Internship report

Managed Aquifer Recharge (MAR)

Suitability maps and standardized suitability index, the case study of the Occitanie region

(South France)
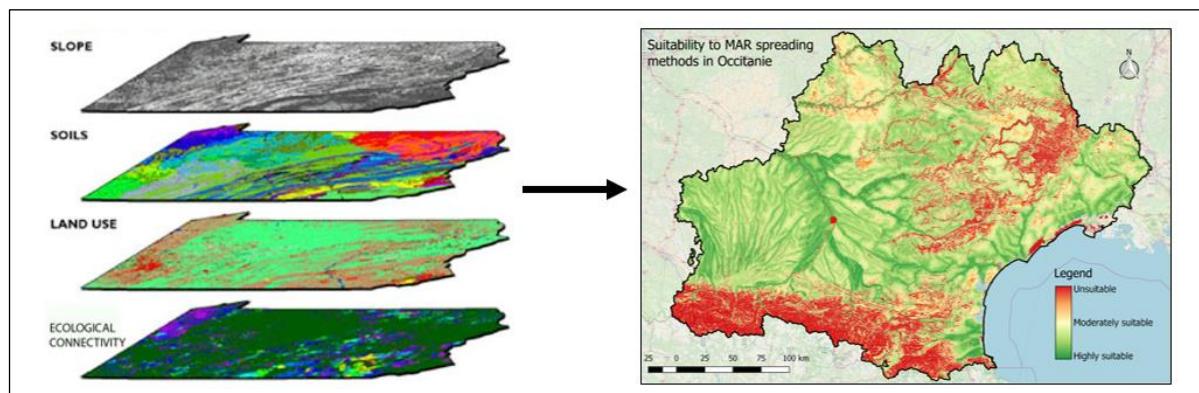
Author
Fanny Dupont

Supervisor IGRAC
Arnaud Sterckx

Supervisor Wageningen University
Roel Dijksma

Abstract

Water resources are under pressure as a result of the combined effects of climate change and population growth. Managed Aquifer Recharge (MAR) is a promising measure to increase the availability of freshwater and become more resilient to climate change. The potential of suitability mapping using GIS-based Multi Criteria Decision Analysis (GIS-MCDA) to promote these methods in the future is investigated.

First, the potential of MAR Site Selection Standardization Index (MARSSSI) as a harmonized method for spreading methods suitability mapping is discussed. A suitability index is created for the Occitanie region (France). Without specific information on the scope of spreading methods in Occitanie, available budgets and potential sources of water, few criteria are used to create this index. Comparison of this index with MARSSSI show that criteria and weights are similar. Accordingly, the two indices give similar high suitability areas. MARSSSI could result in an overestimation of unsuitable areas due to the absence of constraint criteria. The criteria used by MARSSSI reflect the intrinsic suitability of the study area for spreading methods. It is suggested to rename MARSSSI to better reflect the objectives of this index.

Subsequently, an index is developed to assess the intrinsic suitability to all MAR techniques, not only spreading methods. Based on 8 easily available criteria, this new index is very easy to calculate. Using constraints, it is less likely to overestimate the potential for MAR. Applied on the Occitanie region, it shows that 65% of the region has potential for at least one MAR technique. It could be applied to other regions and serve as an efficient visual tool to raise awareness on the wide applicability of MAR and encourage decision-makers to consider MAR for developing water management strategies.

Acknowledgments

Table of Contents

List of figures

List of tables

List of abbreviations

MAR	Managed Aquifer Recharge
MARSSSI	Managed Aquifer Recharge Site Selection Standardization Index
GIS-MCDA	Geographic Information System – Multi Criteria Decision Analysis
IGRAC	International Groundwater Resources Assessment Centre
INOWAS	Innovative web-based Decision Support System for Water Sustainability
TU Dresden	Technical University of Dresden
SAT	Soil Aquifer Treatment
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
BRGM	Bureau de Recherches Géologiques et Minières
DEM	Digital Elevation Model
SRTM	Shuttle Radar Topography Mission
SOTER	Soil Terrain Database
ESDB	European Soil Database
FAO	Food and Agriculture Organization
SANDRE	Service d'Administration Nationale des Données et Référentiels sur l'Eau
DREAL	Direction Régionale de l'Environnement, de l'Aménagement et du Logement
WLC	Weighted Linear Combination

1. Introduction

1.1. Background

Water resources are currently under pressure as a result of the combined effects of climate change and population growth. On one hand, the natural variability of climate, controlling the distribution of water through precipitations, is increasing due to climate change, causing a decrease of freshwater availability. On the other hand, population growth creates an increase of the water demand for food security and economic development. In this context, enhancing water storage below the surface is a promising measure to increase the availability of freshwater and become more resilient to climate change. This enhanced storage can be achieved with various methods called Managed Aquifer Recharge (MAR), defined as the "purposeful recharge of groundwater to aquifers for subsequent recovery or environmental benefits" (Dillon *et al.*, 2009).

MAR encompasses a large variety of applications that can serve for many purposes, in different environments and settings, and at different scales. These applications can be grouped into 5 types describing several similar engineering techniques (Table 1). These techniques can use several types of water as a source such as river water, lake water, rain water, treated wastewater or water from an aquifer if the aim is to improve water quality. The choice of technique depends on several parameters including the type of aquifer to be recharged, the desired use of water, the topography and land cover.

Table 1: Classification of MAR techniques (IGRAC, 2007)

	Main MAR methods	**Specific MAR methods**
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds
		Flooding
		Ditches and furrows
		Excess irrigation
	Induced bank filtration	River/lake bank infiltration
		Dune filtration
	Well, shaft and borehole recharge	Aquifer Storage and recovery (ASR)
		Aquifer Storage, Transfer and Recovery (ASTR)
		Shallow well/shaft/pit infiltration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams
		Subsurface dams
		Sand dams
		Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting
		Barriers and bounds
		Trenches

One of the most popular MAR types worldwide is called 'Spreading methods', referring to techniques aiming at infiltrating water from the ground surface to aquifers, in order to increase water storage and water quality. Groundwater recharge can be achieved by creating infiltration basins, irrigating agricultural lands in excess during dormant seasons or directing flood water to an infiltration area. These techniques are typically applied in flat terrains with permeable soils underlined by an unconfined porous aquifer.

Despite obvious economic and ecological benefits acknowledged by water resources specialists, low awareness and availability of information on existing projects often lead MAR to be perceived as too risky by decision makers. Therefore, the contribution of MAR to water supply systems is still limited. The International Association of Hydrogeologists (IAH) launched in 2015 a research project aiming at producing a global inventory of MAR schemes. The European project DEMEAU (DEMEAU, 2014) lead to an inventory of MAR sites in Europe, which was subsequently upscaled to the world by INOWAS, a research group at Technische Universität Dresden. This inventory was made available to the public by the International Groundwater Resources Assessment Centre (IGRAC) as a web-based GIS platform called 'MAR Portal' (Stefan and Ansems, 2017). By facilitating access and promoting the sharing of information and knowledge on MAR, the portal aims to increase awareness of MAR as a viable solution for sustainable groundwater resources development and management around the world.

Another activity promoting the application of MAR is the creation of MAR suitability maps. Several studies have assessed the suitability of specific areas for MAR projects using a Multi-Criteria Decision Analysis in Geographic Information System software programs (GIS-MDCA). In this process, a decision maker evaluates alternatives combining different decision criteria information to find the best solution to a specific problem. For MAR, the interest is usually to guide decision-makers to determine the most suitable sites for the implementation of a successful MAR application. Research on MAR suitability has been gaining more focus in the past 20 years with the contribution of research institutes such as IGRAC and Acacia Water, for projects in Kenya and Botswana or INOWAS with studies in Costa Rica and the Iberian Peninsula.

Despite the fact that every study using GIS-MCDA equally present their result as 'MAR suitability', each of them is made unique by the method used, including the selection of criteria (nature and number), how they were translated into MAR suitability and what weights were given to each of them. This diversity, although necessary to produce suitability maps that are adapted to specific needs and constraints of the study area considered, renders the process of assessing the reliability of a study more complicated. Indeed, a user looking at two different suitability maps will be unable to directly know if both maps were produced using a similar method or not, or if the method itself was reliable. In addition, the concept of MAR suitability itself can be completely different from one study area to another or from the perspective of different developers.

The research team INOWAS reviewed 62 of these studies to get a better understanding of the current state of the art of MAR suitability mapping using GIS-MCDA. From this review, INOWAS developed a site selection standardization index for MAR spreading methods (MARSSSI). This index is designed as a reference methodology to deal with different MAR suitability maps. MARSSSI uses only three widely available physiographic criteria playing a major role in the suitability for spreading methods: terrain slope, hydrogeology and soil texture. It has been applied so far to three suitability maps developed by INOWAS for the Iberian Peninsula, Costa Rica and China (Vasquez, 2017), and resulted in good similarities between the original suitability map and the map using MARSSSI. However, to bring more insight to the discussion, it appears valuable to apply MARSSSI to a new case study of suitability to MAR spreading methods, using a methodology that is developed independently from INOWAS.

1.2.   Problem statement

The MAR Site Selection Standardization Index is designed by INOWAS as a reference tool to deal with several MAR suitability maps. It uses a minimum number of criteria (terrain slope, hydrogeology and soil texture) which are already included in most studies and can be derived from widely available datasets. It has been applied to three case studies from the same research team and resulted in maps produced with MARSSSI having a good similarity with the initial maps. However, it is not yet known how MARSSSI would perform for a study using a different methodology to create the initial map. The development of a new case study can bring more insight on the advantages and limitations of this index. There is also a need to reflect on its potential use in the representation of MAR suitability for previous and future studies.

1.3.   Research question

The main objective of this research is to investigate the performance of MARSSSI on a new case study developed independently from INOWAS and to reflect on the index's potential future role in the domain of MAR suitability mapping.

From this objective, the following research question is derived:

What is the potential of MARSSSI as a tool to produce MAR suitability maps using a unified method?

To answer this question, the case study of the Occitanie region in the South of France is selected. A GIS-MCDA methodology was developed to create a MAR suitability map for spreading methods, according to the water challenges in the area. A suitability map using MARSSSI is later created and compared with the initial map. The comparison of the two maps is then used to reflect on the advantages, limitations and potential of MARSSSI. After reflecting on the findings of suitability mapping for spreading methods, the potential of applying a methodology similar to MARSSSI for other MAR techniques is investigated. Finally, the potential of suitability mapping for MAR in the future is discussed based on the insights of this study.

2. Theoretical background

2.1. Managed Aquifer Recharge

2.1.1. Definition

Managed Aquifer Recharge (MAR) is defined as the "purposeful recharge of water to aquifers for subsequent recovery or environmental benefits" (Dillon *et al.*, 2009). Its various applications are adaptable to many contexts, although they are still limited compared to traditional surface water storage methods. MAR presents many interests including enhancing the security of water supplies, improving groundwater quality, preventing saltwater intrusion, mitigating floods, maintaining groundwater-dependant ecosystems (Dillon et al., 2009; DWA, 2010).

2.1.2. Interest of subsurface storage

The growing water demand and climate variability requires to increase the water storage capacity, currently ensured for the major part by surface reservoirs contained behind small to large dams. However, large evaporation losses, water quality issues as well as the growing concerns about dam safety, sedimentation, environmental and societal impacts demonstrate the limitations of surface water storage (Tuinhof *et al.*, 2002).

The available water supply can be increased by enhancing the storage of water below the surface in aquifers, although the potential global storage capacity is still difficult to estimate (Tuinhof *et al.*, 2002). Subsurface storage presents the major advantages of storing water for years with little to no evaporation losses, low environmental impact and allowing the removal of certain pollutants during slow percolation of water through the ground (Keller, 2000; Gale, 2005).

2.1.3. Potential sources and uses of MAR

A prerequisite to the use of MAR is to have a sufficient source of water available for recharge, which includes various types such as surface water, rain water, storm water, reclaimed water or groundwater (Gale, 2005; Dillon *et al.*, 2009). Depending on the initial quality of the source water and the desired final use, a phase of pre-treatment before recharge and eventually post-treatment after recovery might be necessary to bring the water to a requested quality standard that ensures the protection of public health and environment (Dillon *et al.*, 2010; DWA, 2010).

After recovery, the recharged water can serve for various uses such as drinking water, irrigation, industry, domestic use or ecosystem sustaining. This additional water supply from MAR can be highly beneficial for securing the water supply in periods of droughts by storing water for several years with little evaporation losses, preventing saltwater intrusion in coastal areas, protecting groundwater-dependent ecosystems by increasing groundwater levels, improving groundwater quality and mitigating flood damages (Dillon *et al.*, 2009).

2.1.4. Hydrogeological control on MAR

The success of a MAR scheme depends largely on the aquifer's storage capacity and the ability of the unsaturated zone to infiltrate water for applications recharging water to the aquifer from the surface (Tuinhof, 2002; Gale, 2005). A good knowledge of the hydrogeological conditions is decisive, including key factors such as the degree of confinement, aquifer properties (hydraulic conductivity, thickness), piezometric surface, water quality, nature and thickness of the unsaturated zone…

The nature of the geological formations composing the aquifer has an important control on the potential storage space available and the ability to recharge and recover water from it. Gale (2005)

identified four categories of potential hydrogeological environments from the perspective of MAR: alluvium, fractured hard rock, sandstones and carbonate aquifers.

