rahmenbedingungen. Ich denke, man kann bestimmte Standortfaktoren auch in Wirtschaftlichkeitsbetrachtungen einbeziehen. Wenn ich natürlich schon den einen Standort definiere, dann bin ich schon nah dran an Einzelstandortfaktoren. Die ganzen verschiedenen Faktoren dann durch zu deklinieren und herauszufinden, wie die sich auswirken können an verschiedenen Alternativstandorten, muss man gegeneinander abwägen.
(Verbindungsprobleme)

LR: Es gibt im Libanon ja leider noch kein MAR-Projekt, aber in anderen Ländern der Region gibt es schon einige. Aus Ihrer Erfahrung: Gibt es da wiederkehrende Probleme, oder gibt es Erfolgsrezepte, die Sie uns mit auf den Weg geben könnten?

RK: Erst einmal: Herausforderungen gibt es überall. Was man in Kuwait gesehen hat, dort haben sie sehr lange Forschungslinien gehabt. Sie haben auch versucht Wasser zu injizieren und haben schon im Labor gemerkt, dass es Ausfällerscheinungen gab. Die hydrochemischen Situationen zwischen dem einzuspeisenden und dem in situ Wasser. Wenn das Wasser was eingespeist wird sich alleine vom pH oder vom Redoxpotenzial verändert oder unterscheidet von dem, was in situ vorhanden ist, dann gibt es immer Ausfällerscheinungen zwischen den beiden Wässern. Man wird ja nicht entmineralisiertes Wasser einspeisen und selbst dann wäre es der Fall. Das weiß im Grunde jeder, der in Bereichen arbeitet wo man entsalztes Wasser mit Grundwasser mischt, muss man diese Wasser aneinander anpassen, damit man solche Sachen nachher nicht im Leitungsnetz hat. Wenn dieses nicht im Leitungsnetz oberirdisch passiert, sondern im Boden, dann wird das Ganze noch viel teurer. Ich habe im Grunde immer das falsche Wasser, was injiziert wird. Da geht es nicht darum, dass dieses Wasser kontaminiert ist, im Sinne von was wir im Libanon sprechen, sondern einfach, dass dieses Wasser nicht die gleiche hydrochemische Zusammensetzung hat, also nicht langsam genug sich anpassen konnte. Wenn es irgendwo durch filtriert, hat es halt seine Zeit, sich an das Gestein anzupassen und alle möglichen Minerale aufzunehmen und zu lösen. (Verbindungsfehler) Das kann man natürlich reduzieren indem man entsprechende hydrochemische Modellrechnungen durchführt. Das würde ich auch empfehlen und das sagen auch viele von den großen Consultingunternehmen, die das in den Golfstaaten machen, das immer mit durchzuführen, auch wenn das nicht ganz günstig ist. Hydrochemische Modellierung ist genau wie eine hydraulische Modellierung relativ wichtig. Das ist eine Sache, die ich mitbekommen habe. Was ich auch sehe ist, dass in vielen dieser Fällen in den Golfstaaten alles privatwirtschaftlich abgewickelt wird. Man leistet sich also eine große internationale Consultingfirma, die das dann umsetzt und es dann auch über viele Jahre beobachtet. Das ist im Libanon ja nicht so zu erwarten, dass man das Geld hat, sich solche Firmen zu leisten. (Verbindungsfehler) Leider gibt es weder eine vernünftige Ausbildung für Hydrogeologen - bis auf eine Dozentin mittlerweile glaube ich an der AUB - aber es gibt eigentlich kaum überhaupt die Möglichkeit im Libanon Hydrogeologie zu lernen. Das wäre ein Ansatz, was man machen kann, dass man auch mehr Kompetenz in den staatlichen Stellen schafft. Viele der Stellen sind ja weiterhin nicht besetzt vom Fachpersonal, weil sie auch nicht besonders attraktiv bezahlt werden. Wie man das verbessern kann - das ist natürlich eine große Governanceherausforderung, aber es wäre schon wünschenswert wenn an den staatlichen Stellen es auch geeignete Fachkräfte gibt, die das überhaupt beurteilen können. Bisher sind das ja reine wissenschaftliche Maßnahmen, die man dann an höherrangige Stellen gibt. (Verbindungsproblem) Auf staatlicher Seite bedarf es an mehr Kompetenz um solche Projekte beurteilen zu können und zwar nicht nur für Pilotmaßnahmen zur Forschung, sondern auch zur Anwendung und auch beratend. (Verbindungsprobleme) Vielleicht kann man das auch durch eine interessantere Aufgabenteilung lösen, dass man Wissenschaftler von CNRS mit einbezieht, die ja eher naturwissenschaftlich ausgelegt sind. Empfehlungen, die man aus anderen Ländern mitnehmen kann: Möglichst nicht an den Menschen vorbei zu planen, sondern offen und transparent zu planen bevor die Planungen weit vorangeschritten sind und dann erst der Öffentlichkeit zu präsentieren. Dann gerät man schnell in die Situation, dass man sofort ein Kontra von der Bevölkerung erfährt. Der Libanon ist durch seine starke Zivilbevölkerung da prädestiniert für, dass man frühzeitig die Bevölkerung beteiligt. Einfach mal hören, was sie so belastet und welche Ängste bestehen, um dann auch darauf reagieren zu können. Frühzeitig, im Vorfeld von konkreten Umsetzungen. Das ist ja aber auch im Westen, bei uns hier nicht so einfach. Manche Planungen werden ja auch da erst nachher durch Bevölkerungen beteiligt. Man kann natürlich viel lernen durch Projekte; dass man Leute dahin bringt, wo Projekte sind, die funktionieren. Aber es macht relativ wenig Sinn, alle Libanesen, die mit MAR zu tun haben, nach Darmstadt zu karren um sich das hessische Riedt anzugucken. (...) Es gibt so viele Beispiele, aber die sind nicht unbedingt explizit auf den Libanon ausgerichtet. Ich denke, der Libanon könnte dazu etwas mehr mit Ländern zusammenarbeiten mit Ländern, die ähnliche Situationen haben. Zum Beispiel Marokko, oder auch im südlichen Europa, wo wir auch starke Winterniederschläge haben. Also Pyrenäen und Alpen. Was es dort an Erfahrung gibt in Italien und Frankreich, wo man auch mit Karst Erfahrung hat, was da an Grundwasseranreicherungsideen entwickelt wurden. Da bin ich jetzt aber selber überfragt, wo es Beispiele gibt, die man herausstellen kann. (...) In Australien oder Kalifornien gibt es glaube ich nicht so tolle Beispiele, weil man im Grunde ganz andere natürliche Rahmenbedingungen hat. Aber im Mittelmeerraum müsste es eigentlich schon ein paar Beispiele geben.

