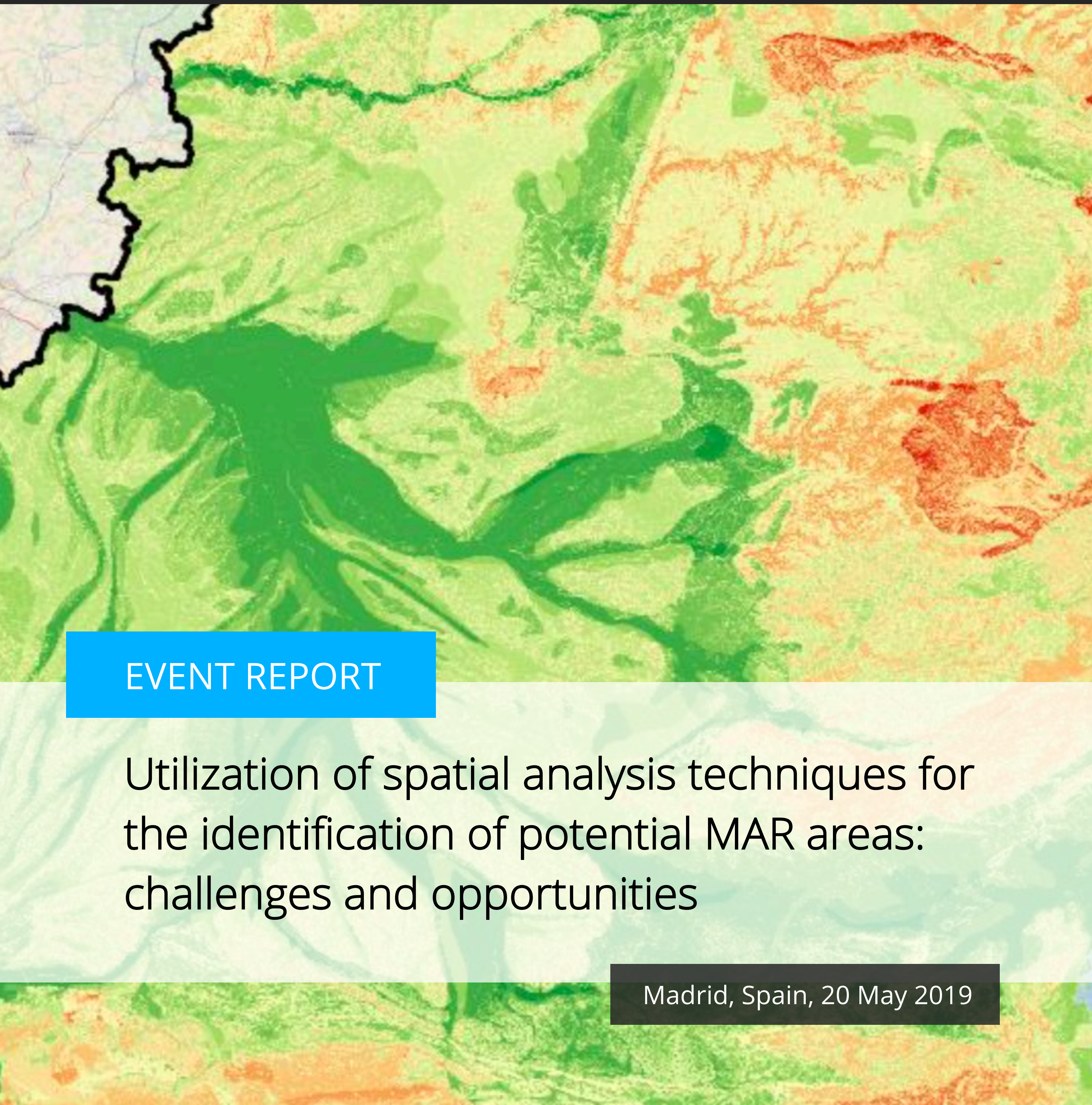
INOWAS

Innovative Groundwater Solutions



EVENT REPORT

Utilization of spatial analysis techniques for the identification of potential MAR areas: challenges and opportunities

Madrid, Spain, 20 May 2019

TECHNISCHE UNIVERSITÄT DRESDEN

igrac International Groundwater Resources Assessment Centre

UNIVERSITY OF CALIFORNIA SANTA CRUZ

International Association of Hydrogeologists the World-wide Groundwater Organisation

WORKSHOP REPORT

Workshop

Utilization of spatial analysis techniques for the identification of potential MAR areas: challenges and opportunities

10th International Symposium on Managed Aquifer Recharge (ISMAR10) in Madrid, Spain
May 20-24, 2019

Moderators:

José Pablo Bonilla Valverde, Instituto Costarricense de Acueductos y Alcantarillados (AyA), Costa Rica

Catalin Stefan, Research Group INOWAS,
Technische Universität Dresden (TUD), Germany

Invited Speakers:

Jana Sallwey[1], Arnaud Sterckx[2], Robert Schlick[1], Galen Gorski[3], Daniel Goode[4]

[1]Technische Universität Dresden (TUD), Germany; International Groundwater Resources Assessment Centre (IGRAC), the Netherlands; [3]University of California, Santa Cruz, USA; [4]United States Geological Survey (USGS), USA

About this report

This document contains the report of the Workshop entitled "Utilization of spatial analysis techniques for the identification of potential MAR areas: challenges and opportunities" organized during the 10th International Symposium on Managed Aquifer Recharge (ISMAR10) in Madrid, Spain, on May 20-24, 2019.

Acknowledgement

The authors would like to thank the ISMAR10 organizers for enabling the inclusion of this Workshop in the Conference agenda and for providing excellent logistic support. Special thanks to all invited speakers and to the workshop participants for their contributions.

Photo cover

Excerpt from the MAR suitability map for spreading methods in the Occitanie region, France (author: Dupont et al. 2017)

Report compiled by

José Pablo Bonilla Valverde (bonilla.jp@aya.go.cr)
Catalin Stefan (catalin.stefan@tu-dresden.de)
Research Group INOWAS
Technische Universität Dresden
Web: www.tu-dresden.de/uw/inowas

(with contributions from invited speakers and workshop participants)

Dresden, January 2020

CONTENT

FIGURES

Executive summary

General context

The generation of maps to identify potential areas where the implementation of Managed Aquifer Recharge (MAR) schemes may render better results is increasing in the last years (Sallwey et al. 2018). Yet, there is no standard methodology nor criteria set used to identify these potential areas. The present workshop aimed at promoting the usage of common GIS-MCDA concepts and terms, and discussing the importance and applicability of these maps with both stakeholders and the scientific community.

The workshop took place at the *Instituto Geológico y Minero de España* (IGME) Headquarters in Madrid, Spain, on the morning section of the preconference seminars and workshops (20.05.2019) of the 10th International Symposium on Managed Aquifer Recharge (ISMAR10). During this event, over 40 participants from 14 different countries representing both stake holders and scientific community discussed over the methods, criteria sets, applicability, scientific value, importance and representativeness.

The workshop was divided in four sections. In the first part of the workshop the common terms and concepts as well as the results from the review on GIS-MCDA – focusing in frequently used criteria and assigned weights – were presented and discussed with the participants (see **Chapter 1. Setting the stage**).

