Site suitability evaluation for Managed Aquifer Recharge (MAR) in Sweden

Master’s thesis in Infrastructure and environmental engineering

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Abstract

This thesis identifies and evaluates existing methodological approaches to the initial stages of the planning phase of MAR, including the localisation of suitable sites. The aim is to compare methodologies for site suitability evaluation in Swedish conditions. Hydrogeological, geological, and hydrological parameters, which are expected to have a large influence on the site suitability for MAR are identified. This is achieved by conducting a literature study of guidelines, scientific articles and case study reports in the field of MAR site suitability analysis. The main difference in the application lies with the parameters recommended for the evaluation, this is mainly due to the geological differences in Sweden compared to the rest of the world. Furthermore, based on the literature analysis, an approach is selected, adjusted, and implemented in a case study on a region in Sweden to evaluate its suitability in Swedish conditions.

The literature review has shown that site suitability evaluation is a crucial part of the planning phase for MAR. The approach of conducting a GIS-MCDA for site suitability evaluation was assessed as possibly suitable for Swedish conditions. To evaluate this, a GIS-MCDA was implemented to the case study with the purpose of identifying suitable areas for MAR. For validation of the results, the outcome of the GIS-MCDA was compared previously identified sites possibly suitable for MAR by Stockholm Vatten AB et al. (1996). As the same areas previously identified as suitable were suggested also in this analysis, the GIS-MCDA was assessed as successful. In conclusion, the methodology found in the literature is assessed as a promising approach to be applied in Swedish conditions.

Keywords: Managed Aquifer Recharge (MAR), Site suitability evaluation, GIS-MCDA, hydrogeology, geology, hydrology,

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Sammanfattning

Detta examensarbete identifierar och utvärderar tillvägagångssätt för tidiga skeden av planering för konstgjord infiltration, inklusive metoder för lokalisering av lämpliga platser för detta. Syftet med rapporten är att jämföra lämpliga metoder för utvärdering av lämpliga platser för konstgjord infiltration i svenska förhållanden. Hydrogeologiska, geologiska, samt hydrologiska parametrar, vilka är bedömda ha en stor påverkan på en plats lämplighet, har identifierats. Detta har uppnåtts genom en litteraturstudie i vilken riktlinjer samt artiklar, som bedömts ha ett stort inflytande på hur en platsutvärdering för konstgjord infiltration skall utföras, har analyserats. Den största skillnaden ligger i vilka parametrar som används vid analysen, vilket till största del beror på de geologiska skillnaderna mellan Sverige och resten av världen. Vidare, baserat på litteraturstudien, valdes en metod ut som applicerades och justerades på en fallstudie i Sverige för att undersöka dess lämplighet på svenska förhållanden.

Litteraturstudien visade på vikten av en väl utförd platsutvärdering för konstgjord infiltration. Att utföra en GIS-MCDA bedömdes vara ett tillvägagånggsätt som skulle kunna vara lämpligt även i svenska förhållanden. För att utvärdera detta genomfördes en GIS-MCDA på en fallstudie, med syftet att identifiera lämpliga platser för konstgjord infiltration. För att validera resultatet jämfördes resultatet av denna GIS-MCDA med tidigare identifierade platser möjligen lämpliga för konstgjord infiltration av Stockholm Vatten AB et al. (1996). Då samma områden som tidigare har påvisats identifierades även i denna analys, bedömdes resultatet som lyckat. Slutligen, metodiken som identifierades i litteraturstudien bedöms som ett lämpligt tillvägagångssgätt även i svenska förhållanden.

Nyckelord: Konstgjord infiltration, lämplighetsanalys av plats, GIS-MCDA, hydrogeologi, geologi, hydrologi

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Gothenburg, June 2023

Lisa Johansson
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1

Introduction

As the natural groundwater recharge changes with a changing climate, sustainable use of groundwater resources is becoming more important. In Sweden, large shifts in the hydrological cycle have been observed, resulting in longer periods with no groundwater recharge (Nygren et al., 2020). These shifts can be expected to steadily intensify, causing a shift in net groundwater recharge towards winter months, but longer periods without recharge during spring and summer (Dubois et al., 2022). Therefore, to buffer this effect, the need to store groundwater recharge will increase. Managed Aquifer Recharge (MAR) could be a possible solution as it has the potential to mitigate water scarcity by artificially increasing groundwater resources. However, finding a suitable location for a MAR facility requires careful consideration of various hydrogeological, hydrological, and geological factors. Therefore, this report aims to investigate how to successfully plan for a MAR facility by establishing a method for identifying sites suitable for MAR, specifically adapted to Swedish conditions. These conditions mainly concern the typical project objectives and geological environment of MAR facilities found in Sweden. This work mainly relies on a comprehensive literature review of guidelines as well as previous studies and projects related to the initial planning phase for MAR. The findings of the literature are applied to a case study to evaluate the applicability to Swedish conditions. The results of this study aim to provide insights into the site evaluation for MAR facilities in Sweden and to contribute to a more systematic and established approach to the planning phase.

1.1 Background

Managed aquifer recharge (MAR) is a water management technique that involves the intentional recharge of water (Dillon et al., 2019). The purpose of MAR is to, in an effective and sustainable way, enhance the quantity of groundwater, but in many cases also to improve the water quality, reduce groundwater depletion, and mitigate the impacts of drought. In Sweden, artificial recharge is mainly implemented as a complement to the conventional treatment for drinking water production (Hanson, 2000b).

The most common method for MAR facilities in Sweden is the utilisation of infiltration ponds as they are effective for the removal of pollutants and, as a result, they are well-suited for use in MAR facilities that are intended for drinking water purposes (Hanson, 2000b). This technique allows for percolation through the unsaturated zone, which exposes the infiltrated water to aerobic biodegradation and filtration which reduces bacteria, viruses and organic material of the infiltrated water. In addition, the quantity of recharged groundwater by pond infiltration normally exceeds the natural groundwater recharge by several orders of magnitude. Infiltration into an unconfined aquifer involves the construction of excavations, dikes, or levees. When both surface and subsurface characteristics of a site allow the aquifer to be recharged from the ground surface level, infiltration ponds are often employed (INOWAS, 2018).

During the year 2020, the total withdrawal of freshwater in Sweden was estimated to be 2530 million m^3. Of these, 71% were extracted from surface waters, 14% from groundwater, 6% from artificial groundwater and 9% were unaccounted for (SCB, 2020). Of the total extracted freshwater, approximately 874 million m^3 was used for the municipal production of drinking water, which provided 89% of the Swedish population with high-quality water. For the municipal production of drinking water, it was estimated that 60% originated from surface waters and 40% from groundwater. The source of groundwater was approximately equally divided between both natural and artificial groundwater (SCB, 2020). Groundwater is often preferred over surface water as the source of raw water for drinking water production. Due to the high quality and relatively stable temperature throughout the year, the risks associated with drinking water production and distribution are decreased when using groundwater (Grönwall, 2022). Even though the artificial infiltration of groundwater could be used for several purposes, all of the freshwater originating from this source was used for drinking water production in Sweden during 2020 (SCB, 2020).

Groundwater management in Sweden is currently divided on different agencies and municipalities (Grönwall, 2022). They are given the task of fulfilling the decisions made by the government with the help of regulations and guidelines. The Water Framework Directive (WFD) 2000/60/EG and subsidiary directives of the European Union outline the foundation for which the Swedish legislation for groundwater management is formulated. The Geological Survey of Sweden (SGU) is assigned with the task of further formulating regulations on groundwater management (SGU, 2020). Four regulations SGU-FS 2014:1 (2014), SGU-FS 2017:1 (2017), SGU-FS 2023:1 (2023) and SGU-FS 2023:2 (2023) regarding groundwater have thus far been published by SGU. However, these regulations only briefly touch upon the subject of artificial infiltration. The European WFD does not either contribute with much guidance on how to develop sites for artificial recharge but rather requires each member state to enact policies on their own (Dillon et al., 2019). Given the information at hand, it is assumed that no specific guidelines on the development of MAR facilities in Sweden. There are however some general regulations for artificially infiltrated groundwater given by the Swedish Food Agency, which are listed below. If the facility satisfies these conditions, the extracted water should be considered as groundwater Livsmedelsverket (2022).

- The infiltrated water has to have a residence time of a minimum of 14 days to be considered groundwater.
- The distance between the infiltration and extraction site has to be a minimum of 40 meters.

- An unsaturated zone of a minimum of 1 meter is recommended.

The Scandinavian geology, especially that found in Sweden and Finland, is in many contexts different to other parts of the world. In this area, Quaternary material deposits are the main host of groundwater, whereas sedimentary aquifers are the most common globally (Kurki et al., 2013). Geographically the Quaternary deposits are sparsely situated and generally consist of well-sorted sand and gravel particles with relatively high hydraulic conductivity. Due to these characteristics, these deposits are often beneficial for the artificial infiltration of groundwater and are frequently used when implementing a MAR facility in Sweden (Hanson, 2000a).

Due to changes in the natural groundwater recharge and the rather extensive use of artificially infiltrated groundwater in Sweden, MAR is expected to be a useful tool in future groundwater-related challenges. However, the lack of information regarding the development of MAR facilities in Sweden might cause future projects to be performed sub-optimally. By performing a preliminary desktop study to identify sites which have a higher possibility to be suitable for MAR, the development process could be made more efficient. Even though systematic guidelines for the development of MAR facilities have been formulated for other parts of the world, these might not be directly applicable to Swedish conditions. It was therefore assessed that an investigation of methodological approaches on the preliminary site identification for MAR in Swedish conditions would be of interest.

1.2 Aim and research questions

The overall aim of this study is to identify and evaluate existing methodological approaches to the initial stages of the planning phase of MAR, including the localisation of suitable sites. This will be achieved by initially conducting a literature study on how to successfully plan for MAR facilities. Secondly, the method found most promising will be implemented in a case study with the purpose to investigate suitable sites for MAR in a Swedish region. The study also aims to identify and evaluate key hydrogeological, geological, and hydrological parameters, which are expected to have a large influence on the site suitability for MAR. Based on these findings, a method for the initial planning phase and site suitability assessment adapted to Swedish conditions will be suggested.

The following research questions are set:

- What does the literature suggest as the recommended approach to the planning phase of MAR facilities in general and in a Swedish context?
- Which hydrogeological, geological, and hydrological parameters are identified as important for site evaluation for MAR, in Swedish conditions?
- Applied on a case study in Sweden, how does the recommended method to the planning phase perform and how could it be further developed?

1.3 Limitations

In this work, pond infiltration is the only considered MAR technique. This constraint was set concerning that the main application of MAR in Sweden is primarily for the improvement of source water as a pre-treatment step in drinking water production. The majority of the existing MAR facilities in Sweden utilise pond infiltration since percolation through the unsaturated zone is assumed to contribute to a significant quality improvement of the infiltrated water. Further, only the technical aspects of site feasibility will be covered. Although MAR can be a sustainable solution and technique, none of the dimensions of sustainability will be considered during the evaluation of key parameters for site suitability.

2

Literature study

The purpose of this literature study was to review methods for how to successfully identify sites with properties likely to support MAR facilities in Swedish conditions. The literature study presented in this section is divided into three parts. The first part covers a review of international guidelines which provide general recommendations on a number of suggested steps, ranging from the initial planning of the project to the closure of the facility. The aim of the first part of this section is to compile existing knowledge on the methodology for the initial planning phase of a MAR project and the identification of a suitable site in particular. Specific parts of the guidelines, concerning the planning phase and site selection, are therefore presented in more detail.

The second part covers a review of international scientific papers, which were identified as heavily influential in the field of MAR site suitability analyses. The purpose of the second part is to gain knowledge on the practical execution of a MAR site suitability evaluation, to be able to perform a similar suitability analysis on Swedish conditions. Finally, the third part covers literature on the development of artificial groundwater management projects in Sweden. Due to the geologic differences between Sweden and other parts of the world, it was assessed that literature concerning groundwater management in Sweden could highlight significant differences compared to international projects. A summary of key parameters for site suitability analysis was also performed, covering all the reviewed literature. This was done to gain insight into which parameters should be used to evaluate a site's suitability for MAR. The gathered knowledge from the review was used to aid in the choice of site screening method and the selection of key parameters for the identification of suitable sites in Swedish conditions.

The literature study was carried out by using electronic academic databases such as Scopus, Google Scholar, and Chalmers Library along with the search engine Google. The search for literature on guidelines was set to mainly be based on publications by national and international agencies, or by generally recognised institutions. Guidelines of high influence on other literature, recently issued, or with proximity to Sweden were regarded as more significant. The gathered knowledge of the review on international guidelines was composed into a summary of a general international for the planning phase of MAR. The international scientific papers on the subject of MAR suitability analysis were chosen due to their large influence on the topic. The literature on Swedish groundwater management was assessed to provide an overview of the customary approach to the planning phase and the site suitability analyses, applied during the development of groundwater management facilities in Sweden.

During the search for information on the development of the planning phase for existing MAR facilities in Sweden, it was assessed that expert knowledge in the field could provide additional valuable insights. For this reason, a consultation was arranged with Per-Olof Johansson, a senior hydrogeologist with a doctoral degree in hydrogeology from the Royal Institute of Technology in Stockholm. During his career, Dr Johansson has been involved in numerous groundwater-related projects in Sweden, including those concerning the artificial recharge of groundwater. Some examples of projects are the development of an emergency water supply for northern Stockholm, which is based on artificial recharge, followed by other research and development projects concerning artificial recharge in Sweden. He has also been involved in international projects which studied the use of artificial groundwater recharge to increase water supply safety and bridge draughts in Namibia and Botswana (Artesia, n.d.).

2.1 International guidelines on the planning phase for MAR facilities

In this section, findings from the literature review regarding international guidelines on the planning phase of MAR facilities are presented. Four publications of guidelines with the potential to support the development of a y were identified.

2.1.1 Australian guidelines and their simplified version

The *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2): Managed Aquifer Recharge* published by NRMMC-EPHC-NHMRC (2009) is one of four parts in a collection of guidelines for groundwater management and water recycling in Australia. The guidelines provide general guidance on risk management, applicable to both existing MAR facilities and those under development, with the purpose to provide protection of aquifers and ensure the quality of the recovered water. These risk-management guidelines cover various types of source waters, aquifers, infiltration methods, and end uses of water. A four-step approach is suggested by the guidelines and is made up of an initial *Entry-level assessment*, followed by three steps of risk assessments. Only the Entry-level assessment was deemed to be of interest to this work. In this step, only readily available data are required to implement a desktop study to determine whether a project is viable and assess the degree of difficulty of the project. To perform this, the Entry-level assessment is divided into two parts; the *Viability assessment* and *Assessment of the degree of difficulty.*

In the past, the Australian guidelines have been successfully applied in case studies by Page et al. (2010), who performed risk assessments and developed risk management plans to assess human health risks for international MAR facilities. However, the implementation of the Australian guidelines for the evaluation of MAR for drinking water purposes in India was unsuccessful, due to a lack of data on water quality (Dillon et al., 2020). Recognising this problem, an alternative document on risk management guidelines was published by Dillon et al. (2014). The simplified and less data-demanding guidelines were based on the Entry-level assessment, suggested in the Australian guidelines, in combination with the WHO's Sanitary survey approach (World Health Organization, 2012). The guideline by Dillon et al. (2014) aims to provide a transnational framework, which could be applied to existing artificial infiltration facilities to identify a need for water quality improvement measures, or to new projects as a screening tool for the identification of sites where there is a potential to produce water of high quality. The proposed method consists of a desktop study of basic and readily available information, which aims to evaluate the impact on the groundwater quality of MAR. The guideline provides a logical order assessment procedure and supplies the operator with a checklist consisting of questions with a Yes or No answer. The checklist is divided into five parts, which are described below. More detailed information about the checklists and the reasoning behind them are given in Dillon et al. (2014).

- *Simple assessment* - Is the initial set of questions, developed to determine whether to directly proceed with the project or to conduct the Viability assessment.
- *Viability assessment* - Aims to initially evaluate the feasibility of the suggested facility. The evaluation should be able to identify any fatal flaws in the project based on the following four key factors:
    - Water demand - The demand for water should be sufficient to justify the investment in a MAR facility.
    - Water source - A raw water source with sufficient excess volumes, quality and reliability to provide the mean annual water demand, should be identified.
    - Aquifer - An aquifer with suitable characteristics (e.g. recharge rate and storage capacity) needs to be identified.
    - Detention storage - Securing sufficient space for infiltration and additional treatment if needed.
- *Investigation of applicability* - Since these simplified guidelines are limited to specific conditions, it should be investigated whether the project falls under these conditions or if the inherent risk of the project is too high.
- *Sanitary survey* - Aims to identify possible hazards in the catchment area for the source water, in the recharge facility and the area for water recovery. The process should be capable of identifying any shortcomings or weaknesses of the system which could cause contamination. The sanitary survey is able to provide information on the likely quality of water in different stages of the operation in situations where insufficient water quality data is available for detailed evaluation.
- *Aquifer assessment* - A similar procedure as for the sanitary survey is suggested. A survey concerning the properties of the intended aquifer is used for

the identification of possible hazards and suggests possible means of mitigation.