LR: Ich habe in Süditalien tatsächlich ein MAR-Projekt gefunden, wo tatsächlich gesäubertes Abwasser direkt in ein Schluckloch infiltriert wird. Sie kämpfen dort zwar noch mit zu hohen E.coli-Werten, aber im Prinzip funktioniert es immerhin. Es bekämpft auf jeden Fall die Versalzung. Das ist im "Absatz" des Stiefels von Italien, also wirklich umgeben von Wasser und man hat dort Versalzung. Dort wird im Prinzip das ganze Jahr durch infiltriert.

RK: Wenn man das Wasser gezielt aufbereitet, wenn ich mehr Geld in die Aufbereitung stecke und dann gezielt die natürlichen Gegebenheiten, die man hoffentlich dann schon kennt... Ich meine, das ist der andere Punkt, im Libanon gibt es bis auf die Sache mit dem Jeitaprojekt sehr wenig Tracerversuche, die dokumentiert haben, wo denn ein sinkhole in Verbindung zu einem Brunnen steht. Davon gibt es relativ wenig. Das wäre meiner Ansicht nach viel Zielversprechender, wenn ich weiß, dass eine bestimmte Doline oder sinkhole im Oberlauf steht einem Brunnen in einer Verbindung. Dann kann ich natürlich diese Doline fördern oder dort etwas einspeisen, aber dafür muss ich dann noch eine Etage höher gehen um das Wasser dort schon abzufangen. Unter Umständen ist das eine Methode, die schlauer ist, als irgendwo einzuspeisen ins Grundwasser und dann nur zu hoffen, dass es auch dem Grundwasser zugutekommt. So hätte ich zu mindestens eine Förderung der Quelle.

LR: Aber in diesem Fall würde man doch, wenn man in diese Doline oder Schluckloch einspeist bei einem Tracertest... Dann kommt es doch schon nach einem Tag am Brunnen wieder an. Man würde doch nicht viel dadurch gewinnen im Libanon, wo man eigentlich eine Speicherkapazität von einem halben Jahr bräuchte, um die Trockenzeit zu überbrücken.