The second section of the workshop consisted in flash presentations from MAR suitability mapping experiences in three different regions of the world with distinct environmental conditions: the Merti transboundary aquifer (shared between Kenya and Somalia), the region of the Ramotswa transboundary aquifer (shared between Botswana and South-Africa) and the countries of Jordan and Costa Rica. A presentation and discussion on the quality and quantity of criteria (scale, resolution, sources of origin, interpolation) followed the flash presentations (see **Chapter 2. Best practices**).

Two available tools to construct the MAR suitability maps were presented in the third section: the *INOWAS web-based tool for GIS-MCDA* and the *Web-based tool for visualizing sensitivity during the map-making process* (see **Chapter 3. Tools development**). In the fourth section, the relation between the MAR suitability maps and implementation of MAR schemes was discussed (see **Chapter 4. Practical relevance**).

The conclusions from the workshop as well as the next steps into building the common language as well as a standardized methodology are given in **Chapter 5. Conclusions**.

Workshop objectives

1. Initiate a network of scientists and stakeholders to share experiences on MAR suitability mapping.

2. Improve the usage of common GIS-MCDA concepts and terms in the construction of maps for identifying and selecting suitable areas for MAR.

3. Discuss the importance and applicability of maps for identifying and selecting suitable areas for MAR.

4. Discuss the data quality (availability, resolution, formats, etc.) and methods for integration of the criteria.

5. Propose the formulation of a MAR suitability mapping guidelines.

Workshop agenda

Time	Format	Topic	Presenter
09:30		Welcome	Stefan / Bonilla
09:35	Presentation	Common terms and concepts regarding GIS-MCDA	Bonilla
09:45	Presentation	Overview of frequently used criteria and assigned weights for different MAR schemes	Sallwey / Bonilla
09:55	Flash	Current applications of MAR suitability maps for Jordan, Africa and Costa Rica	Goode / Sterckx / Bonilla
10:10	Interactive	Participants' preferences and opinions regarding criteria to be used	Sallwey / Bonilla
10:30	Presentation	Findings related to critical data	Goode
10:40	Interactive	Quality and quantity of criteria (scale, resolution, sources of origin, interpolation)	Goode / Bonilla
11:00	Presentation	INOWAS web-tool for GIS-MCDA	Sallwey
11:10	Interactive	Utilization of the INOWAS web-tool for GIS-MCDA	All attendees
11:30		Break	
12:00	Interactive	Bridge between MAR suitability maps and implementation of MAR Schemes	Sterckx
12:30	Presentation	Proposal of a standardized suitability mapping methodology: MARSI – MAR suitability index	Bonilla
12:45	Interactive	Criteria and weights for a standard MAR suitability tool	All attendees
13:15	Discussion		All attendees
13:50		Collective summary & photo	All attendees

...

Chapter 1
Setting the stage

Terminology, criteria, data quality. After the welcome and short introduction, the workshop continued with two presentations given by José Bonilla and Jana Sallwey. The aim of the talks was to stablish a common base knowledge and terminology and to introduce the frequently used criteria weight. Based on this, a discussion with the participants was initiated in the last part of the section.

INVITED SPEAKERS:

JOSÉ PABLO BONILLA VALVERDE
Instituto Costarricense de Acueductos y Alcantarillados (AyA), Costa Rica
Common terms and concepts regarding GIS-MCDA

JANA SALLWEY
Technische Universität Dresden (TUD), Germany
Overview of frequently used criteria and assigned weights for different MAR schemes

INTERACTIVE SESSION:
Participants' preferences and opinions regarding the criteria to be used.

Common terms and concepts regarding GIS-MCDA

JOSÉ PABLO BONILLA VALVERDE
Instituto Costarricense de Acueductos y Alcantarillados (AyA), Costa Rica
email: bonilla.jp@gmail.com

Geographic Information Science – Multicriteria Decision Analysis (GIS-MCDA) is the integration of two distinct areas of science: spatial analysis and decision support (Malczewski and Rinner 2015). Geographic Information Science (GIScience) refers to the nature of geographci information and phenomena providing theotetical foundations to the Geographic Information Systmes (GIS) particulary as a decision support tool (*ibid.*). Multicriteria Decision Analysis (MCDA) is defined as a set of tools to design, evaluate and prioritize the choice between alternatives (Eastman 1995; Malczewski 2006).

Site search/selection (SSS) of suitable sites for any particular activity is one of the eight decision/evaluation problems tackled by GIS-MCDA recognized by Malczewski (2006). MAR suitability mapping is one of the SSS among other uses, this makes the general use of GIS-MCDA diverse, thus, different terms are found in literature that refer to the same concepts. Because of this, the first step is to properly defined the basic terms and concepts to be applied. The basic terms and concepts where presented based on Eastman (1993) and Malczewski and Rinner (2015) definitions, these term are:

- MCDA: set of tools to design, evaluate and prioritize the choice between alternatives.
- Decision-maker: responsible entity for making a decision in MCDA, formed by one or more individuals that share the same goal in respect to the decision.
- GIS-MCDA: comprises the evaluation of spatial alternatives based on the decision-makers goals and preferences. The basic components of a GIS-MCDA are: criterion value scaling, criteria set weights and the decision rule.
- Criterion: basic element in GIS-MCDA, it can be measured and evaluated. The term criterion comprises the objective and attribute concepts. The objective concept refers to the perspective or desired state of an attribute by the decision-maker and the attribute concept refers to the measurable properties of a geographic entity.
- Value scaling: process of transforming the evaluation criteria to comparable units.
- Criteria set weight: relative importance among criteria. More significant criteria are given higher weights than the less important ones.
- Decision rule: defines how the criteria values and weights are integrated

Futhermore, the criterion and criteria set ideal characteristic acording to Malczewski and Rinner (2015) were presented. For these authors, a criterion should be comprehensive (unambiguous and understandable) and measurable (a number or the preference can be assigned) and the criteria set, on the other hand, should be: complete, operational, decomposable, non-redundant, and minimal, where:

- Complete: covers all aspects of the decision.
- Operational: meaningful and understandable.
- Decomposable: refers that it can disaggregate the decision into parts.
- Non-redundant: avoid double counting
- Minimal: enough to keep the criteria set as small as possible.

The metholodology proposed to be standardized for GIS-MCDA for MAR is taken from Rahman *et al.* (2012) and it is shown in Figure 1.

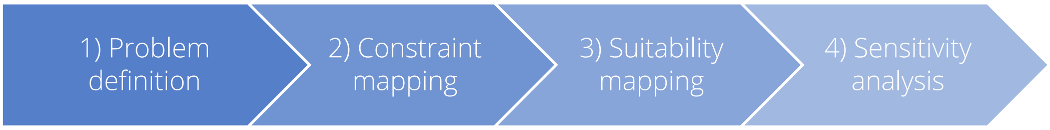


Figure 1. Proposed methodology GIS-MCDA for MAR (modified by Bonilla Valverde 2018 from Rahman et al. 2012).

According to the review of GIS-MCDA studies focusing on MAR done by Sallwey *et al.* (2018), almost half of the 63 cases analysed included the second step (constraint mapping) – and less than a quarter performed the last (sensitivity analysis). The problem definition is a basic step as it defines, as well as the data availabity, the criteria set, values and weights. And yet, 15 of the reviewed studies did not specify the MAR technique for which they were built. Suitability mapping is the core of the GIS-MCDA, thus, all of them included this step.

The importance of the problem definition lays as it defines the criteria set to be used. The problem definition should not only specified the MAR technique for which the GIS-MCDA is conducted, but it should include as well the type of source water, end use of the recharge water among other variables. Two distinct problems can render completely different results in the same area – even using the same criteria set.