2.1.5. MAR types and techniques

MAR encompasses a wide range of possible methods that may be applied in various contexts, some examples are shown in Figure 1.
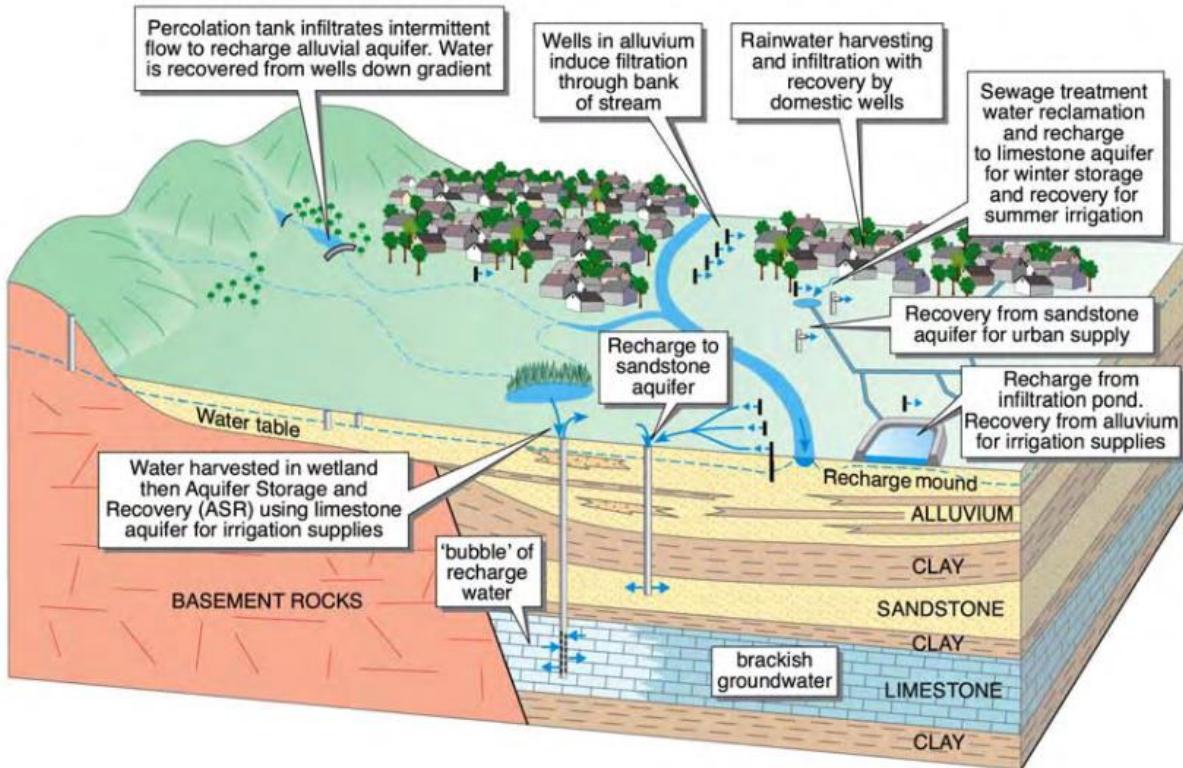
Figure 1: Example of MAR applications to several contexts (Dillon et al., 2009)

IGRAC (2007) suggested a classification of existing MAR schemes in five main types according to the main objective and type of method (Table 1). The main techniques included in these five classes are briefly described below; details on specific requirements for application, advantages and limitations of each technique are available in Appendix A, based on IGRAC (2007), Dillon *et al.* (2009) and INOWAS (2018a):

Spreading methods

Spreading methods refer to MAR applications which aim at infiltrating water from the land surface to underlying aquifers. Possible schemes include diverting water to infiltration basins or trenches that will enhance infiltration through the unsaturated zone (localized land infiltration). Other possible techniques include irrigating crops in excess or diverting flood water to specific areas to allow infiltration (diffuse land infiltration). The recharged water is stored in the underlying aquifer and recovered in periods of high demand through wells. Spreading methods can be beneficial for increasing water storage as well as water quality due to the filtration process occurring when the water travels through the unsaturated zone.

Induced bank filtration

In cases of low quality of surface water (river or lake), a series of wells can be installed parallel to a water body to enhance the infiltration of water through the ground induced by pumping. The water

recovered at the wells will be of better quality as it benefited from the filtration process taking place when travelling through the river or lake bed, removing dissolved and suspended pollutants. This MAR type can also be applied to sand dunes, where water infiltrating through the sediments is recovered down-gradient with an increased quality.

Well, shaft and borehole recharge

In this class of MAR application, water is infiltrated through wells directly into the target aquifer. These techniques can typically be applied when the unsaturated zone does not allow water to infiltrate, when the aquifer is covered by a confining layer or to reuse existing shallow wells. The water is stored in the aquifer and can be recovered either at the injection well (ASR) or at a different well to benefit from an additional treatment process by extending the water residence time in the aquifer (ASTR).

In-channel modification

Several MAR techniques consist in modifying the stream flow to enhance infiltration of water. Some of them aim at intercepting the flow in intermittent streams with dams built across the streambed. These structures can be used to control the release of water downstream to match the capacity of infiltration to the underlying aquifer or to enhance the infiltration of water behind the recharge dam. In impermeable streambeds, sands and gravels can be accumulated upstream of the dam to form an artificial aquifer storing storm water runoff. In intermittent streams with shallow bedrock, underground dams of low permeability material can be built across the streambed to retain storm water runoff in the alluvium. In permanent streams, the river flow can be modified by installing L shaped levees that allow enhancing recharge by increasing the infiltration area and decreasing the flow velocity.

Runoff harvesting

Rainwater can be harvested at the scale of a household to a village and directed to storage tanks that can contribute to groundwater recharge. Several structures allow collecting rainwater such as trenches or reverse drainage. Rooftop rainwater harvesting is being increasingly used in urban areas, helping to sustain groundwater levels and mitigate storm water runoff.

2.2. Suitability mapping with GIS-MCDA

2.2.1. General definition

In the field of environmental sciences, spatial decision problems typically involve a large set of feasible alternatives defined by multiple, conflicting and incommensurate evaluation criteria (Malczewski, 2006). Decision-makers require information and tools to incorporate their value judgments and understand the inherent trade-offs of a spatial problem (Greene *et al.*, 2011). Multi Criteria Decision Analysis (MCDA), also known as Multi Criteria Evaluation (MCE), encompasses several techniques and procedures for structuring spatial decision problems as well as designing, evaluating and prioritizing alternative decisions. MCDA is commonly used in combination with a computer-based geographic information system (GIS) integrating spatially referenced data (GIS-MCDA). GIS-MCDA can be defined as a process that transforms and combines geographical data according to the decision-maker's judgement to obtain information for decision making (Eastman, 2005; Malczewski, 2006; Malczewski & Rinner, 2015).

2.2.2. Applications to MAR suitability

The selection of suitable areas for the implementation of a MAR site can be a complicated process as several factors need to be considered, including in priority information on the hydrogeological context and surface characteristics such as the geology, land cover slope… In addition, considerations of the social and financial context, policy and regulations, environmental impacts and others can appear decisive in the definition of suitable area, therefore adding much complexity to the decision process.

In Rahman *et al.* (2012), GIS-MCDA is presented as a method providing adequate solution procedures to deal with the complexity of MAR suitability at low costs, in comparison with traditional decision support systems and GIS-based analysis methods. This method allows identifying priorities in the considerations of a given MAR project, using and manipulating geographical data according to the decision-maker's preferences.

2.2.3. Steps

The process of a GIS-MCDA involves several steps to solve a spatial problem, such as finding suitable areas to implement MAR, depicted in Figure 2 and described in the following section.

1. Set the goal/define the problem

The first necessary step to conduct a successful GIS-MCDA is to clearly define the goal of the study. The spatial problem should be characterized by one or several specific and measurable objective(s), attainable in the time frame available. The problem definition is a decisive step as it will greatly affect the rest of the study by influencing the selection of criteria and their respective weights.

2. Determine the criteria (factors/constraints)

The criteria form a set of spatial information that contributes to represent the multi-criteria nature of the decision situation (Keeney, 1992). Malczewski & Rinner (2015) state that each criterion should be comprehensive, measurable, decomposable, complete, operational, non-redundant and that the set of criteria should be kept minimal. The information represented by each criterion can be spatially measurable (*e.g.* slope), an attribute of the study area (*e.g.* land use) or a value derived from spatial information (*e.g.* drainage density). The set of chosen criteria should reflect the characteristics of the study area with a sufficient level of precision to answer the problem formulated.

3. Define the criteria values

There are two approaches to deal with each criterion, defining them either as a *constraint* or as a *factor* (Eastman, 2005). Constraint criteria will typically be represented by a Boolean statement of suitability for the decision considered, where the criterion is described by a binary system (true/false, 1/0…). This type of criterion serves to limit the alternatives under consideration by defining restrictive features for which an area will necessary be considered unsuitable. Constraint criteria are typically represented on a map with a separate mask layer, commonly called 'Constraint mapping'.

For factor criteria, the approach is to give more quantitative information by describing the criterion as a continuous or step function, expressing varying degrees of suitability for the decision considered. All factor criteria have to be expressed with a common scale of suitability allowing to combine them on the same level, commonly called 'Standardization'.

4. Determine the weight of each factor

Several techniques exist to determine the weight of each factor criterion, with the most used in literature being the 'Pairwise comparison method', the 'Rating method' and the 'Ranking method' (INOWAS, 2018b). The 'Pairwise comparison method' is part of the Analytical Hierarchy Process (AHP), developed by Saaty (1980), being a framework to evaluate a problem by decomposing it into a hierarchy of sub-problems. In this method, the decision maker builds a matrix to compare each criterion to the other criteria, by evaluating its importance with a value from 1 to 9 (1: the criterion is considered equally important than the one compared; 9: the criterion is considered extremely more important than the one compared). Each method result in a numerical value assigned to each weight, with all weights summing up to 1.

5. Aggregate the criteria

The last step to produce the decision map is to calculate the final suitability score using a 'Decision rule' combining the criteria together using their relative weights. The most common method is the Weighted Linear Combination (WLC), in which the composite suitability score S is calculated for each cell using the following formula (Estoque, 2011):

$$S = \sum w_i x_i \times \prod c_j$$

Where:
S is the composite suitability score
w_i is the weight assigned to the factor criterion i
x_i is the index of the factor criterion at the cell considered i
c_j is the value of the constraint factor j
$\sum$ is the sum of weighted factor criteria
$\prod$ is the product of constraint criteria (1=suitable; 0=unsuitable)
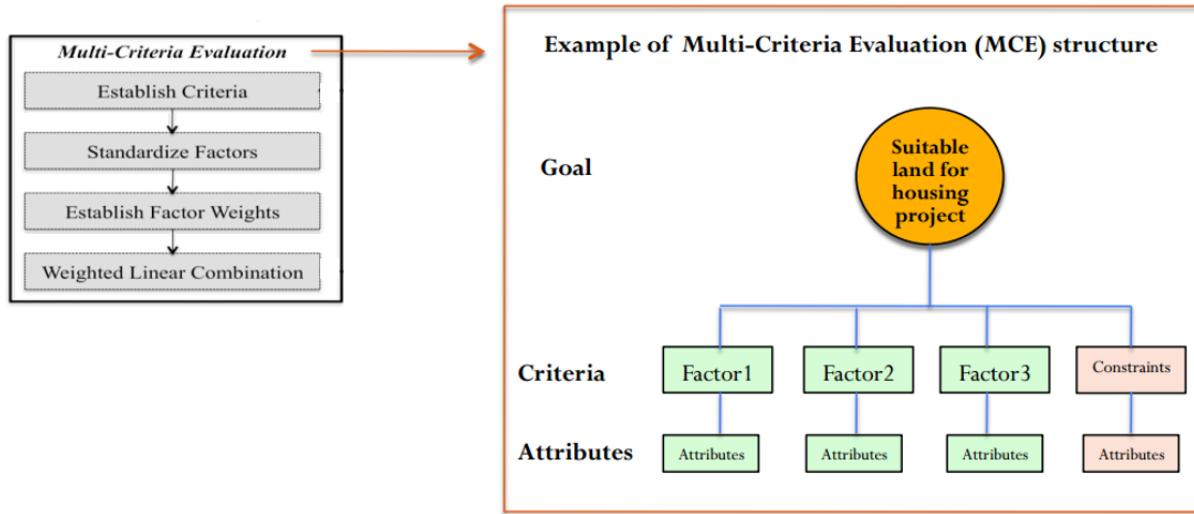
Figure 2: Example structure of a GIS-MCDA (or MCE) (adapted from Eastman, 1995)

6. Validate/verify the result

The process of a GIS-MCDA highly reflects the value judgements of the decision-maker in the selection of criteria, the choice of constraints, the standardization of factor criteria and the weights assigned for aggregation. This subjectivity results in a potentially high uncertainty of the decision and is complicated to evaluate for problems which cannot easily be verified by field measurements. For instance, the suitability for MAR is not a straight forward variable that can directly be measured.

One method to assess the reliability of the results is to perform a 'Sensitivity analysis', in which the effect of altering one or several component of the GIS-MCDA is investigated. This can include altering the set of criteria by adding or removing a criterion or by modifying the respective weights of factor criteria. The decision-maker can reflect from the effects of these alterations whether the result appears reasonably close to reality or not. It is however important to note that this step does not decrease in any way the uncertainty of the results but rather contributes to acknowledge and communicate the subjectivity of the decision resulting from a GIS-MCDA to other users.

The reliability of a suitability map can however partially be assessed if some points are available for validation. In the case of MAR, existing sites can be used to assess the ability of a map to predict high suitability. In addition, the results can be verified by selecting sample areas to conduct an in-depth field survey.

3. Study area

3.1. Choice of study area

The process of selecting the study area to evaluate the potential of MARSSSI followed a set of conditions. One requirement was to have several operating MAR sites in the area, with at least 3 or 4 sites using spreading methods and ideally a few sites using other MAR techniques. These sites are required for validation of the suitability map. In this step, the suitability at each site location is examined to evaluate the reliability of the produced suitability map. The 1200 sites inventoried on the MAR Portal[1] were used to identify regions satisfying this first condition (Figure 3).

Figure 3: MAR sites inventoried in the MAR Portal

For obvious reasons, one condition was to select an area which has not been studied for MARSSSI potential yet, therefore excluding the Iberian Peninsula, Costa Rica, China as well as Arizona (ongoing study). The chosen study area must also have a high availability and quality of spatial data such as elevation, soil, geology… Areas with available datasets in French, English, Spanish or Portuguese were preferred. Therefore, areas where language might be a constraint to data collection such as Sweden, Iran or Tunisia were discarded. Finally, the selected area should present a potential need for new projects of managed aquifer recharge, as a mean to increase water storage and/or water quality. This condition is necessary to design a hypothetical problem as close as possible to a real context requiring a suitability assessment.

From the requirements listed above, the Occitanie region of France appeared as the most suited area to create a suitability map for MAR spreading methods and apply the standardized index. In this region, 9 MAR sites are inventoried, including 6 using spreading methods. Being a French native speaker, the author was also already acquainted with the national or European datasets available.