2.1.2 American Society of Civil Engineering

The *Standard Guidelines for Managed Aquifer Recharge* by the American Society of Civil Engineers (2020) was developed with the intention of providing standard guidelines for recommended activities in order to successfully implement a MAR project. The guidelines are formulated so that they are applicable to various projects, covering many types of recharge techniques and hydrogeological, geological, and hydrological conditions. According to American Society of Civil Engineers (2020), the MAR project normally consists of a series of four phases; planning and evaluation, design, construction, operation, maintenance and closure, which are all described in detail within the document. However, due to the scope of this work, only the *Planning and evaluation phase* will be further considered. In turn, the planning and evaluation phase consists of a three-step procedure for the planning of MAR projects including; *Initial project scoping*, *Initial planning: Data evaluation* and *Detailed planning: identifying potential sites.*

The initial project scoping involves the definition of MAR objectives as well as the development of a preliminary conceptual plan. The defined objectives should constitute a basis for developing the criteria upon which the potential MAR sites should be evaluated. If multiple objectives are defined, the guideline suggests that these should be ranked based on their relative importance, such as primary or secondary objectives. The report provides several suggestions on possible objectives of MAR, e.g. management of water supply and quality. When the objectives have been ranked and defined, a conceptual plan should be constructed. This plan should aim to create a framework for the data acquisition needed for further evaluation. The second step of the planning phase, the initial planning, consists of the development of evaluation criteria and data gathering. A list of criteria that can be used for the purpose of evaluating the feasibility of the project based on the defined objectives should be established. The identified criteria might differ between projects based on factors such as the amount of available data, project size, location and anticipated recharge method. However, the guideline suggests that the following criteria should be taken into consideration: *Water sources and demand*, *Site hydrology*, *Environmental conditions*, *Implementation constraints* and *Regulatory considerations.* The guidelines provide a few parameter recommendations for each main category. Some examples of criteria are given below, and a list of possible detailed criteria is proposed in the guideline.

- *Site hydrogeology:* The hydrogeologic characteristics of the site, including geology, hydrology, and groundwater quality. The receiving aquifer characteristics should be considered, including its permeability, porosity, and storage capacity.
- *Water source and demand:* The availability of water from a reliable source, such as surface water or treated wastewater. This also includes the water quality of the source water and the receiving aquifer which should be evaluated

to ensure that the water can be successfully treated and stored in the aquifer without causing adverse impacts on the environment or public health.

- *Environmental conditions:* The aquifer water quality with respect to standards should be considered. Also, habitat concerns, including the presence of threatened and endangered species as well as effects on wetlands should be evaluated.
- *Implementation considerations:* This includes land ownership and land use considerations, existing infrastructure, and proximity to areas with demand.
- *Regulatory consideration:* The regulatory framework governing MAR projects in the area should be evaluated to ensure that the project complies with all applicable laws, regulations, and guidelines.

In the final part of the planning phase, a two-step approach to identify MAR project sites is recommended to initially reduce the potential sites and later undertake a more detailed evaluation. The first of these two steps, the initial project screening, should aim to eliminate areas that clearly fail to provide essential criteria for the feasibility of the project, based on readily available data. The guidelines suggest the *Viability assessment* of the Australian guidelines as a possible method for the initial project screening. For the second step, the detailed evaluation, a more quantitative approach is recommended. Here the guideline proposes that the criteria are assigned a score based on how well they favour the project, and should be defined by specific quantitative measures. For example, an area with soil of high hydraulic conductivity would receive a higher score as a high value of this criteria would favour artificial groundwater infiltration. According to the guideline, the process of scoring is an iterative process, which should be performed collaboratively by professionals, the public, and other stakeholders. As the project is likely to cover a wide range of parameters and these probably will be of different importance, it is also recommended that the criteria should be weighted based on their influence. By scoring and weighting based on the judgement of professionals, and possibly stakeholders, the aim is to more easily identify sites with high suitability relative to the objectives of the project. A following sensitivity analysis should be performed to identify any potential biases in the assessment. To facilitate the site evaluation, the guideline highly recommends the use of a GIS database to analyse and visually model the spatial data. Additionally, the guideline suggests that the *Assessment of the degree of difficulty* proposed by NRMMC-EPHC-NHMRC (2009), could assess to what extent further investigations are required to complete following risk and regulatory assessments. Which in turn could be used to further rank the alternative sites.

2.1.3 DEEPWATER-CE

DEEPWATER-CE was a project developed to facilitate the protection of water resources in Central Europe. The project was funded by the European Union via the European Regional Development Fund and lasted during the years of 2019 until 2022 (Interreg CENTRAL EUROPE, 2023). The project's objective involved the development of a comprehensive and integrated approach for implementing solutions for MAR. The results of the project were a number of reports which, amongst others, included a proposed methodology to aid in the process of site selection for MAR facilities. This methodology was presented in *Transnational Decision Support Toolbox for Designating Potential MAR Location in Central Europe* and was the only report which contained information relevant to the scope of this work and the only one further considered.

In the report, a decision-support toolbox for identifying sites suitable for MAR in Central Europe is presented (Imig et al., 2020). The authors emphasise the need for careful site selection to ensure the success of the project and highlight the need for a systematic and objective approach to site selection. In the presented guideline, the process of selecting a suitable site for MAR is based on the assessment of both current and estimated climate conditions of the future, geologic and hydrogeologic conditions and the sensitivity to climate extremes of the different MAR techniques. To perform the assessment, the use of a GIS-Multi Criteria Decision Analysis (GIS-MCDA) is suggested to analyse the spatial information of the previously mentioned conditions. Variation in data availability is described as something that might impose limitations on the analysis. To address this difficulty a four-step procedure is recommended: *Exposure to climate extremes*, *General screening of geological and hydrological conditions*, *Specific screening of geological and hydrological conditions*, and *Sensitivity analysis of MAR schemes to climate.*

The investigation on exposure to climate extremes analyse the change in water demand due to climate change in Central Europe, by using climatological models and parameters to identify areas threatened by groundwater scarcity. The second step, the general screening, is the production of a constraint map identifying areas suitable for MAR with general geological and hydrogeological selection criteria. The analysis is applied on a national scale and uses Boolean logic to classify areas as either suitable or unsuitable based on these general criteria. The areas considered feasible in the preliminary analysis are thereafter further investigated, using more specific criteria to evaluate the suitability on a three-level scale (low, moderate, high). This step is performed on a sub-regional scale and uses more specific parameters in the analysis. To be able to rank areas, the parameters are assigned scores and weights based on how well they favour MAR. Finally, a suitability map is produced to illustrate the most favourable areas. The fourth step is an analysis of the feasibility of the site(s) found suitable in the previous step. The feasibility studies are described as site-specific fieldwork at the identified pilot sites. These studies seek to further investigate geologic and hydrogeologic parameters, sensitivity to climate extremes of the MAR, water demand and supply, risk management and cost-benefit analysis. More detailed information on the feasibility study is described in other work packages and is made available on the project web page Interreg CENTRAL EUROPE (2023).

To support the selection of criteria for the analyses, sets of parameters for the general and specific screening are presented in the guideline. Three main categories of parameters are included; *Water source characteristics*, *Surface characteristics*, and *Aquifer characteristics.* These categories include parameters that were assessed to be able to consider critical to the technical feasibility of a MAR facility. The guideline developed predefined selection parameters for the general and the specific screening. Different sets of parameters were developed for different MAR techniques. The evaluating parameters varied somewhat depending on the MAR technique, but the structure of the sets remained the same. Depending on the intended MAR technique, a few general parameters are listed along with a feasibility threshold value to compare with the analysed area to define whether it is deemed feasible or not. The same structure applies to the specific parameters. However, instead of providing a feasibility threshold, a level of suitability (low, moderate or high) is associated with a parameter value. A predefined parameter weight is also given by the guideline to be used in the specific screening. In general, Imig et al. (2020) primarily focus on the features of the surface and the aquifer. Little regard is given to the quantity and quality of both the source water and the groundwater.

2.2 International scientific papers investigating MAR site selection

This section presents a review of international scientific papers which were key references in the field of MAR site selection. The study aims to investigate the implemented methodology as well as the practical execution and to identify suitable tools and strategies.

The use of Spatial Multi-Criteria Decision Analysis (SMCDA) for site suitability evaluation has previously been utilised in practical examples (Saraf & Choudhury, 1998; Krishnamurthyl et al., 2000; Brown et al., 2004). However, Rahman et al. (2012) identified a lack of investigations and compilation in the analysis techniques applied to modern GIS-MCDA for MAR site selection. The MCDA is an approach to aid in the process of decision-making by taking multiple factors into account when evaluating and selecting alternatives. By combining spatial data, spatial analysis and the visualisation tools provided by the GIS and the methods for decision-making of MCDA, the GIS-MCDA provides a rigorous approach to the decision-making of spatial problems (Malczewski & Rinner, 2015). Variations in the applied methods for GIS-MCDA, especially concerning the choice of parameters and the classification and weighting of these, were especially considered by Rahman et al. (2012). In the article, the authors provide a comprehensive review of, at the time existing, information on how Analytical Hierarchy Process (AHP), suitability mapping, and weighting have been involved in the analysis of site suitability evaluation. The authors also present a methodology for how to perform an SMCDA analysis for site selection. Further, an application of the suggested method is also presented.

The article by Rahman et al. (2012) presents the main steps involved in site selection as well as the types of data required for the GIS analysis. The data types required for the analysis are described as highly dependent on the objective of each specific case. Data such as geological maps, infiltration rate, soil texture, and land use are presented as commonly used for evaluating surface characteristics. Infiltration rate, transmissivity, and recharge capacity are some parameters defined as common for characterising the subsurface. Also, groundwater quality is proposed as an important parameter for MAR even though it is not usually applied for site selection. The authors define the map overlay as the most important step of the site selection procedure. The most conventional methods such as Weighted Linear Combination (WLC) or Boolean Logic were found in previous studies while Ordered Weighting Averaging (OWA) was not. This article also presents a comparison between the use of AHP-WLC and AHP-OWA which had not been done in any previous study.

The methodology suggested in this article is described as a non-site-specific, adaptive, and comprehensive tool for site selection. AHP is utilised for developing the hierarchy after the selection of criteria, doing a Pairwise Comparison to assess criteria importance, and undergoing construction of the composite weight and is, therefore, the core of the methodology. The main steps presented by Rahman et al. (2012) for their site selection tool are:

1. Problem definition - Project objectives are defined.
2. Constraint mapping - Constraint mapping is described as the same procedure as described previously by Imig et al. (2020). Boolean logic is used to exclude areas deemed as not suitable for MAR.
3. Suitability mapping - To perform the suitability mapping, the authors have divided this step into five sub-steps. The purpose of this step is to generate a suitability map based on the criteria and sub-criteria defined.
    - Choice of Criteria and Subcriteria - The criteria and subcriteria which were included in the analysis were chosen.
    - Hierarchy of Criteria and Subcriteria - The hierarchy of the analysis is divided into three levels which are (1) The goal of the analysis/problem, (2) Specific criteria with regards to the objective, and (3) More specific criteria which relate to the defined surface, subsurface, and regional characteristics.
    - Standardisation of sub-criteria maps - Each sub-criteria is represented by a map, which has been standardised to a common scale in order to reduce the dimensionality of the analysis.
    - Relative Weights of Criteria and Subcriteria - Pairwise comparison and direct weighting are later used to assign weights to each criterion and sub-criteria.
    - Combination of Criteria and Subcriteria maps - To find the overall suitability index of each alternative, which is given to the cells of the maps, the produced maps were combined. For this step, the authors used both WLC and OWA.
4. Sensitivity analysis - The final step of the methodology is to perform a sensitivity analysis to study the robustness of the generated suitability map.

The approach suggested by Rahman et al. (2012) has later been utilised in many case studies and the importance of having a systematic and objective planning process has been further discussed. Two examples are Russo et al. (2015) and Varouchakis et al. (2022), which performed site suitability evaluations for MAR facilities by using a GIS-MCDA. In the article published by Russo et al. (2015), both a GIS-MCDA and a numerical analysis were performed to assess the regional suitability for MAR and to quantify the impact MAR could have on groundwater levels and seawater intrusion, respectively. The authors found that a combination of GIS and a numerical groundwater model constructed with MODFLOW could aid to assess site suitability. Further, they also suggest that their approach could improve the understanding of the relationship between geology, hydrology, and MAR. The approach suggested by Russo et al. (2015), is essentially the same as described by Rahman et al. (2012). Contrary to other studies, Russo et al. (2015) took an interesting approach to how to include parameters in the GIS-MCDA analysis. Instead of evaluating all data sets as independent indicators, they combined data sets that were assumed to influence one another into one parameter. The parameters using combined data are presented below.

- Soil infiltration capacity - An equation which incorporated land slope and roughness was developed to estimate the soil infiltration capacity.
- Effective transmissivity - Spatial data of hydraulic conductivity and the thickness of the aquifer was used to estimate a spatial effective transmissivity of the aquifer.
- Available storage space of the aquifer - By combining the specific yield with the thickness of the unsaturated zone, the available storage of the aquifer was estimated.

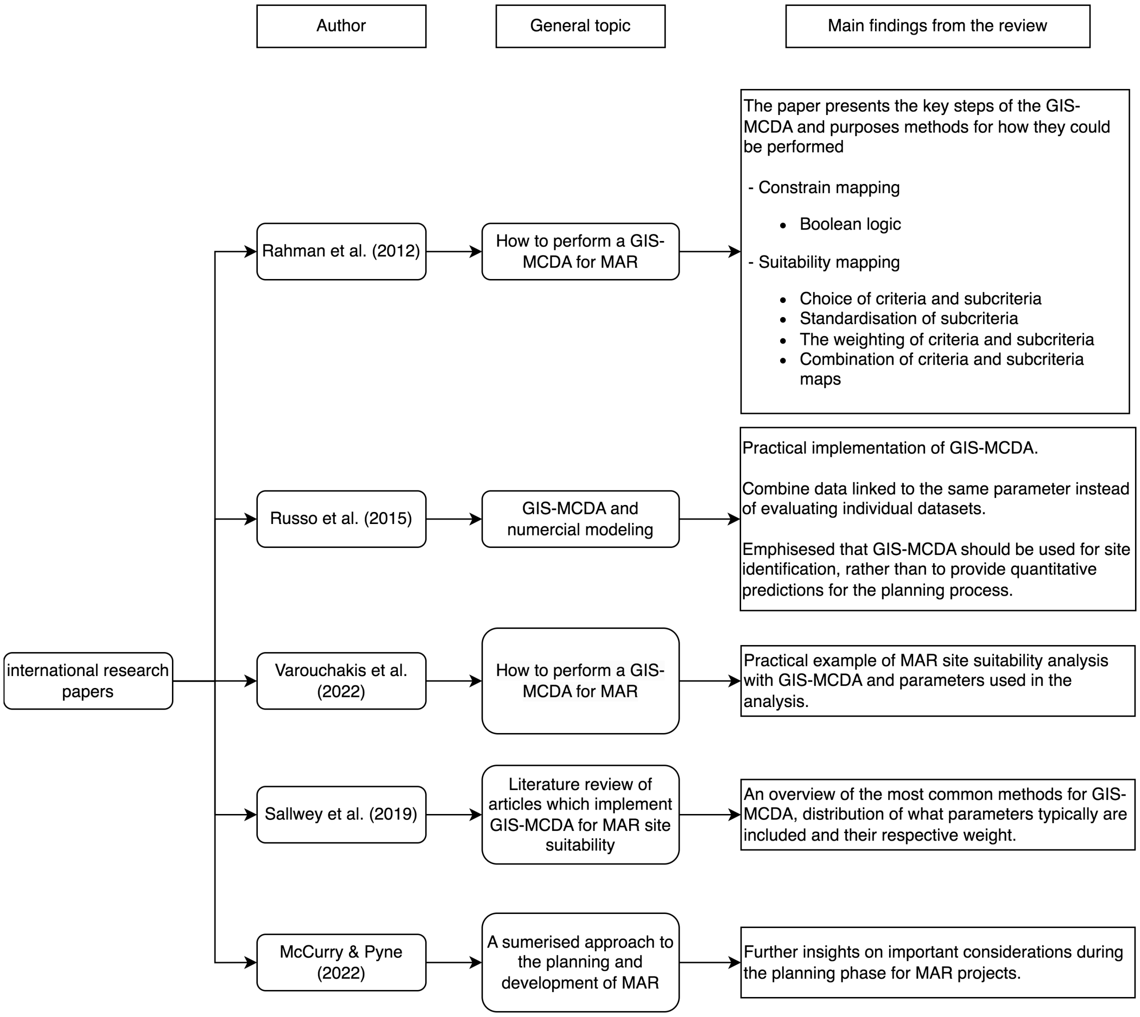
The steps of standardisation, weighting, and calculating a MAR suitability index were performed as described in earlier studies. In addition to the above-mentioned parameters, the surficial geology and the recent change in the groundwater head were also included. These parameters were, however, not evaluated using a combination of data sets. A WLC was used to combine the parameters into a MAR suitability index. The soil infiltration capacity and available storage were assigned the highest weight of 5, while surficial geology and effective transmissivity were assigned 4. The lowest weight of 2 was given to the depth of groundwater due to uncertainties in interpolation from measured values. The MAR suitability index was only calculated for sites where previous records of recharge rates were not available. If a previous measurement had been done, these were used to estimate the suitability index. Throughout the discussion, the authors emphasised the importance to use the approach of a GIS-MCDA to find suitable sites as a guide for MAR placement rather than a quantitative prediction for planning purposes. It was also concluded that GIS and modelling provide a promising approach to identifying suitable MAR sites, as they integrate multiple data sets and allow for the visualisation and analysis of spatial data.

The purpose of the work of Varouchakis et al. (2022) was to apply their suggested approach to a case study located in Crete, Greece to find areas suitable for aquifer recharge. Similar to Rahman et al. (2012), the data sets were handled individually and not in combination as done by Russo et al. (2015). The parameters included by Varouchakis et al. (2022) were; slope, land use, hydrogeology, rainfall groundwater level, soil texture and distance to source water. Each criterion was standardised according to a suitability index ranging from 1 to 5, where 1 indicated low suitability and 5 indicated high suitability. The study analysed four different scenarios where the criteria were either differently weighted or combined. Each criterion was given a weight using the Pairwise Comparison method as a part of AHP. In this method, the importance of each criterion is methodically compared to every other criterion and assigned a weight. The final product is a weight matrix, describing the relative importance of every parameter. From this, a standardised final weight is defined for each parameter. The result of the weighting of the authors proposed that slope, hydrogeology, and water source distance were the most important criteria and that land use and rainfall were the least important. To investigate the sensitivity of the analysis, the authors compared the result from the four different scenarios where the weights were assigned differently. Since the same areas were identified as most suitable for MAR in every scenario, the method was assessed as successful.

To gather knowledge regarding how to perform a successful MAR site suitability mapping with GIS-MCDA, Sallwey et al. (2019) conducted a literature review of 63 international articles on the topic. In their review, the authors stated that GIS-MCDA is a useful tool for evaluating possible sites for MAR, especially for assessing the suitability of MAR by applying the spreading methods or in-channel modifications. Statistical findings on the same four main steps; problem definition, constraint mapping, suitability mapping and sensitivity analysis, as suggested by Rahman et al. (2012), were presented. Regarding the problem definition, it was observed that the choice of the MAR technique had a large impact on the workflow of the suitability analysis. Approximately 50% of the articles used a combination of constraint and suitability mapping, and roughly 40% directly performed a suitability mapping. The final 10% only used constraint mapping for site identification. The majority used less than 10 parameters for the site evaluation and a slight difference in the selection of parameters could be seen dependent on the MAR technique. Pairwise Comparison was the most popular choice for weight assignment and Weighted Linear Combination was the most frequently used decision rule. Sensitivity analyses were only performed in 25% of the reviewed articles. Surface characteristics were the parameters most commonly used for site identification, but were not always considered the most influential parameters. According to the authors, the heavy use of surface characteristics could be explained by large data availability. When subsurface data were available, these parameters were instead assigned with the highest weight. The availability and quality of data were seldom discussed in the reviewed articles. Since GIS-MCDA relies on readily available data, the authors emphasised that a few articles mentioned that parameters which would have been significant to include in the analysis, were excluded due to poor data quality. In conclusion, Sallwey et al. (2019) provides a comprehensive review of the use of GIS-MCDA for creating suitability maps for MAR projects. The review suggests that the approach of constraint mapping, suitability mapping by using pairwise comparison, WLC or AHP and a sensitivity analysis is to be used for MAR site identification. The authors highlight the potential benefits of using GIS-MCDA to prioritise areas for MAR but also note the need for a more thorough evaluation of GIS-MCDA studies and the importance of tailoring criteria and weights to the specific needs of the project.

A further discussion covering the aspects of planning for MAR facilities has been carried out by McCurry & Pyne (2022). The paper outlines the same approach as described by American Society of Civil Engineers (2020) and further highlights the importance of having a systematic and objective planning process. The authors also emphasize that planning for MAR projects should be an iterative process including an increase in information as potential sites are identified. Further, the importance of coordinating engineers and hydrogeologists at an early stage in the planning process is important to increase the likelihood of a successful project. The development of project objectives is described as important since that will determine which information that should be collected during further studies. It will also determine which evaluation criteria that are relevant to the project. The authors state that the criteria should at least include factors such as *Water availability* and *Suitability of the potential source of recharge*, as well as *Hydrogeologic suitability* of the potential recharge site. The methodology described in this paper does not necessarily outline a constraint map and a suitability map, as described by previous papers, but is rather a recommendation as to what should be included in a site suitability evaluation. The authors do not give information on how the feasibility should be conducted in terms of which database is recommended. The selection of a site for MAR project is divided into an initial screening with the intention to screen out areas regarded as non-feasible and a second screening involving a more careful and thorough investigation.

Figure 2.1 summarises the main findings from the international scientific papers described above. The purpose of the flowchart is to present the main findings of the articles, which subsequently will be utilised for the development and implementation of the methodology.



The paper presents the key steps of the GIS-MCDA and purposes methods for how they could be performed

- Constrain mapping
  - Boolean logic
- Suitability mapping
  - Choice of criteria and subcriteria
  - Standardisation of subcriteria
  - The weighting of criteria and subcriteria
  - Combination of criteria and subcriteria maps

Practical implementation of GIS-MCDA.

Combine data linked to the same parameter instead of evaluating individual datasets.

Emphisesed that GIS-MCDA should be used for site identification, rather than to provide quantitative predictions for the planning process.

Practical example of MAR site suitability analysis with GIS-MCDA and parameters used in the analysis.

An overview of the most common methods for GIS-MCDA, distribution of what parameters typically are included and their respective weight.

Further insights on important considerations during the planning phase for MAR projects.

Figure 2.1: Flowchart describing the main findings of the international articles.

2.3 Literature on the planning of MAR facilities in Sweden

Due to the special geological conditions generally found in Sweden, as described in Section 1.1, the criteria for what is deemed a suitable location for a MAR facility varies from other parts of the world. This is expected to cause difficulties in trying to implement international guidance for MAR development in Swedish conditions. Therefore, a further review of Swedish literature has been conducted with the aim of identifying critical differences in the development of MAR facilities.

In 2015 a project was assigned to SGU by the Region of Gotland to report on the possibilities for increased capacity of groundwater resources on the island (Dahlqvist et al., 2017). The aim was to perform an initial study of the geological and hydrogeological conditions on the island to find suitable ways to increase the volumes of groundwater and thereby increase the capacity of the raw water sources for drinking water production. Secondly, the report also aimed to develop a method for identifying the local conditions of a site, which could be considered significant for a successful implementation of wetlands, with the purpose of increasing the groundwater recharge. The suitability of wetlands to provide additional infiltration at several operating groundwater extraction sites was investigated. This assessment was based solely on geologic and hydrogeologic conditions and no consideration was taken to any conflict of interest. During the project, a workflow was developed as a method for identifying the local conditions which would indicate a site suitable for groundwater infiltration by wetlands. The suggested workflow is described in the following steps.

1. Collection of data in the form of GIS layers for an initial investigation.
2. Processing of the collected data. For this step, a watershed area was assessed as an example.
3. A workshop for the preliminary selection of suitable areas.
4. 3D-visualisation of the primary selected areas.
5. Field visits.
6. Workshop for a final decision on which area(s) to move forward with, and proposal for the location of extraction wells.
7. Groundwater modelling with MODFLOW.

In the report, the data requirements needed to perform an assessment of the suitability of each parameter were further investigated. From this, three key parameters were identified: Proximity to surface water, Infiltration capacity and Aquifer storage capacity. To assess the geologic conditions of the groundwater extraction sites, data from SGU regarding wells, soil type, soil thickness, bedrock and hydrogeology were used. Additionally, spatial geophysical data were used to evaluate the sites where previous measurements were available. Based on this evaluation the sites were ranked into three classes, where the lowest rank indicates the most favourable conditions.

Additional projects further investigating the possibilities of increasing the capacity of groundwater sources on the island of Gotland have later been carried out. In a report by Almqvist (2018), methods for increasing groundwater storage and suitable locations were investigated. Hydrological and hydrogeological parameters which could indicate areas with satisfactory properties were determined, followed by a mapping of suitable areas with the help of a GIS-based analysis. The most notable hydrogeologic parameters used in the study for the assessment of groundwater storage were *Specific capacity* and *Storage*. The specific capacity of areas was derived from data retrieved from the Well Archive of SGU. The specific capacity of wells was interpolated and converted into areas with a representative value. The *Storage* of an aquifer was estimated from a model within the GIS tool based on the geologic data of soil depth, soil type, rock type, topography and kinematic porosity.

In another study by Dahlqvist et al. (2019), a GIS-MCDA method was implemented to investigate the feasibility of MAR on the island of Gotland. This was done by identifying sites suitable for infiltration in the proximity to a raw water source and estimating the possibility to increase recharge and extraction of groundwater. The performance of MAR in comparison to alternative solutions in terms of cost and water availability was also investigated. Three common criteria used for evaluation of the suitability of a site to MAR were identified, Aquifer storage capacity, Geomorphology, and Soil. The site screening conducted within the study utilised a GIS-based method for the analysis of five parameters. In the analysis, Boolean logic was applied and no weighting of the parameters was conducted. The following parameters were considered in the initial screening:

1. *Aquifer storage capacity* - To assess the aquifer storage capacity, a national model for groundwater storage capacity (Eveborn et al., 2017) was used in combination with another national model for groundwater recharge (Rodhe et al., 2006). By combining these, a map of the ratio of groundwater recharge over storage capacity was created. A ratio below 1.0 would indicate sites with the potential for storing additional water and be therefore assessed as suitable.

2. *Depressions in bedrock surface* - Assuming that sites with depressions in bedrock surfaces are generally favourable for storing groundwater, a map of depressions in the bedrock was created.

3. *Thickness of soil* - Areas with sand and gravel, and a thickness of greater than four meters was identified. These areas were deemed suitable due to high hydraulic conductivity.

4. *Areas for surface storage of water* - Sites with top soil covers of clay or till with a thickness greater than four meters, were identified with the possibility to store surface water and deemed suitable for raw water storage.

5. *Surface waters* - During the analysis, a buffer was applied to surface waters and areas within a sufficient proximity was assessed as suitable.

Two additional analyses were conducted, combining the results of the initial screening. In this step, a method of overlaying of rasters was used to assess *Areas suitable for infiltration and groundwater storage* and *Areas close to raw water sources and suitable for surface storage*. To assess the suitability of the area for infiltration and groundwater storage parameter 1-3 was used, while parameter 4 and 5 was used to assess the feasibility of water supply in terms of proximity to water source and surface storage. In the analyses, the resulting areas were ranked into three classes based on the number of overlaying pixels from the previous maps of parameters. To assess the final suitability the two rasters of surface and subsurface parameters were overlaid and ranked. The lowest rank was given to the most suitable areas, those where the most pixels from the initial rasters overlay each other. A final map was produced, presenting the ranking of areas which were assessed to be suitable for MAR.

In 1996, Stockholm Vatten AB et al. (1996) performed an investigation on the possibilities to supply the Stockholm region with drinking water utilising MAR. The scope of the report aimed to look into what water quality could be obtained from MAR, along with the infiltration area and the land claim needed in order to supply the future water demand of Stockholm by MAR. Additionally, the report also aimed to identify sites suitable for MAR with the purpose of drinking water production. The results of the report present possibly suitable areas for MAR, based on a hydrogeological and hydrochemical assessment. The methodology adopted in the work of Stockholm Vatten AB et al. (1996) has been roughly outlined and a brief summary of each section is given below.

- Estimation of future water demand - To be able to get an estimation of the required water production, the initial step of the report was to estimate the future water demand for the region. Prognoses of the population increase and the change in water demand were used to derive an estimation for the total water demand of 10 m^3/s in the year 2100.

- Identifying a suitable water source - Lake Mälaren was assessed to be the only water source with a sufficient mean flow to supply the large water demand. The water quality was investigated with data from previous measurements and was evaluated to standard values for raw water sources for drinking water production, set by the National Food Agency.

- Initial site investigations and data gathering - The glaciofluvial esker Uppsalaåsen was in the early stages of the work and identified as a glacial deposit which was likely to inhibit sites with hydrogeological and hydrochemical conditions suitable for artificial recharge. The esker was divided into eleven sections, within the vicinity of existing water treatment plants, which were further investigated. The work consisted of the collection and analysis of readily available data of geological, hydrogeological and topographical maps, groundwater investigations and details from the Well Archive of SGU. Soil and groundwater sampling was also conducted at approximately ten locations within the designated areas.

- Evaluation of data - With the aid of the collected data, the suitability of the eleven sections was evaluated. The data collected from the boreholes were used to evaluate soil stratification and groundwater quality at the sites. To be able to purpose which sites should be further investigated in more detail, a ranking system for the sites was created. The sites were divided into three ranks (high, moderate or low) based on their suitability. The classification was based on the following set of parameters:
  - *Potential infiltration surface* - Here the total area of the identified site is given.
  - *Extraction capacity* - Based on the field study of existing artificial recharge facilities and hydrogeological knowledge, the extraction capacity of each site was estimated.
  - *Required basin area* - The total required basin area was estimated based on the assumed infiltration rate of 1 $m^3/m^2/d$.
  - *Total required area* - The total facility area, including basins, extraction wells, roads etc. was estimated to be 3-6 times larger than the basin area.
  - *Raw water source* - The distance to the intended raw water intake.
  - *Water treatment plant* - The distance to the intended water treatment plant.
  - *Competitive land use* - Any conflict of interest regarding land use was stated.
  - *Risks* - The areas' characteristics regarding safety and contamination risks were stated.
  - *Factors which might affect the treatment* - The characteristics of the area which might affect the final treatment were stated.

2.4 Results of the literature study

The initial literature study concluded that site suitability evaluation was a crucial part of the planning phase for MAR. It was assessed, based on the findings within the literature and consultation with an expert in the field, that a GIS-MCDA would be a suitable tool for the analysis. The following section presents a summarised methodology of the site suitability analysis, along with identified key parameters. An identified methodology has been derived from the findings of the presented guidelines and practical examples of international and Swedish site suitability analyses. The identified key parameters used for MAR suitability analyses are presented and their applicability to a Swedish case study is discussed.

During the consultation with Per-Olof Johansson, findings from an initial literature review on MAR were presented. The material covered findings of the development methodology and various modelling techniques frequently used in the planning phase of MAR. Based on this, a discussion followed on the structure of the project. It was suggested that a site suitability evaluation for MAR should be performed by applying a methodology well adapted for the Swedish conditions, inspired by the findings from the literature review (Johansson. P-O, personal communication, February 28, 2023). The purpose of this site evaluation was specified to validate the derived methodology. To conduct the site screening, the use of GIS-MCDA was deemed suitable for the analysis and the evaluation should be adjusted to fit the Swedish conditions. To justify the results, it was advised that the analysis should be performed in a region where the artificial recharge possibilities had previously been assessed. The area of Mälardalen has previously been thoroughly investigated during the development of the water supply plans for the Stockholm area and this area was therefore chosen for the analysis.

2.4.1 Identified methodology

The guidelines on MAR provided by NRMMC-EPHC-NHMRC (2009) and Dillon et al. (2014) aim to provide guidance on risk management and quality of both aquifer and recovered water. American Society of Civil Engineers (2020) and Imig et al. (2020) provide guidelines on a different part of the planning phase of MAR and rather aim to provide a structured methodology for deriving possibly suitable locations for further feasibility studies. By reviewing the suggested methodologies of the planning process in the international guidelines, it could be concluded that the proposed structure for site identification is in many ways similar. A step-wise approach has been recommended by both American Society of Civil Engineers (2020) and Imig et al. (2020). As presented in Section 2.2, both the reviewed international and Swedish case studies have applied a similar structure in their methodology. According to Sallwey et al. (2019), initial data gathering was based on the defined objective, followed by a constraint mapping using Boolean logic and suitability mapping using Pairwise Comparison and WLC or AHP. In some cases, a final sensitivity analysis was also performed. A very similar methodology was also defined by Rahman et al. (2012), who adopted the steps of; problem definition, constraint mapping, suitability mapping, and sensitivity analysis, into their tool for site selection of MAR. When McCurry & Pyne (2022) suggested a methodology for the planning phase of a MAR project, it consisted of a very similar procedure.

An adaptation of the general structure for the site suitability analysis, identified from the literature has been summarised in a four-step procedure. This methodology is presented below and outlines the foundation for the case study presented in Chapter 3.

1. Project objective - An initial definition of the project objective is highlighted as a crucial first step in all of the guidelines. According to American Society of Civil Engineers (2020), the scope of a MAR facility could cover several objectives and is generally favoured by decision-makers when having more than one purpose. Increasing the capacity for the extraction of groundwater is one example. As stated by Imig et al. (2020), increased resilience to climate

extremes or environmental benefits could be other motives for constructing a MAR facility.

2. Evaluation criteria and data collection - Gathering and evaluating data is commonly recommended as a second step. The perception of which parameters to include did however vary somewhat in the literature, but a set of generic categories for the parameters could be identified. These are further discussed in Section 2.4.2. The use of GIS-MCDA is recognised as a suitable tool to perform site screening. To perform the MCDA in a transparent and objective way, a selection of methods for valuing, weighting and combining parameters has to be decided upon. Based on the findings from the international scientific papers the following methods were identified as the most common ones:
    - Valuing - Standardisation and Value function.
    - Weighting - Pairwise comparison.
    - Combination - Weighted linear combination.
3. Site screening - A common suggestion is that the site screening should be divided into two parts, a general screening, followed by a specific screening. The general screening should be performed on a national or regional scale, and aim to constrain possible sites which possess satisfactory fundamental conditions. Boolean logic is often used to produce constraint maps. The specific screening should rather aim to further expand on the general screening and in greater detail rank the initially identified areas into three classes; high, moderate, or low, based on their suitability for hosting a MAR facility. This is often done by overlaying pixels of each parameter, which has previously been assigned a value and a weight.
4. Sensitivity analysis - Only the revised guidelines provided by American Society of Civil Engineers (2020), suggested a sensitivity analysis as a recommended step in the site screening. Sallwey et al. (2019) also identified an absence of sensitivity analyses in the majority of the reviewed articles. However, due to the nature of MCDA, it is inevitable to introduce uncertainties in the processes of implementing the parameters due to the subjective assessment of the analyst. Therefore, a sensitivity analysis could provide useful insights into how uncertainties in the analysis affect the results.

The methodology for site identification in Swedish projects was mainly covered by Dahlqvist et al. (2017), Stockholm Vatten AB et al. (1996) and Dahlqvist et al. (2019). The workflow of these reports was more or less similar to the general structure for site suitability analysis, identified from international literature. The workflow of Stockholm Vatten AB et al. (1996) mainly contains the same step as the general approach but in a different order. The difference in the order of the workflow might originate from the difference in geological conditions of the investigated area, in relation to other parts of the world. The investigations were early on constrained to Uppsalaåsen, most likely due to the Quaternary deposits of glaciofluvial material which makes up the esker. Since these soil deposits often provide aquifers with highly beneficial conditions for artificial recharge and have in the past hosted several successful MAR projects in Sweden, a constraint to these areas during an initial site screening is assessed to be reasonable. The investigations of Dahlqvist et al. (2017) and Dahlqvist et al. (2019), are both performed on the island of Gotland. Here the geologic conditions are quite different from the Quaternary deposits of Uppsalaåsen and the largest aquifers are instead found in the sedimentary bedrock (Dahlqvist et al., 2017). These conditions are more comparable to those found in other parts of the world for example Central Europe. The geological similarity could explain the more comparable structure of the projects in relation to the general international approach, even though the projects performed on Gotland utilise more advanced data compared to the international scientific papers. Due to the geological differences, the process of evaluating a site suitable for MAR is not expected to be directly transferable to Swedish conditions. Of the reviewed literature, only Stockholm Vatten AB et al. (1996) directly covered MAR in glaciofluvial aquifers. The main findings from the international studies along with the Swedish case studies have been summarised and are presented in Figure 2.2 below.

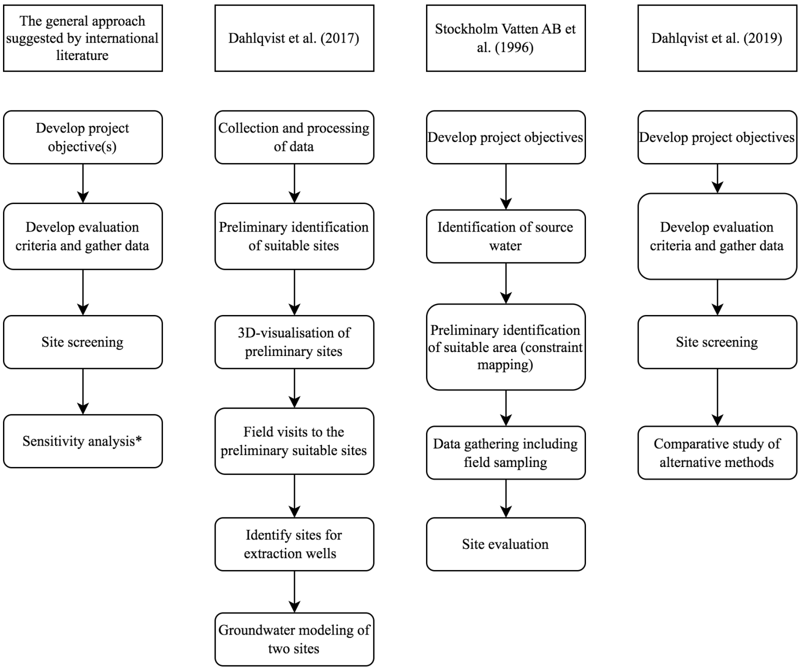


Figure 2.2: Flowchart describing the main findings from the international articles and the Swedish case studies. *A sensitivity analysis was performed in some of the international studies.

2.4.2 Identified key parameters

Parameters that were used or suggested for MAR suitability analysis in the reviewed literature have been identified. An overview of the suggested parameters has been summarised and divided into categories. These are presented in Appendix A.1. The most common categories used to evaluate if an area provides conditions for the technical feasibility of a MAR project are linked to the characteristics of the water source, the aquifer and the surface. In some cases, the reviewed literature also suggests categories for the evaluation of other aspects, such as environmental impact. These are however not included in the summary due to the scope of this work.

In the article by Sallwey et al. (2019) an interesting finding was that surface characteristics were the most commonly applied parameters for evaluation, but when subsurface data were available these were assigned a higher weight. This could be interpreted as the subsurface data providing a better indication of whether a site is suitable or not. A similar trend could be seen for the parameters in Figure 2.3, where the count of the nine most commonly applied parameters identified in this work is presented. The majority of the most commonly recommended parameters fall under the category of aquifer characteristics, while a few concern the source water and only infiltration capacity is related to the surface characteristics. Further, Sallwey et al. (2019) found that the extensive reliance on surface characteristics could be caused by more available data, but that less accessible data such as aquifer characteristics were often preferred. The authors also stated that data availability and uncertainties were also seldom discussed in the reviewed articles. The site evaluation in Swedish cases mostly relied on readily available data for an initial investigation but was often supplemented with more advanced data. For example, both Dahlqvist et al. (2017) and Stockholm Vatten AB et al. (1996) conducted field visits. During these visits, additional data were gathered on parameters such as hydrology, flow of surface waters and aquifer capacity. In the investigation by Dahlqvist et al. (2019), a national model of the aquifer storage capacity, created by the SGU, was utilised in the assessment. Similarly, Almqvist (2018) modelled the available groundwater storage, based on a set of geological parameters. The use of more advanced data in the Swedish cases is most likely also explained by data availability, similar to the findings of Sallwey et al. (2019). From the review, it was also found that Stockholm Vatten AB et al. (1996) paid much attention to the possible quality improvement by artificial recharge and the quality of source water. Beyond this study, consideration of the source water quality parameter was only identified as significant in the guidelines of NRMMC-EPHC-NHMRC (2009) and Dillon et al. (2014). Since drinking water production is a common scope of these works, a focus on water quality is expected. Contrary to this, Sallwey et al. (2019) found that very few studies included surface water quality in their assessment of site suitability. This variation in which parameters are used for site evaluation is estimated to originate in the different objectives of the MAR project. As earlier discussed, geological differences also impact the site evaluation process. Some parameters used to evaluate a suitable site in certain geological conditions, might not contribute to a similar suitability in another condition. For example, when evaluating the suitability of an area where the bedrock constitutes the majority of an aquifer, the storage capacity of the bedrock would have a large impact and should therefore be included in the analysis. Contrarily, the storage capacity of the soil layer would instead be expected to have a larger impact on the suitability in regions where the geologic conditions are such that the majority of the aquifer is instead found in the soil layer. It is therefore assessed that the parameters included in the site suitability analysis should be selected based on the project objective and conditions.

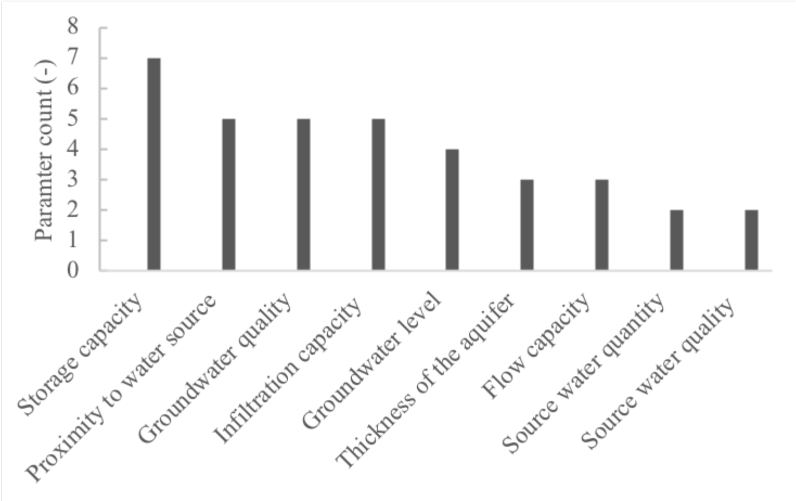


Figure 2.3: The count of the nine most commonly applied parameters identified in the literature review.

2.4.3 Identified workflow

Based on the findings of the literature review regarding the identified methodology and key parameters, a workflow which aims to aid the implementation to the implementation of MAR for drinking water purposes in Swedish conditions has been identified, see Figure 2.4 below. The main steps of the workflow are similar to the previously described four-step procedure in Section 2.4.1, as it was considered a non-site-specific approach with potential applicability in Swedish conditions. Additionally, the selection of parameter recommendations for the screenings was primarily based on the findings of the literature review, but also on the availability of relevant data suitable for GIS analysis.

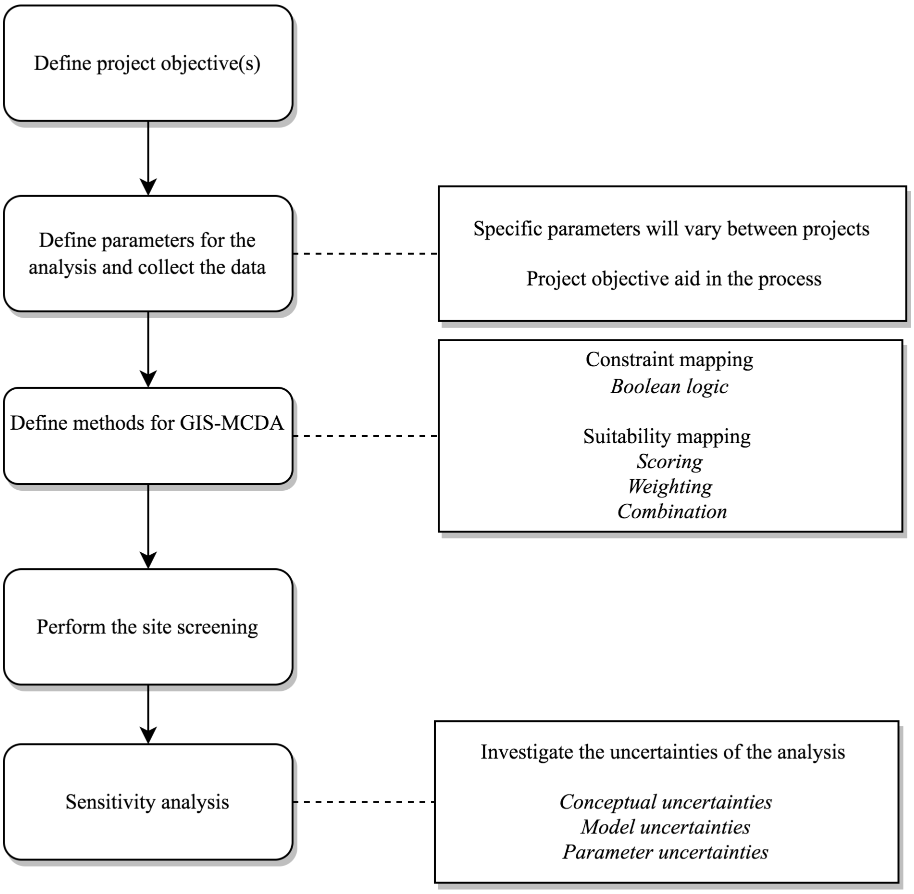
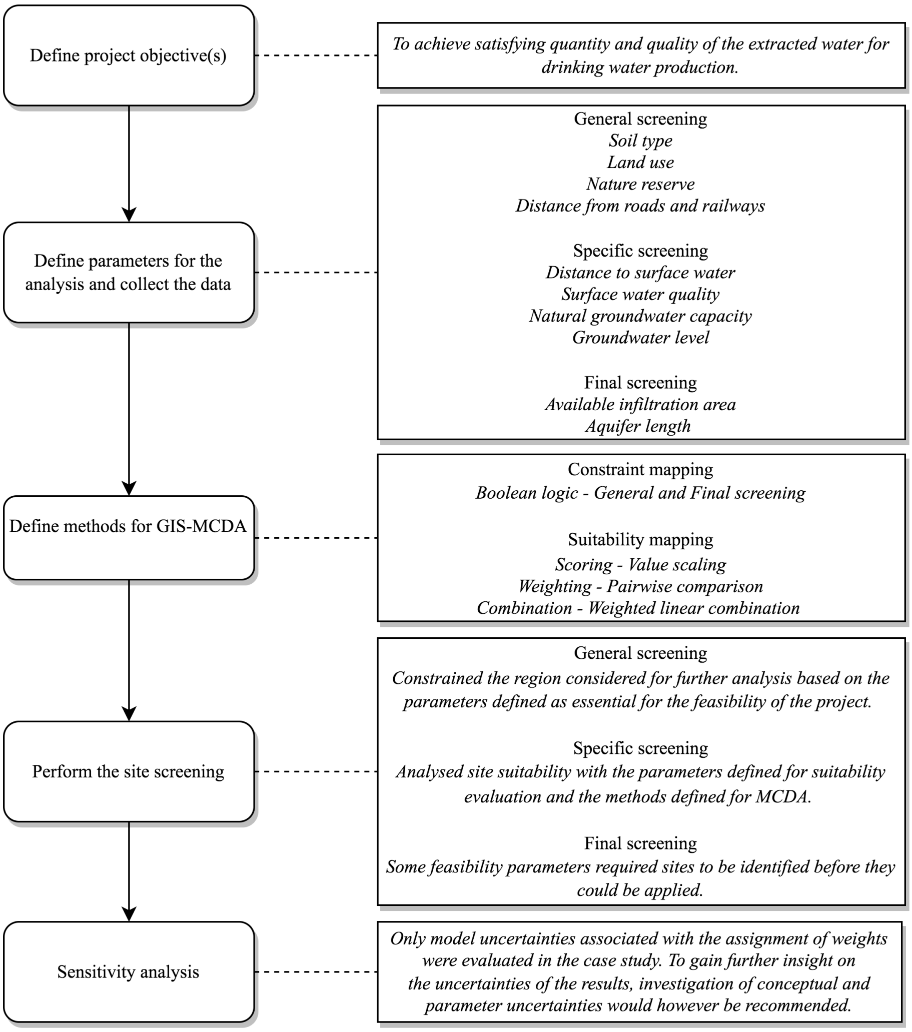


Figure 2.4: Suggested workflow to aid in the planning of MAR in Swedish conditions.

3

Method

This section describes a case study for which the identified workflow, presented in Figure 2.4 is applied to a MAR site suitability analysis in Sweden. By applying the workflow, the practical applicability could be evaluated and its limitations recognised. An elaborated version of the workflow given in Figure 2.4, describing how the workflow was applied in more detail during the case study is presented in Figure 3.1. This figure aims to provide a practical example of the application of the identified workflow.



To achieve satisfying quantity and quality of the extracted water for drinking water production.

Constrained the region considered for further analysis based on the parameters defined as essential for the feasibility of the project.

Analysed site suitability with the parameters defined for suitability evaluation and the methods defined for MCDA.

Some feasibility parameters required sites to be identified before they could be applied.

Only model uncertainties associated with the assignment of weights were evaluated in the case study. To gain further insight on the uncertainties of the results, investigation of conceptual and parameter uncertainties would however be recommended.

Figure 3.1: A detailed version of the workflow applied during the case study.

The analysis was performed on the region of Mälardalen, which includes the same areas as investigated by Stockholm Vatten AB et al. (1996), to be able to compare the outcome of the case study towards a previously performed site suitability evaluation. The purpose of this comparison of results aimed to provide some assessment of the validity of the results. The area for the analysis is illustrated in Figure 3.2.

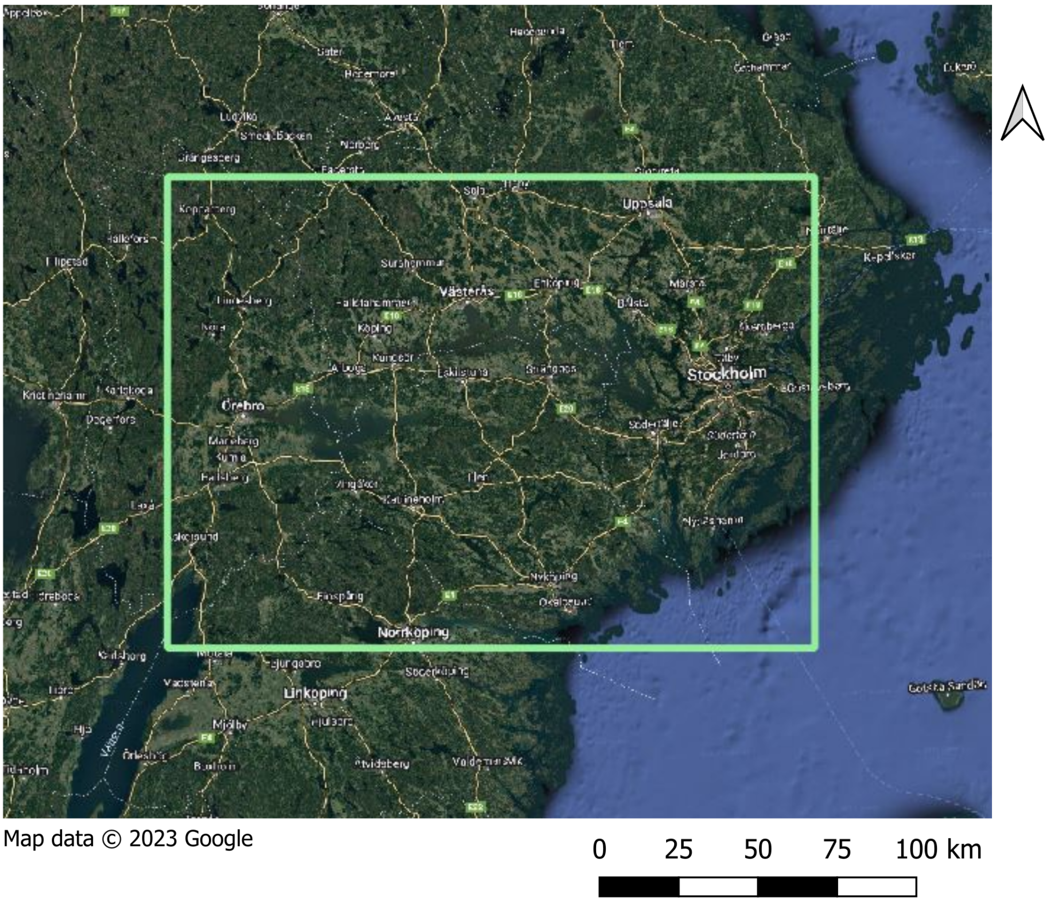


Figure 3.2: Area defined from the site suitability evaluation using GIS-MCDA.

To evaluate the feasibility and applicability of the methodology established as relevant in the literature study, a GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) has been performed. The approach of a GIS-MCDA has been described as similar to the conventional models of an MCDA. The integration of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) is advantageous for site evaluation due to their complementary functionalities. GIS enables the storage, management, analysis, and visualisation of geospatial data, while MCDA provides a systematic framework for facilitating the decision-making process. The main approach of an MCDA could be described as the development of decision alternatives which are evaluated on the basis of a set of criteria, established by the decision-makers. The parameters are assigned scores and weights with respect to the set objectives (Malczewski & Rinner, 2015). There are numerous methods for the combination of scores and weights, but one of the most commonly used is WLC, which has also been utilised in this analysis. A detailed step-wise description of how the GIS-MCDA has been performed in the case study is presented in Appendix E.

3.1 Define objective(s)

The first step of the analysis was to define the project objectives. For this analysis, the aim of the project was to find a suitable location for MAR with the purpose of using the extracted water for drinking water production in the region of Mälardalen. In this investigation, pond infiltration was the only MAR technique considered. The project objectives were defined based on what was considered satisfactory quantity and quality of the extracted water for drinking water purposes. To be able to validate the result of this project to the findings of Stockholm Vatten AB et al. (1996), the extraction capacity was set to be of a similar quantity. Stockholm Vatten AB et al. (1996) assumed the future water demand of the region to be 10 m^3/s in the year 2100. Additionally, the authors also estimated the capacity of the sites identified in their study to range between 0.5 to 4.0 m^3/s. It was therefore estimated that a MAR facility should be able to supply at least 25% of the total demand, and the quantitative objective was defined as 2.5 m^3/s. While the quality of the water should obtain an acceptable level required by the National Food Agency, defining a numeric objective for the water quality of the extracted water was not possible, since a reasonable estimation of treatment efficiency during MAR could not be done. The objective of satisfactory water quality was however still considered during the evaluation by including quality parameters in the site suitability analysis.

3.2 Define parameters and data collection

The following step of the procedure was to define parameters relevant to the objectives of the project. Since the goal of the planning phase is to examine how a site suitability evaluation could be conducted without additional field investigations, the parameters were limited to already existing data of the area. The parameters set for the screenings were derived based on a combination of expert suggestions and literature recommendations. However, data on all the parameters which were desired to include in the analysis could not be retrieved. This issue was either due to the limitation of available data or the formatting of available data. The mean flow of water courses, groundwater quality and available aquifer storage were parameters which initially were intended to be included in the analysis but were excluded due to issues with the formatting of data and the compatibility with the GIS tool.

The parameters for which data could be retrieved were divided into either the general or the specific screening. The parameters assigned to the general screening were assessed to include vital information on the feasibility of the project, and parameters assigned to the specific screening rather contained information on the suitability of the site. The data was collected from national authorities and organizations such as the Geological Survey of Sweden (SGU), the Land Survey (Lantmäteriet), and the Swedish University of Agricultural Sciences (SLU). The format of the gathered data files was mainly shape files and to perform the analysis all data were converted to rasters. The conversion of the data into rasters was required to perform the GIS-MCDA. To match the level of detail of the input data the pixel size of the rasters was set to 15 x 15 m. The files obtained along with the source and file type are summarized in Appendix B.1. A short description and motivation as to how and why the parameters were used in the analysis is given below.

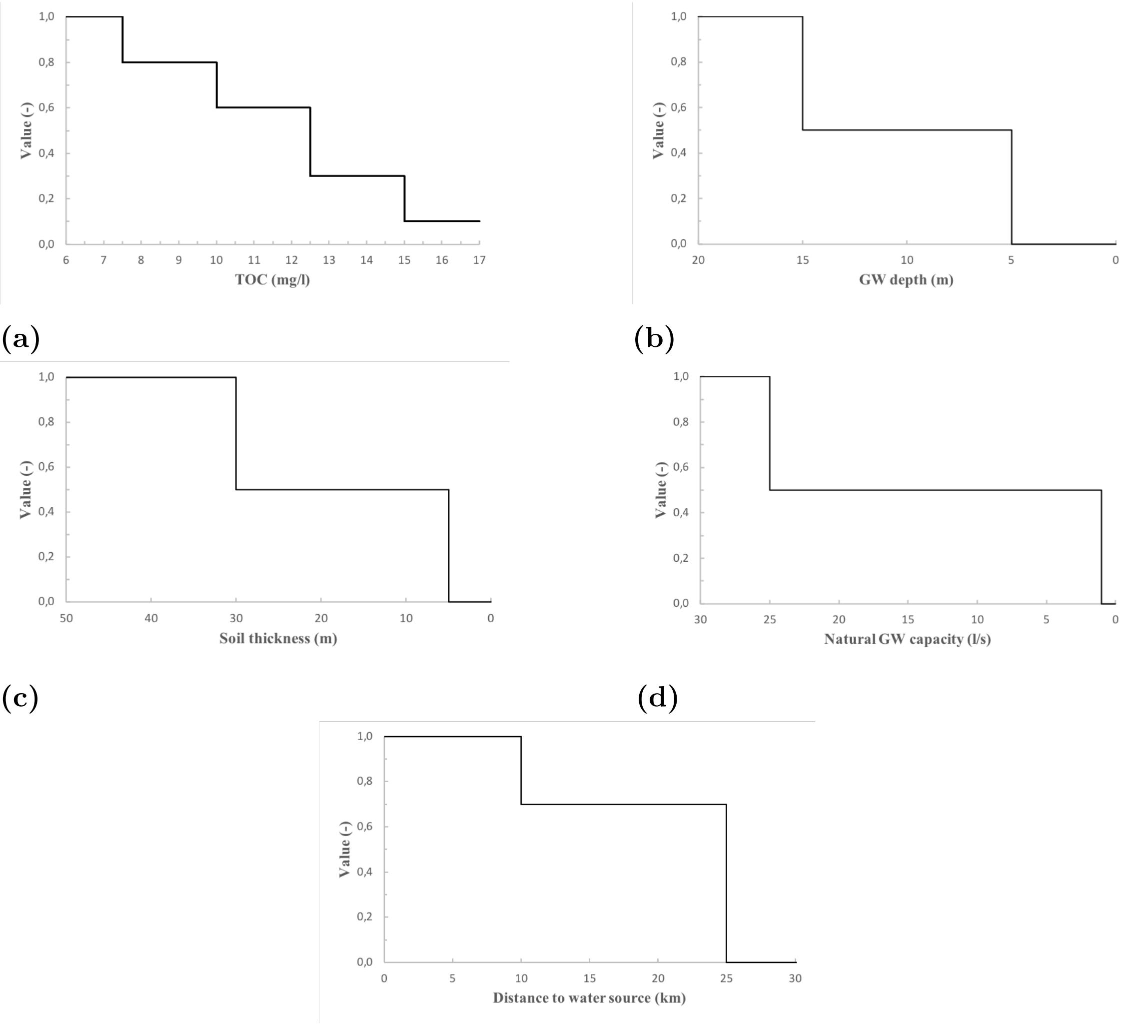
- Parameters for general screening
  - Soil type - Only areas which had glaciofluvial deposits, gravel, or sand as the geological top layer was identified as sites feasible for artificial infiltration, as these soil types are assumed to possess a high hydraulic conductivity.
  - Land use - The purpose of including this parameter was to exclude urban areas and other land uses which would obstruct the construction of a MAR facility. For this parameter, agricultural land, forest, and open land were considered feasible.
  - Nature reserve - Due to regulations that prohibit the construction of MAR in nature reserves, these were considered unfeasible.
  - Distance from roads and railways - To avoid conflict of interest with other infrastructure, areas within the proximity of 50 meters to large roads and railways were considered unfeasible.
- Parameters for specific screening
  - Distance to surface water - The surface waters considered were lakes with a surface area larger than 10 km^2. A site within a defined proximity to a water source was assigned higher suitability. During this evaluation, rather large distances were considered suitable. Since the quantity objective of the project was to infiltrate a large amount of water, longer transportation of surface water could be justified.
  - Surface water quality - To evaluate whether surface water was of sufficient quality, the Total Organic Carbon (TOC) levels of the water were used as an indicator. The data consisted of point measurements taken during a three-year period. Data points within lakes were identified and the mean value of the TOC measurements was assigned to the lake.
  - Natural groundwater capacity - Mapping of the natural groundwater capacity was used to identify suitable sites. Areas with higher natural capacity are assumed to have a higher hydraulic conductivity and therefore provide favourable conditions for MAR.
  - Depth to groundwater - To avoid the risk of waterlogging a groundwater depth of a minimum of five meters was assumed to be needed. A larger groundwater depth is related to a thicker unsaturated zone which is estimated to promote quality improvement of the infiltrated water, therefore a large groundwater depth would also be beneficial from this perspective.

    - Soil thickness - It was assumed that a thick soil layer could indicate an area where the aquifer could have a large storage capacity. It was therefore assessed that the parameter could be beneficial to the suitability of MAR.

- Final screening
    - Area available for infiltration - Sufficient area for the infiltration ponds is required to meet the required infiltration capacity. The infiltration capacity of the geologic material was estimated to be 1 $m^3/m^2/s$. To satisfy the objective of an infiltration capacity of 2.5 m^3/s, the required area was estimated to be 32.5 ha.
    - Length of aquifer - To acquire a satisfactory retention time of the infiltrated water, a minimum length of 400 m was set for the aquifer. The Swedish Food Agency has set a minimum of 14 days for residence time before the infiltrated water could be regarded as groundwater (Livsmedelsverket, 2022).

3.3 Define methods for the GIS-MCDA

After deciding on what parameters should be included in the analysis and the required data had been gathered, the method for the GIS-MCDA was defined. It was assessed that Boolean logic was a suitable approach for the general screening. This was done by assigning pixels with feasible properties as 1 and unfeasible with 0 to the rasters of the general screening. The concept of Boolean constraints utilised the *AND* operator for multiple raster analysis to exclude unfeasible sites from further analyses. The general screening generated the constraint map of the analysis. To perform the specific screening and creating the suitability map, three main concepts for spatial analysis were used; standardisation, criterion weighting and a combination rule (Malczewski & Rinner, 2015). To be able to compare and evaluate multiple parameters with different units, the data of the specific parameters were transformed into comparable units by standardisation. The range of the score for each parameter was divided onto a scale from 0 to 1, where 0 represented the least desirable parameter value and 1 the most. The process of assigning a unit value to a specific score was aided by consultation with Dr Johansson. The assigned value function used in the scoring of the unit ranges is presented in Figure 3.3.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 3.3: Assigned value functions of the specific parameters a) TOC, b) Groundwater depth, c) Soil thickness, d) Natural groundwater capacity, e) Distance to water source.

It was assessed that the specific parameters did not contribute with equal importance to the final suitability of a site. For example, it was assessed that the natural groundwater capacity is of more importance in comparison to the distance of a surface water source when assessing the suitability of a site. To reflect these differences, weights were assigned to each specific parameter in regard to their estimated influence. Pairwise Comparison was chosen for the assignment of weights (Saaty, 1987). In this method, the importance of each parameter was evaluated with respect to each other. The Pairwise Comparison was based on the recommendations made by Imig et al. (2020), the findings in Sallwey et al. (2019), and with regards to the known uncertainties of the data. For example, the data set for the criteria Depth to groundwater was created by interpolating data from wells and due to this, it was assessed as highly uncertain and was therefore assigned a low weight. The total process of the Pairwise Comparison can be seen in Appendix C.1 and the final weights are shown in Table 3.1. Weighted linear combination was the method chosen for combining the standardised scores of the parameters and their respective weights. In GIS-MCDA, the WLC combines the scoring and weighting by multiplication, within the raster of the corresponding parameter. The values of the overlaying pixels of each raster are added together to a final value (Malczewski & Rinner, 2015). To assess the impact the weighting had on the results maps both with and without parameter weighting were created.

Table 3.1: The final weights and their corresponding rank assigned for the specific screening.

Parameters	**Weights**	**Rank**
Groundwater capacity	0.36	1
Depth to groundwater	0.08	3
Soil thickness	0.16	2
Distance to source water	0.05	4
Surface water quality	0.36	1
Sum	1.00	

3.4 Perform the site screenings

The next step was to generate the maps which were initially divided into a general and a specific screening. The general screening was performed with the set of parameters evaluated as restricting, or general parameters, investigating the feasibility of a site. The approach was therefore to exclude areas unable to host MAR facilities. For a pixel to be recognised as feasible it had to possess all the required attributes of the general parameters. Following this, a specific screening was performed to assess the suitability of the identified areas. This step was performed by overlapping the classified data sets to find areas valued as highly suitable, by taking the specific parameters into account. Two analyses of the specific screening were done, one using the classified parameters with no weighting and one where the parameters had weights assigned. The generated constraint map from the general screening was combined with the suitability map from the specific screening to generate a map displaying the feasible areas and their suitability. However, the feasibility constraints concerning available areas for infiltration and aquifer length could not be applied in the general screening. The assessment of the available area for infiltration and the aquifer length required a preliminary site suggestion. Therefore, a third and final screening, which also applied Boolean logic, was performed. Here, a threshold value of 80% was set to extract areas for further analysis, meaning that areas receiving a suitability score higher than 80% of the total range were further analysed. From these, areas larger than 32.5 ha and with an aquifer length longer than 400 m were extracted. This generated a final suitability map, presenting areas which pass through the three screenings.

3.5 Sensitivity analysis

Finally, a sensitivity analysis was performed by excluding parameters one at a time. This was performed on the weighted suitability analysis, where the proportions of the weights were maintained on the remaining parameters. The purpose of this analysis was to evaluate the impact each parameter had on the final results. The weights of the remaining parameters for each analysis have been summarised in Table 3.2. The procedure of this sensitivity analysis was performed five times, where each parameter was removed while the rest remained. The steps were the same as described for the original analyses but with the purpose of asses the total area of suitable sites that could be identified with one parameter excluded.

Table 3.2: Assigned weights for the sensitivity analysis.

	Weights	**Weights_1**	**Weights_2**	**Weights_3**	**Weights_4**	**Weights_5**
Groundwater capacity	0.36	-	0.39	0.43	0.38	0.56
Depth to groundwater	0.08	0.12	-	0.09	0.08	0.12
Soil thickness	0.16	0.24	0.17	-	0.17	0.24
Distance to source water	0.05	0.08	0.05	0.06	-	0.08
Surface water quality	0.36	0.56	0.39	0.43	0.38	-
Sum	1.00	1.00	1.00	1.00	1.00	1.00

A second sensitivity analysis was performed with the same purpose as above, to evaluate the impact the weighting had on the results. However, instead of excluding parameters, the weights were altered for each parameter. This was performed in two steps. In the first analysis, higher weights were assigned to the parameters affecting the aquifer characteristics, i.e., groundwater capacity, depth to groundwater, and soil thickness. In the second analysis, higher weights were instead assigned to parameters affecting the surface water characteristics, i.e., distance to source water and surface water quality. The weights for both analyses have been summarised in Table 3.3 below. Further, the same steps as described for the previous analyses were carried out.

Table 3.3: Assigned weights for the sensitivity analysis evaluating the impact of both aquifer characteristics and surface water characteristics respectively.

	Weights - aquifer characteristics	**Weights - surface water characteristics**
Groundwater capacity	0.30	0.10
Depth to groundwater	0.30	0.10
Soil thickness	0.30	0.10
Distance to source water	0.05	0.35
Surface water quality	0.05	0.35
Sum	1.00	1.00

4

Results

The results presented in this section are the outcomes of the site screenings followed by the final results of the performed GIS-MCDA. The identified sites along with the comparison to the previously suggested sites by Stockholm Vatten AB et al. (1996) are also presented. Furthermore, the results of the sensitivity analyses are displayed.

4.1 Results from the site screenings

The output of the GIS analysis produced raster maps. The three screenings were performed in three steps, which are further described in this section. The first screening performed was the constraint mapping, and the results are illustrated in Figure 4.1. The map displays areas deemed feasible or not feasible. One of the main constraining parameter is the soil type criteria due to the limiting extent of the glaciofluvial deposits, sand and gravel.

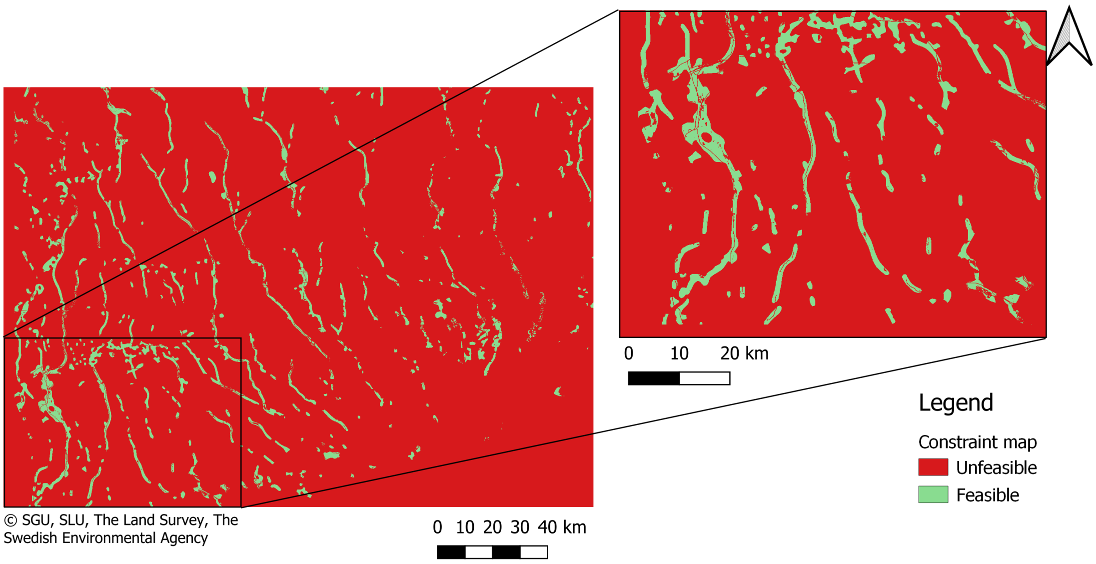


Figure 4.1: The resulting constraint map, both the entire area analysed and a smaller scale of the area

During the specific screening, or suitability mapping, a raster was produced for each parameter. The resulting suitability maps for each parameter have been attached in Appendix D. These were then combined with the constraints from the general screening of the areas which were deemed unfeasible. The resulting maps for both the weighted analysis and the unweighted analysis are shown below in Figure 4.2 and 4.3 respectively. This step of the analysis only considered the outcome of the combined map, which consisted of a combination of the constraint map and suitability map. When comparing the weighted and unweighted analyses, the results showed some similarity in the results as the areas identified with high suitability are comparable in both cases.

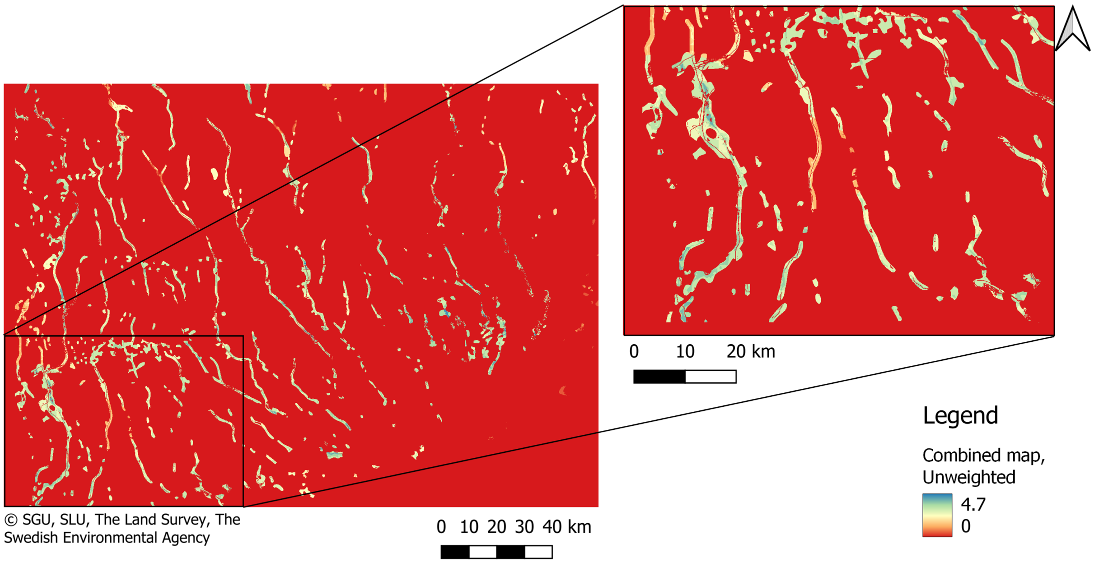


Figure 4.2: The combined map of the constraint map and suitability map for the unweighted analysis.

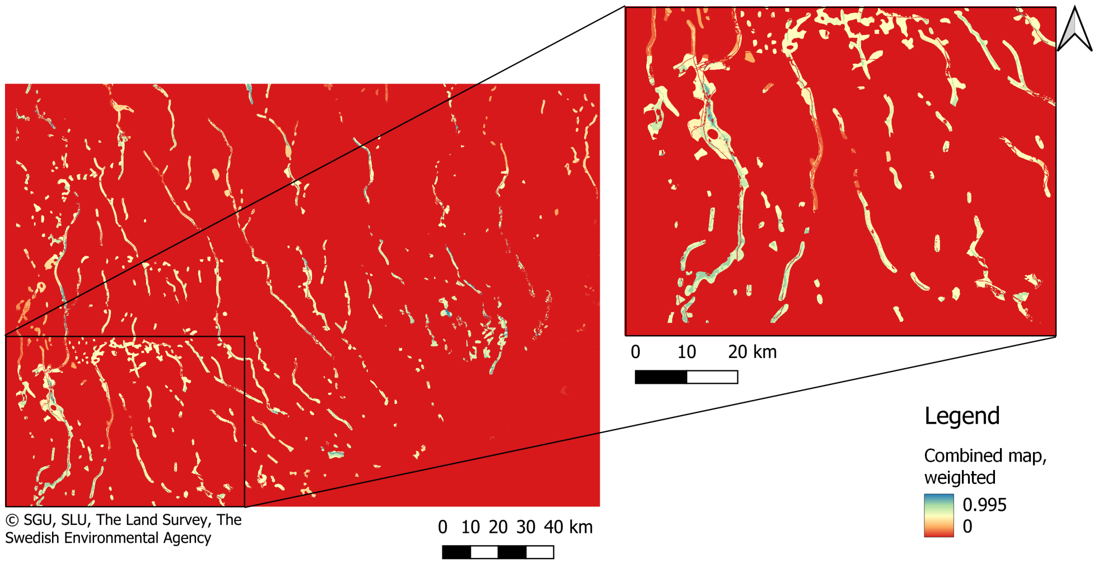


Figure 4.3: The combined map of the constraint map and suitability map for the weighted analysis.

4.2 Site selection

The final results of the analysis, and thereby the sites suggested, were the areas that passed through the general and specific screening and received a final score higher than 80% of the total score range from the suitability mapping. These sites were further analysed in the final screening were sites with a sufficient area and length of the aquifer were the sites finally suggested as suitable. In Figure 4.4, the result of the unweighted (blue points) and the weighted (red points) analyses are shown. In general, both analyses identified the same places as suitable, but there was some variation in the location of the suggested sites. There were also some differences in the number of sites which passed the suitability screening, with 42 sites identified from the unweighted analysis and 31 from the weighted analysis. In general, the sites suggested in the weighted analysis were all also identified in the unweighted analysis, but some additional sites were located in the unweighted analysis. The total area identified as suitable from both analyses did not differ significantly, with a total area of 66.66 km^2 identified in the unweighted analysis and a total area of 58.53 km^2 suggested from the weighted analysis.

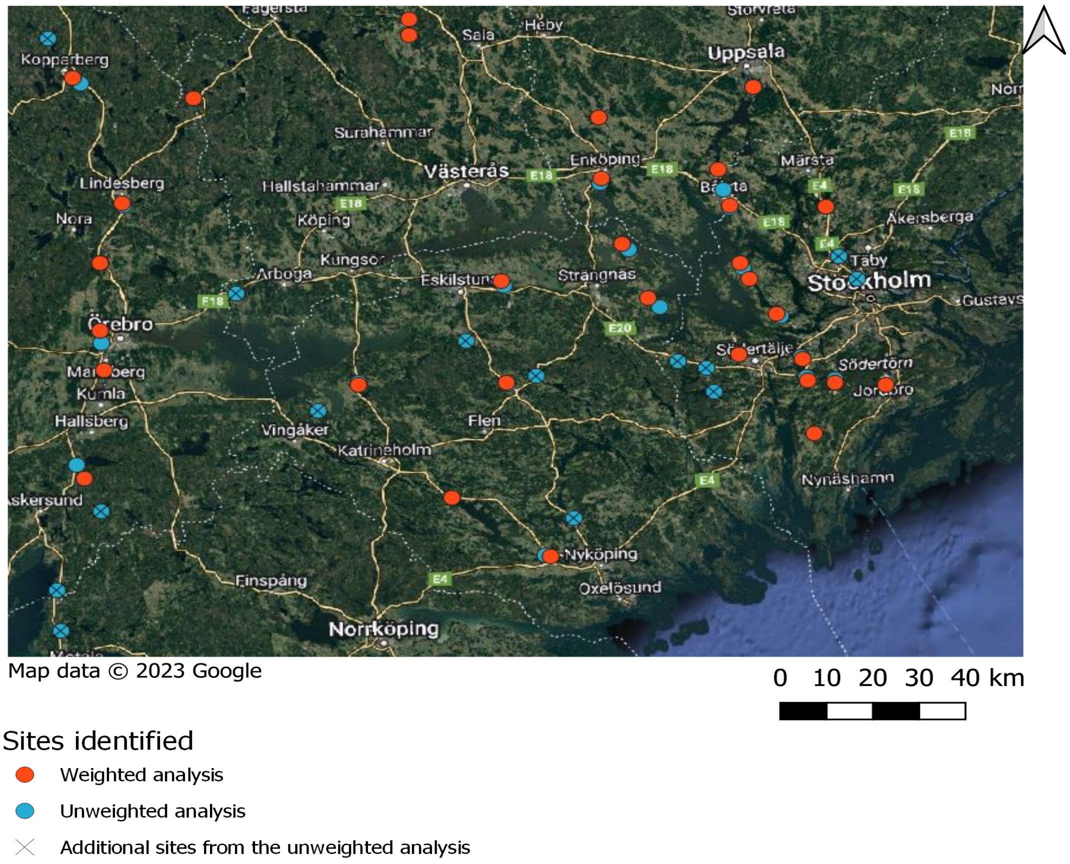


Figure 4.4: Locations identified as suitable for MAR for both analyses (red points - weighted analysis & blue points & marked blue points - unweighted analysis.

The comparison, and the validation, to the previously identified sites was performed on a smaller scale of four areas. Figure 4.5 shows the comparison of the unweighted analysis, which are illustrated in green. The areas in turquoise are the sites previously identified as suitable to MAR by Stockholm Vatten AB et al. (1996). The total area identified as suitable in the unweighted analysis was 3.85 km^2 and the previously identified sites had a total area of 5.3 km^2.

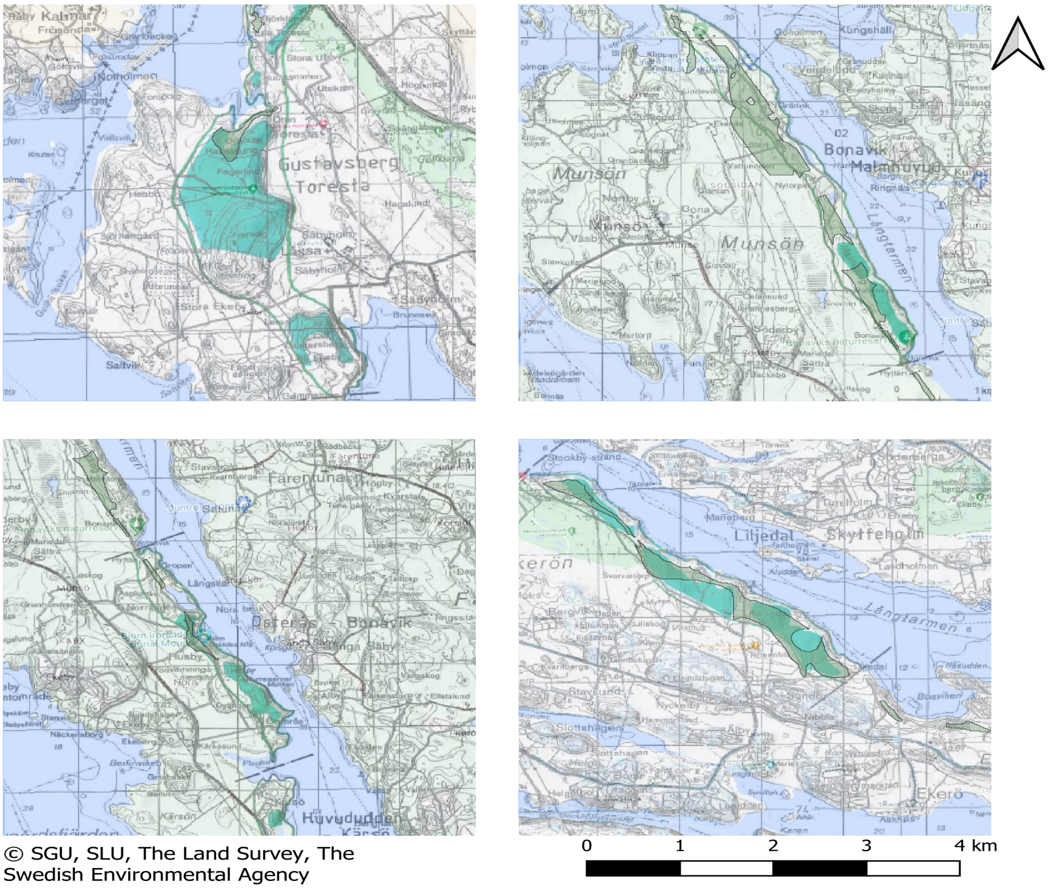


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Figure 4.5: Comparison of results from the unweighted analysis shown in green and the previously identified suitable sites, shown in turquoise, by Stockholm Vatten AB et al. (1996).

Figure 4.6 shows the comparison of the areas suggested in weighted analysis, which are shown in yellow, and the previously identified sites. The total area identified in the area by the weighted analysis was 3.2 km^2, which is comparable to the total area identified in the unweighted analysis.

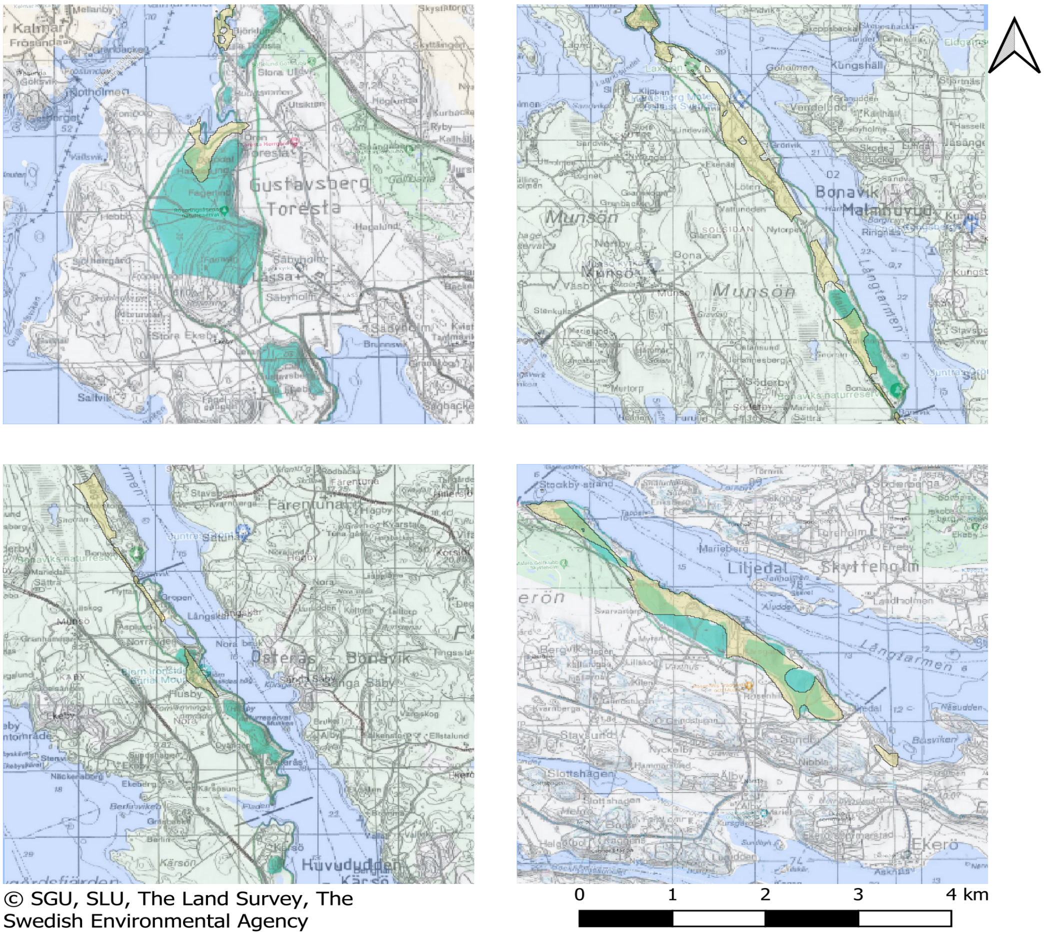
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Figure 4.6: Comparison of results form the weighted analysis shown in yellow and the previously identified suitable sites, shown in turquoise, by Stockholm Vatten AB et al. (1996).

4.3 Sensitivity analysis

The sensitivity analysis was initially performed by iterative removal of one parameter at a time and comparing the result to the initial analysis. This analysis was only performed on the weighted parameters. The results of the total area, along with the percental difference of identified area compared to the reference scenario (w), are presented in Table 4.1 below. Overall, the outcomes of the sensitivity analysis did not show a significant difference in the total area suggested. However, the most substantial difference is evident in the scenario where groundwater capacity was excluded, suggesting an area of 281.63 km^2, corresponding to a difference of almost 400%. The investigation that excluded depth to groundwater generated the second-highest contrast in comparison to the initial analysis.

Table 4.1: Results from sensitivity analysis. Excluded parameters: w: no parameter excluded, w1: groundwater capacity, w2: depth to groundwater, w3: soil thickness, w4: distance to source water, w5: surface water quality.

	Area (km^2)	**Difference (%)**
w	58.53	-
w1	281.63	381.17
w2	77.95	33.18
w3	56.89	-2.80
w4	58.35	-0.31
w5	67.38	15.12

The findings from the second sensitivity analysis are presented in Table 4.2. The outcomes reveal that a lowering of the weights of the aquifer characteristics exerts the most substantial influence on the results, as the area increases significantly in this case. A lowering of the surface water characteristics did not influence the results noticeably.

Table 4.2: Results from the second sensitivity analysis.