Overview of frequently used criteria and assigned weights for different MAR schemes

JANA SALLWEY
Technische Universität Dresden (TUD), Germany
email: jana.sallwey@tu-dresden.de

GIS-MCDA studies are increasingly used to locate suitable areas for MAR application. A review of 63 GIS-MCDA studies (Sallwey et al. 2018) revealed that 90% have been published during the last 10 years. Suitability maps are mostly used to locate sites for spreading methods and in-channel modifications. 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 analysed studies used constraint mapping to restrict unsuitable areas. Most studies used fewer than 10 criteria with a large focus on surface characteristics, such as slope and land use (Figure 2).

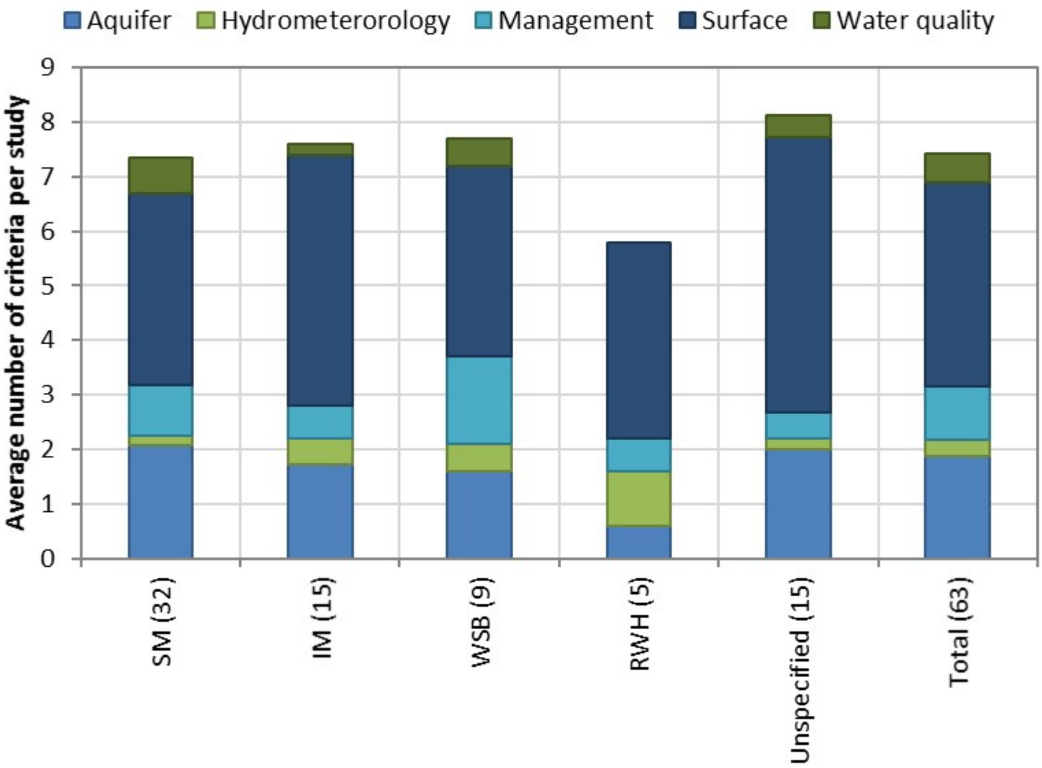
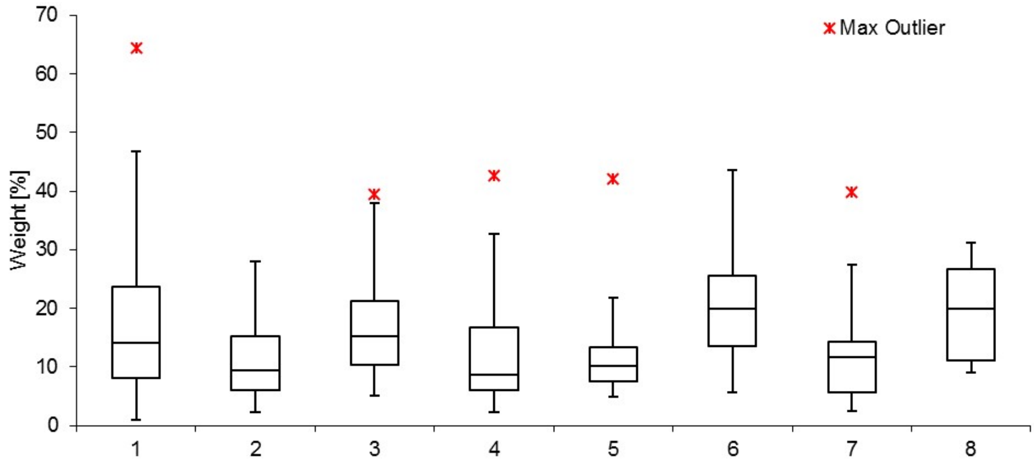


Figure 2. Average number of criteria per main criteria category, calculated based on number of studies per MAR method (given in brackets) with SM – surface spreading methods, IM – in-channel modifications, WSB – well, shaft and borehole recharge, RWH – Rainwater harvesting methods (taken from Sallwey et al. 2018)

Analysing 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 reviewed but geomorphology and hydrological soils were given the highest weights (Error! Reference source not found.).



Criterion	Slope	Land use	Geology	Soil type	Drainage density	Geomor-phology	Aquifer thickness	Hydrolog-ical soils
Count	55	41	29	29	23	21	20	19
Median	14.1	9.5	15.3	8.7	10.2	20.0	11.6	20.0
~ Rank	3.0	3.4	2.8	3.8	3.8	2.4	3.3	2.2

Figure 3. Ranges and average values of weights assigned to most used criteria of all 63 studies. Only highest outlier is shown in boxplot (taken from Sallwey et al. 2018)

Regarding the MCDA methodologies used, 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 data from the reviewed studies was further compiled into a web-based query tool that makes the information easily accessible and the utilization of the database more user friendly. The tool can be accessed under https://inowas.com/tools/t04-database-for-gis-mcda/.

Chapter 2
Best practices

Examples. Three flash presentations of MAR suitability mapping in Jordan, Africa and Costa Rica were given by Daniel Goode, Arnaud Sterckx and José Bonilla. These talks presented case studies from around the world using different criteria set for distinct problem definitions. The case studies were used in the last part of the section for the discussion with the participants on criteria quality and quantity.

INVITED SPEAKERS:

DANIEL GOODE
United States Geological Survey (USGA), USA
MAR suitability mapping in Jordan

ARNAUD STERCKX
International Groundwater Assessment Centre (IGRAC), the Netherlands
MAR suitability mapping in Africa

JOSÉ PABLO BONILLA VALVERDE
Instituto Costarricense de Acueductos y Alcantarillados (AyA), Costa Rica
MAR suitability mapping in Costa Rica

MAR suitability mapping in Jordan

DANIEL GOODE
United States Geological Survey (USGS), USA
email: djgoode@usgs.gov

The USGS is working with partner universities, research centers, non-governmental organizations, and government agencies, including: American University of Beirut; An-Najah National University; Arab Water Council; Hydrology.nl; Jordan Ministry of Water and Irrigation; Jordan National Center for Research & Development; Lebanon Ministry of Energy and Water; and Palestinian Water Authority with the support of the USAID in the programm *"Accelerating Aquifer Storage & Recovery in the Middle East and North Africa (MENA) Region"*.