---

[1] https://apps.geodan.nl/igrac/ggis-viewer/viewer/globalmar/public/default

3.2. The Occitanie region

3.2.1. General information

Located in the south of France at the border of Spain and Andorra, the Occitanie region covers an area of 72,724 km^2, or 13.2% of the total surface area of France. It hosts two major urban areas, Toulouse and Montpellier, for a total of 5,774,185 inhabitants (https://www.laregion.fr). The region is composed of a large variety of landscapes and topographies with two mountain ranges, the Pyrenees in the south along the Spanish border and the Massif Central in the north, the long coastline of the Mediterranean Sea in the east and the Garonne river valley in the west (Figure 4).
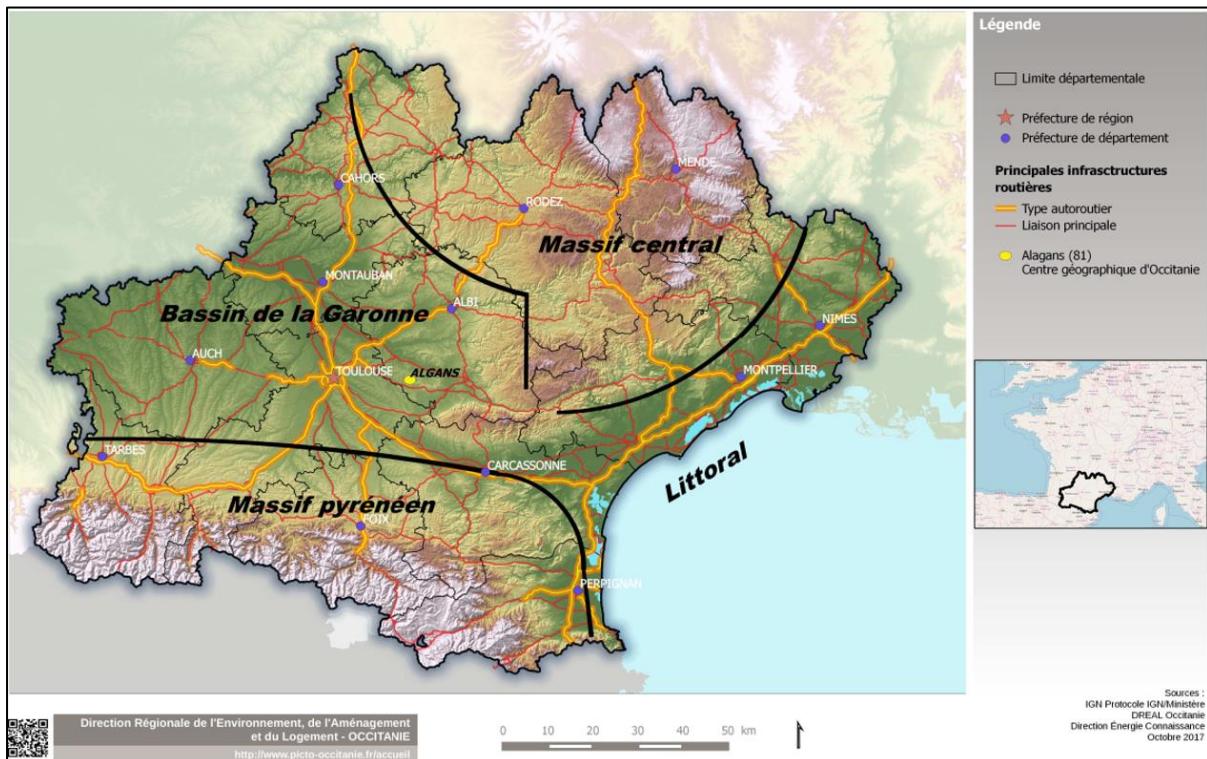
Figure 4: The four geomorphologic ensembles of the Occitanie region (adapted from DREAL Occitanie)

The Pyrenees, composed of Eocene geological formations, are part of the alpine belt and cover 15,000 km² of the region area in a west-east direction. The topography is characterized by narrow encircled valleys of direction south-north and the highest peak, the Vignemale, culminates at 3,298 m. The Massif Central is composed of eroded Hercynian geological formations and covers 26,000 km² of the region area. This old mountain range is characterized by a smooth topography of hills and plateaux and is composed of karstic systems, volcanic and granitic domains. The Pic de Finiels, highest in Occitanie, culminates at 1,699 m (http://www.observatoire-des-territoires.gouv.fr). Half of the Garonne River flows across the Occitanie region, as well as 9 of its main tributaries, forming a wide river valley surrounded by high plains and sweeping hillsides (https://www.laregion.fr).

The region receives dominantly Mediterranean semi-arid climate conditions characterized by warm and dry summers, encouraging the start and propagation of forest fires, followed by intense autumn rainfall, occasionally causing floods on vulnerable areas. The Pyrenees and Massif Central receive more mountainous climate conditions with generally higher precipitations. The average annual precipitation in the region is 930 mm but can reach 1,500 mm in the mountains (Région Occitanie, 2017).

3.2.2. Water resources

The water demand in Occitanie is highly variable and reflects the unequal population density with a higher pressure on the coast and around Toulouse, the region's major town. The main use of water resources is for irrigation, followed by drinking water and industry. The drinking water supply is ensured by both surface water and groundwater, with a share depending on the availability of both resources. This share highly differs between the eastern part of Occitanie, where 84% of the drinking water comes from groundwater abstraction and the western part where groundwater only represents 48% of the supply because of the higher availability of surface water in the Garonne River basin (Région Occitanie, 2017).

The state of groundwater resources in Occitanie is highly variable in space and time. Groundwater levels are regularly observed at moderately to very low levels, often resulting in water shortage in periods of low precipitation (http://propluvia.developpement-durable.gouv.fr).

The water resources in the region are also very vulnerable to diffuse pollution, particularly to nitrates from the use of fertilizers in agriculture. Concentrations of nitrates in surface water and groundwater are regularly monitored and many are observed above the European threshold of 50 mg/l. These measurements are used to define the vulnerable area in which measures are imposed to farmers to reduce nitrate leaching in soils and water bodies, which covers 34% of the region (Figure 5).
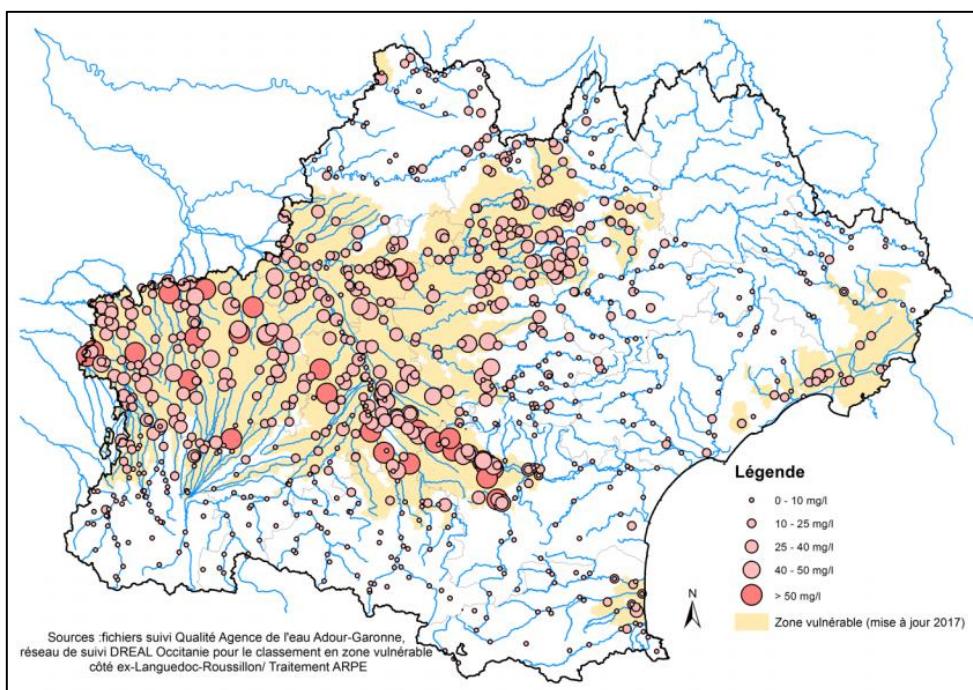
Figure 5: Maximum nitrate concentration observed in surface water bodies in 2014 and nitrate vulnerable area in 2017 (Région Occitanie, 2017)

Currently, several sites located in the Occitanie region use MAR techniques such as infiltration basins or ASTR to decrease the high nitrate concentration observed in the Garonne alluvial aquifer, exploited by drinking water wells. The sites of Lavelanet-de-Comminges, Plaine de Millegrand and Vauvert are successful examples of MAR to improve the state of groundwater resources as they allow preserving the piezometric levels as well as maintaining nitrate concentrations below the threshold of 50 mg/l (Casanova *et al.*, 2013).

3.3. Managed aquifer recharge in France

The French geological survey BRGM presented the state of the art of MAR in France (Casanova *et al.*, 2013). They inventoried with certainty 50 sites using artificial recharge, including 17 abandoned sites, 16 with an uncertain activity and 17 still in activity in 2013. The reasons for interruption of activity were often that another source of water became available in the area or that the quality of the water recharged was insufficient for the site to be sustainable (*e.g.* clogging of infiltration basins).

In most cases, MAR sites have been implemented in the years 1950-1960 near drinking water wells and have for objective to maintain the groundwater level in prevention of successive droughts. In the years 1970-1980, a few sites have been implemented in Occitanie with the objective to dilute high nitrate concentrations observed in alluvial aquifers.

All MAR sites in France recharge alluvial aquifers or aquifers connected to an alluvial aquifer. In most cases, the source water is surface water (mostly river water, but also a few sites extracting groundwater from wells or springs for water quality improvement). Of the inventoried sites, 56% were using infiltration basins. Other sites used well injection, infiltration pits or a combination or different techniques.

4. Assessment of MARSSSI potential

4.1. Method

4.1.1. Suitability map for MAR spreading methods

The mapping of the suitability of the Occitanie region to MAR spreading methods was developed for this study based on the knowledge of the study area and followed the scheme for a GIS-MCDA as described in 2.2.3.

4.1.1.1. *Problem definition*

The brief introduction to the environment and state of water resources in the Occitanie region and the state of MAR in France helped to develop a hypothetical context in which the regional water board wants to know where they could implement a new MAR site using spreading methods. The main need for MAR in the region is to ensure the stability of piezometric levels especially in drought periods and eventually to help decreasing the nitrates concentrations in surface water and groundwater below 50 mg/l.

A suitable site for MAR spreading methods should typically have a source of excess water available nearby, be located in a flat area with permeable soils and be underlined by an unconfined aquifer.

Being based only on a hypothetical need of MAR suitability, financial and legislative matters are not included in the process. Indeed, it is difficult to suggest a reasonable estimate of the budget that could be allocated to a potential MAR project as costs involved in existing MAR projects in France are not easily accessible (Casanova *et al.*, 2013). Legislation in the domain of water resources is also quite complex in France as it refers to several authorities and levels of decision-making. For similar reasons, matters of objective quality and volumes of water to be infiltrated are not considered here either.

4.1.1.2. *Choice of criteria*

One important source of variability in MAR suitability maps comes from the initial choice of criteria. INOWAS collected from the 63 papers reviewed all the criteria used and made a ranking of how many times one criterion was used in a suitability study. The list of the 20 most used criteria in literature for MAR spreading methods was used to determine the most relevant criteria to include in the Occitanie case study, depending on the aim of study, the knowledge of the area and data availability:

Table 2: Discussion of possible criteria based on the 20 most used criteria in literature (adapted from INOWAS, 2018b). Selected criteria are in bold.

Criteria	Number of studies	Role in suitability to MAR spreading methods	Relevance	Data availability
Slope	**29**	**Influences the infiltration of water from the surface. Spreading methods require a flat terrain to optimize infiltration and minimize runoff**	**High**	**High**
Land cover	**21**	**Defines the availability of the land and possible environmental disturbances associated with the implementation of a MAR project**	**High**	**High**
Geology/ Lithology	16	Determines the ability to store water in the ground as a function of the hydraulic conductivity and the continuity (fractures, karst) of the medium	High	High
Aquifer thickness	14	Influences the amount of water that can be stored in the aquifer. However, considerations of infiltration volumes are difficult to make in a hypothetical project	Medium	Low
Hydrological soils	13	Determine the ability to infiltrate water through the unsaturated zone. This is mainly controlled by the soil particle size (soil texture)	High	Medium
Soil texture	**12**	**Determines the ability to infiltrate water through the unsaturated zone. Soil thickness also plays an important role but has lower data availability**	**High**	**High**
Geomorphology	10	Combination of the criteria slope, geology and land cover	Medium	High
Drainage density	8	Reflects the slope and permeability of soils: steep slopes and soils of low permeability typically result in a high drainage density. This could be understood as decreasing MAR suitability as the environment is not favourable to infiltration but also increasing MAR suitability as there is more surface water available	Low	High
Groundwater - Salinity	8	There is no significant issue of saltwater intrusion in groundwater for the Occitanie region	Medium	Low
Groundwater level	8	Plays an important role for spreading methods sites aiming at improving water quality as it influences how good the filtration of water through the unsaturated can take place. However, the variability of groundwater level in space and time and the data coverage makes this criterion difficult to include without a high uncertainty	Medium	Medium
Distance to source water	**7**	**Implementing a MAR site is only possible if there is a source of water available at a reasonable distance**	**High**	**High**
Aquifer transmissivity	6	Combination of the geology (hydraulic conductivity) and aquifer thickness	Medium	Low
Distance to urban areas	6	This criterion is difficult to deal with in a hypothetical project as being close to an urban area could be considered as increasing MAR suitability as the water demand is more important at urban areas; or decreasing MAR suitability as the water might be more polluted near urban areas.	Medium	High
Hydrogeology	**5**	**Determines the ability to store water in the ground as a function of the hydraulic conductivity, the continuity (fractures, karst) of the medium and the confinement or not of the aquifer**	**High**	**High**
Unsaturated zone thickness	5	The influence of this criterion on the suitability for spreading methods is similar to the criterion 'Groundwater level'.	Medium	Low
Lineament density	4	This criterion includes a lot of uncertainty as a geological fault is complex and can act either as a preferential flow path if rather recent or as an obstacle to flow if older, likely filled with minerals	Low	High
Distance to roads	4	This criterion is difficult to deal with in a hypothetical project as the preferable distance to road will likely be dictated by budget and legislative constraints	Medium	High
Rainfall	4	Variation of rainfall influences stream discharge, therefore the potential availability of water for MAR. However, the water will preferentially be withdrawn during high discharge periods and stored as groundwater for the dry season.	Low	High
Groundwater - Chloride	3	There is no significant issue of chloride in water resources for the Occitanie region.	Low	Low
Groundwater - Nitrates	**3**	**High nitrate concentration in water resources is an important concern in the Occitanie region. Several existing sites have the objective to help solving this issue**	**High**	**High**

From the analysis of the 20 most used criteria in previous studies presented in Table 2, the criteria combining a high relevance and high data availability, and providing unique information (*e.g.* hydrogeology already includes geology) were selected to assess the suitability of MAR spreading methods in Occitanie:

➢ Slope
➢ Land cover
➢ Soil texture
➢ Distance to source water
➢ Hydrogeology
➢ Groundwater – Nitrates.

More details on the original datasets used to derive these criteria are presented in Appendix B.

4.1.1.3. Constraint criteria

Constraint criteria serve as restrictions under certain circumstances that are assumed to define the unsuitability for implementation of MAR sites. Here, slopes higher than 30% are ruled out as the potential for infiltration would be insufficient. Wetlands, bare rock and water bodies are also excluded as they are necessarily not suited for infiltration. Soils classified as 'non-soils', usually corresponding to dense urban areas, are also set as unsuitable. The choice was made not to exclude the land cover 'Artificial areas' as these areas are not available in the near future but can eventually become available in the long term. These constraints are usually represented in the final suitability map as an individual mask layer, it is however included within the 'Unsuitable' class of suitability mapping here to facilitate the comparison with MARSSSI.