RK: Im Prinzip ja, aber andererseits: So lange ich gar nicht weiß, wie schnell das Wasser von der Doline zur Quelle kommt, macht alles sehr wenig Sinn. Es kann durchaus auch vorkommen, dass ein Tracer erst viel später dann an der Quelle ankommt. Gerade in dem Jeitagebiet hat man relativ schnelle Gängigkeiten gefunden, aber das war auch das Ziel. Wenn ich gezielt nach Dolinen oder natürlichen Versickerungsorten suche, von denen das Wasser länger braucht, um an der Quelle rauszukommen, dann hätte ich ja auch Bereiche gefunden, wo entsprechender Zwischenspeicher vorhanden ist. Man hat dann zwar immer noch nicht sichergestellt, dass bei höherem Wasserstand dieses Gängigkeit noch immer gegeben ist, also normalerweise ist es ja so, dass bei Niedrigwasser eine Karstverbindung dann eventuell weg ist... Mit mehr Tracerversuchen hätte man zumindest auch die Möglichkeit, diese Quellen und ihre Einzugsgebiete besser zu charakterisieren und zu bestimmen, wo eine zusätzliche Ergänzung Sinn macht. Weil die Quellen versiegen fast alle zum Spätsommer. Wenn man eine kleinere Speichermöglichkeit im Oberlauf schafft, die die Winterniederschläge länger im Oberlauf belässt um sie dann nach und nach versickern zu lassen über die natürlichen Wegigkeiten, dann würde man die Quellen mit Geoengineering länger aktivieren. Das Hauptproblem ist aber, dass ich Speichermöglichkeiten schaffen muss. Ich befürchte einfach, dass wenig große Speichermöglichkeiten geschaffen werden können, trotz der Pläne der Regierung. Die meisten von diesen Staudämmen werden sehr viel Beton brauchen um sie abzudichten. Mit kleineren Maßnahmen kann man immer mal... Da ist es auch nicht so schlimm, wenn dann dieses Kleinstreservoir für Grundwasserreservoir... Wenn man das bewusst macht, evtl. eine

Geomembran einbaut, dass es bewusst versickert, aber eben nicht so schnell. Es gibt ja haufenweise Rückhaltebecken in den Bergen, die für Landwirtschaft betrieben werden. Im Grunde um Wasser aufzuhalten, um dann über die Kanäle abzufließen und zu bewässern. So etwas gibt es ja schon. Wenn man da jetzt auch gezielt Orte findet... Es gab z.B. von dem BGR-Vorhaben einen Vorschlag, wo man MAR-Staudämme im Kleineren bauen könnte, weil es dort das Gestein auch erlauben würde, das Grundwasser zu erneuern. Witziger weise ist einer dieser Standorte jetzt als Staudammprojekt geplant, also genau das Umgekehrte, man will jetzt versuchen das Versickern dort zu verhindern... Man muss halt für diese Schlucklöcher meistens relativ weit nach oben gehen und frühzeitig das Wasser ableiten. Der Vorteil davon ist natürlich, dass das Gewässer je weniger belastet sein sollte, desto weiter man nach oben geht. Es gibt in dem Sinne nicht die automatische, klare Antwort im Libanon. Gerade im Karstgebirge wird es immer wieder Probleme mit dem Karst an sich geben und meine Empfehlung wäre eben, nicht nur dahin zu gucken sondern auch dahin, wo Landwirtschaft betrieben wird, in den Tallagen, wo dann auch verstärkt Grundwasser gefördert werden muss und dieses auch immer weiter abgesenkt wird über die Jahre. Man spart im Grunde Energie, wenn das Wasser nicht so weit abgesenkt werden würde, weil es dann nicht aus der Tiefe hoch zu fördern ist. Es wird allerdings nicht damit getan sein, dass man Grundwasser anreichert, sondern man muss gleichzeitig auch schauen, ob man denn die aktuellen Grundwassernutzungen regulierend in den Griff bekommt, damit die nicht weiter ausufern.

LR: Es wird deutlicher, dass die MAR-Karstprojekte nicht so einfach sind, wie ich am Anfang angenommen habe. Man mag zwar viel infiltrieren können, aber ob man genug wieder fördern kann ist eine andere Sache.