This program aims to improve water security in the MENA region by accelerating aquifer storage and recovery (ASR). This will be achieved by demonstrating new methods to identify high potential ASR sites, with three study areas for testing and replication in other MENA countries; and by building capacity of the MENA water institutions to develop non-conventional water resources.

Particularly for Jordan, a previous study performed by the USAID in 2001 analysed the options for MAR with reclaimed water both in Amman-Zarqa Basin and the Jordan Valley (MWI 2001). Salameh *et al.* (2019) reviewed previous MAR projects in Jordan, based in this review the authors proposed a flow chart to design a MAR project (Figure 4). Step 3 in the proposed flow chart deals with spatial analysis for the identification of potential MAR areas.

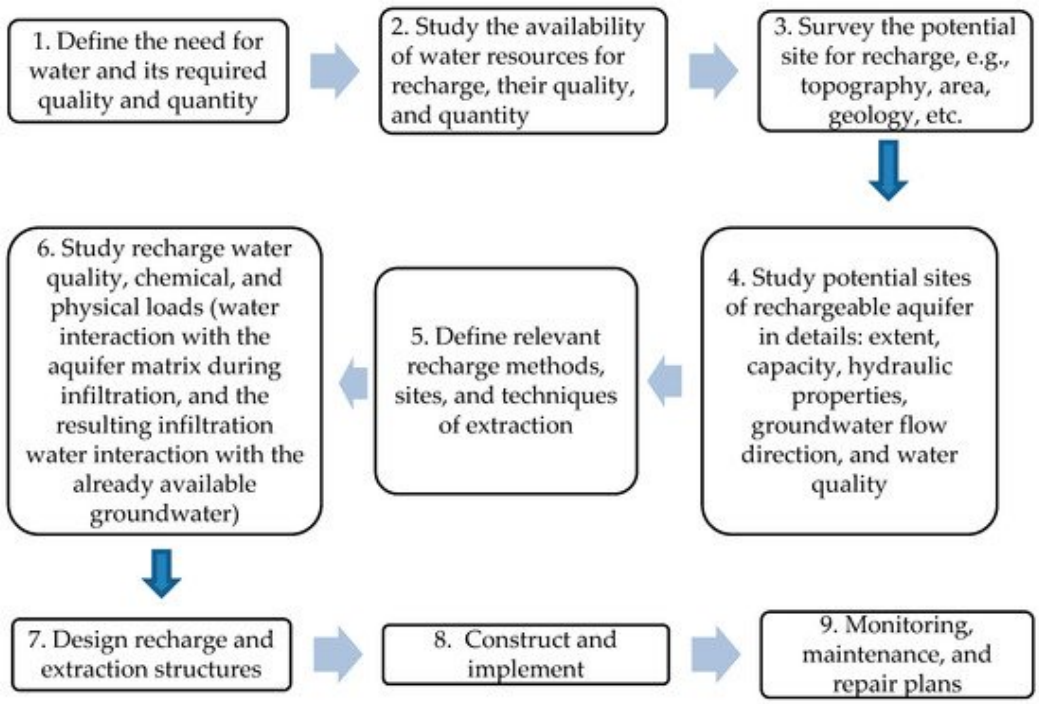


Figure 4. Flow chart of MAR design considerations (Salameh et al. 2019).

MAR suitability mapping in France

ARNAUD STERCKX
International Groundwater Assessment Centre (IGRAC), the Netherlands
email: arnaud.sterckx@un-igrac.org

In 2014 and 2015, IGRAC collaborated with Acacia Water, a Dutch water consulting company, on a MAR mapping project commissioned by IGAD-INWRMP (Inland Water Resources Management Programme), a EU-funded programme aiming at strengthening the national and regional capacities in the field of water resources management and at the development of regional dialogue and cooperation for sustainable water resources management in the Horn of Africa. The project aimed at assessing the potential for MAR in the Merti transboundary aquifer, shared between Kenya and Somalia. The methodology consisted in dividing the region into classes based on physiographic, hydrogeological and environmental criteria. Then, for each class, the potential for various MAR and water harvesting methods was assessed. More info at https://www.un-igrac.org/special-project/igad-mar.

In 2017, IGRAC supervised a M.Sc. thesis that aimed at assessing the potential for installing infiltration basins in the region of the Ramotswa transboundary aquifer, shared between Botswana and South-Africa. The study was hindered by the low availability, resolution or reliability of datasets. More info at https://www.un-igrac.org/resource/gis-multi-criteria-decision-analysis-identify-potential-managed-aquifer-recharge-mar.

MAR suitability mapping in Costa Rica

JOSÈ PABLO BONILLA VALVERDE
Instituto Costarricense de Acueductos y Alcantarillados (AyA), Costa Rica
email: bonilla.jp@gmail.com

This flash presentation summarized the main results from the first assessment for the identification of suitable areas for the implementation of MAR (spreading methods in this case) in Costa Rica published in the MPDI journal Water (Bonilla *et al.* 2016). To the best of the authors' knowledge, this is the first asssesment of this type carried out in the American continent – with the exeption of the United States (Sallwey *et al.* 2018). This study follows the methodology proposed by Rahman *et al.* (2012), which is based on four steps (see Figure 1): problem definition, constraint mapping, suitability mapping and sentivity analysis.

The first step is the problem definition, which in this case states: *"the identification of sites with the best intrinsic conditions for Spreading Methods in Costa Rica based on four criteria"* (Bonilla *et al.* 2016). According to this problem definition, the third step should only indentify suitable areas for one specific MAR Technique (spreading methods). Furthermore, the final map only includes phisical criteria, not demand nor source water availability, even though demand is the main driver for any MAR project (Government of India 2007; Dillon et al. 2009; NRMMC-EPHC-AHMC 2009).

Two criteria were used for the constraint mapping (step 2): terrain slope and soil texture (which also included conservation areas). The integration of these criteria was carried out by a Boolean Logic ("OR" connector). The results indicate that less than 40% was screen out, leaving more than half of the country's surface as suitable for MAR by spreading methods (Bonilla *et al.* 2016). As mentioned by Bonilla *et al.* (2016), it is important to draw attention to the fact that more than a quarter of the area of Costa Rica is under some kind on protection, then, as a parting point, at least 25% of the country is screen out.

The third step (suitability mapping) was carried out with the available spatial criteria in the country scale: hydrogeological aptitude, terrain slope, top soil texture and drainage network density. Even though Costa Rica is a relative small country, the spatial information that cover all of it was scarce, and the scale not optimal (1:500 000 for hydrogeological aptitude and top soil texture). The weight assignment was obtained by the multi-influence factor method (MIF) where the relationships between the criteria are established in a graphical way. (for more details on this weight assignment method refer to Shaban *et al.* 2005; Magesh *et al.* 2012; Bonilla *et al.* 2016). The relationships established by Bonilla *et al.* (2016) are shown in Figure 5 and the final suitability map in Figure 6.

The sensitivity analysis (step four) was applied to the criterion weights assignment by changing the weight assignment by adding or removing relationships between the criteria in the MIF method, thus altering the decision rule (Bonilla *et al.* 2016). For each new weight scenario (16 in total) a new map was obtained and compare with the original. Furthermore, Bonilla Valverde (2018) compared the 16 distinct weights scenarios obtained by this variations with the weight estimated by the ranking and pairwise comparison methods. The results for this comparison showed that the variation of the weights by the sensitivity analysis was higher than the variation between methods.