4.1.1.4. Standardization of factor criteria

The standardization of the factor criteria follows an index ranging from 0 (minimum suitability) to 1 (maximum suitability), as presented in Table 3. It is important to note that assigning values to criteria mostly reflects the developer's preferences based on personal judgment and knowledge of the study area.

Table 3: Correspondence between scale of standardization index and suitability level

Suitability class	Index
Highly suitable	1
Suitable	0.75
Moderately suitable	0.5
Low suitability	0.25
Unsuitable	0

Slope

Terrain slope is a crucial criterion to characterize a site suitability to spreading methods. Indeed, an optimal infiltration will be achieved in areas where runoff is minimal, which is only the case in flat terrains. Previous studies have used various ways to characterize the slope in terms of suitability to MAR spreading methods. In this study, the classification of slope degree from the SOTER model (Table 4) was used to characterize slope suitability to spreading methods as a linear function, presented in Figure 6. The slope was derived from a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) of the USGS, with a resolution of 1-arc second, or 30 meters.

Table 4: Classification of slope degree from the SOTER Model (Van Engelen and Wen, 1995)

| Slope (°)	Description	Groundwater potentiality	Landform	Elevation (m)
<2	Flat	Very high	Alluvial fan	5–20
2–8	Undulating	High	Valleys	20–60
8–15	Rolling	Moderate	Upstreams	60–150
15–30	Moderately	Low	High lands	150–700
30–60	Steep	Very low	Mountain	>700

$y = -0.0353x + 1.0485$
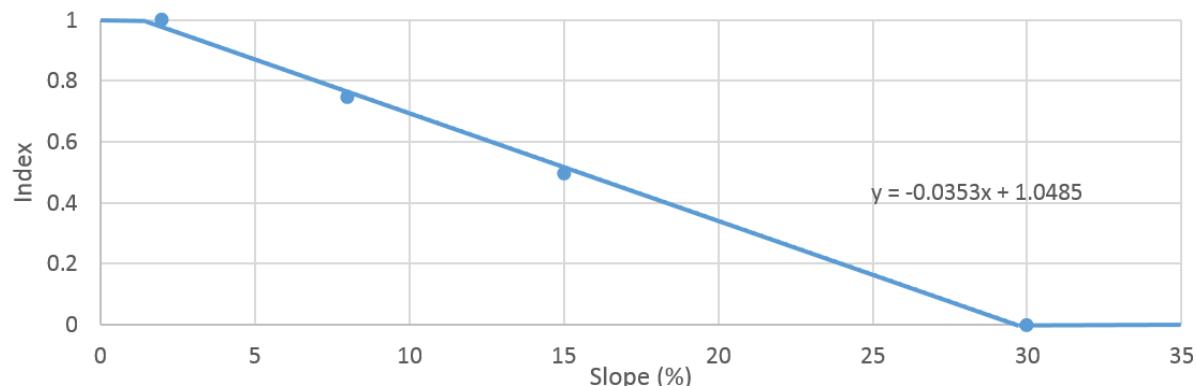
Figure 6: Slope criterion

Land cover

The land cover has an influence on surface runoff and gives information relative to the availability of land for implementation of MAR sites. For this study, 5 suitability classes group the main land cover listed in the Corine database[2] according to their influence on infiltration and surface runoff, availability and potential environmental impact as presented in Figure 7. The detail of land covers included in each class and the reason behind this choice is as follow:

➢ Highly suitable: scrub and/or herbaceous vegetation associations (32); sparsely vegetated areas (333) as these terrains are likely to offer large areas for spreading methods, with soils of sufficient infiltration potential and little conflict in term of land disturbance as they usually do not have a specific use.

➢ Suitable: pastures (23), arable land (21), land principally occupied by agriculture with significant areas of natural vegetation (243) as these terrains are also likely to offer large areas for spreading methods, with soils of sufficient infiltration potential. However, it could be more complicated to convince the owners to transform part of their land, which has a clear use as part of their professional activity, for an activity of which they might not perceive the direct benefits.

➢ Moderately suitable: permanent crops (22), annual crops associated with permanent crops (241), complex cultivation patterns (242), agro-forestry areas (244) as these lands might present significant constraints to convert to spreading methods as they are used for a type of activity that is effective during the whole year (*i.e.* no available period for excess irrigation).

➢ Low suitability: forests (31) as this land use type is not suitable for spreading methods as the available area and infiltration potential are low. Moreover, converting forests into sparsely vegetated areas should not be done intentionally, but is not considered definitely unsuitable for spreading methods as the situation can change.

---

[2] http://www.statistiques.developpement-durable.gouv.fr/clc/fichiers/

➢ Unsuitable: artificial areas (1), bare rock (332), glaciers and perpetual snow (335), wetlands (4), water bodies (5).
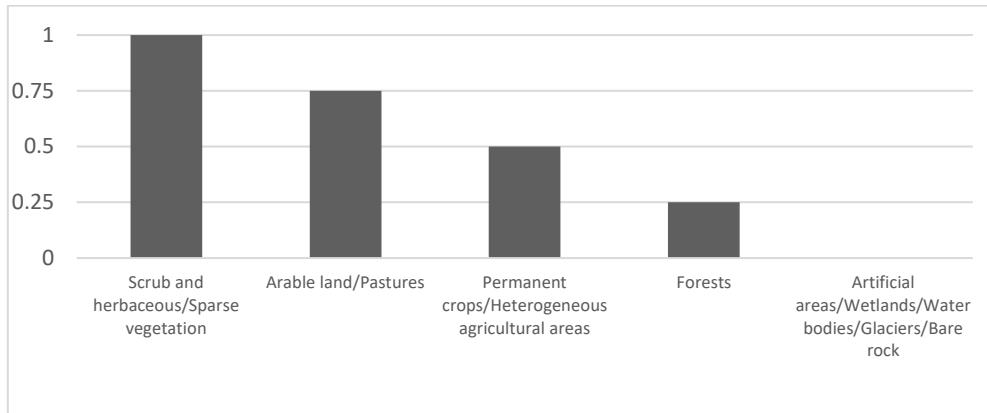
Figure 7: Land cover criterion

Soil texture

Soil texture gives indications on the amount of water that can infiltrate through the unsaturated zone to reach the aquifer. Soils with larger particle size will be the most suitable for surface infiltration as the infiltration rate increases with the particle size (Hillel, 1998). For this criterion, the parameters "dominant texture of the topsoil", "dominant texture of the subsoil" from the European Soil Database and the relation to the FAO classification (Figure 8) and associated infiltration rate are used to standardize the soil texture criterion, as shown in Figure 9.
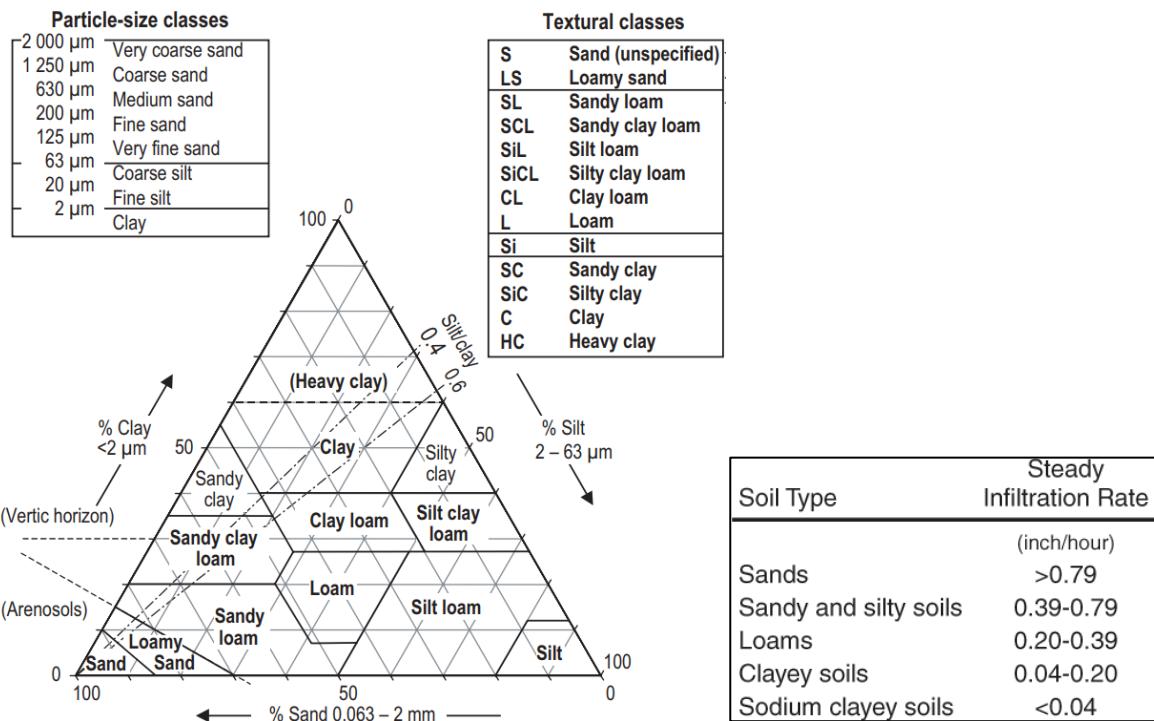
Figure 8 left: FAO soil texture classification (FAO, 2015); right: associated infiltration rates (Hittel, 1998)
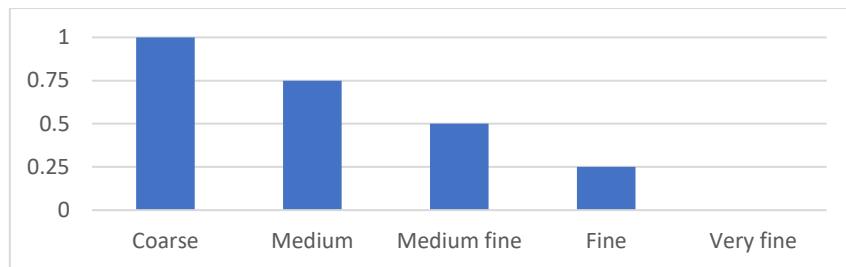
Figure 9: Soil texture criterion

The rank 'Unsuitable' was given to soils with no information on topsoil and/or subsoil texture (corresponding mostly to non-soils) as well as soils with very fine soil texture for topsoil and subsoil or only subsoils, as the top layer can be removed if not too thick. In cases of different texture between topsoil and subsoil, the finest soil texture was selected as it is a limiting factor. This is because the suitability for spreading methods will be optimal for coarse soils (maximal infiltration capacity) and low clay content (minimal risk of clogging in the infiltration layer).

Hydrogeology

Characterization of hydrogeology in Occitanie is obtained from the Hydrogeological map of France produced by SANDRE-BRGM[3], which divides France into hydrogeological entities. The database includes information related to the type, state, theme and medium of hydrogeological entity, which have been ranked in terms of MAR suitability in Figure 10 and combined with an equal weight.

➢ **Type of hydrogeological entity** (Figure 10a): the standardization of this criterion is quite straightforward as the most suitable situation for spreading methods is to have an aquifer underneath (referred to aquifer system/unit in the dataset for respectively regional/local level). The suitability is moderate when the hydrogeological entity underneath is of low productivity, (referred to in the dataset as hydrogeological domain/semi-permeable unit for respectively regional/local level). The area is unsuitable for spreading methods if underlined by an impermeable unit.

➢ **State of hydrogeological entity** (Figure 10b): the suitability for spreading methods is maximal in areas underlined by an unconfined aquifer, moderate when the underlining aquifer is a mix of confined/unconfined or alternating between unconfined and confined units (requires more in-depth studies) and minimal when the underlying aquifer is fully confined (or unknown).

➢ **Theme of hydrogeological entity** (Figure 10c): the suitability for spreading methods is considered maximal in alluvial aquifers as it is the most permeable and continuous medium for storing water, therefore will show more predictable behaviour than any other aquifer. Porous aquifers are also good environments for storing groundwater, however they are ranked with a lower suitability than alluvial as the grain size will have an important influence on the suitability. Bedrock aquifers have a potential to store groundwater in fracture networks, however the non-continuity of the fractures requires extensive study to predict the behaviour of groundwater, therefore are assigned a moderate suitability for spreading methods. Intensely folded mountainous and volcanic entities are assigned to the lowest suitability indexes as they are usually too complex to present a sufficient potential for groundwater storage.

➢ **Medium (type of porosity) of hydrogeological entity** (Figure 10d): the suitability for spreading methods is considered maximal in porous formations with or without fissured/fractured

---

[3] https://www.data.gouv.fr/fr/datasets/referentiel-hydrogeologique-francais-bdrhfv1/

matrix, as they will present the highest potential for groundwater storage. Fissured formations and formations with three levels of porosity are assigned to a moderate suitability as they might present a good potential of groundwater storage but require more in depth study. Finally, all karstic formations are considered to be the least suitable for spreading methods since the flow of groundwater is highly unpredictable in these formations.
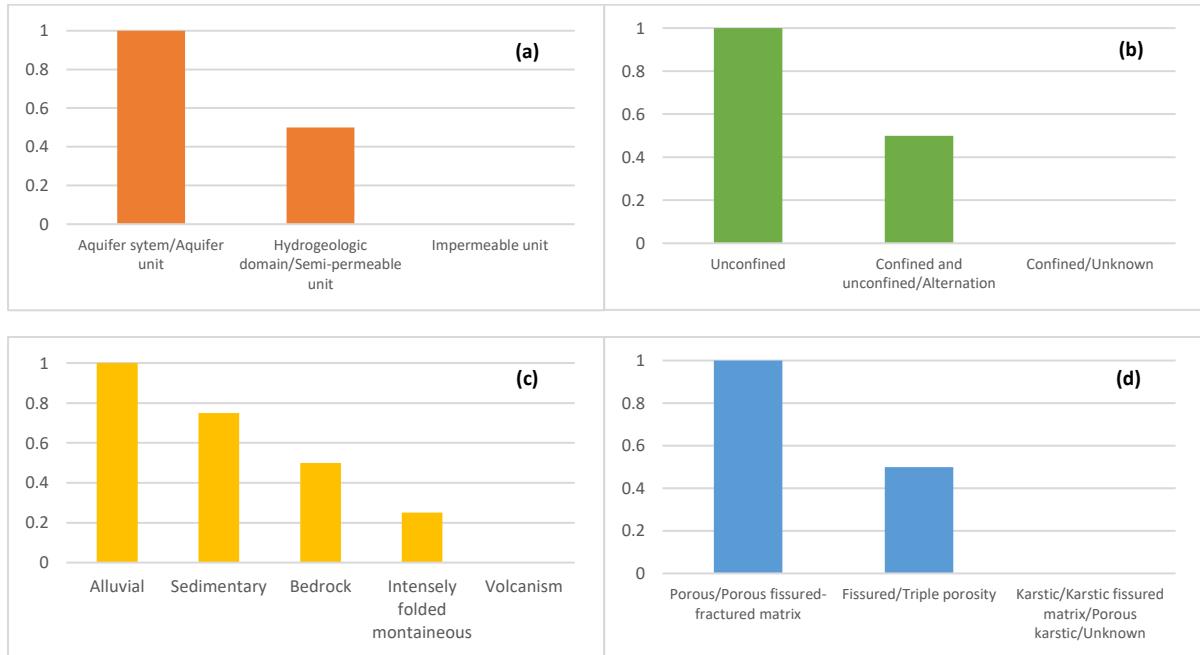

Figure 10: Hydrogeology criterion with type (a), state (b), theme (c) and medium (d) of hydrogeological entity

Distance to source water

One requirement to implement a MAR site for spreading methods is to have an excess of water available at a distance that is small enough to withdraw it in an economically viable way. For this study, the dataset 'Water bodies – Rivers' from data.gouv.fr was used, defined as "a distinct and significant part of surface water such as a river or a canal, part of a river or a canal". All the entities called 'streams' and 'rills' were removed as they might not give sufficient amounts of water for MAR. Other sources of water such as lakes or treated wastewater were not considered here as almost all MAR sites in France use river water.