RK: Ja, das ist eine Herausforderung. In bestimmten Teilen von Nordlibanon wird auch der Oberflächenabfluss sehr stark Sedimente mit sich führen. Wenn ich das nun aufstaue und das aufgestaute Wasser in dem Becken versickern lassen möchte, habe ich relativ schnell Sedimente, die es relative abdichten werden. Da gibt es durchaus Erfahrungen aus anderen Ländern, auch aus der Region, auch etwas das sich explizit dort entwickelt hat. Im Oman wird zum Beispiel gezielt nicht oberhalb des Staudamms sondern unterhalb des Staudamms infiltriert. Man nutzt den Staudamm also eher als Sedimentrückhaltebecken und infiltriert dann im Unterstrom in Bereichen, die explizit für Infiltration vorbereitet sind. Diese Flussabschnitte sind dann auch explizit darauf vorbereitet. Im Oman sind das zwei bis drei Hochwasserereignisse im Jahr, das haben wir im Libanon etwas anders. Wenn dann die Flüsse doch lange Zeit nach dem Niedrschlagereignis im Winter Wasser führen bis auch der Schnee geschmolzen ist. Das ist auch eine etwas andere Situation. In wieweit das eine Rolle spielt müsste man vor Ort schauen, ob man das Wasser vor oder hinter dem Staudamm nutzen möchte. Das hängt immer auch von der Sedimentfracht des jeweiligen Flusses ab.

LR: Im Libanon ist die Landverfügbarkeit auch ein Problem, die solche Staudammprojekte schwierig macht.

RK: Insbesondere wenn man in Stadtrandbereiche kommt ist vieles natürlich schon besiedelt oder für andere Sachen verplant. Mit Horizontalgalerien braucht man weniger Oberflächenplatz. (...) Eine andere Möglichkeit wäre es eventuell, Regenwasser nah an den Häusern zu infiltrieren. Da man aus Kostengründen keine großen Infiltrationsbecken bauen kann, könnte man sich überlegen, ob man das nicht auch vertikal infiltrieren kann. Wie Brunnen quasi, Drainagetrennwände am Haus kreieren. Also Hohlräume, die dann wieder mit Bauschutt gefüllt werden, damit man da die Infiltrationskapazitäten erhöht. Dass man da im städtischen Bereich ein paar Möglichkeiten schafft um dort zu infiltrieren, bevor es verunreinigt. Es läuft darauf hinaus, dass bessere Lösungen immer dezentral stattfinden (Verbindungsfehler). Wobei, die große Herausforderung bei dezentralen Maßnahmen ist halt, das von einem zentralen Staat zu planen. Ähnlich wie bei Solarzellen. Das ideale wäre, wenn sich jeder einfach so ein Ding aufs Dach stellt. Ich kann so etwas aber nicht einfach sich selber dezentral organisieren lassen, weil es viel komplexer ist, als sich eine Standard-Solarzelle auf's Dach zu setzen und dann einzuspeisen.

LR: Vor allem, weil es doch auch um Wasserqualität geht. Die wäre doch durch zentrale Maßnahmen viel eher zu beherrschen, mit Kläranlagen.

RK: Richtig. Der einzige andere Punkt wäre, dass man durchaus von der Baugesetzgebung im Lande darauf Wert legen könnte, dass die Leute ihre Häuser so bauen, oder dass es da bestimmte Insentives gibt, dass die Leute Wasser Versickerungsmöglichkeiten mit einplanen. Die Verbindung zwischen der nichtvorhandenen Kläranlage und der Regenversickerung am Haus wäre natürlich ideal. (...) Ich denke, ein Punkt, den wir häufig auch vernachlässigen ist Versiegelungsflächen, aber solange es sich wirklich um Regenwasser handelt muss das Wasser, so lange es nicht über Verkehrsflächen geflossen ist, nicht so stark belastet sein, dass es nicht im Untergrund versickert werden kann. Gut, auf den Hausdächern liegt natürlich haufenweise Luftverschmutzung durch die Dieselgeneratoren usw. Man müsste mal überlegen, ob es nicht Optionen gibt, dass man das mit in die Baugesetzgebung einbezieht. Die Wasserqualität des Wassers, das infiltriert wird ist das entscheidende, ob das Wasser nachher auch sinnvoll genutzt werden kann, unabhängig davon, ob es denn auch an der richtigen Stelle rauskommt. Wenn es natürlich so belastet ist, dass die Nutzung danach nicht mehr gegeben ist, dann macht es überhaupt keinen Sinn es einzuspeisen. Das ist ein kleiner Unterschied zu den Golfstaaten. Ein Problem, das einige von den Golfstaaten haben ist, dass sie so hohe Mengen an Abwasser haben, dass sie wieder aufbereiten in Bahrain oder Katar... Es ist dann im Grunde die Umwelt nicht belastendes Wasser, dass dann aber meistens ins Meer abgegeben wird. Es ist für die wirtschaftlich gesehen ein bisschen schade drum, dass sie so viel in die Aufbereitung gegeben haben und es dann nur dem Ökosystem Meer wiedergegeben wird, anstelle dass sie es doch irgendwo wiederverwenden. Diese Situation haben wir im Libanon wenig, weil das Abwasser nur wenig aufbereitet wird. Und es gibt auch nur wenig geplante Aufbereitungsanlagen, die oberhalb gebaut würden, die eine Wiederverwendung unterhalb der Kläranlage noch möglich machen. Die meisten Kläranlagen sind unten am Meer oder in der Bekaaebene, aber im Grunde an einem relativ niedrigen Ort, sodass eine Weiterverwendung dieses geklärten Abwassers energetisch schwierig ist, weil es gleich wieder heißt man muss es den Berg erst mal wieder hochpumpen. Dieser Energiefaktor für das Wiederverwenden des aufbereiteten Abwassers ist auch ein Punkt.