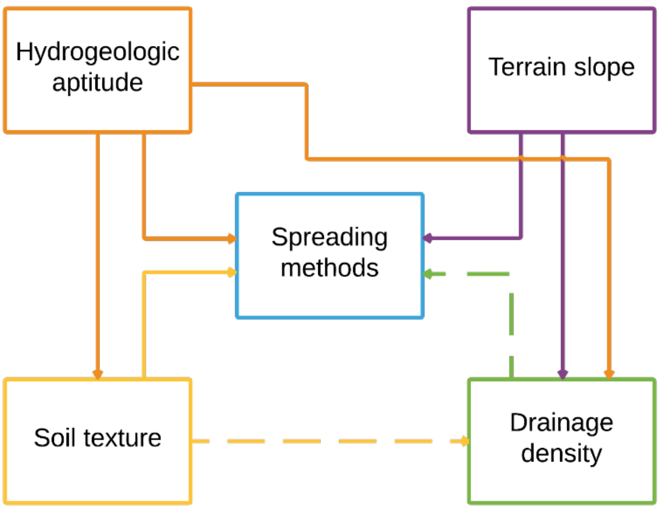


Figure 5. Criteria and weight assignment by multi-influence factor method (MIF) (Bonilla et al. 2016).

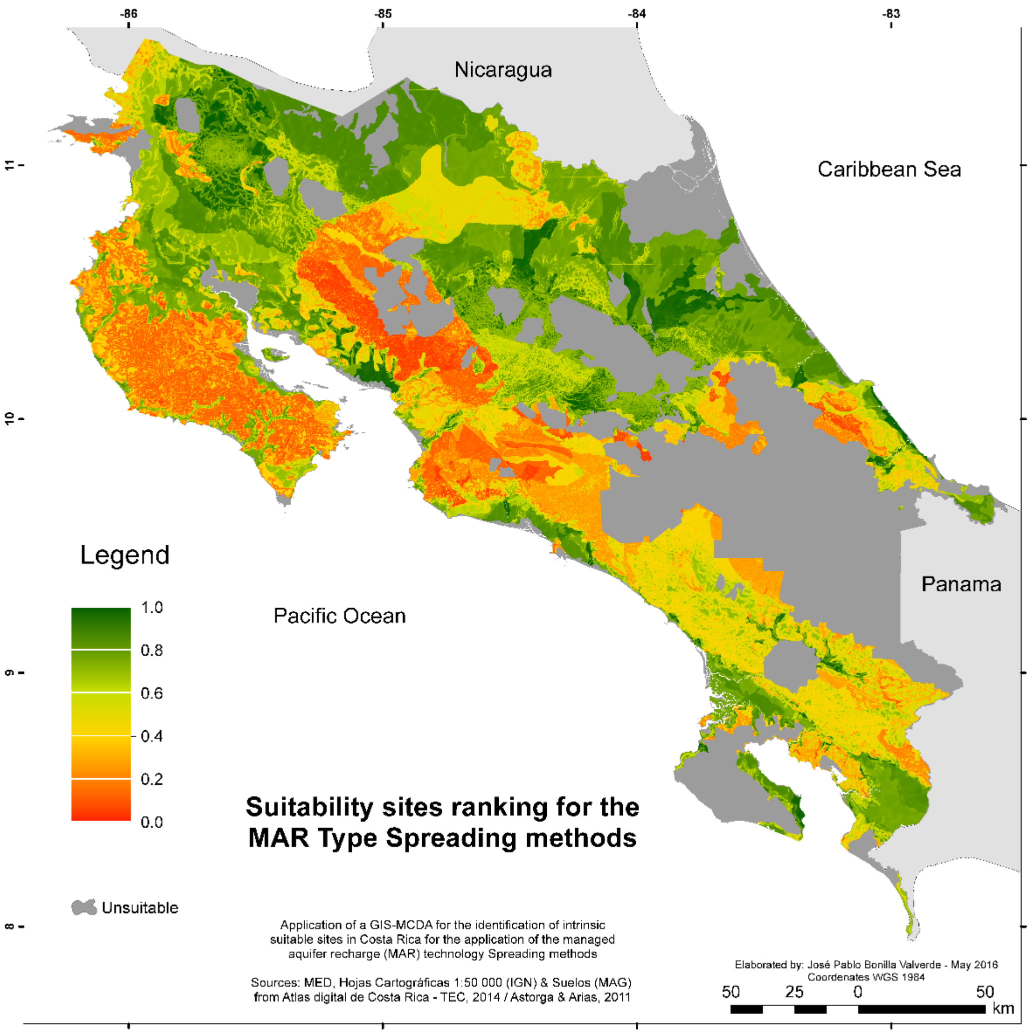


Figure 6. Identification of suitable sites for spreading methods in Costa Rica (Bonilla et al. 2016).

The resulting suitability map for spreading methods (Figure 6) represents a useful tool for various decision-makers in the country. The users may overlaid the spatial distribution of their demand and source recharge water with this map to obtained the optimal areas for their specific needs (Bonilla Valverde 2018). As the map only has intrinsic criteria, it is an open tool for any potential water user, such as drinking water suppliers, agriculture sector and others. As the original aim of the map was to prioritized areas for further research, it is important to recall that the map is not intended for the actual selection of sites for the implementation of a full-scale MAR project (Bonilla Valverde 2018). For the last (actual site selection), more information at a better scale is needed as well as a feasibility study of the proposed MAR project.

Quality and quantity of criteria (scale, resolution, sources of origin, interpolation)

INTERACTIVE SESSION
Moderator: José Pablo Bonilla Valverde

The discussion focused on the potential use of the produced maps rather than in the quality and quantity of criteria used to built them. It was clear that all participants were intereseted in the relation with this maps and real MAR applications. All participants agreed that the suitability maps are useful to raise awareness regarding the potential of MAR.

There were two clear defined positions: the scientific community questioning the scientific base of the results and the stakeholders that have a positive reaction to maps themselves. The scientific community questioned the real application of the maps, and the lack of scientific evidence that the maps actually identified successful MAR projects. To the best of the authors knowledge there is no case published where the complete process proposed in Figure 4 has been done.

As stated before, all participants agreed the there is high potential to use these tools to raise awareness among the stakeholders. It was also concluded that only by completing the process proposed in Figure 4 could there be scientific evidence to prove if the maps actually identified successfull areas to implement a MAR project.

Chapter 3
Tools development

Web-based tools. The development and utilization of two web-based tools for MAR suitability mapping were demostrated by Robert Schlick and Galen Gorski. Both tools are open source with the one developed by the INOWAS group at TU Dresden being fully functional and the one at UC Santa Cruz still under development.

INVITED SPEAKERS:

ROBERT SCHLICK
Technische Universität Dresden (TUD), Germany
INOWAS web-based tool for GIS-MCDA

GALEN GORSKI
University of California, Santa Cruz, USA
Web-based tool for visualizing sensitivity during the map-making process

INOWAS web-based tool for GIS-MCDA

ROBERT SCHLICK
Technische Universität Dresden (TUD), Germany
email: robert.schlick@mailbox.tu-dresden.de

Based on the overview of frequently used criteria for the selection of suitable sites for different MAR schemes (Sallwey et al. 2018), the INOWAS group designed a free web-based tool that combines GIS-based geospatial analysis with expert-based multi-criteria decision analysis (Sallwey et al. 2019). The tool is built upon a step-by-step approach including constraint mapping and suitability mapping with GIS data standardization and criteria weighting (see Figure 7). Several weight assignment methods were included so that next to pairwise comparison, the decision-maker can utilize rating and ranking method as well as multi-influence factor method. Weights can be combined either by weighted linear combination or by analytical hierarchy process (AHP). While some methods for their simplicity or advantage in visual decision-making, the combination of pairwise comparison with AHP must be highlighted as the methodologies with the highest increase in usage and the most benefits.

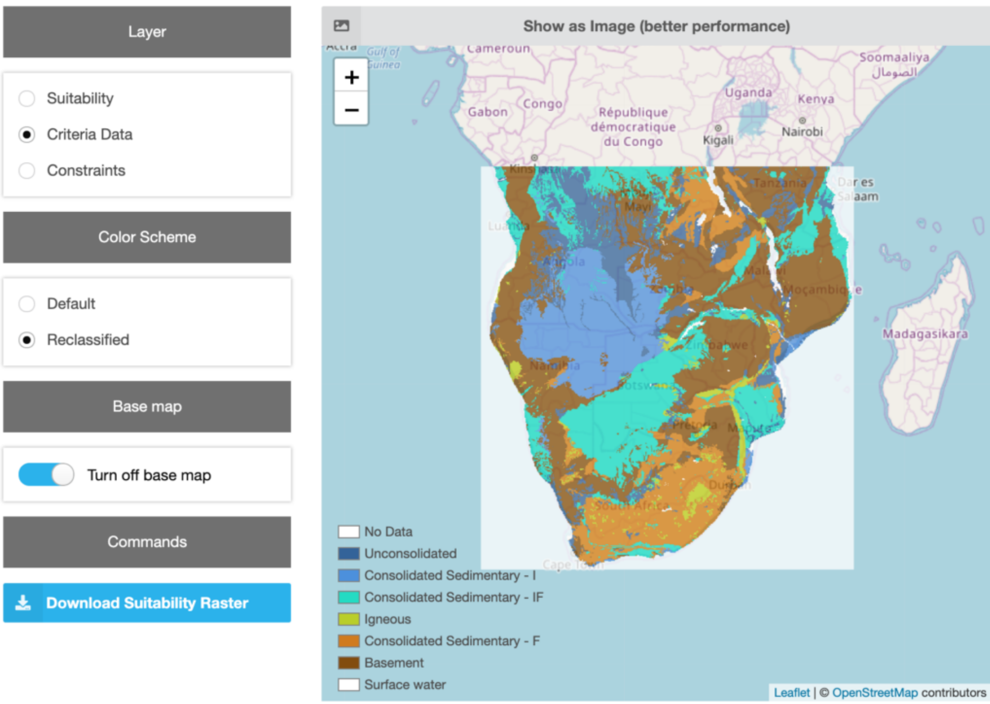


Figure 7. INOWAS GIS-based multi-criteria decision analysis tool

The tool includes all basic GIS data handling steps. The clearly outlined process of map generation enforces standard methodology. This will help to generate maps that are better comparable due to the common methodological approach. While the tools can outline the map generation process, they cannot standardize one of the main sources of uncertainty - the quality of the datasets and subjectivity of weights assigned. Nevertheless, a web-based MAR mapping tool will help to promote MAR suitability as well as improve communication with stakeholders. The tool can be accessed on the INOWAS platform at www.inowas.com, with detailed documentation available at https://inowas.com/tools/t05-gis-mcda/ (tool T05).

Web-based tool for visualizing sensitivity during the map-making process

GALEN GORSKI
University of California, Santa Cruz, USA
email: galen.gorski@gmail.com

Each step in the process of making an MAR suitability map requires subjective decisions that may significantly affect the final map in ways that are difficult to discern without a formal sensitivity analysis. This can result in suitability maps of unknown or limited use to decision makers trying to effectively site new projects. We have developed an open source interactive web application that allows users to classify, weigh, and combine spatial layers to produce suitability maps easily. This is a general tool composed of a graphical user interface and underlying code that allows the user to quickly visualize spatial data and quantitatively explore the effect that different classification schemes, weights and aggregation methods have on the composite landscape suitability. Figure 8 shows one of the app visualizations.

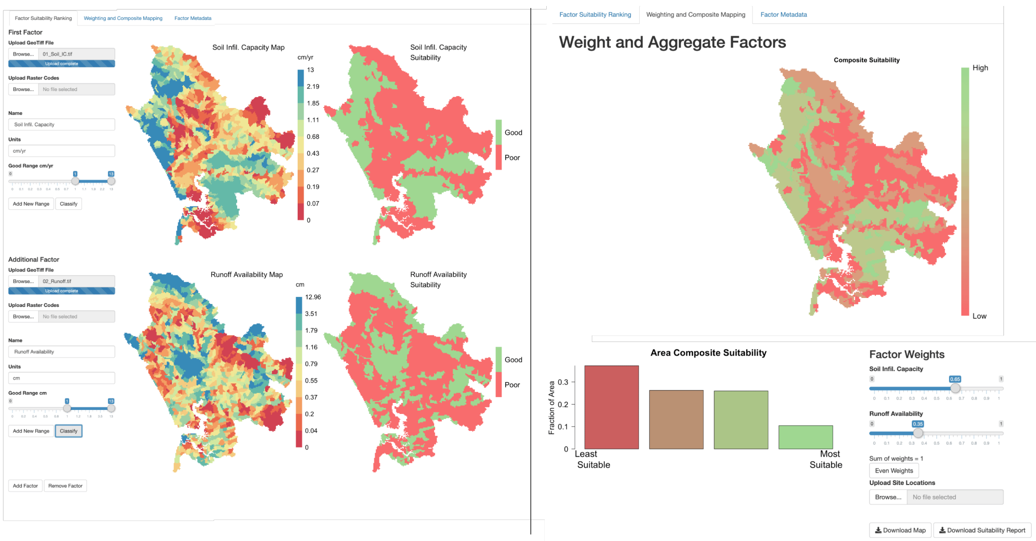


Figure 8. Sensitivity visualization app. The left panel shows the data input and factor classification and the right panel shows the factor weighting and aggregating with slider bars to interactively toggle classification and weights and see their effect on the suitability map in real time.

Maps update in real time in response to changes in input values, resulting in better process understanding and allowing the user to develop intuition about the effects of the subjective decisions made during the map making process. Intermediate and final maps, as well as metadata documenting workflow and user input, can all be downloaded and used in other mapping software for subsequent analysis. The tool is currently in beta form, which can be accessed through the following link: https://ggorski.shinyapps.io/mar-maps/

A tutorial and the source code could also be access through this link. The author would be happy to discuss potential applications and collaborations at any point.

Chapter 4
Practical relevance

Stakeholders. In an interactive session, Arnauld Sterckx identified gaps between MAR suitability mapping and the implementation of MAR. Solutions were put forward to bridge these gaps.

INVITED SPEAKERS:

ARNAUD STERCKX
International Groundwater Assessment Centre (IGRAC), the Netherlands
Bridge between MAR suitability maps and implementation of MAR schemes

Bridge between MAR suitability maps and implementation of MAR schemes

ARNAUD STERCKX

International Groundwater Assessment Center (IGRAC), the Netherlands

email: arnaud.sterckx@un-igrac.org

The purpose of MAR suitability maps is to demonstrate the potential of MAR over a region and/or to identify the right places where to implement new MAR sites. MAR suitability maps are supposed to trigger feasibility studies (e.g. field investigation, modelling, piloting, cost analyses) and, eventually, the creation of new MAR sites. Figure 9 shows a stepwise process for implementing a MAR scheme.

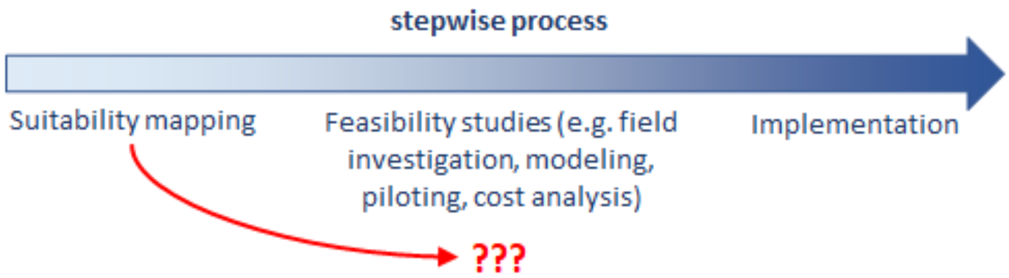


Figure 9. Stepwise implementation of MAR, starting from suitability maps. There is quite often a gap between suitability mapping and subsequent phases of MAR development.

For example, a MAR suitability mapping study was made as part of the Comprehensive Everglades Restoration Plan (CERP) in Florida (Brown *et al.* 2005). MAR suitability mapping was used to narrow down the regional study area and identify the places where to conduct field investigations, groundwater modelling, geochemical testing, groundwater sampling, ecological studies, etc. Objectives of the study were clearly defined, and the suitability map was built accordingly. In this example, the main partners who made the suitability mapping study (e.g. U.S. Army Corps of Engineers, South Florida Water Management District, U.S. Fish & Wildlife Service) were also engaged in the subsequent phases of the project, including the feasibility studies and the implementation of new MAR sites. They were both makers and users of the suitability maps.

This example is however quite an exception. Although many MAR suitability mapping studies have been made and published, in many countries, there are few evidences that MAR suitability maps have been used to implement new MAR sites. A tentative explanation is that in most cases, unlike the example of the Everglades, the persons or organisations engaged in MAR suitability mapping don't have the capacity to implement MAR. A quick survey during the workshop revealed that most of the attendees are making or could make MAR suitability maps, but very few of them have or would have the capacity to build and maintain a MAR site. For example, academic researchers can do excellent MAR suitability maps, but they can't implement MAR beyond the pilot stage.

Apparently, there is a gap between the makers and the users of MAR suitability maps (see Figure 9). There are three ways that can help bridging the gap between MAR suitability maps and the implementation of MAR.

1. Identify the users of MAR suitability maps.

When making a MAR suitability map, it is important to identify the beneficiaries who will use it. During the workshop, several types of organisations were identified that can implement MAR, finance it or decide on the implementation of MAR:

- Water management institutions, like water supply and sanitation organisations
- Regional policymakers and planners
- Funding agencies and donors
- Business companies (e.g. water bottling companies, farmers, landowners)
- Communities
- NGOs (e.g. organisations supporting communities or the environment)

Even though consultancy companies are very often engaged in the implementation of MAR, they were discarded because they need to be contracted to operate. Research institutions can bring MAR suitability maps to the level of feasibility studies, but they can't implement MAR.

2. Identify the objectives of MAR suitability maps.

There are many different ways to create a MAR suitability map. Choosing a right methodology depends on the objective of the map: what does the map have to show? This question is strongly related to the previous: to whom is the map addressed?

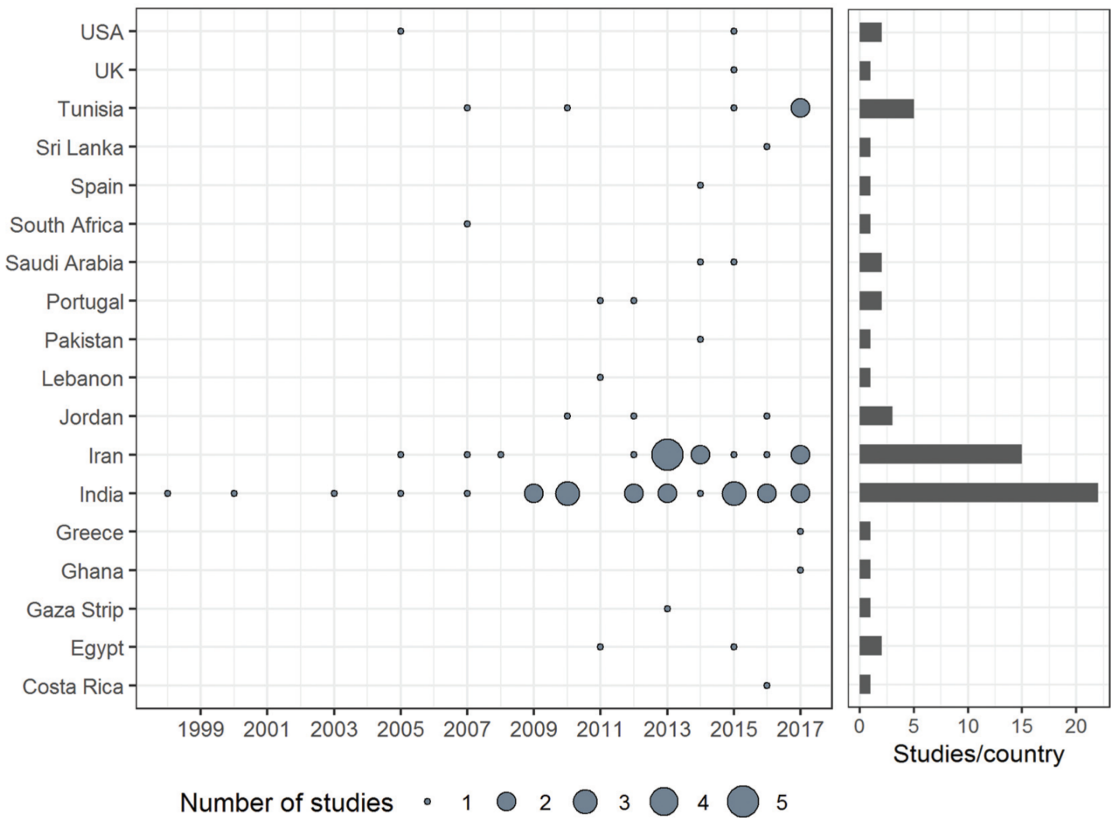


Figure 10.Occurrence of MAR suitability mapping studies per countries (from Sallwey et al. 2018)).

When MAR suitability maps are addressed to persons who are not or little aware of MAR, an important objective of MAR suitability maps is to raise awareness. A review of MAR suitability mapping studies (Sallwey et al. 2018) revealed that most studies were made in countries where MAR is not yet diffuse (Figure 10). Very few studies were reported from regions where MAR is applied on a larger scale (e.g. USA, Australia, EU). It is then surprising that only 30% of the studies reviewed considered the suitability to all MAR methods. Other studies, while aiming at raising awareness on MAR, only considered one or a few MAR methods and discarded the others.

3. Disseminate the results.

As illustrated in Figure 11, there are several ways to present and share groundwater information. Maps are a good mean to share information with a wide range of stakeholders, including non-experts. Yet, maps need to be forwarded to the beneficiaries or they won't be used. The best way is probably to meet with the beneficiaries personally. Brochures and leaflets could be printed. Information systems can also be used. For instance, the MAR Portal (marportal.un-igrac.org) contains a selection of MAR suitability maps. On the contrary, scientific publications and reports, like those reviewed by Sallwey et al. (2018), are usually not an efficient channel to reach out non-expert stakeholders.