	Total area (km^2)
Aquifer characteristics	34.39
Surface water characteristics	308.17

5

Discussion

The results of the GIS-MCDA suggest that the identified workflow could be an adequate approach for evaluating potentially suitable sites for MAR. The comparison between the suggested sites of the case study and the areas identified as suitable by Stockholm Vatten AB et al. (1996) showed a relatively low total degree of overlap. However, the areas identified in these results are only preliminary estimations and not exact delineations of sites suitable for MAR. The case study's capability of identifying the same locations is therefore regarded to be of more interest in comparison to achieving an exact overlap in areas of the previously identified sites. Since the case study managed to identify the same locations, the results of the analysis were consequently assessed to be successful.

It was further observed that the weighted and unweighted analyses yielded different outcomes. The location of the identified sites was similar in both cases, but the weighted analysis identified fewer sites and a smaller total area with high suitability. As some parameters have a greater significance regarding the project objectives, weighting is deemed necessary in a site evaluation to identify areas with the characteristics to satisfy the objectives. It is therefore assessed that the weighting of parameters in the case study successfully removed some areas which might be suitable for MAR, but not with the intent of drinking water production. With this in mind, the use of weights was therefore considered necessary for the analysis and is suggested to be implemented in other similar investigations.

Based on the review of key parameters, it was considered that the choice of which parameters should be included in the site evaluation essentially comes down to the project objectives and the available data. Since the objectives and available data will vary between projects, it is further assessed that the parameters are best chosen for each project individually. However, if the objective of the site selection analysis concerns the technical feasibility of MAR, the source water-, aquifer- and surface characteristics would be criteria recommended to be included in the evaluation. As the most common objective of MAR facilities in Sweden is related to drinking water production, and is often used as an additional step in the conventional treatment of surface waters for drinking water production, the parameters associated with water quality are expected to be significant for the site evaluation. Even though no recommendations on general parameters are given, a clear trend in the use of water quality parameters was seen when MAR was used in drinking water production.

For the case study, the natural groundwater capacity and surface water quality were assessed to be the parameters with the largest relevance to the project objectives. They were therefore considered to be the most influential parameters during the site selection. The choice of which parameters to include in the analysis was mainly based on expert consultation and the findings from the literature review but the choice was in some cases limited by data-related issues. For instance, the infiltration capacity was considered to be a highly interesting parameter to include in the case study, but for which specific data were not readily available. Instead, the natural groundwater capacity and the limitation to glaciofluvial material were used to indicate soils where the hydraulic conductivity was assumed to be high. Not every region will have the same data availability as the next one, but an indication of desirable parameters could be estimated similarly without direct measurements.

As further concluded from the literature review, some differences in the choice of methodology and parameters for the site suitability analysis could be identified between the international literature and the Swedish projects. The variation in the structure of the project is considered to originate from the differences in geological conditions and project objectives. For example, as done by Stockholm Vatten AB et al. (1996), who constrained the analysis to the glaciofluvial material of Uppsalaåsen, which in turn significantly decreased the area for further evaluation. The glaciou-fluvial material provides well-suited geological conditions for MAR implementation which are are to come by in other geological formations found in Sweden. Thus, this limitation could be favourable for locations with similar geological conditions, as such constraints could reduce the area further considered in the suitability mapping and thereby simplify the analysis. However, it is important to carefully consider what parameters are used for constraint mapping, since a possibly suitable location might be removed due to a wrongfully applied constraint. The large differences in Swedish geology could make the use of constraint mapping more or less applicable. Considering the development of a MAR project in regions with glaciofluvial material, similar to the conditions investigated by Stockholm Vatten AB et al. (1996), the approach is most likely useful. However, in other projects where the areas of interest are not as clearly confined, constraint mapping should be used with caution. For example, as displayed by Dahlqvist et al. (2019) who perform their analysis on the island of Gotland where the largest aquifers are found in the sedimentary bedrock, the analysis was performed without the use of constraint mapping.

For the site suitability analysis in Mälardalen, it was assessed that a constraint to glaciofluvial deposits was reasonable since the material in general provides very beneficial conditions for MAR. There were, however, some issues regarding the constraint mapping discovered when validating the result of the analysis to the results of Stockholm Vatten AB et al. (1996), which could be one of the factors contributing to the low degree of overlap. This was considered to be mainly related to the parameter for Nature reserve included in the general screening. Specifically, it was discovered that some nature reserves were established in the areas after the year 1996 and were therefore not included in the results of Stockholm Vatten AB et al. (1996). This would imply that some of the previously suggested sites are no longer viable and were consequently removed during the construction of the constraint map.

The sensitivity analyses of the case study revealed that the criterion of Depth to groundwater had the second highest impact on the final results, but the results also showed that the criterion of Groundwater capacity was by far the most influential.

Both sensitivity analyses indicated a significant increase in the total suggested area when either excluding or assigning a low weight to the Groundwater capacity. Considering the high weight in the original analysis, the significance of this criterion in the final outcomes was deemed reasonable. However, given that the criterion of Groundwater level had a relatively high impact despite being assigned a low weight, it is assumed that there should be some further explanation for the high impact of the Groundwater capacity criterion. One possible explanation for this is the limited extent of the data for this criterion as it was restricted to the aquifers, which had a smaller extent than the areas deemed feasible in the constraint map. As a result, this criterion received a score of zero in many of the areas that were considered feasible in the constraint map. Therefore, the inclusion of this criterion results in a large variety in scores, which could explain the significant increase in the suggested area when this criterion is excluded. As mentioned in Section 2.4.1, an absence of literature employing a sensitivity analysis as a step of the GIS-MCDA was identified. However, based on the outcomes of the sensitivity analyses performed and the impact both the nature of the data and the assigned weights could have on the final results, it is considered an important step of the GIS-MCDA.

Even though the sensitivity analysis in the case study investigates some of the effects the assigned weights had on the outcome, there are however additional uncertainties in the analysis which were not analysed. The model-, conceptual-, and parameter uncertainties, are examples of uncertainties which were not included in the sensitivity analysis but still contribute to the total uncertainty of the analysis. The model uncertainties of the case study include for example the methods which were chosen for the MCDA and the threshold value of suitability. Different methods for deriving the value functions or the combination of scores and weights are examples which could possibly yield different outcomes of the analysis. The choice of which criteria to include in the suitability analysis is an example of conceptual uncertainty, which considers the uncertainty of to what extent a criterion actually does contribute to a site's suitability. For example, the parameter Natural groundwater capacity was used in the case study to indicate hydraulic conductivity. However, since the Natural groundwater capacity is merely an indication which could correspond to hydraulic conductivity, there are uncertainties regarding whether this parameter actually contributes to the suitability of a site. Parameter uncertainties are mainly associated with the uncertainty in the data chosen to represent each parameter. Similar to the findings of Dillon et al. (2020), it was observed during the case study that it was not always possible to retrieve data of high quality for each parameter included in the analysis.

After the specific screening in the case study, areas which received a suitability score of 80% or higher of the total score range were defined as suitable. Throughout the literature review, a lack of information concerning a reasonable threshold level used for the final suitability mapping was identified. Defining a general threshold value would however not be possible, since the final suitability scores are dependent on various project-specific decisions, for example, the criteria implemented in the analysis, the defined value functions, assigned weights etc. A common suggestion was, however, that the sites were divided into either high, moderate or low suitability dependent on the final score, but how to assign the threshold values of each class was not discussed in detail. In the final suitability map produced by Rahman et al. (2012), the suitability score ranged from 0 to 100 and was divided into four classes. The threshold value of 80 and upwards was set for the most suitable sites. Similarly, the threshold value for the most suitable sites in the case study in this work was set to 80% of the total score range. However, as this threshold value was based primarily on assumptions, it could have led to an exclusion of sites possibly suitable. A possible measure to handle the model uncertainty associated with the threshold could be done by performing an additional sensitivity analysis, altering this value and examining the change in total area and the number of identified sites suggested.

Furthermore, the value functions for each parameter determining the scoring process were to some extent based on recommendations of the reviewed guidelines, but mainly on expert consultation and assumptions. The outcome of the analysis is highly influenced by the value functions and introduces a lot of uncertainty to the analysis. It is therefore assessed that an additional sensitivity analysis, looking into the use of different value functions could also have been beneficial for a further evaluation of the results.

During the analysis of Mälardalen, some parameters were assessed to possibly contribute valuable information but which could not be included in the analysis. This regarded the parameters listed below, for which data were available but could not be included due to issues related to data formatting and compatibility with the GIS tool.

- Groundwater quality
- Mean flow of water source
- Degree of filling of the aquifer

The inclusion of additional parameters in the analysis could potentially provide vital information for the success of the project. The groundwater quality or mean flow of the water source could for example indicate whether the project objectives of satisfactory water quantity and quality could be achieved. However, an abundance of parameters could contribute to the introduction of additional uncertainties in the analysis. Since the analysis is based on readily available data provided by an external source, the reliability of the data is hard to validate. Some description of the quality of the data used in the case study could often be found but was in general poorly described. Similar to the findings of Sallwey et al. (2019), it was also found that handling the uncertainty in data was seldom discussed in the literature. An approach to handle these uncertainties would be to look for an indicating parameter with sufficient data, that could provide comparable information. By doing so, it would perhaps be possible to mitigate the uncertainties of the parameter while still obtaining the desired information for the analysis. This brings attention to the importance of managing the parameter uncertainties during the site selection. However, no method for handling uncertainties in data was identified in the literature. During the case study, an attempt was made to include Monte Carlo simulations to investigate the uncertainties related to the parameter values used for the suitability mapping. Due to complications with the implementation of a plug-in tool into the GIS software, providing the possibility to perform the Monte Carlo simulations, this attempt was abandoned. This method could however be an interesting approach to be able to investigate the analysis sensitivity towards parameter uncertainties, which could possibly be further investigated in future studies.

The use of GIS-MCDA for remote evaluations of aquifer characteristics other than site suitability might prove difficult. As Russo et al. (2015) emphasised, the GIS-MCDA is a suitable tool for MAR placement, but should not be considered for quantitative predictions. Further, Russo et al. (2015) took an interesting approach to the parameters included in their GIS-MCDA. Instead of using indicating parameters directly in the analysis, several data sets were combined to assess more complex aquifer characteristics used for the site suitability evaluation. In a later stage, these parameters were also used in the numerical model constructed to evaluate the preliminary identified aquifers in more detail. Similarly, Almqvist (2018) combined geologic data to model the aquifer storage, which was later used as a parameter in the site suitability evaluation. During the case study of Mälardalen, the use of combined parameters such as extraction capacity, aquifer storage and treatment efficiency was considered but rejected. This was due to the data needed to evaluate the combined parameters was not available or of too low quality. Instead, parameters which were rather able to indicate such properties were used in the site evaluation. The use of indicator parameters was deemed to be sufficient in an initial analysis identifying a selection of sites, which most likely possess characteristics suitable for MAR. However, as the next step following the planning phase in a MAR project most likely requires more detailed investigations of the preliminary identified sites, a derivation of more complex parameters could still be of interest. As discovered in the case study, poor data availability might be an issue and indicating parameters would have to be used to estimate the complex parameters. This would of course introduce additional uncertainties in the already uncertain parameters, but still considered an interesting method to investigate in future studies.

6

Conclusion

The initial stages of planning for MAR play a vital role in ensuring the success of the project. By identifying a suitable location for the facility, and considering hydrogeological, geological and hydrological characteristics that are beneficial for MAR capacity, the likelihood of project success is significantly enhanced. The predominant approach found in the literature for the site suitability evaluation for MAR has been summarised in Figure and a step-wise procedure along with a more detailed description of each step has been suggested.

The method found most suitable for the evaluation of sites is a GIS-MCDA. Following the review and the implementation of this method, the method was deemed a suitable initial approach for site selection as it produced satisfactory results despite relying solely on readily, simple data. Contrary to the Swedish case studies, which conducted extensive analyses for site identification, such as numerical modelling, comprehensive quality analyses, and field visits, the GIS-MCDA requires less preliminary work and can be regarded as primarily a desktop study. It is, however, important to note that GIS-MCDA cannot replace the more comprehensive methods which are required to determine the capacity of a site, but could instead be considered a valuable indication for identifying sites that are deemed suitable for further investigations.

From the identification of key parameters for MAR, it could be concluded that the choice of input parameters for the analysis is highly dependent on the project objective and the availability of data. However, for implementation of MAR for drinking water purposes it was found that *Water source-, Aquifer-, and Surface characteristics* are the most common group of criteria applied for site suitability assessment. While these groups of criteria give an indication of what type of criteria to include in the assessment, any specific parameters have not been recommended. From the findings concerning the geological differences between Sweden and the rest of the world along with the availability of data, there is some variation of the parameters to be included in the analysis. The parameters established in the suggested workflow are based on the objective of the analysis of the case study performed within this work, the findings from the literature review, and the availability of data for the specific region and could be seen as suggestions on parameters to include in the evaluation.

To validate the results of the case study, the identified sites were compared to previously identified sites in the same region. Based on the validation it is assessed that the general approach possesses the potential to successfully identify sites suitable for MAR in Swedish conditions. By applying the general approach, the case study was able to identify similar areas as the validating study. It is therefore assessed that the use of GIS-MCDA and the available data were sufficient to identify sites suitable to MAR. The validation of the results was evaluated as successful since the areas suggested in the analysis within this work had also been identified in previous investigations.

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A

Appendix

A.1 Identified key parameters

Table A.1: The parameters identified in the literature review are sorted into criteria.

Source	**Criteria**	**Parameters**
NRMMC-EPHC-NHMRC (2009)	Water source characteristics	Source water quantity Source water quality Reliability Proximity to water source
	Aquifer characteristics	Recharge rate Storage capacity
	Implementation considerations	Infiltration area Other area
American Society of Civil Engineers (2020)	Aquifer characteristics	Infiltration capacity Storage capacity Recidence time Induced seismicity
	Implementation considerations	Land use Cost Conditions of site
	Regulatory consierdations	Permitting and other regulatory requirements
Imig et al. (2020)	Water soruce characteristics	Proximity to source water
	Aquifer characteristics	Groundwater level Thickness of the aquifer Thickness of unsaturated zone Lithology of the aquifer
	Surface characteristics	Lithology of the surface formations Slope Land use
McCurry & Pyne (2022)	Water soruce characteristics	-
	Aquifer characteristics	-
Sallwey et al. (2019)	Water source characteristics	Source water quality
	Aquifer characteristics	Storage capacity Flow capacity Groundwater quality
	Surface characteristics	Geology Hydrography Geomorphology
	Hydrometeorology	Precipitation Runoff
	Implementation considerations	Cost Impact assessment Land use
Dahlqvist et al. (2017)	Water soruce characteristics	Proximity to source water
	Aquifer characteristics	Storage capacity
	Surface characteristics	Infiltration capacity
Almqvist (2018)	Aquifer characteristics	Extraction capacity Storage capacity
Dahlqvist et al. (2019)	Water soruce characteristics	Proximity to source water
	Aquifer characteristics	Storage capacity Groundwater recharge
	Surface characteristics	Available infiltration area Thickness of soil
	Implementation consideration	Area for surface storage of source water
	Geomorphology	Depressions in bedrock surface
Stockholm Vatten AB et al. (1996)	Water soruce characteristics	Proximity to source water Source water quantity Source water quality
	Aquifer characteristics	Hydraulic conductivity Thickness of unsaturated zone Groundwater level Groundwater gradient
	Surface characteristics	Potential infiltration area Thickness of soil
	Implementation consideration	Distance to water treatment plant Land use

B

Appendix

B.1 Parameters included in the site screenings

Table B.1: The parameters included in the site screenings, the name of the input data, file format and data source

Parameters	**Input data**	**File format**	**Source**
General screening			
Soil type	Jordarter, 1:1 miljon	.shp	SGU
Land use	GSD Property map, Vector	.shp	Lantmäteriet
Protected areas / Nature reserve	Skyddade områden, naturreservat	.shp	The Swedish Environmental Agency
Distance from roads and railways	GSD Road map, vector format	.shp	Lantmäteriet
Specific screening			
Distance to surface water	GSD Property map, Vector	.shp	Lantmäteriet
Surface water quality	Miljödata - MVM,	.xls	SLU
Groundwater capacity	Grundvattenmagasin	.shp	SGU
Groundwater level	Brunnsarkivet	.shp	SGU
Soil thickness	jorddjup$_{1}0x10m/jorddjup_{1}0x10m.tif$	.tiff	SGU

C

Appendix

C.1 Pairwise comparison

Table C.1: The steps performed for the pairwise comparison and assignment of weights.

		Groundwater capacity	Depth to groundwater	Soil thickness	Distance to source water	Surface water quality	
Step 1	Groundwater capacity	1.00	5.00	3.00	7.00	1.00	
	Depth to groundwater	0.20	1.00	0.20	3.00	0.20	
	Soil thickness	0.33	5.00	1.00	2.00	0.33	
	Distance to source water	0.14	0.33	0.50	1.00	0.14	
	Surface water quality	1.00	5.00	3.00	7.00	1.00	
	Sum	2.68	16.33	7.70	20.00	2.68	**Weights**
Step 2	Groundwater capacity	0.37	0.31	0.39	0.35	0.37	**0.36**
	Depth to groundwater	0.07	0.06	0.03	0.15	0.07	**0.08**
	Soil thickness	0.12	0.31	0.13	0.10	0.12	**0.16**
	Distance to source water	0.05	0.02	0.06	0.05	0.05	**0.05**
	Surface water quality	0.37	0.31	0.39	0.35	0.37	**0.36**
	Sum	1.00	1.00	1.00	1.00	1.00	**1.00**

D

Appendix

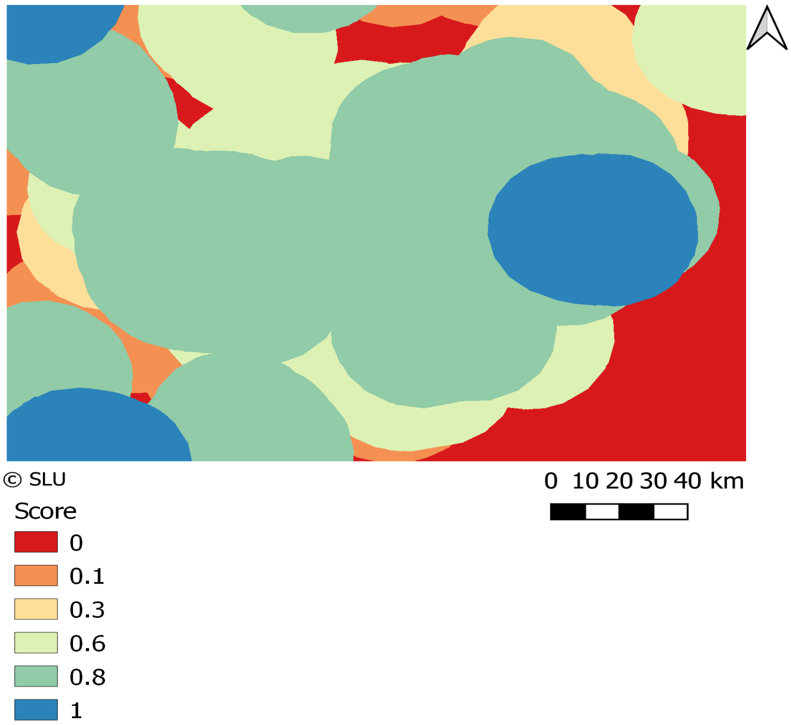

Figure D.1: The suitability map for the parameter Surface water quality.

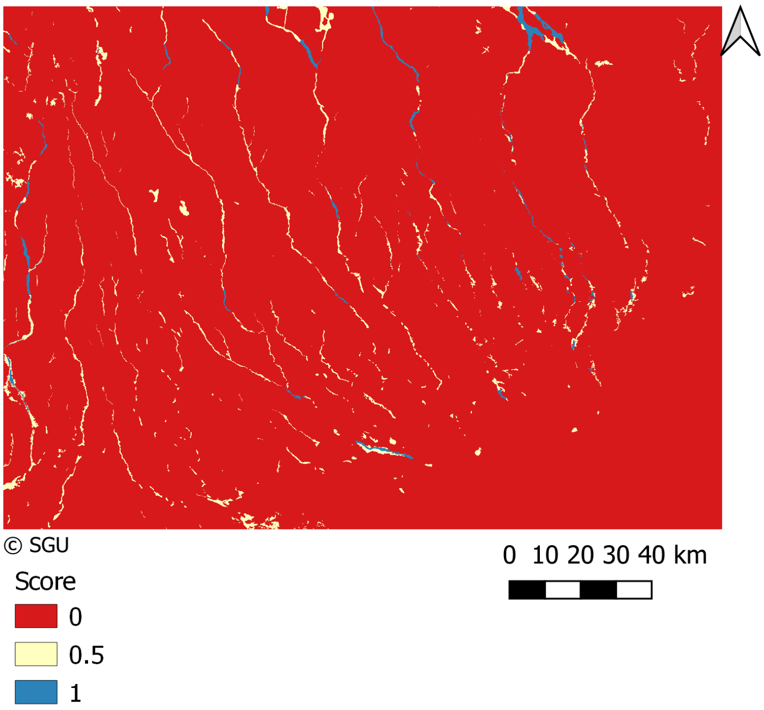

Figure D.2: The suitability map for the parameter Groundwater capacity.

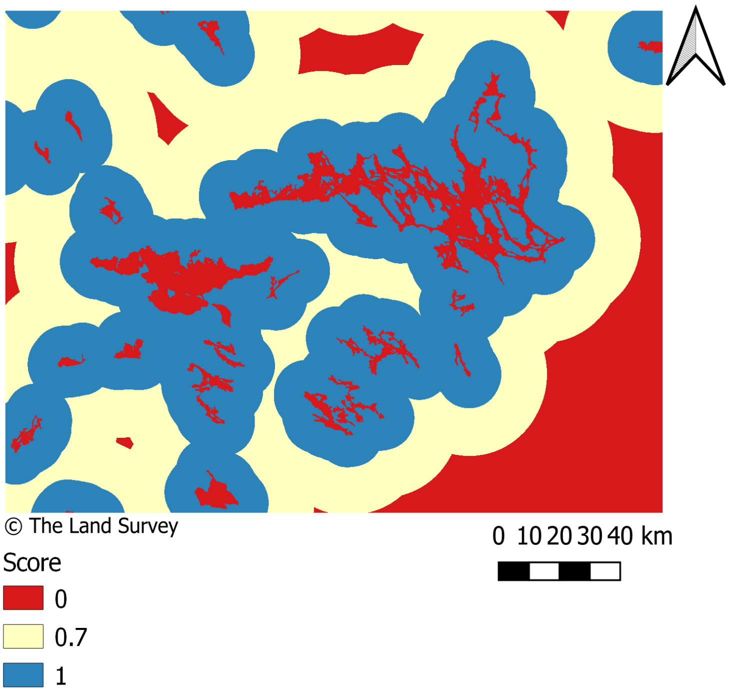

Figure D.3: The suitability map for the parameter Distance to surface water.

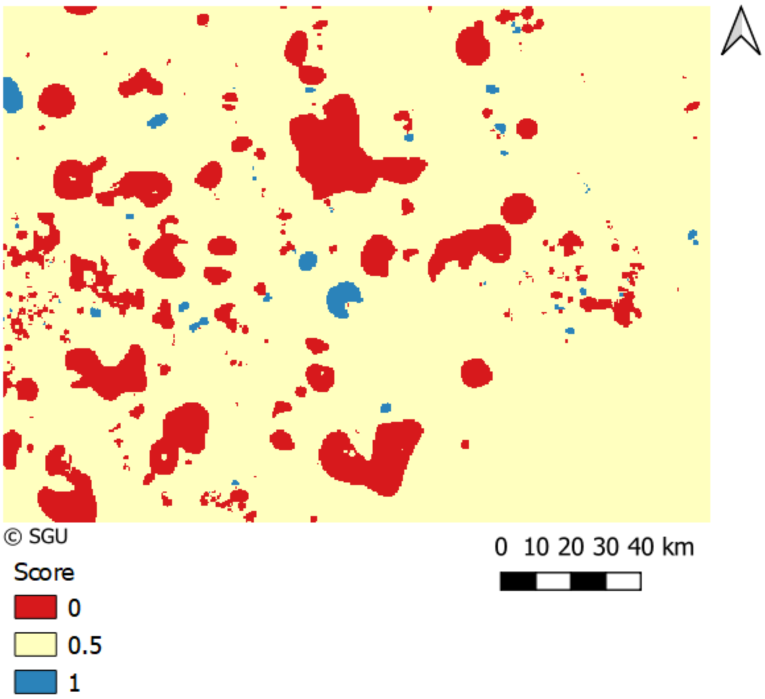

Figure D.4: The suitability map for the parameter Depth to groundwater.

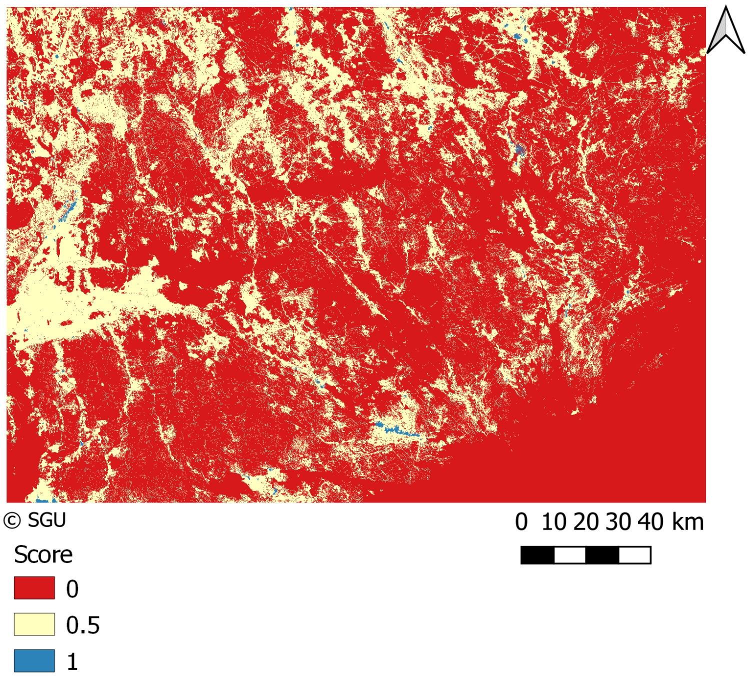

Figure D.5: The suitability map for the parameter Soil thickness.

E

Appendix

E.1 Detailed description of the GIS-MCDA

This section goes through the workflow for the GIS-MCDA.

1. The first step of the analysis was to gather all relevant raw data and add it to GIS. The files used for the analysis along with their source have been specified in Table B.1.

2. The next step was to convert and process the data to the desirable form for the analyses. This was performed in two separate steps, one for the data implemented into the constraint map, and one for the data in the suitability map. The procedures have been performed in the Graphical model in QGIS and these will be described separately in more detail.

3. The model for the handling of data for the constraint map have been illustrated in Figure E.1, and will be further described and clarified. The procedure was similar for all parameters, and the main step was to convert the vector files to raster files, with a pixel size of 15x15 m. The layers were then reclassified according to the set thresholds for each parameter. Below follows a more detailed description for each step.

    - Soil type - the rasterization process was performed with regards to the numerical attribute of the soil types. This was followed by reclassifying the layer by assigning 1 to the soil types of glaviofluvial deposits, sand, and gravel and 0 to the remaining.

    - Distance to roads - The input data for this parameter was, before implemented in the model, altered to only include roads with a speed limit above 70 km/h. A proximity of 50 metres to any larger roads and railways was set to prevent any sites located close to any roads. The reclassification was performed by assigning 0 to a proximity of 50 metres from all roads and railways and 1 to remaining area.

    - Nature reserve - any nature reserve was deemed unfeasible for a MAR facility and the rasterization process was performed by assigning 0 to all areas of a nature reserve, and 1 to the remaining area.

    - Land use - the rasterization process for this parameters was, similar to soil type, performed with regards to the numerical attributes of the land use. The reclassification was thereafter performed by assigning 1 to the land uses of open land, farmlands, and forests. The remaining land use types were assigned with 0.

To ensure that all raster layers were aligned to each others, the tool "Raster alignment" was utilised. The aligned raster layers representing each parameter were then combined by using the raster calculator and the concept of Boolean constraints utilised the AND operator for all layers creating the constraint map.

4. Once the constraint map was created, the conversion of the parameters for the suitability map was performed. The model has been illustrated in Figure E.2, and as with the constraint map, the steps will be further described below.

    - Depth to groundwater - the input layer for the groundwater levels was a point layer that was interpolated. But before the process of interpolation was performed, only the data points located within an aquifer were extracted using the same data layer as for the parameter Groundwater capacity. The extracted points were then interpolated and reclassified according to the value function set for the parameter.

    - Groundwater capacity - the process for this parameters was simply to rasterize the input data set with regards to the attribute of the groundwater capacity, followed by a reclassification according to its value function.

    - Distance to surface water - the process for this parameters was similar to the constraint parameter Distance to roads and railways. The layer was rasterized and a proximity distance of 25 km was set. Once this was done, the layer was reclassified according to its value function.

    - Surface water quality - the indicator for this parameter was measurements of TOC. The measurements were presented in an Excel file, with coordinates for each measurement. These were digitised by creating a point layer for each measurement. To be able to use it for further analysis the mean value for each lake was assigned to the same input layer used for the parameter Distance to surface water. Once this was done, the layer was rasterized followed by calculating a proximity of 25 km to cover the same areas as Distance to surface water. The last step was the same as for the rest of the parameters, to reclassify the layer according to the value functions.

    - Soil thickness - as this was already a raster file, a conversion was not necessary. Therefore, it was only reclassified according to its value function.

As with the constraint mapping, the layers were then aligned. The next step was to assign the weights and the suitability map combined with the constraint map was created. For the weighted analysis, this was performed using the raster calculator and the following expression.

```
((0.36 * "GW_capacity_raster) + (0.08 * "GW_ levels_raster") + (0.16 *
"Soil_ thickness_raster") + (0.05 * "Distance_ surface_water_raster) + (0.36 *
"Surface_water_ quality_raster)) * ("Constraint_ map" != 0 )
```

The combined map for the unweighted analysis was created using the same expression, but without the weights.

5. The threshold value for an area assessed as highly suitable was set to 80%, and the next step of the analysis was to exclude all areas that did not receive a score of at least 80% of the total range of score. This was performed using the raster calculator.

6. The areas remaining in the analysis were converted into polygons for the final screening. This was done to be able to calculate the area of the sites remaining, and to exclude the sites with an area below 32.5 ha. Further, the length of the connected area to each site was, by hand, evaluated to ensure the length was at least 400 m.

7. Once this was done, the final sites were determined and the only step left was to perform the comparison to the previously identified sites. This was performed by simply digitising the maps of the previously identified sites and place the final sites above.

8. The sensitivity analyses were performed following the exact same steps but by either exclude one parameter at a time or by alternating the weights which were assigned in step 3.

E.2 Model for the constraint map

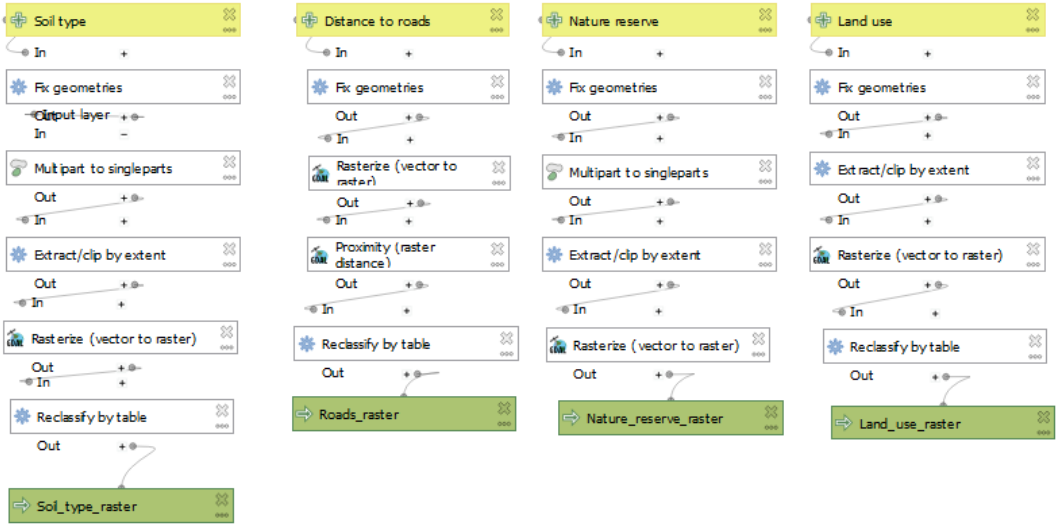

Figure E.1: The model for the process of converting the parameters for the constraint map

E.3 Model for the suitability map

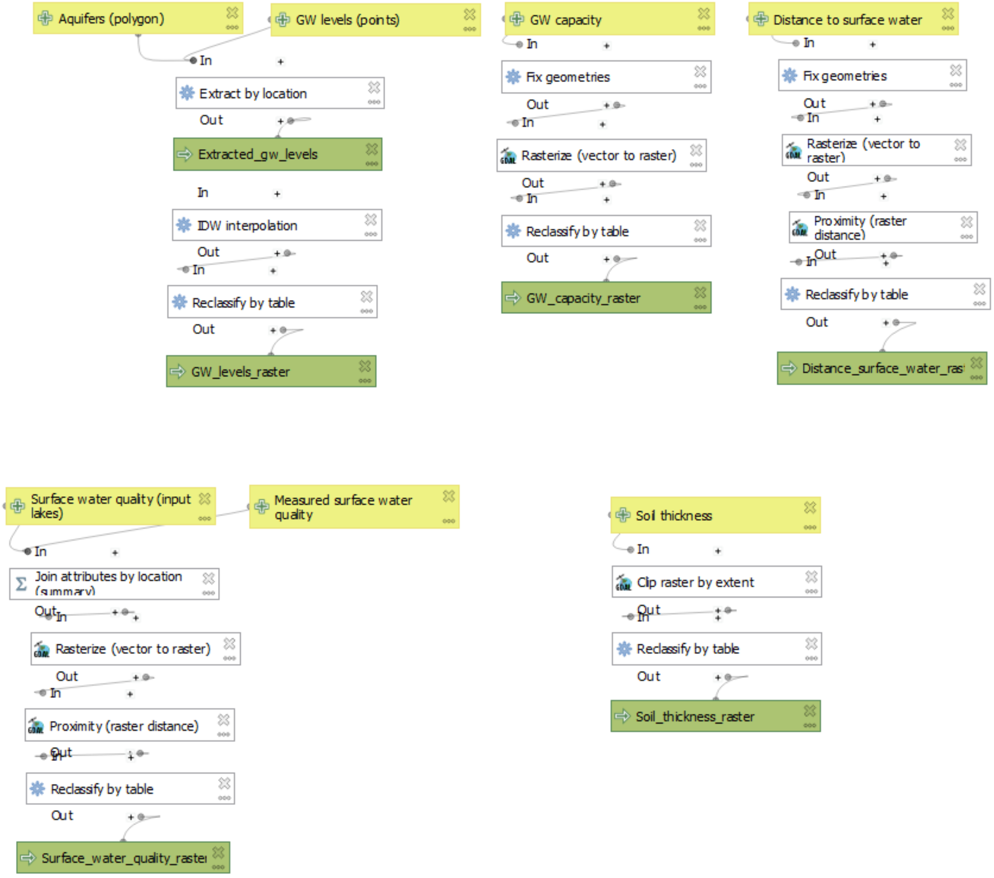

Figure E.2: The model for the process of converting the parameters for the suitability map

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