This criterion is not easily quantifiable as it depends mostly on the budget available and the cost associated to the transfer of water from the river to the MAR site. For this study, a distance inferior to 1km away from the water source is considered optimal for MAR. The suitability decreases moving away from the water source until 5km, distance after which it is considered to be too costly to implement a MAR site for spreading methods. The standardized index for suitability mapping is defined as a step function, as depicted in Figure 11.
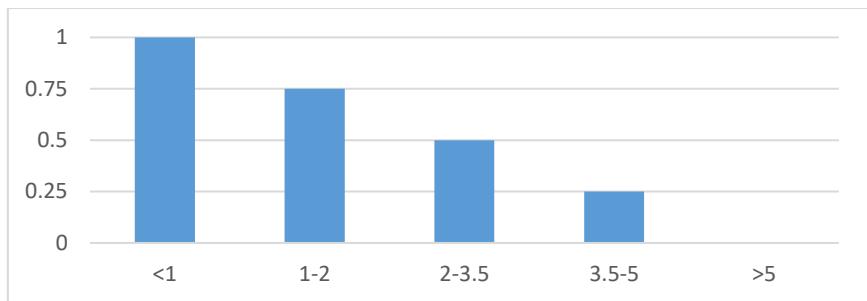
Figure 11: Distance to source water criterion (km)

Groundwater – Nitrates

High nitrates concentrations in water resources is a regular concern in Occitanie. For this reason, the vulnerability to nitrate contamination is considered as a criterion increasing the suitability for MAR spreading methods. The available map for this criterion, produced by the regional authority for environment and coastal planning (DREAL Occitanie[4]), considered as vulnerable each area where surface water and groundwater used for drinking water supply has been sampled with a nitrate concentration close to or above 50 mg/l and where surface water shows a tendency to eutrophication which could be efficiently prevented by reducing nitrogen input.

The resulting standardized index is a step function (Figure 12) in which vulnerable areas are considered highly suitable for the implementation of spreading methods sites in which the objective is to decrease nitrate concentration in surface water and groundwater. Within a 10 km radius outside of vulnerable areas, the implementation of spreading methods is considered to still have an interest to reduce nitrate loads. Areas beyond the 10 km buffer are no more considered as presenting an interest to decrease nitrate concentrations using MAR, however they could still present an interest in terms of quantitative groundwater recharge.
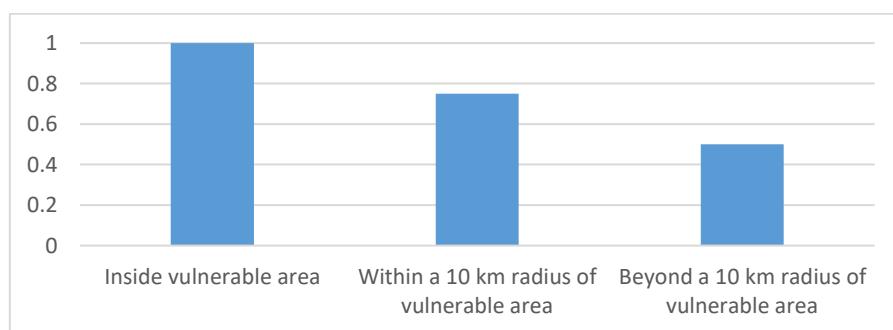
Figure 12: Groundwater - Nitrate criterion

4.1.1.5. Weight assignment

Weights need to be assigned to each criterion reflecting their relative importance within the set of criteria. Several methods exist to assign criteria weights, including the 'Pairwise comparison', developed by Saaty (1980) as part of the AHP.

Each criterion is compared one by one to every other criteria in a pair-wise comparison matrix (Table 5) in which a grade from 0 to 9 reflecting the importance of one criterion compared to the other (below 1, the criterion is judged less important than the other; 1 means that both are judged equally

---

[4] https://geo.data.gouv.fr/fr/datasets/11ba3cbd980e1f0307e089054a9f91548ec40912

important; from 2 to 9, the criterion is judged more important than the other) is assigned. Each score is then normalized and converted into relative weights (Figure 13).

This method resulted in 'slope', 'hydrogeology' and 'distance to water source' as the most important criteria, according to the following reasoning: spreading methods cannot be applied on steep slopes even if all other criteria are highly suitable as most of the water available will be lost by runoff. Hydrogeology was considered as important as slope for spreading methods as there must be a suitable aquifer to store water. Therefore, the criterion 'hydrogeology' resulted second most important. The criterion 'distance to source water' was ranked higher than 'soil texture' as the absence of an excess of water will be a limiting factor to MAR implementation, whereas low suitability for soil texture is depending on more parameters (clay fraction, thickness and depth of low permeability soil layer…). Finally, the criterion 'vulnerability to nitrate resulted in the lowest weight as it does not limit the suitability to implement a MAR site but only enhances it.

Table 5: Pairwise comparison matrix for suitability of MAR spreading methods in Occitanie

	Slope	Land cover	Soil texture	Hydro-geology	Distance to water source	Groundwater Nitrates
Slope	1.00	5.00	1.00	1.00	5.00	7.00
Land cover	0.20	1.00	0.33	0.20	0.25	5.00
Soil texture	1.00	3.00	1.00	0.33	0.20	3.00
Hydrogeology	1.00	5.00	3.00	1.00	1.00	7.00
Distance to water source	0.20	4.00	5.00	1.00	1.00	5.00
Groundwater-Nitrates	0.14	0.20	0.33	0.14	0.20	1.00
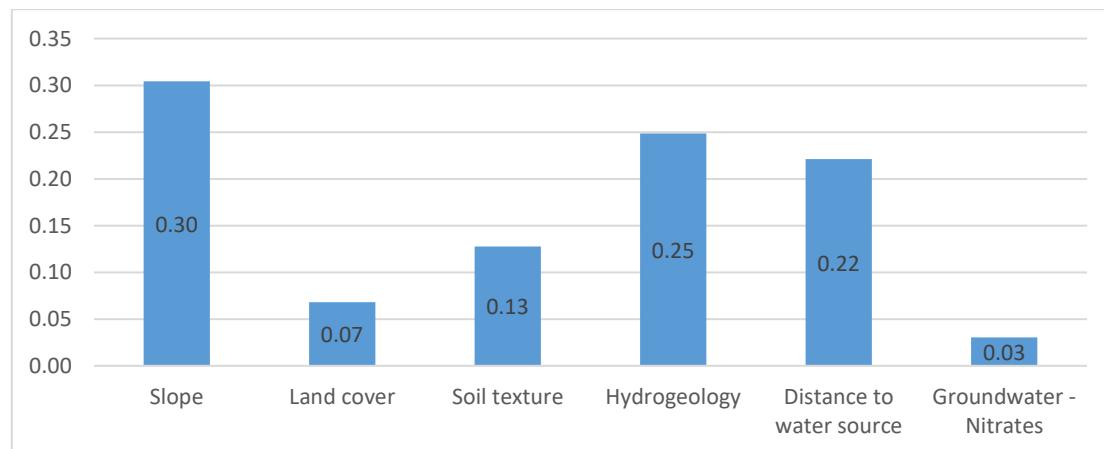
Figure 13: Resulting criteria weights

4.1.1.6.   Sensitivity analysis

In many studies of MAR suitability, the author performs an automated sensitivity analysis to the response of the model results to changing inputs. Accounting for the data uncertainty and the subjectivity in decision-making, analysing the sensitivity is a way to give indications of the trustworthiness of the methodology used and the robustness of the results. However, the uncertainty of the suitability map is initially acknowledged in this study as an inevitable element resulting in the definition itself of a GIS-MCDA (see 2.2) and the focus is put on the potential of using MARSSSI with a

map including uncertainty in its methodology design. For this reason, combined with time limitations, it was chosen not to include a proper sensitivity analysis in this study.

Instead, the reliability of the resulting maps is assessed by site validation, where the suitability index at the location of existing MAR sites is investigated. The map should predict a high suitability where a MAR site is already in place. However, this process should not be understood as a performance criterion as there is no site that allows verifying the other degrees of suitability of an area. Therefore, a map only showing high suitable areas cannot be considered reliable because it predicted the suitability at the locations of existing MAR sites well. This step must rather be understood as a way to reflect on the consistency of the results with what would be expected in reality.

4.1.2. MARSSSI

The suitability map for MAR spreading methods in Occitanie using a standardized index was realized using the method presented in Vasquez (2017). The 3 criteria used are terrain slope, hydrogeology and top soil texture. The suitability index also ranges from 0 to 1 (0; 0.25; 0.5; 0.75; 1) as the suitability increases.

The standardization of the MARSSSI 'Slope' criterion is based on Chowdhury et al. (2010) and Singh et al. (2013), as a simple continuous function with two breaking points at 5% (highest suitability) and 30% (lowest suitability), presented in Figure 14.
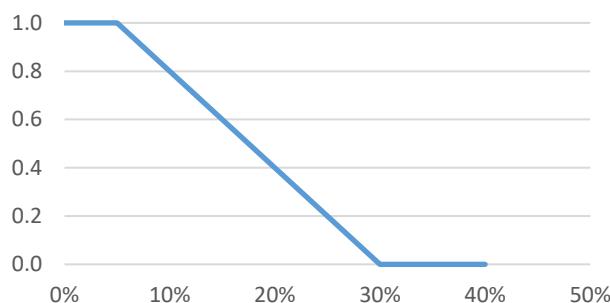

Figure 14: Slope criterion used for MARSSSI

The standardization of the MARSSSI "Hydrogeology" criterion is based on Kruseman and de Ridder (1994), classifying the main lithological types into 3 categories describing the hydrogeological potential and results in the standardization presented in Figure 15:

1) Aquifers – unconsolidated sand and gravels, permeable sedimentary rocks (limestone, sandstone), heavily fractured/weathered volcanic and crystalline rocks;
2) Aquitards – clays, loams, shales;
3) Aquicludes – unfractured igneous or metamorphic rocks.

This classification implies that in cases where more detailed geological maps are available, a reclassification should be performed prior to standardization.
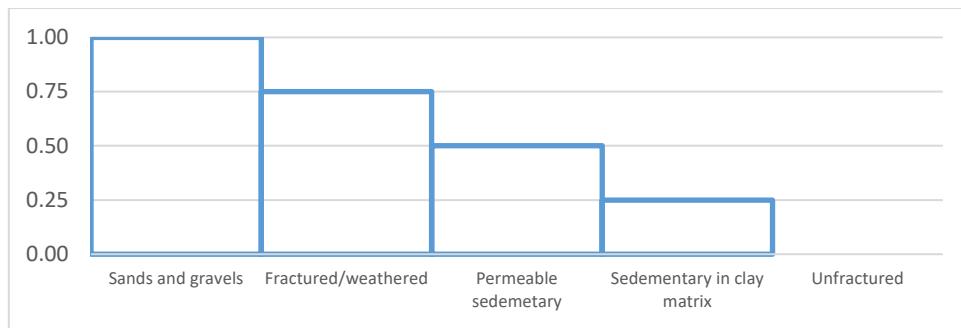
Figure 15: Hydrogeological context criterion used for MARSSSI

The standardization of the MARSSSI 'Soil texture' criterion is based on classification of the FAO (2014) differentiating soils as a function of their sand/silt/clay content and particle size, as showed in Figure 16 and resulting in the standardization presented in Figure 17.
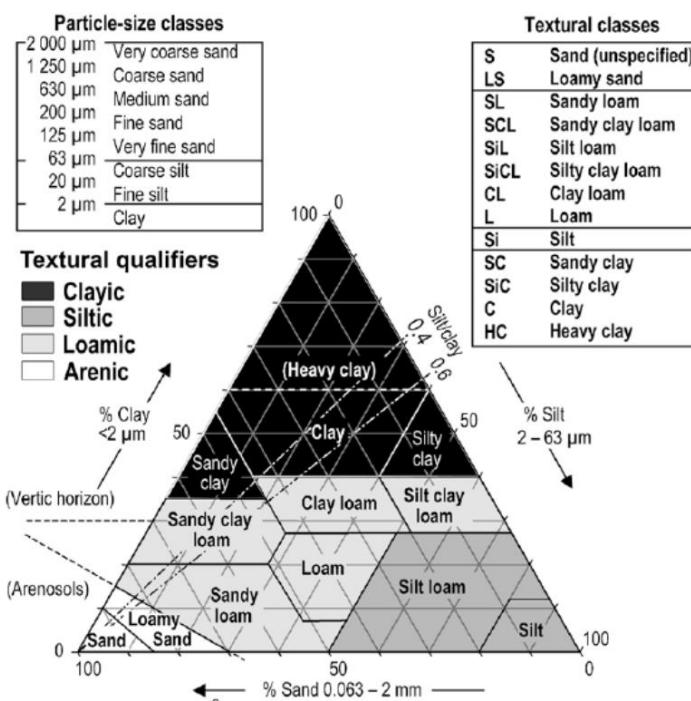
Figure 16: FAO classification of soil texture used in MARSSSI (FAO, 2014)
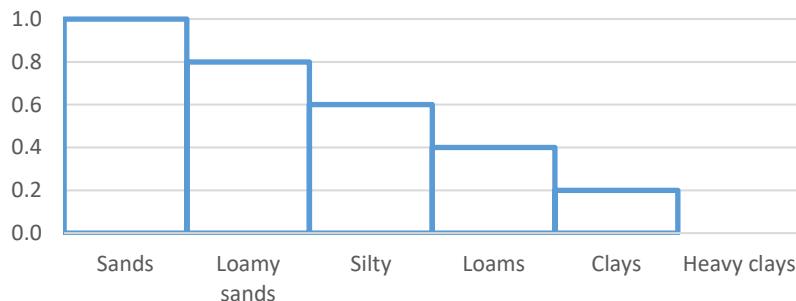
Figure 17: Topsoil texture criterion used for MARSSSI

The weights assigned to the three criteria have been determined using WLC. This resulted in the weights presented in Figure 18, with similar weights assigned to the three criteria. A slightly lower weight was assigned to soil texture as slope and geology were generally ranked higher in the reviewed studies.