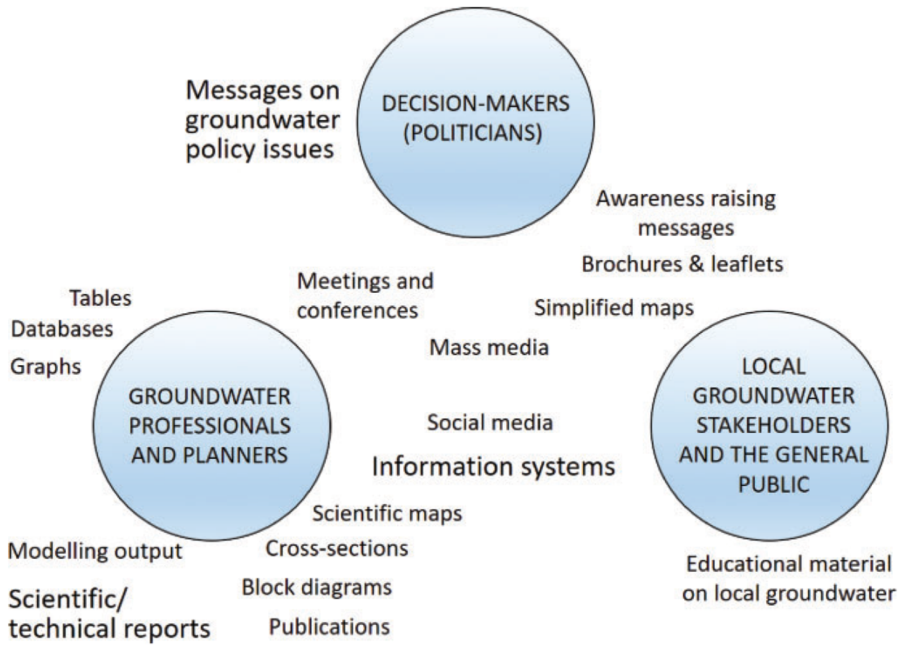


Figure 11.Selected forms of presenting groundwater data and information, in relation to envisaged users (van der Gun, 2018).

.

Chapter 5
Conclusions

Conclusions and the way forward. The section includes the final conclusions as well as futher steps that could follow this workshop.

General conclusions

In general the participants attending the workshop agreed that suitability mapping is a useful tool for raising awareness among the diferent stakeholders in the right context. As discussed by many authors (Malczewski 1999; Rahman et al. 2012; Malczewski and Rinner 2015; Bonilla Valverde 2018; Sallwey et al. 2018) an oversimplification of the criteria may render a result that is completely useless.

These suitability maps have the potential to transmit a positive mesagge from the scientific community. Still, more work is needed to standardized some basic criteria sets, and to establish a minimum scale and resolution resulting from the criteria themselves.

The web-tools presented during the workshop represent a great opportunity for all users to creat their own maps and to quickly perform different weights configurations. Still, this oversimplification could also led to results that do not represent the actual suitability of a certain area to develop a successful MAR project.

Regarding the first discussion, the recommendation from the participants to build a strictly physical and intrisic suitability map that can be overlaid on water demand and water sources will be futher explored. For the second discussion, until the full cycle is done, it will be possible to really contrast this maps with real applications.

Further steps

The present working group under the IAH Commission on Managed Aquifer Recharge (https://recharge.iah.org/mar-suitability-mapping) aimed at sharing experience, taking stock and advancing calculation and use of MAR suitability mapping. Particulary, the working group want to propose a general guideline directed at the standardization of the methodology for constructing MAR suitability maps. All participants and interested contributors are welcome to work on this guideline (check more info on the working group website of the IAH-MAR Commission).

One further activity initiated by the INOWAS research group at TU Dresden is to built a standardized MAR suitability mapping approach (working title: “MARSI”) based on a minumum and basic criteria (i.e. geology, slope and soils). This activity will continue to be developed and will be presented and discussed in future workshops.

References

Bonilla J, Blank C, Roidt M, et al (2016) Application of a GIS Multi-Criteria Decision Analysis for the Identification of Intrinsic Suitable Sites in Costa Rica for the Application of Managed Aquifer Recharge (MAR) through Spreading Methods. Water 8:391. https://doi.org/10.3390/w8090391

Bonilla Valverde JP (2018) Managed Aquifer Recharge Assessment to Overcome Water Scarcity During the Dry Season in Costa Rica. Dissertation. Technische Universität Dresden, Germany

Brown CJ, Weiss R, Verrastro R, Schubert S (2005) Development of an Aquifer, Storage and Recovery (ASR) Site Selection Suitability Index in Support of the Comprehensive Everglades Restoration Project. J Environ Hydrol 13:1–13

Dillon P, Pavelic P, Page D, et al (2009) Managed aquifer recharge: an introduction. Waterlines Report Series, No. 13. National Water Commission, Canberra

Dupont F, Sterckx A, Dijksma R (2017) Managed Aquifer Recharge (MAR) Suitability maps and standardized suitability index, the case study of the Occitanie region (South France)

Eastman JR, Kyem, P.A.K., Toledano, J., Jin, W. (1993) GIS and decision making. Vol. 4. Explorations in Geographic Information System Technology, UNITAR, Geneva.

Government of India (2007) Manual on Artificial Recharge of Ground Water. Government of India, Ministry of Water Resources, Central Ground Water Board, Faridabad, India

Magesh NS, Chandrasekar N, Soundranayagam JP (2012) Delineation of groundwater potential zones in Theni district, Tamil Nadu, using remote sensing, GIS and MIF techniques. Geosci Front 3:189–196. https://doi.org/10.1016/j.gsf.2011.10.007

Malczewski J (2006) GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci 20:703–726. https://doi.org/10.1080/13658810600661508

Malczewski J (1999) GIS and multicriteria decision analysis. John Wiley & Sons

Malczewski J, Rinner C (2015) Multicriteria decision analysis in geographic information science. Springer

MWI M of W and I (2001) Options for Artificial Groundwater Recharge with Reclaimed Water in the Amman-Zarqa Basin & Jordan Valley - 2001 - MWI. Amman, Jordan

NRMMC-EPHC-AHMC (2009) Australian Guidelines for Water Recycling. Managed Aquifer Recharge. Canberra

Rahman MA, Rusteberg B, Gogu RC, et al (2012) A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J Environ Manage 99:61–75. https://doi.org/10.1016/j.jenvman.2012.01.003

Salameh E, Abdallat G, Valk M (2019) Planning Considerations of Managed Aquifer Recharge (MAR) Projects in Jordan. Water 11:182. https://doi.org/10.3390/w11020182

Sallwey J, Bonilla Valverde JP, Vásquez López F, et al (2018) Suitability maps for managed aquifer recharge: a review of multi-criteria decision analysis studies. Environ Rev 1–13. https://doi.org/10.1139/er-2018-0069

Sallwey J, Schlick R, Bonilla Valverde JP, et al (2019) Suitability Mapping for Managed Aquifer Recharge: Development of Web-Tools. Water 11:2254. https://doi.org/10.3390/w11112254

Shaban A, Khawlie M, Abdallah C (2005) Use of remote sensing and GIS to determine recharge potential zones: the case of Occidental Lebanon. Hydrogeol J 14:433–443. https://doi.org/10.1007/s10040-005-0437-6