LR: Wir haben hier in dem Projekt wiederaufbereitetes Klärwasser erst mal abgeschrieben, weil die Kläranlagen im Libanon sowieso noch nicht funktionieren.

RK: Ich denke auch, da gibt es noch eine ganze Menge Herausforderungen. Wichtig ist, dass man sich überlegt, wie weit kann ich hoch gehen im Gebirge, um das Wasser so sauber wie möglich zu fassen und welche Aufbereitungsanlagen brauch ich trotzdem damit Wasser injiziert werden kann. Libanon ist ja kein Land, was gerade mit Energie gesegnet ist. Auch da muss überlegt werden, wie kann man energiekostengünstig das Wasser versickern. Bei der Wasserversorgung im Libanon ist Energie häufig eines der teuersten Aspekte, weil häufig das Wasser von den Wasseraufbereitungsanlagen hochbefördert werden muss in die Dörfer. Was da an Energie rein geht um dieses Wasser wieder hoch zu fördern ist relativ groß. Wenn man das versuchen kann zu optimieren, dass man es direkt im Vorhinein in solchen Infiltrationsprojekten mit berücksichtigt, das wäre schon günstig. Da gibt es bestimmt auch Fördermöglichkeiten.

LR: Das ist tatsächlich auch noch eine spannende Idee. Wer da als potenzieller Geldgeber in Frage käme.

RK: Genau dafür gibt es im Moment ja relativ viel Geld. Es gibt sehr viele Länder, die schon relativ fit sind, sich über den Global Climate Fund Mittel abzusichern im großen Stil. Da geht es eben nicht um 2 Mio. $ sondern Minimum ist glaube ich 20 Mio $ Projekte und bis viel größere. Es sind durchaus eine ganze Menge Länder, die weit fortgeschritten sind solche Wassermanagementfragen zu engagieren. Es wäre eine interessante Frage, ob das nicht auch was für den Libanon interessant ist. Also aus Klima- oder Adaptationfonds... Zu argumentieren, dass man Wasser verliert durch den Klimawandel und dadurch dann Projekte zu finanzieren. Da müsste dann auch Umwelt- und Wasserministerium zusammenarbeiten, was ja leider nicht so ganz klappt.

Appendix VII: Spread Sheets (digital appendix)

The digital appendix to this thesis is a Microsoft Excel file with the following spread sheets:

- Criteria Catalogue: Digital version of Appendix I
- Data Collection: Data of the nine assessed MAR sites compiled in the criteria catalogue
- Lebanon MCA: Overview of the criteria considered in the multi criteria analysis carried out for the nine MAR sites in Lebanon, given in form of a score matrix
- Weights: A matrix of the applied weights as assigned by the expert Koos Groen
- Uncertainties: A matrix of the applied score uncertainties as assigned by the expert Koos Groen
- Selected Sites: An overview of the characteristics of the nine selected potential MAR sites
- MAR Designs: An overview of the assumed designs and associated costs of the different MAR schemes at the nine sites

Statement of originality of the MSc thesis

I declare that:

1. this is an original report, which is entirely my own work,

2. where I have made use of the ideas of other writers, I have acknowledged the source in all instances,

3. where I have used any diagram or visuals I have acknowledged the source in all instances,

4. this report has not and will not be submitted elsewhere for academic assessment in any other academic course.

Student data:

Name: Lukas Rolf

Registration number: 5684269

Date: 26-06-2017

Signature: