Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies

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Suitability maps for managed aquifer recharge: a review of multi-criteria
decision analysis studies

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Abstract: Suitability maps for managed aquifer recharge (MAR) sites hold a strong potential for integration into sustainable groundwater management plans. An uprising method to identify sites suitable for MAR implementation is GIS-based multi-criteria decision analysis (GIS-MCDA). There are no guidelines or common understanding on how suitability mapping should be conducted, and there is considerable variability as to what factors are assessed and how they are weighted. To increase knowledge on GIS-MCDA, a database has been built based on 63 studies applying GIS-MCDA in the context of MAR site selection. Information on used criteria, assigned weights and utilized methodologies has been retrieved from the documents. Statistical analysis of the database depicts the current state of art for suitability mapping methodologies as well as specific information for the different recharge methods. We further incorporated the compiled information into a web-based query tool that makes the information easily accessible and the utilization of the database more user-friendly. This review as well as the created web-tool will help planners of MAR sites to engage in the MCDA in a more structured way by referring to previously conducted studies and by finding information suitable for their specific project. The application potential of suitability maps is discussed along with the shortcomings of this methodology.

Key words: Managed aquifer recharge, MAR, artificial groundwater recharge, GIS, multi-criteria decision analysis, MCDA, site selection, suitability analysis, suitability maps, potential recharge zones

1. Introduction

Groundwater is crucial for the sustainable water supply of many regions worldwide but is often affected by quantitative and qualitative mismanagement. To outbalance the negative effects on groundwater, managed aquifer recharge (MAR) is increasingly being applied (Stefan and Ansems 2017). MAR is defined as the intended recharge of groundwater for later use or environmental benefits (Dillon 2005). Worldwide, it is successfully utilized to improve the quantity and quality of groundwater resources, to recover depleted groundwater levels, to prevent salt water intrusion, to control land subsidence, to mitigate floods or to enhance ecological benefits (Stefan and Ansems 2017). A large variety of recharge techniques are summarized under the term MAR, e.g. spreading methods (SM), in-channel modifications (IM), well, shaft and borehole recharge (WSB), rainwater and runoff harvesting (RWH) and induced bank filtration (IBF) (IGRAC 2015).

Most of the available guidelines on MAR emphasize on the need of carefully planning the MAR schemes to ensure sustainability and controllability (Government of India 2007; NRMMC-EPHC-AHMC 2009; SEMARNAT 2009; MOP 2014). The selection of a suitable recharge site is another critical step in the design stage of a MAR project, as the site influences the selection of an appropriate recharge technique, the operation strategy and the maintenance of the MAR schemes (Dillon 2005; Shankar and Mohan 2005; Rahman et al. 2012; Russo et al. 2015). MAR comprises various recharge techniques, thus it is adaptable to sites with very different characteristics. Finding the appropriate techniques for a given site is one of the reasons for assessing the site suitability.

Site suitability analysis for MAR is often based on intrinsic factors like hydrogeology, topography, soil type, land-use and climate as these factors control the groundwater recharge process. Even though all these parameters are relevant, their importance depends on the respective MAR technique. Deep or confined aquifers require injection techniques to recharge the desired aquifer. Thus, subsurface geology and hydrogeology play a more important role than surface processes. Spreading methods and in-channel

modifications, on the other hand, require an unconfined aquifer and are highly dependent on the surface characteristics.

The site suitability assessment for MAR can be achieved by combining multi-criteria decision analysis (MCDA) for solving spatial problems with geographical information systems (GIS). The conjunctive use of these two distinct fields of science is known as geographical information systems multi-criteria decision analysis (GIS-MCDA) (Malczewski 1999). It combines the spatial analysis capacity of GIS with MCDA methodology that guides the decision making process (Malczewski and Rinner 2015). The site selection procedure is undertaken by combining and weighting the geospatial data characterizing the study area based on the study's objectives. In terms of site selection for MAR, GIS-MCDA has been carried out for various settings and scales all over the world. A small review on the usability of GIS-MCDA for selection of MAR sites was conducted by Jha et al. (2007) as part of a major review on the use of remote sensing and GIS applied to groundwater. Rahman et al. (2012) reviewed GIS-MCDA studies for MAR and retrieved information on the site selection process. Russo et al. (2015) compared weights assigned to different criteria by a variety of GIS-MCDA studies. Singh et al. (2017) presented an extensive review on site selection studies conducted for rainwater harvesting and partially for MAR. The dissertation of Bonilla Valverde (2018) was the basis for this review and comprises an analysis of 25 GIS-MCDA studies for MAR.

Other approaches to identify suitable locations are statistical methods (frequency ratio, logistic regression, classification trees and others) (Guru et al. 2016), field investigations (Alesheikh et al. 2008; Beganskas and Fisher 2017) and determinist modelling (Russo et al. 2015). The advantage of GIS-MCDA over these approaches is that the remote sensing data on surface and subsurface characteristics is available worldwide in an increasing spatial and temporal resolution. Using remote sensing data is especially advantageous for areas where little geologic and cartographic field information exists.

To the best of the authors' knowledge, there are no guidelines available on how the site selection process should be conducted. The Indian guidelines for MAR implementation define the selection of suitable sites as the final step in the compilation of ground facts (Government of India 2007). Rahman et al. (2012)

developed a GIS-based tool for MCDA site selection analysis and structured the methodology of site suitability mapping. The study exemplifies a first attempt to standardize GIS-MCDA methodology for MAR site selection. Even though many studies have used GIS-MCDA for MAR site selection, there is no common understanding on criteria, weights and methods to be used. In fact, methods used for classification and weighting show a great variety. This can be attributed to data availability, local characteristics but also to the expert opinion and the problem statement. Russo et al. (2015) compared criteria weights used in different GIS-MCDA studies highlighting a high variance in weights assigned to the same criterion. Chowdhury et al. (2010) showed that even among experts the relative importance of a criterion is highly debatable.

With this study, we aim to increase knowledge about GIS-MCDA application for MAR suitability mapping. We analyzed in what context the maps are used and what methodologies and datasets were applied to derive the suitability maps. For this, we collected 63 case studies and assessed them regarding the applied MAR methods, location characteristics as well as criteria, weights and decision rules used. The collected data has been summarized in a database and was further used to develop a web-based tool that makes the data accessible through a MAR decision support system. The analyzed data shows the clear tendencies in applied GIS datasets and the weighting. It further differentiates the results regarding the different MAR methods. The results of this study highlight the methodologies used the most frequently for map generation. This accumulated information will help planners of MAR sites to engage in the MCDA in a more structured way, pointing the way to previously conducted studies that fit the scope of their own project. The results for most used criteria and assigned weights can guide the decision makers in their own MCDA process. Analyzing the most commonly used practices and methodologies in MCDA for MAR suitability mapping could constitute as a starting point for the discussion of standardizing the mapping procedure.

2. Approach

2.1 GIS-MCDA: processes and definitions

GIS-MCDA is defined as a set of tools to design, evaluate and prioritize the choice between alternatives (Malczewski 2006). In the particular case of MAR site selection, GIS-MCDA ranks the entities that compose

the study area based on the decision makers' goals and preferences (Malczewski and Rinner 2015). Those entities are generally referred to as criteria and they are the basic element of GIS-MCDA (Eastman 1995). The set of criteria should be complete, non-redundant and minimal (Malczewski 1999). All criteria of the set need to be standardized to convert them into a common scheme. The standardization scale should clearly differentiate between more acceptable and less acceptable values and represent variability in the study region.

A holistic approach to GIS-based site selection should follow the scheme of 1) problem definition, 2) screening of suitable areas (constraint mapping), 3) suitability mapping including the classification of thematic layers or criteria, standardization, weighting of the criteria and layers overlaying and 4) sensitivity analysis (Rahman et al. 2012).

The problem definition outlines the whole MCDA process. In terms of site suitability analysis for MAR, it could include information on the proposed MAR method, the purpose of MAR application or the water source. Based on the information, the criteria set for the GIS analysis is chosen.

Constraint mapping comprises the elimination of parts of the study area that are not suitable for application of MAR. The reasons for non-suitability can be manifold, e.g. distance to water source or existence of protected areas or aquicludes. Constraint criteria and their threshold values need to be defined and to be excluded from the map by applying Boolean logic.

In contrast to constraint mapping, suitability mapping does not eliminate areas that are unsuitable for MAR but rather ranks the study area regarding its suitability for the application of MAR. Suitability mapping comprises the assignment of weights to the criteria and the combination of the weights and criteria by decision rule. The weights of the criteria describe the relative importance of one criterion among the criteria set (Eastman 1995). Assigning weights to the criteria can be undertaken by rating method, ranking method, the multi-influence factor (MIF) and the pairwise comparison.

The rating and the ranking method comprise manual weight assignment on a predetermined scale (Malczewski and Rinner 2015). For the ranking method, the weights are calculated based on previously assigned ranks (Malczewski and Rinner 2015). The MIF method has been described by Shaban et al. (2005) and Magesh et al. (2012). Weights are derived from a graphical representation of the criteria utilizing the number and the importance of linkages between the criteria. For pairwise comparison, weights are assigned through comparing pairs of criteria based on a matrix by Saaty (1980). This method includes the calculation of the consistency ratio, an indicator of the consistency of the pairwise judgement and thus a reference factor for the goodness of the decision maker's judgement.

The decision rule states how datasets and their weights are integrated to generate the site suitability map (Malczewski and Rinner 2015). The combination of values and weights can be based on threshold values (Boolean logic) or more elaborate integration rules like weighted linear combination (WLC). WLC has been developed further to derivatives like ordered weighted averaging (OWA) or analytical hierarchical process (AHP).

The final suitability map should be verified by a sensitivity analysis. As the criterion values and weights are the main sources of uncertainty in the MCDA process, conducting a sensitivity analysis allows for more robust decision-making. Sensitivity analysis is used to display the effect of different criterion weights on the spatial pattern of the suitability map. Methods for the sensitivity analysis are summarized by Malczewski (1999, p.261).

2.2 Review process

To assess the criteria and MCDA methods used for MAR suitability analysis, a search for relevant studies was carried out collecting scientific papers, conference proceedings and freely available reports written in English. Publications were searched for through search engines and online databases and through reference lists of already found publications. Research terms included: MAR, managed aquifer recharge, artificial aquifer recharge, GIS, spatial multi-criteria decision analysis, MCDA, GIS based MAR site selection, suitable site selection, suitability mapping, remote sensing, AHP and Boolean logic. The review only

considers literature that specifically stated the identification of suitable sites for MAR implementation. A lot of literature is available on the analysis of potential recharge zones (PRZ) that does not focus on managed but rather on natural groundwater recharge. This analysis does not regard literature on PRZ, although natural recharge processes are very similar to those of MAR. However, the problem definition is different. In the discussion section, a summary on PRZ literature is given and used to put the results from MAR specific literature into perspective.

The data collected has been divided into general and MCDA relevant information (Table 1). General information comprises publication relevant information, but also information on the area regarded for site selection, MAR method considered as well as the objective of MAR application and the water source considered. The MAR method classification used for this study is based on the classification by IGRAC (IGRAC 2015) and only considers the main MAR methods, namely spreading methods (SM), in-channel modifications (IM), well, shaft and borehole recharge (WSB), rainwater and runoff harvesting (RWH) and induced bank filtration (IBF). Literature with no mention of a MAR method was classified as unspecified MAR method. Main objectives of MAR application comprise agricultural, domestic, industrial use as well as ecological and recreational benefits.

MCDA relevant information collected includes the number of used criteria, their name and given weight. When available, information on criteria standardization was included with given minimum and maximum values for the criteria values. Weight assignment methods and decision rules are categorized based on the methods explained in the section 2.1. Constraint mapping and sensitivity analysis comprise information on whether this step was applied in the respective study and for constraint mapping the constrain criteria and thresholds are included.

The raw data collected was modified to allow for comparison and statistical analysis. The diversity of criteria used was high which necessitated harmonization and grouping of the criteria. Authors have used different terms for criteria that in their scientific meaning might differ slightly but with respect to solving a specific

problem in GIS-MCDA essentially have the same implication, e.g. landforms and geomorphology. These criteria were unified.

The harmonized criteria sets have then been grouped into classes of two different hierarchy levels (Figure 1). Aquifer and surface criteria correspond to all physiographic subsurface and surface criteria of the lithosphere. Hydrometeorology criteria include atmospheric processes as well as hydrologic processes, in this case only referring to processes of runoff accumulation. Management criteria encompass economic considerations of MAR implementation and impact assessment.

The collected criteria weights were standardized to compare them and evaluate them statistically. Standardization followed the methodology from Russo et al. (2015) and is based on equation 1:

$$Weight [\%] = \frac{Criterion\ weight \times subcriteria\ maximum\ weight [\%]}{\sum (Criterion\ weight \times subcriteria\ maximum\ weight [\%])} \qquad Eq. 1$$

This standardization also regarded the effect of subcriteria values, namely the maximum possible value for a criterion. In this context, subcriteria is referring to the standardized values of the criterion classes.

Criteria used only for constraint mapping were excluded from this step. All other criteria were assigned a value between 0 and 100% with all criteria of one study adding up to 100%. Next to the standardized criteria weight, the rank of the criteria was determined based on the given weights. The highest weighted criterion was assigned rank one. The second highest weighted criterion was assigned rank two and so forth.

All accumulated information was saved in table S1. The database structure is based on the number of retrieved criteria per study. Thus, every reviewed document has the same number of database entries as the number of criteria selected by the author.

2.3 The MCDA-Review Tool

To help visualize the results and to enhance the usability of the database, a web-based query tool based on a pivot table approach was created. Pivot tables are useful tools to query information in a flexible and intuitive way. Users can sort, average or sum up database content by creating tables and graphs. Filters can

be used to make very specific queries, e.g. MAR method-based studies. Hierarchical analysis of criteria is possible by means of different criteria hierarchy levels. The tool is embedded into the INOWAS online platform for managing groundwater recharge (<https://inowas.hydro.tu-dresden.de>). The INOWAS platform is a comprehensive collection of analytical and numerical web-based models. It is an open source web-service aimed to solve groundwater related issues with a focus on the planning, management and optimization of MAR applications.

The INOWAS platform and the review tool are accessible with any state of the art web browser. The review tool is developed with the latest version of ReactJs, a JavaScript library for building user interfaces and based on an open-source 3rd party project (<https://github.com/nicolaskruchten/pivottable>).

The database given in the supplementary table S1 is the basis of the query tool. However, not all information of the database was included into the tool. A selection to the most useful information for display was made to ensure that the tool is simple and concise.

3. Findings

In the context of this review, 63 studies were identified that applied GIS-MCDA for MAR site selection. Six studies either conducted a combined study on the identification of potential recharge zones (PRZ) and MAR or did a PRZ analysis and in the conclusions mentioned the applicability of the results for MAR application (Magesh et al. 2012; Palaka and Sankar 2015; Satapathy and Syed 2015; Raviraj et al. 2016; Selvam et al. 2016; Saidi et al. 2017). These studies were included in the discussion.

The first study found linking MAR site selection and GIS-MCDA was published in 1998 (Saraf and Choudhury 1998). MCDA studies for MAR site selection started to be increasingly used since 2007 and in recent years, there have been six to ten studies per year (Figure 2). India was the first country to apply this methodology for MAR site selection. Other country studies followed 2005 with Iran, Lebanon and USA.

India is still one of the focus regions for GIS-MCDA studies with 22 studies conducted between 1998 and 2017. The other country with many applications (15) is Iran. There is a focus on countries with a dry climate

(Egypt, Iran, Saudi Arabia, among others) and less on tropical regions (Costa Rica, Sri Lanka) or moderate climates (UK).

The sections of the results analysis follow the methodology proposed by Rahman et al. (2012) and differentiate information retrieved on problem statement, constraint mapping, suitability mapping and sensitivity analysis.

3.1 Problem statement

The problem statement can comprise many aspects of site selection, including differentiation between exclusively intrinsic analysis and consideration of social and economic aspects. In this analysis, we focus on only two MAR specific aspects that were mentioned in almost all studies regarded, namely the MAR method and the water source. The MAR method regarded is one of the main factors influencing the MCDA workflow. Each technique enforces different key aspects and problem specifics.

Spreading methods (SM) are discussed the most in the GIS-MCDA literature (32 studies). In-channel modifications (IM) have been the focus of 23 studies and well, shaft and borehole recharge (WSB) of 9 studies. Five studies were found for rainwater harvesting (RWH) site selection in combination with MAR techniques. More literature is available on site selection for RWH but it is often not specified how the collected water is stored. Only two studies were found on induced bank filtration (Jaramillo Uribe 2015; Romero-Esquivel et al. 2016). As the requirements for site selection along riverbanks differ significantly from those of the other MAR techniques, the studies were excluded from this analysis.

Fifteen studies did not specify the MAR technique that was going to be applied but rather investigated the general potential of the aquifer for managed recharge. Seven studies regarded more than one MAR method in their analysis, e.g. a study on a wide variety of MAR techniques with criteria weights differing for each method (Fernández Escalante et al. 2014).

Consideration of the recharge water source is of relevance as type and location of the water to be used does not only influence the suitability of an area for MAR application but also the MAR method to be used.

However, the water source is not the key factor for the suitability of a site as water can be transported from the source to the recharge site, but this generally involves high financial investment.

Stormwater or surface runoff was the water source to be utilized in 38 studies. This water resource can be easily collected and can often be used without significant treatment. RWH in combination with aquifer recharge is found to be a promising approach for sustainable water management and addressing water scarcity (Singh et al. 2017). Locating of RWH sites and aquifer recharge sites can be combined in one GIS-MCDA study (Ramakrishnan et al. 2009; Singh et al. 2017; Amineh et al. 2017). Eleven studies elaborated on the use of treated wastewater for MAR. These studies are quite specific as locations need to be close to the treatment facilities but injection of treated waste water requires different soil characteristics than infiltration of natural surface waters (Kallali et al. 2007; Anane et al. 2008; Pedrero et al. 2011; Gdoura et al. 2015; Ahmadi et al. 2017; Tsangaratos et al. 2017).

3.2 Constraint mapping

About half of the studies (48%) used constraint mapping as a tool to exclude unsuitable areas before the actual suitability study. 38% of the studies did not include constraint mapping. The rest of the studies used Boolean logic alone to conduct the suitability analysis. Thus, constraining is not considered even though Boolean logic is used.

The criteria that are constraint depend on the objective of the study but also on the MAR method considered. Almost all studies constraint the type of land use (84%). Some constraints depend on the MAR method chosen, e.g. in case of the surface infiltration method flooding only agricultural land is considered in the analysis (Nasiri et al. 2013; Zare and Koch 2016). Surface water bodies are often constraint (Krishnamurthy et al. 1996; Owusu et al. 2017) and even buffers around those bodies are mapped (Gdoura et al. 2015; Ahmadi et al. 2017) as MAR site interference with water bodies should be minimal. Some studies impose a positive boundary on water bodies, as they are used for MAR supply and thus sites should be located within their vicinity (Brown et al. 2005; Jasrotia et al. 2007). Other land use types considered are urban areas (Riad et al. 2011; Fernández Escalante et al. 2014), forests (Sethupathi et al. 2010; Rahman et al. 2013), traffic

278 routes (Ahmadi et al. 2017; Owusu et al. 2017) and vulnerable or protected natural areas (Bonilla et al. 2016;
279 Tsangaratos et al. 2017).

280 Slope as a constraint criterion is considered in 48% of the studies. The constraint threshold ranges from
281 restricting areas with slopes of more than 3% (Rahman et al. 2013) to areas with slopes of more than 40%
282 (Bonilla et al. 2016).

283 Geology was used as constraint in one third of the studies. Consolidated formations were mentioned in some
284 studies as constraint (Ghayoumian et al. 2005; Sethupathi et al. 2010). Others excluded every geology type
285 but quaternary units (Jasrotia et al. 2007; Jamali et al. 2014). Depths to groundwater table or thickness of
286 the unsaturated zone were considered in 29% of the constraint studies. Groundwater depths was constraint
287 to be at least 5 m by (Anane et al. 2008; Gdoura et al. 2015). Other studies constraint it with 20 m as a
288 threshold value (J. Ghayoumian et al. 2007; Mahdavi et al. 2010).

289 Soil type or soil infiltration capacity was constraint in seven studies. Those studies focused solely on surface
290 infiltration methods. Constraint infiltration rates thresholds were either 60 cm/d (J. Ghayoumian et al. 2007;
291 Mahdavi et al. 2010) or 25 cm/d (Rahman et al. 2013). Further constraints used regarding soil
292 characterization were soil salinity (Anane et al. 2008) and soil texture with less than 10% clay (Gdoura et
293 al. 2015).

294 Other factors considered in constraint mapping are faults/lineaments (3 studies), groundwater
295 quality/salinity (4 studies), presence of/distance to pollution sources (5 studies) and distance to other water
296 supply infrastructure (4 studies).

297 3.3 Suitability mapping

298 Number of criteria

299 The number of criteria used for a site selection study depends on the problem definition, e.g. whether it only
300 regards physical intrinsic factors or also socio-economic criteria. Analysis of the number of criteria used in

the studies revealed a wide range of criteria sets with the minimum number of criteria used being four. The study with the biggest criteria set used 21 criteria (Fernández Escalante et al. 2014). On average 7.4 criteria were used for a GIS-MCDA study. Figure 3 shows that most of the studies (90%) used ten or less criteria with four to six criteria being the dominating number of criteria sets.

Criteria clusters

All 467 criteria found through the literature review have been harmonized and regrouped according to Figure 1. Analysis of the five main criteria groups (Level 1) shows that the focus of application is on surface characteristics. Figure 4 summarizes the criteria distribution based on the main criteria grouping. Findings are separated by MAR method. Results show that on average half of the criteria used in each study are surface characteristics. The criteria used the least are hydrometeorology and water quality criteria. RWH studies used the smallest criteria sets and had the largest focus on hydrometeorology criteria among the studies. Management criteria were found to be the most important for WSB studies.

Surface criteria have been divided into five sub-criteria (Level 2). Geomorphology is the most used criterion for all MAR methods among those criteria used to describe the surface. It includes the slope criterion, which is the overall most used individual criterion. It is used in 87% of all studies. Soils is another important criteria category used for all MAR techniques (used 59 times). Out of the 59 soil criteria, 49% have been used to describe the soil type and 32% to describe the infiltration capacity of the soil (criteria category name: hydrological soils). The soil category is especially relevant to SM methods. The hydrography category is of biggest relevance to IM studies and comprises information on drainage density and drainage order numbers. Next to slope, land use is the other individual criterion that has been used the most to describe surface characteristics, namely in 65% of all studies.

Aquifer characteristics are the second most used criteria group after surface characteristics. The focus of this group is on storage capacity of the aquifer, which is indicated by single criteria such as aquifer thickness (used in 32% of studies), or groundwater level (27% of studies). The most used single criterion in the aquifer characteristics group is general information on geology/lithology (46% of studies).

Management criteria are used throughout all MAR method studies. These criteria comprise a large variety of parameters that i.e. cover economic aspects of MAR site selection, such as distance to infrastructural entities or to water supply sources. For impact assessment, they either indicate the impact of the MAR site on water bodies or ecological preserves or they indicate the impact of an entity on the MAR site, e.g. distance to groundwater pollution sources or urban areas. Many of the criteria in this category have been used only a few times. Mapped information is usually not readily available and thus entails tedious digitalization of geographical information. The most used parameters within this category are “Distance between water supply sources and MAR site” (13 studies) and “Distance to urban areas” (8 studies). The latter is an example for a criterion that has been interpreted differently depending on the problem statement of the respective study. If a soil aquifer treatment site is planned, it should not be situated too close to urban areas. Thus, larger distances are classified as good. Contrary, MAR sites should be situated in proximity to the end user. In this case, a smaller distance to urban areas would be classified as good.

Hydrometeorology parameters are used the most for studies with stormwater or surface runoff as the source for recharge. 84% of all criteria used within this category coincide with this water source. The other studies using hydrometeorology parameters did not specify the water source. This indicates the indirect use of these parameters for the selection of MAR sites as they are rather used for detecting the best site to harvest runoff water. Both cannot be considered independently, as for a MAR site using surface runoff a suitable rainwater harvesting location needs to be in close vicinity to the suitable recharge site.

The last criteria group groundwater quality has its biggest focus on the quality of the groundwater to be recharged. Ten studies were concerned with the salinity of the groundwater, which is also the most used parameter in this criteria group followed by assessment of chloride and nitrate (each used in 4 studies).

Weight assignment methods

The first GIS-MCDA studies on site selection used either rating or ranking as methodology to assign weights to the criteria chosen. Both methods distinguish themselves through their simplicity and are still being used in recent studies. Overall ranking has been used in nine studies, rating in thirteen studies (Figure 5).

The most common weight assignment method is pairwise comparison. It has first been used by Anane et al. (2008) in this context of MAR site selection. After 2012, it has been the dominating weight assignment method and has been used in 24 studies overall. Compared to rating/ranking, this assignment method is relatively more complex but also gives a more sophisticated background to the decision-making process. It further offers a verification for the consistency of assigned weights.

Boolean and fuzzy logic were applied throughout the entire time span considered. While Boolean logic is a common method and has been used in twelve studies, fuzzy logic only plays a minor role with three applications. This can be attributed to the complexity of fuzzy logic. It also has not been applied solely in a study but rather in combination or comparison with Boolean logic (Ghayoumian et al. 2007; Mahdavi et al. 2013) or pairwise comparison (Gdoura et al. 2015).

A few studies compared different weight assignment methods through the retrieved criteria weights, e.g. using MIF and pairwise comparison (Jamali et al. 2014; Selvarani et al. 2017) or rating method and Boolean logic (Riad et al. 2011).

Weights assigned

Weights have been evaluated for all studies as a whole but were also disaggregated based on MAR methods. In each case, the seven or eight most used criteria have been selected for comparison of assigned weights. Results are visualized in a box plot with a table added below that shows the number of studies where the criterion was used, the median weight from the boxplot and the average criteria rank.

The most used criteria for all 63 studies evaluated are slope, land use, geology, soil type, drainage density, geomorphology, aquifer thickness and hydrological soils (Figure 6). Slope and land use stand out with significantly larger usage numbers than the other criteria. While geomorphology and hydrological soils have not been used as often, they are the criteria with the highest median weights and the highest criterion ranks applied. The next highest weighted criterion is geology. Again, it is not the most used (29 studies) but has been assigned a high median weight and the third highest criterion rank. Land use, on the other hand, has

been used frequently but is assigned one of the lowest weight and criteria rank. Slope is used in many studies, with a medium criterion rank and weight. It stands out for its wide range of weights assigned with an interquartile range (IQR) of 15% while the other criteria have an IQR around 10%. The difference between the highest and lowest weight assigned to the slope criterion is 63%. The importance of slope for the individual studies seems to differ more significantly than for the other criteria.

Considering the MAR method SM, the most used criteria change only slightly. The first four criteria stay the same. The last three are similar and only change their position with respect to criteria count (Figure 7). For SM slope is the most used criterion (29 studies) but like the overall analysis, the median weight and average rank are intermediate. Geomorphology and hydrological soils are the highest weighted criteria. Land use and soil type have the lowest weights. The largest IQR can be stated for hydrological soils, while slope has the highest overall range.

The 15 studies found for the IM MAR method show significant differences to the SM methodology. As this MAR method is restricted to riverbeds or points with high surface runoff accumulation, criteria reflecting this characteristic become more important (Figure 8). Geomorphologic criteria are among the most used and have the highest median weight and criteria rank. Drainage density and lineament density were of lesser importance for SM methods but for IM methods have been used frequently with average weights around 10%. Geology and slope are again among the most used and highest weighed criteria. They also cover the largest ranges among assigned weights. Importance of land use increased compared to overall and SM analysis.

Assessing the WSB studies, slope is again the most used criterion (Figure 9). Behind slope, the focus shifts slightly as transmissivity has not shown much importance for the previous MAR methods but for WSB it is ranked as the second most used criterion along with land use and soil type. The highest ranked criterion by far is geomorphology with a median weight of 20%. Land use, soil type and lineament density are assigned weights around 10% with very little variation. Highest variations for assigned weights can be found for geology and geomorphology. It should be kept in mind that the WSB analysis is only based on nine studies.

As for RWH only five studies were found, no in depths analysis was conducted. The most used criteria are slope (5 times), land use (4 times), runoff coefficient, soil type and hydrological soils (3 times) and rainfall and groundwater level (2 times). Runoff coefficient and rainfall are specific to this MAR method and they influence the applicability of a region for MAR with rainwater harvesting greatly. Runoff coefficient is also notable as it is a secondary parameter derived from other GIS maps (slope, land use, ...).

Decision rules applied

The most commonly used decision rule is weighted linear combination (30 studies). It is the first method used (Saraf and Choudhury 1998) and has been prevalent ever since (Figure 10). A variety of WLC is the analytic hierarchy process, which has been first used by Anane et al. (2008). Since 2013, its use has been increasing and today it is used as often as standard WLC. Overall AHP has been used for 19 studies. It is evident that both the use of AHP and pairwise comparison show similar patterns of application over time (compare Figure 5). A combined use of AHP and pairwise comparison could be accounted for in 17 studies.

The third most popular combination method is Boolean logic, which has been used in 15 studies. Other decision rules play only a minor role and have been used little over time, like Fuzzy logic, or are used only in one study within this context (Decision Tree, PROMETHEE (Brans et al. 1986)).

Few studies compared or combined several methods of criteria combination, e.g. Boolean Logic, WLC and Fuzzy logic (Dashtpajerdi et al. 2013) or Fuzzy logic and WLC (Alesheikh et al. 2008; Malekmohammadi et al. 2012).

3.3.4 Sensitivity analysis and verification of suitability maps

Only 14 out of the 63 studies reported on the type of sensitivity analysis conducted. Even though verification of the resulting maps should be an integral part of each site selection analysis, this step is often left out or not reported. In some studies the resulting maps were verified by comparing the results to actual MAR sites (Ghayoumian et al. 2005; Kallali et al. 2007; Alesheikh et al. 2008). When the location of the actual sites was in accordance with the more suitable areas of the map, the map was considered reasonable.

Most studies conducted non-probabilistic sensitivity analyses by changing the weights of the criteria. A number of combinations of weights were calculated and the resulting suitability maps compared to a base map (Shankar and Mohan 2005; Gdoura et al. 2015; Steinel et al. 2016). The smaller the differences between the base map and the maps with varying weights, the more robust the assigned weights were assumed to be. Satapathy and Syed (2015) not only analyzed the criteria weights but also removed one criterion at a time to assess their significance in the site selection process. Some weight assignment methods already include standardized procedures for sensitivity analysis. For MIF, weights can be analyzed by adding or erasing relationships between the criteria (Bonilla et al. 2016). For the OWA method, fuzzy linguistic quantifiers are used as a variable for sensitivity analysis (Rahman et al. 2013).

3.4 The review tool

The review query tool can be accessed through the website <https://inowas.hydro.tu-dresden.de>. Upon registration, the tool can be chosen from the tool box in the dashboard (tool T04). The tool is utilized by dragging and dropping attributes from the database into the column or row fields (Figure 11). The user can filter the content of each attribute, can specify how the information is displayed and can add conditional or numerical operators to the pivot table. Results are displayed in different forms of tables and heat maps or be exported. Conditional and mathematical operator are included to obtain specific results, such as “Count”, “Count Unique Values”, “List Unique Values” and “Sum”. Filters can be applied to attribute content. By clicking on the attributes, a list of the information contained will be displayed and the information to be displayed and counted can be selected. Documentation explains the database background of the tool and gives three example that help to get the user acquainted with the functionalities of the tool (<https://inowas.hydro.tu-dresden.de/tools/t04a-database-for-gis-based-suitability-mapping/>).

4. Discussion

GIS-MCDA studies are increasingly used to locate suitable areas for MAR application. Out of the 63 studies found for this review, 90% have been published during the last ten years. Suitability maps are mostly used to locate sites for the MAR methods spreading methods and in-channel modification. There is still a large

variation in criteria and methods used for identification or selection of MAR sites. However, there are some consistent patterns in the application of this approach. Half of the studies used constraint mapping to restrict unsuitable areas. Most studies used less than ten criteria with a large focus on surface characteristics, such as slope and land use. Analyzing the different MAR methods, a variation in the criteria sets could be found. However, slope, land use, geology and soil type remain as important criteria for spreading methods and in-channel modifications. It was further established that the most used criteria do not generally correspond to the highest weighted criteria. Slope was the criterion used the most in the studies found but geology and hydrological soils were weighted the highest. Pairwise comparison is the most applied weight assignment method and weighted linear combination the most applied decision rule. Only one fourth of the studies conducted a sensitivity analysis to verify the retrieved results.

The focus on surface criteria could be explained by the data availability. Even though more and more remote sensing data products for groundwater are becoming available (Landerer and Swenson 2012; Lakshmi 2016), remote sensing data on surface characteristics is more frequently obtainable. Land-use, slope and even soil type are remote sensing data sets that are available worldwide in an increasing resolution. Thus, it does not surprise that those are the criteria used the most in GIS-MCDA studies regarding MAR. As surface infiltration MAR methods are mostly characterized by these readily available criteria, they can be more easily assessed than direct injection techniques. For the latter, a more precise characterization of the aquifer is needed which is often unavailable through GIS data sets. When subsurface information was available for the study, it was ranked as one of the most important criteria. Thus, the fact that this information was used less often than surface criteria must be attributed to data unavailability.

Data availability is an important issue for criteria selection that is rarely discussed in literature about GIS-MCDA for MAR. Even though this review can point to the most used criteria for site selection studies, it cannot regard quality and availability of the data. Thus, data might be solely excluded from the decision-making process because of its unavailability or poor quality. Only a few authors (Malekmohammadi et al. 2012; Singh et al. 2013) stated that their studies were based on the information available to them. Discussion

about data availability and uncertainties within the used datasets was undertaken by Steinel et al. (2016). Russo et al. (2015) also discussed data availability and criteria missing from their study. The study specifically mentions water availability as one of the key factors for MAR implementation that had not been regarded in the analysis and needed to be merged with the resulting suitability map. As few authors give information on data availability, it cannot be regarded in this review. In general, authors of the studies did not mention which data was missing from their analysis or which data sets they would have preferred to use.

This review does not consider literature on PRZ studies. A quick review on PRZ delineation studies of the past 10 years retrieved more than 50 studies and displayed similarities to MAR suitability mapping. Focus region of these studies is also India and publications have been steadily increasing to 10-15 studies per year. There is more literature available on GIS-MCDA for PRZ assessment than on MAR. About half of the evaluated studies used pairwise comparison and AHP as methodologies for MCDA. Most used criteria are very similar to MAR studies with geology, drainage density and slope as the most used criteria. The biggest difference is the rainfall criterion, which ranks under the top used criteria for PRZ but not for MAR studies. This can be attributed to potential recharge depending on rainfall as water source. The highest ranked criteria are geology and geomorphology. These results indicate that PRZ delineation studies could very well be used as reference for MAR site suitability analysis. They further confirm the trend of using more structured methodology for groundwater (recharge) potential mapping.

The information collected in this review will help planners of MAR sites to engage in the MCDA in a more structured way, referring to previously conducted studies, learning from other authors experience on GIS-MCDA applications for MAR site selection and even help with finding the criteria most suitable for their specific project. Weight assignment is one of the most difficult factors of multi-criteria decision analysis, as well as one of the main sources of uncertainty (Malczewski 1999). This review helps to decrease the uncertainty associated with weight assignment. It displays the general importance of a criterion for a specific

MAR technique and pinpoints to criteria sets used the most. However, it is not possible to extract specific weights for a given criteria set from this review.

To date, there is no common understanding on how to generate suitability maps. Findings from this review suggest that following the approach of constraint mapping, suitability mapping by using pairwise comparison and WLC or AHP and a subsequent sensitivity analysis is the methodology used most often. The AHP methodology has its advantages in robust decision making while keeping the process clearly laid out. AHP comprises a very systematic procedure, representing all aspects of the problem statement. When combined with pairwise comparison, the user must only give priorities on a lower hierarchic level, considering two criteria at a time. Cinelli et al. (2014) discussed the shortcomings of this method, which include inability to include threshold values, no direct measure to assess robustness of criteria standardization values and possible rank reverse issues. Nevertheless, studies show that AHP and pairwise comparison are increasingly used for other environmental issues (Gounaridis and Zaimis 2012), sustainability-related research (Cinelli et al. 2014) and nature conservation (Esmail and Geneletti 2018).

Thus, the consideration of a structured GIS-MCDA process that emphasizes on sensitivity analysis can help to generate more robust and usable suitability maps. Validation is one of the limitation of MAR suitability maps. Thus far, very few studies have tried to verify their results, and this was generally restricted to comparing the maps to actual MAR sites. Better verification of the maps can only be reached by comparison to field measurements or by reevaluation through MAR projects that are built within the mapped area.

The purpose of suitability maps is still a matter of discussion. Often these maps are created without an actual application in mind but rather as an overview over sites that could be potentially interesting for MAR development (Winnaar et al. 2007; Raviraj et al. 2016; Selvam et al. 2016; Saidi et al. 2017). Only few studies are used to pinpoint to sites for actual MAR project implementation (Brown et al. 2005; Rahman et al. 2013). Rather, they are thought to be integrated into sustainable groundwater management plans and to serve as guidelines and decision-making support for areas that may be used for groundwater enhancement (Magesh et al. 2012; Agarwal et al. 2013; Singh et al. 2013). By displaying locations for MAR

implementation, they can also depict investment options for farmers and policy makers (Owusu et al. 2017). Without a specific purpose or applicant in mind, these maps are often published with best intentions but perish thereafter. A suggestion to increase their visibility is the collection and display of such maps, as started by IGRAC (Stefan and Ansems 2017). If conducted and validated properly, these maps can find their way into sustainable water management plans of environmental entities of the government.

The advantage of such maps for water management plans lies within the spatial display through maps (Winnaar et al. 2007) and the quickness and simplicity of the analysis (Selvam et al. 2016). In addition, the comparative assessment of different MAR methods and their location have been given as key feature of this type of analysis (Raviraj et al. 2016). The maps even hold the potential to plan the implementation of future water management by regarding projections of climate scenarios, population growth or land use changes (Saidi et al. 2017).

However, it was also made clear that the suitability maps should be used in the early planning phase (Jamali et al. 2014). Russo et al. (2015) mention that their map should not be the primary basis for an explicit decision on MAR placement and operational strategies but rather a guidance tool to focus on certain sites for further investigation. In a few studies, GIS-MCDA was combined with subsequent numerical modeling to further explore the effect of MAR implementation on the groundwater resources in the suitable areas (Brown et al. 2005; Russo et al. 2015). The combination with numerical groundwater models allows for more detailed planning and assessment of the effects of MAR but also requires more data. Areas that have been identified as suitable for MAR should be investigated with subsequent in-situ measurements to characterize the hydrology and hydrogeology of the site (Jamali et al. 2014; Satapathy and Syed 2015; Selvam et al. 2016).

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Figures

Figure 1. Grouping of criteria used in the evaluated GIS-MCDA studies

Figure 2. GIS-MCDA studies for MAR site selection sorted by year of publication and study location

Figure 3. Number of criteria used in GIS-MCDA site selection studies

Figure 4. Average number of criteria per level 1 criteria category, calculated based on number of studies per MAR method (given in brackets) with SM – surface spreading methods, IM – in-channel modifications, WSB – well, shaft and borehole recharge, RWH – Rainwater harvesting methods

Figure 5. Weight assignment methods used in analyzed GIS-MCDA studies for MAR site selection with MIF – multi-influencing factor method

Figure 3. Ranges and average values of weights assigned to most used criteria of all 63 studies. Only highest outlier is shown in boxplot.

Figure 7. Ranges and average values of weights assigned to most used criteria for spreading methods studies. Only highest outlier is shown in boxplot.

Figure 8. Ranges and average values of weights assigned to most used criteria for in-channel modification studies. Only highest outlier is shown in boxplot.

Figure 9. Ranges and average values of weights assigned to most used criteria for well, shaft and borehole recharge studies.

Figure 10. Decision rules used in reviewed GIS-MCDA studies for MAR site selection

Figure 4. Review tool interface with specific adjustable functions.

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Figure 1. Grouping of criteria used in GIS-MCDA studies

Figure 2. GIS-MCDA studies for MAR site selection sorted by year of publication and study location

168x162mm (300 x 300 DPI)

Figure 3. Number of criteria used in GIS-MCDA site selection studies

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4	10
5	9
6	10
7	7
8	8
9	6
10	7
11	2
12	0
13	1
14	1
15	1
16	0
17	0
18	0
19	0
20	0
21	1

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Figure 4. Average number of criteria per level 1 criteria category, calculated based on number of stud

lies per MAR method (given in brackets) with SM – surface spreading methods, IM – in-channel modi

fications, WSB – well, shaft and borehole recharge, RWH – Rainwater harvesting methods

	SM (32)	IM (15)	WSB (9)	RWH (5)	Unspecified (1
Aquifer	2.1	1.7	1.6	0.6	2.0
Hydrometerorology	0.2	0.5	0.5	1.0	0.2
Management	0.9	0.6	1.6	0.6	0.5
Surface	3.5	4.6	3.5	3.6	5.1
Water quality	0.7	0.2	0.5	0.0	0.4

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Total (63)

1.9

0.3

1.0

3.7

0.5

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Figure 5. Weight assignment methods used in analyzed GIS-MCDA studies for MAR site selection w

hod NA

with MIF – multi-influencing factor method

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Criteria_weights_assignment	1998	2000	2003
Boolean logic			
Fuzzy logic			
MIF			
Pairwise comparison			
Ranking method	1	1	
Rating method			1
NA			

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2005	2007	2008	2009	2010	2011	2012
1	2		2	1	2	1
	1					1
		1		1		1
2	1			1		
	1	1		2	2	1
						1

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2013	2014	2015	2016	2017	Summe
2		1			12
1		1			3
	1		3	1	6
5	4	5	1	6	24
	1	1	1		9
	1	2	1	1	13
1					2

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Figure 1. Ranges and average values of weights assigned to most used criteria of all 63 studies. Only highest outlier is shown in boxplot.

Figure 7. Ranges and average values of weights assigned to most used criteria for spreading methods studies. Only highest outlier is shown in boxplot.

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Figure 9. Ranges and average values of weights assigned to most used criteria for well, shaft and borehole recharge studies.

Figure 10. Decision rules used in reviewed GIS-MCDA studies for MAR site selection

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Decision_rules	1998	2000	2003	2005
AHP				
PROMETHEE				
Boolean logic				1
Decision tree				1
Fuzzy logic				
Genetic algorithm				
WLC	1	1	1	1
OWA				

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2007	2008	2009	2010	2011	2012	2013
	1		1			4
						1
2		2	2	2	2	3
1	1				1	2
2	1		2	2	3	2
					1	1

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2014	2015	2016	2017	Summe
3	4	1	5	19
				1
	1			15
				1
				5
1				1
3	4	5	2	30
				2

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Table 1. Information collected from accumulated MAR-MCDA studies

General information	MCDA relevant information
Publication type	Criteria used
Title/Authors/Publication year	Criteria weight
Country/Specific location	Criteria standardization (minimum/maximum of criteria values)
MAR method	Weight assignment method
Water source	Decision rules
Main objective of MAR application	Constraint mapping (+ constraints used)
	Sensitivity analysis

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Table 1. Number of criteria per specific criteria category regarding MAR method with SM – surface spreading methods, IM – in-channel modifications, WSB – well, shaft and borehole recharge, RWH – rainwater harvesting methods (number of regarded studies given in brackets). Note that one study can have more than one criterion that falls into a specific category

		SM	IM	WSB	RWH	Unsp.	Total
Level 1	Level 2	(32)	(15)	(9)	(5)	(15)	(63)
Aquifer	Flow capacity	9	7	5	0	7	23
	Storage capacity	35	13	6	3	11	58
	Storage/flow capacity	22	6	5	0	12	37
Hydrometeorology	Precipitation	5	3	2	2	2	9
	Runoff	1	4	3	3	1	10
Management	Economical	17	7	10	0	4	35
	Impact assessment	13	2	6	3	3	26
Surface	Geological	9	9	5	1	11	22
	Geomorphological	40	24	11	6	21	80
	Hydrography	11	12	6	2	16	33
	Land use/ Land cover	22	11	5	4	12	43
	Soils	30	13	8	5	16	58
Water quality	General	1	0	2	0	1	4
	Groundwater quality	19	3	2	0	4	26
	Surface water quality	1	0	1	0	1	3