23
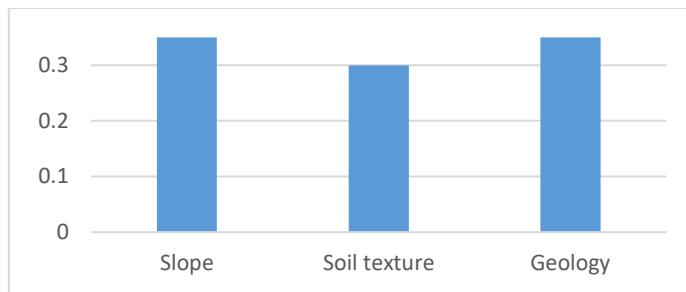
Figure 18: MARSSSI criteria weights

4.2.   Results

4.2.1. Suitability mapping

4.2.1.1.   Criteria maps
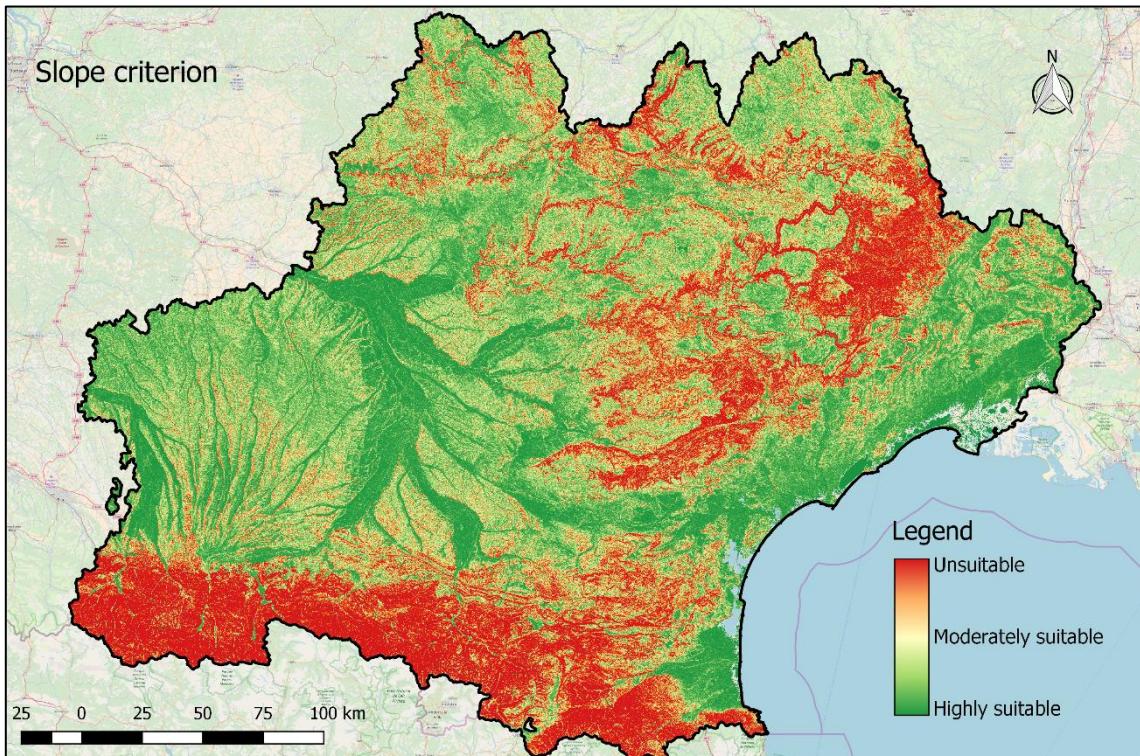
Figure 19: 'Slope' criterion map for MAR suitability in Occitanie
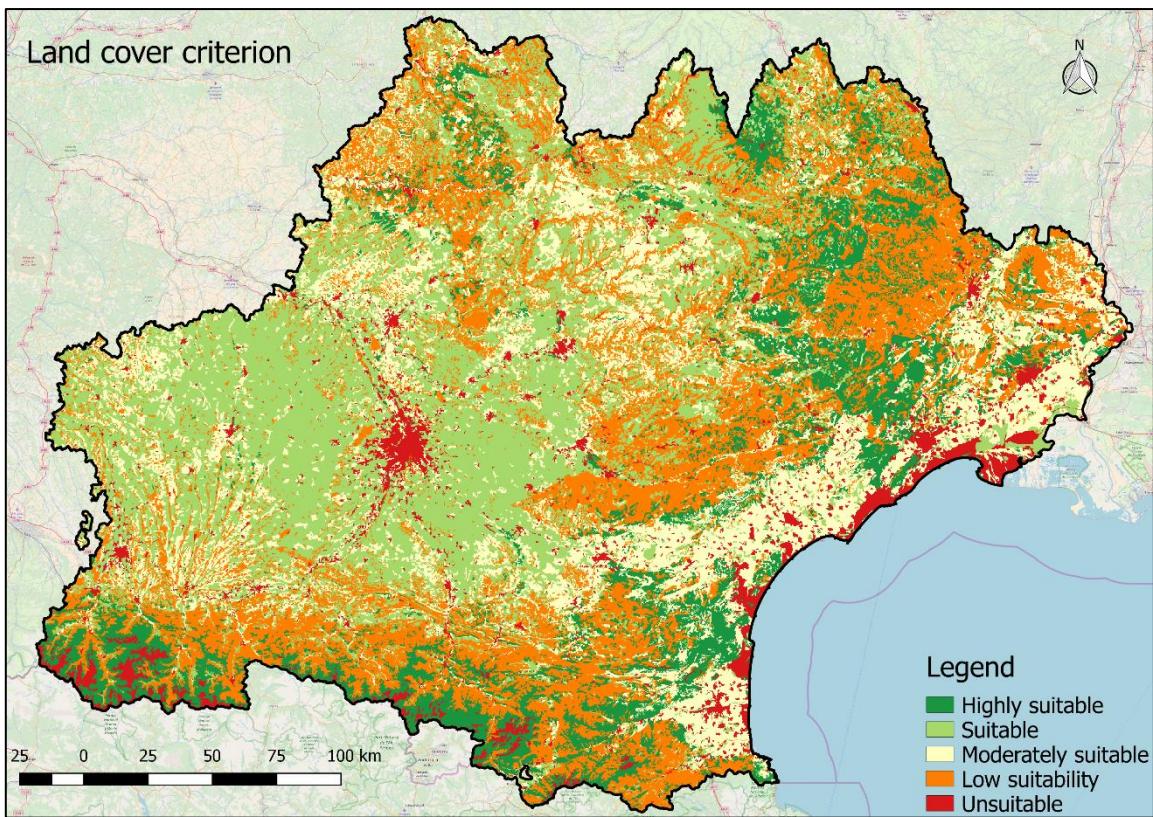
Figure 20: 'Land cover' criterion map for MAR suitability in Occitanie
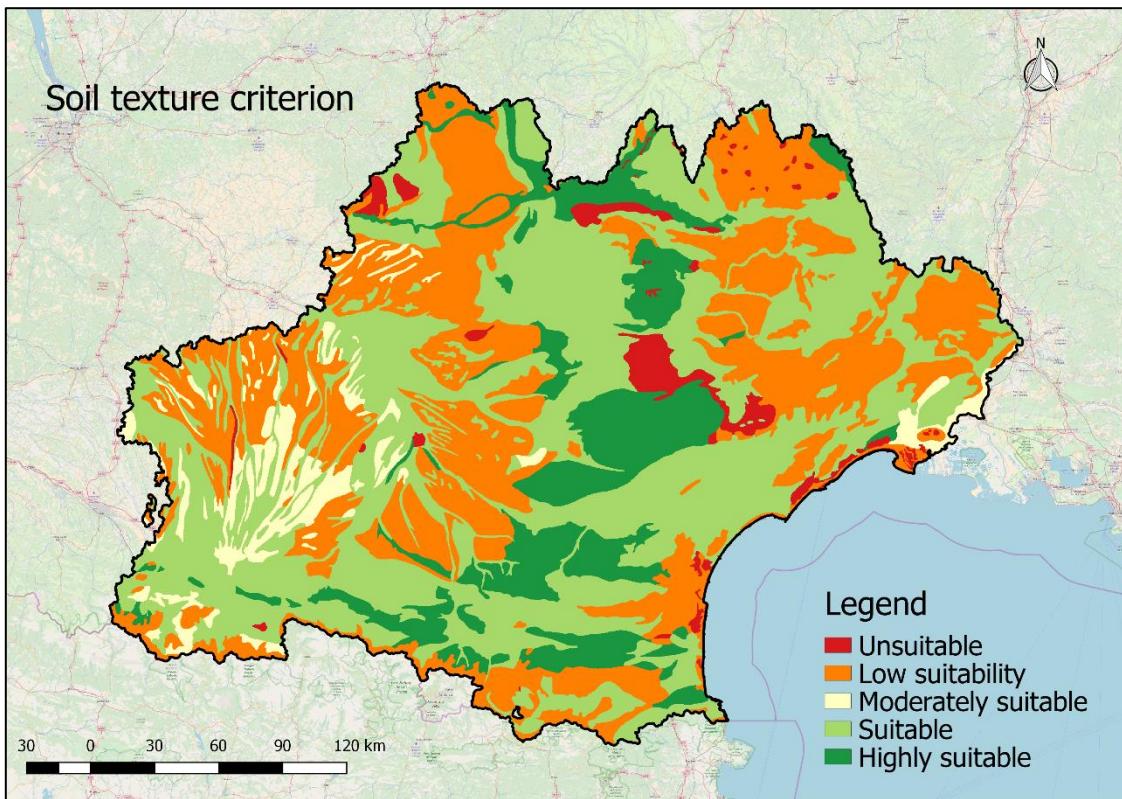
Figure 21: 'Soil texture' criterion map for MAR suitability in Occitanie
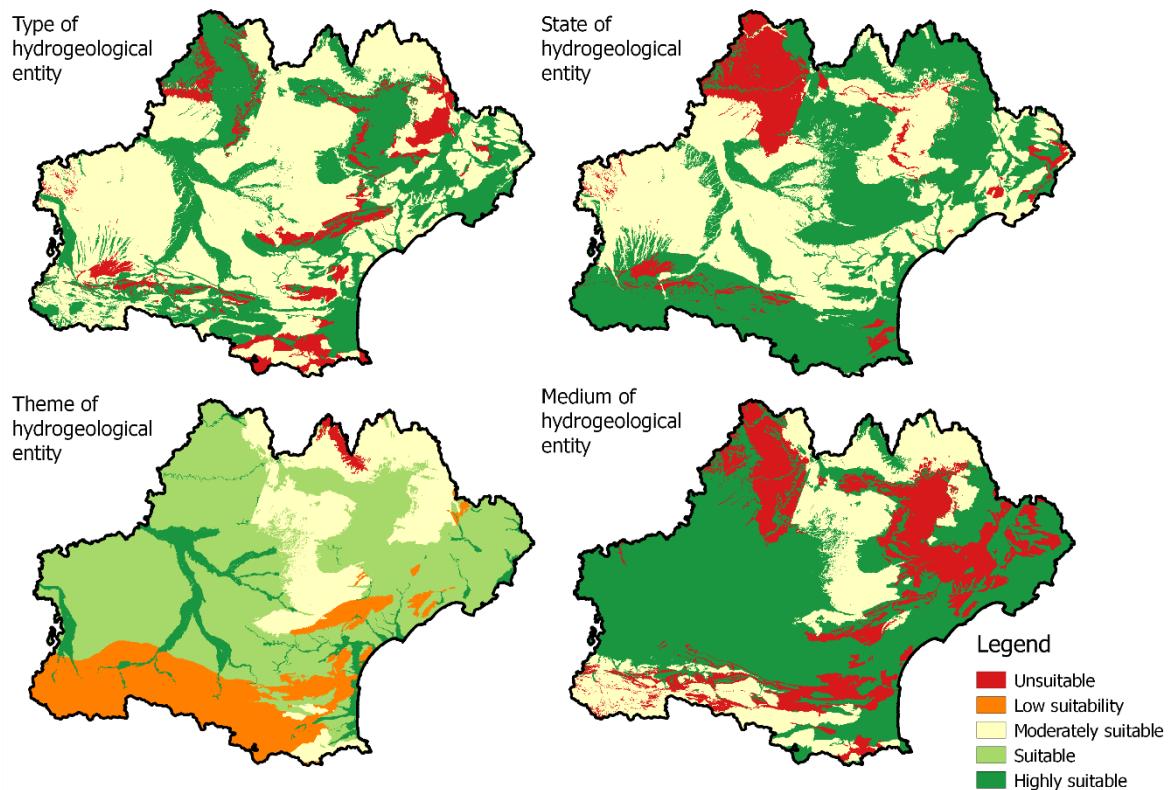
Figure 22: Sub-criteria maps for the 'Hydrogeology' criterion
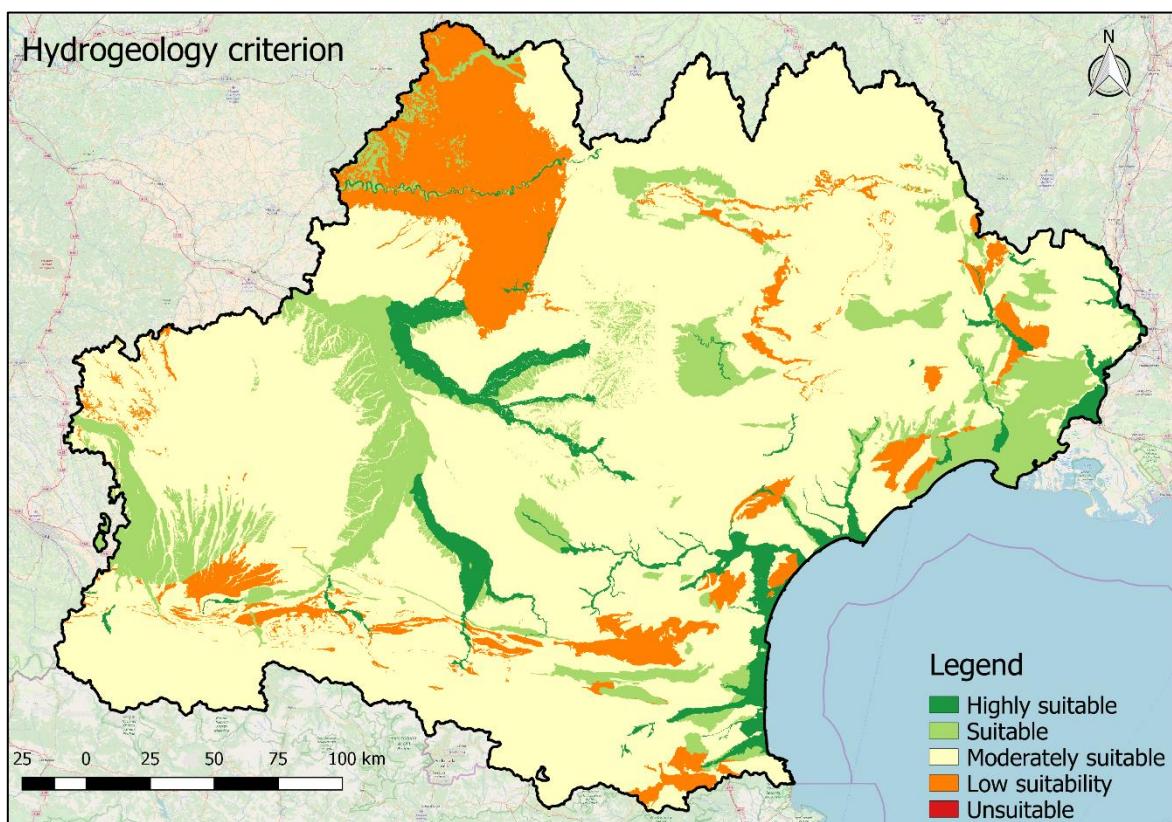
Figure 23: 'Hydrogeology' criterion map for MAR suitability in Occitanie
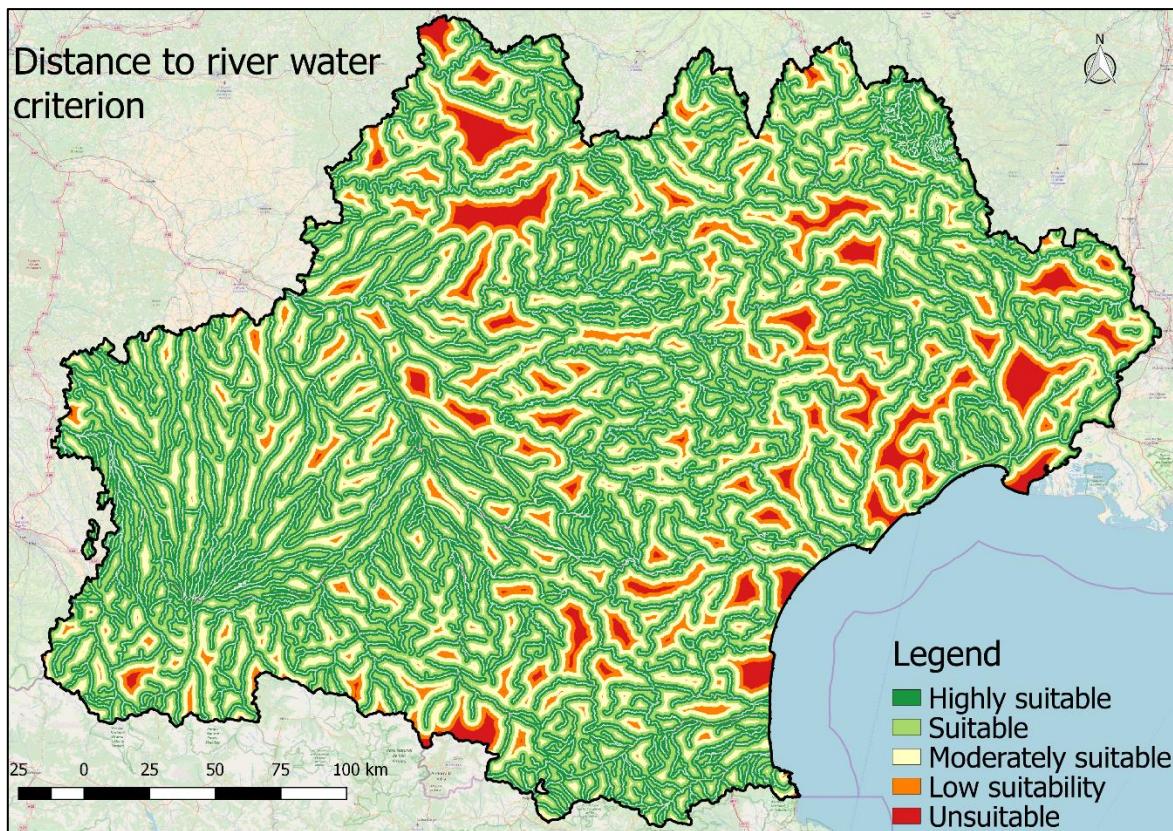
Figure 24: 'Distance to water source' criterion map for MAR suitability in Occitanie
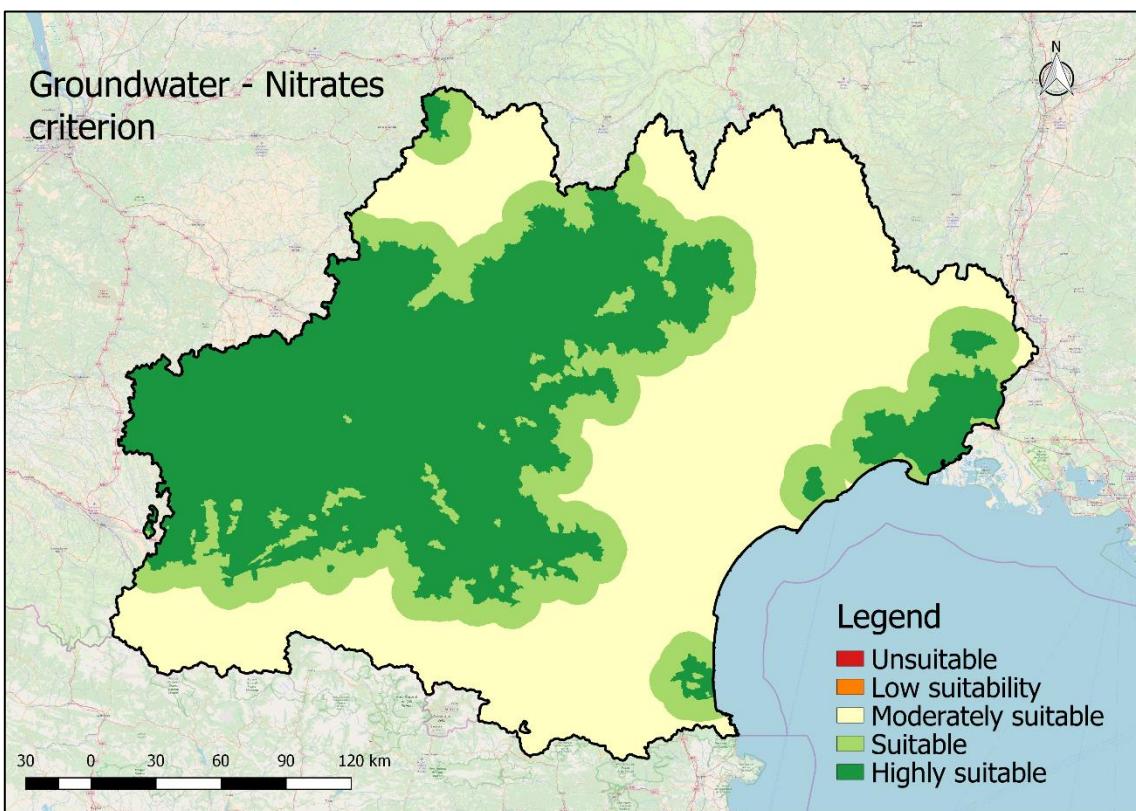
Figure 25: 'Groundwater - Nitrates' criterion map for MAR suitability in Occitanie

The 6 criteria maps are all converted to a raster format and combined using the weight presented in 4.1.1.5.
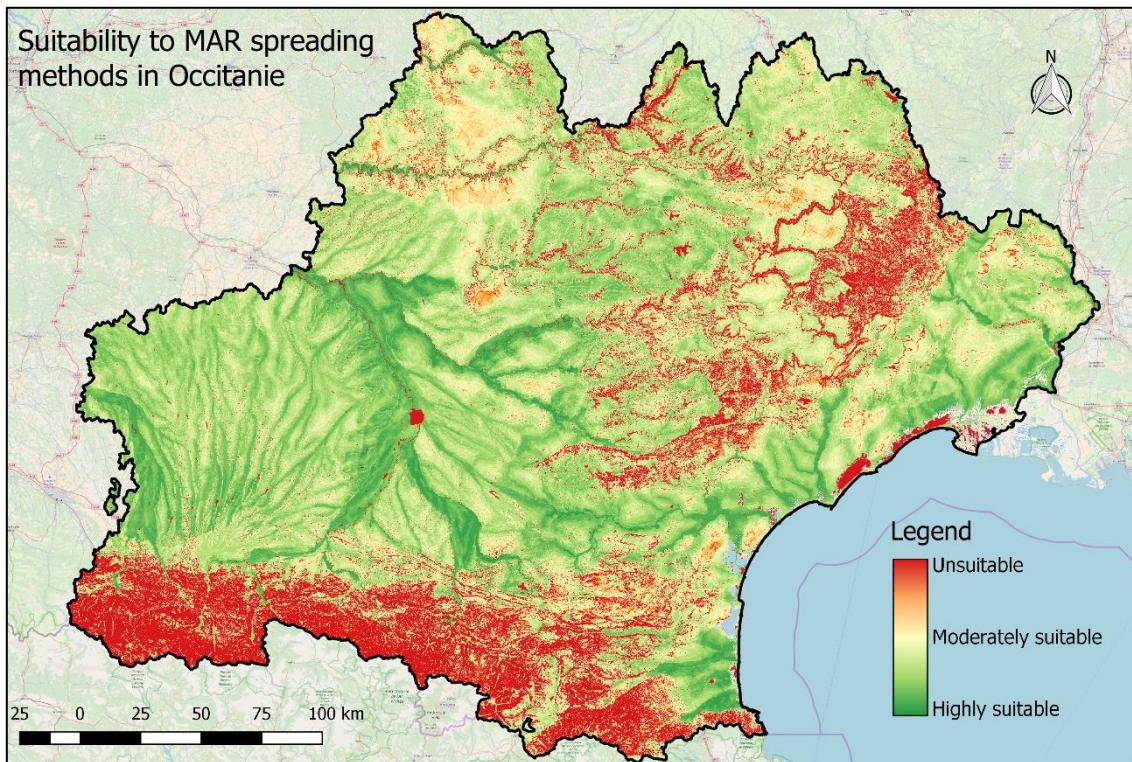
Figure 26: Suitability map for MAR spreading methods in Occitanie

The suitability map resulting from the GIS-MCDA (Figure 26) indicates that the highest suitability for MAR spreading methods in Occitanie covers the western part of the region, particularly around the Garonne River valley and on the Mediterranean coast. Unsuitable areas are mainly located in the Pyrenees and the Massif Central, reflecting the slope constraint for steep terrains. Areas of low suitability can be found in the northwest of the region, characterized by volcanic formations which resulted in a low index for the 'Hydrogeology' criterion. The small unsuitable area appearing in the centre of the map corresponds to the constraint 'non-soil' covering the dense urban area of Toulouse.

4.2.2. MARSSSI
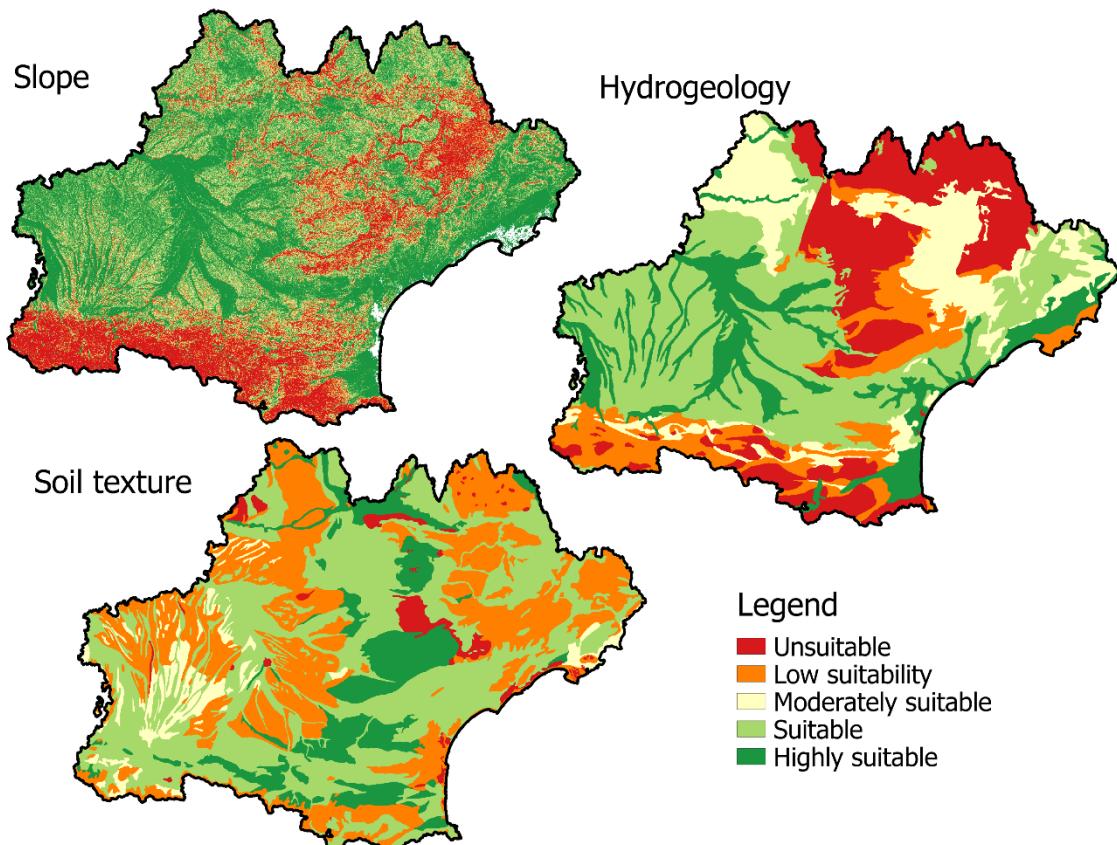
Figure 27: Criteria maps for MAR suitability in Occitanie using the standardized index
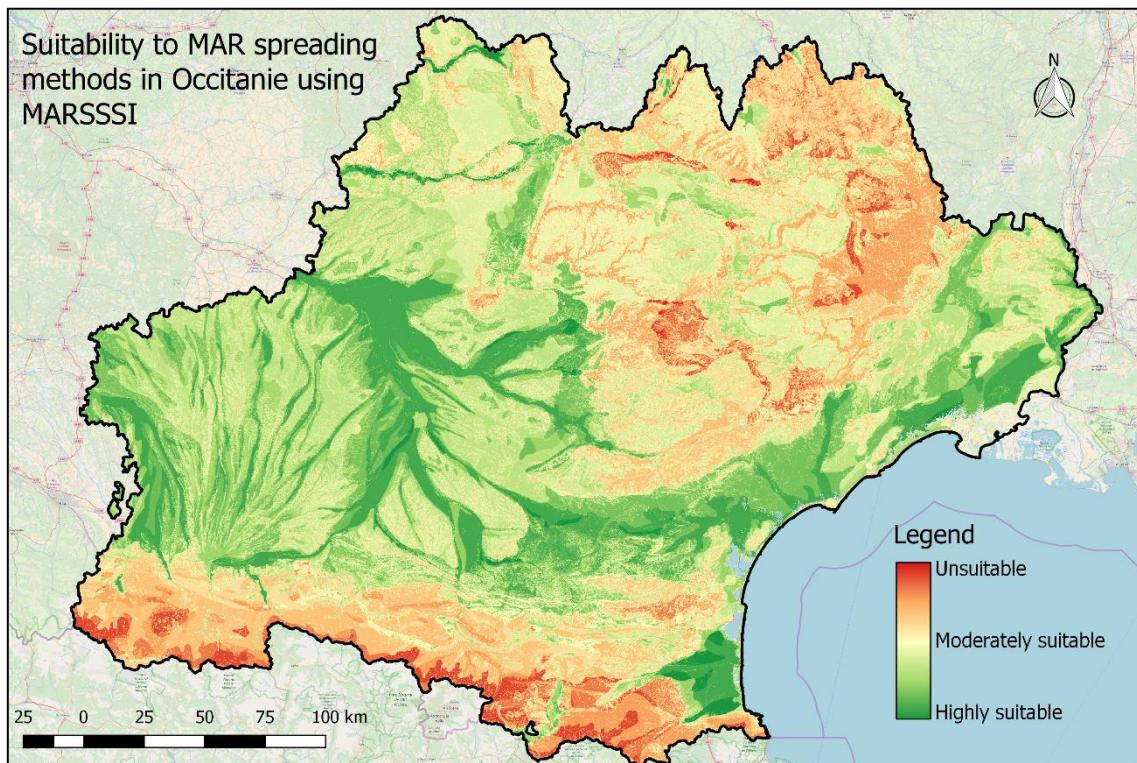
Figure 28: Suitability map for MAR spreading methods in Occitanie using the standardized index

The suitability map using the standardized method MARSSSI (Figure 29) indicates similarly to the original map that the highest suitability for MAR spreading methods in Occitanie covers the western part of the region, particularly around the Garonne River valley and on the Mediterranean coast. Low suitability areas cover mainly the Pyrenees and the Massif Central. In general, areas that were ranked 'unsuitable' in the original map are ranked 'Low suitability' on the map produced with MARSSSI.

4.2.3. Comparison and site validation

The comparison between the resulting suitability for the two maps is done by direct visual observation (Figure 29) and using the percentages of cover for each class of suitability (Figure 30). The major difference is related to the unsuitability class in the suitability map that appears with a higher suitability in the MARSSSI map, which can be explained by the absence of constraint criteria.
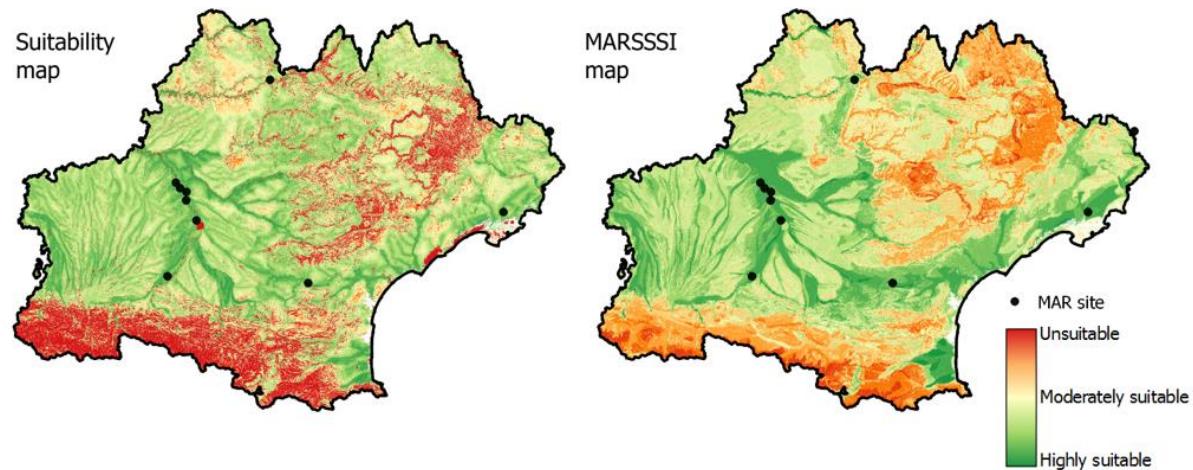
Figure 29: Location of MAR sites on the suitability and MARSSSI maps
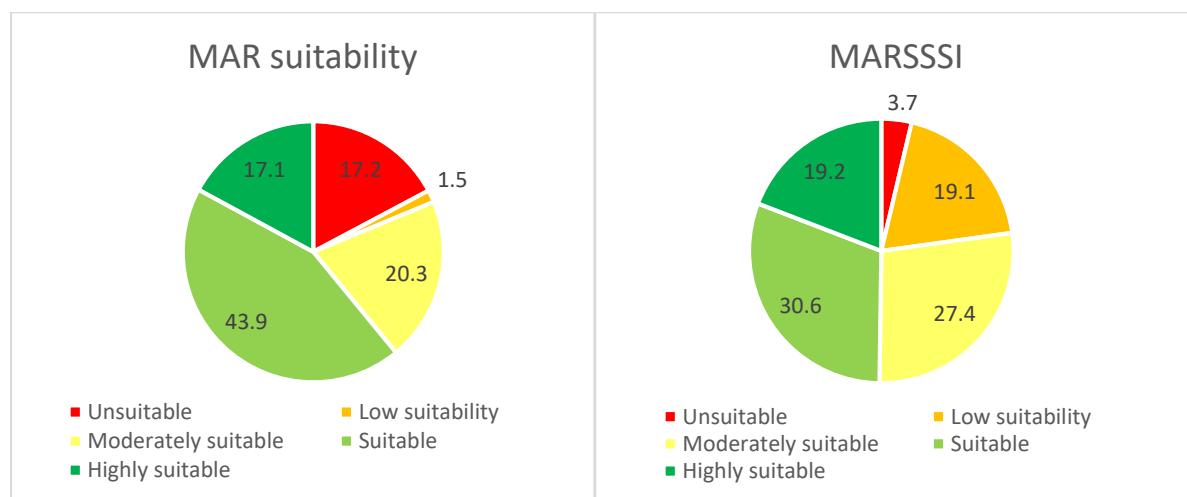
Figure 30: Percentage of cover for each suitability class

In order to assess the reliability of both maps, the resulting suitability at each MAR site location in the region was extracted (Table 6). It appears that both maps predicted a high suitability for the 6 sites using spreading methods. It could be argued from this fact that the additional criteria included in the original map do not add any value to the performance of the suitability map as both give equally good predictions. However, if both maps predict well the high suitability at existing sites, it does not give any indication of their ability to predict a site's unsuitability. One map could very well give too optimistic predictions of site suitability, therefore any potential MAR project should be preceded by more in-depths field investigations.

Table 6: Suitability index at MAR sites locations in Occitanie

Site name	Specific MAR method	Suitability map	MARSSSI
Blagnac	Infiltration Basins	**Highly suitable**	**Highly suitable**
Grenade	Infiltration Basins	**Highly suitable**	**Highly suitable**
Verdun-sur-Garonne	Infiltration Basins	**Highly suitable**	**Highly suitable**
Grisolles	Infiltration Basins	**Highly suitable**	**Highly suitable**
Mas-Grenier	Infiltration Basins	**Highly suitable**	**Highly suitable**
Lavelanet-de-Comminges	Infiltration Basins	**Highly suitable**	**Highly suitable**
Plaine de Millegrand	Infiltration Pit	**Highly suitable**	**Highly suitable**
Capdenac-Gare	Induced Bank Filtration	**Highly suitable**	**Highly suitable**
Vauvert	ASTR	**Suitable**	**Highly suitable**

By subtracting the pixel values from the suitability map produced using MARSSSI to the original map, the similarity between two maps can directly be observed (Figure 31). It appears that the maps show more similarity in the areas of high suitability in the Garonne River Valley and the coast. The suitability using MARSSSI appears much higher in the Pyrenees, where the original map used slope as constraint, which is a very important requirement for spreading methods. The suitability in the Massif Central is lower with MARSSSI than in the original map as the area was mostly ranked 'unsuitable' for the 'Hydrogeology' criterion, which also has a larger weight than in the original map.
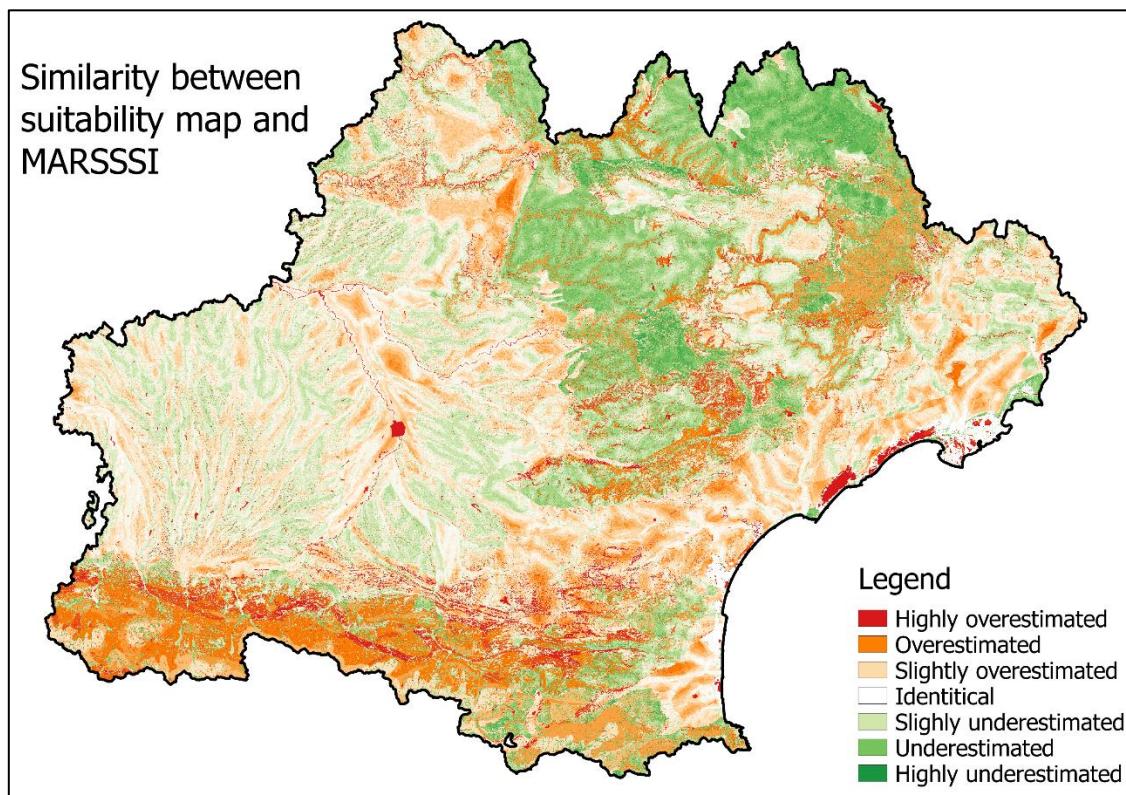
Figure 31: Map resulting from the subtraction of MARSSSI to the original suitability map; legend indicates the degree of similarity of MARSSSI compared to the original map

4.3. Discussion

The development of a suitability map for MAR in Occitanie was an opportunity to reflect on the process of suitability mapping in general and how to assess the reliability of a map. It appeared clearly that a suitability map needs to be adapted to the context of the study area, as well as data availability. Therefore, no uniform method for mapping MAR suitability could be developed without neglecting many important aspects. Accepting the necessary diversity of methodology, one important way of ensuring the reliability of a map is to show transparency in presenting the methodology. Other users should be able to understand exactly how the map was created and why certain choices were made.

One important difference between the original suitability map and the map produced with MARSSSI is the inclusion of constraint criteria, creating 'locked' unsuitable areas in certain circumstances, independent from the values of other criteria. The impact of constraint criteria is significant only in 'unsuitable' or 'low suitability' classes as their purpose is to restrict the suitability in certain conditions. The risk of using only a set factor criteria like in the methodology of MARSSSI is to overestimate the suitability in some areas presenting a feature restricting the implementation of MAR (such as a confined aquifer or impermeable soils) which would still be ranked with a good index of suitability if all the other criteria are ranked with a high suitability. On the other hand, the risk of using only a set of constraint criteria is to underestimate the suitability by excluding areas that could be highly suitable but appear as unsuitable due to the low resolution of one or several datasets used. Therefore, the decision made by the developer on the nature of the selected criteria have a large influence on the resulting suitability map.

One part of the objective of the suitability map in Occitanie was to identify potential areas to implement a MAR site aiming at reducing the nitrates load in water resources. However, the criterion related to nitrates vulnerability is only given a negligible weight of 3%, which has almost no influence on the final map. This resulted from the choice that was made to consider nitrates only as secondary in defining the site suitability to spreading methods. If the problem was defined differently so that the primary concern of water managers is to improve water quality by decreasing the nitrates concentrations using MAR, this criterion would have been given a more significant weight.

The case of the criterion 'Groundwater – Nitrates' illustrates an issue that was encountered for many of the criteria usually considered in studies of MAR suitability. Characterizing a criterion in terms of MAR suitability is difficult without knowing the scope of the potential MAR site, including concerns such as the budget, preferred source of water, desired volumes of water infiltrated, final use of water, regulations, etc. This is however not the case for the criteria included in MARSSSI, as they relate to the inherent suitability of a site to MAR spreading methods and are not dependant on time or scope of the MAR project. Other criteria such as land cover or source water can be considered equally important in defining the success of a MAR site, however only slope, hydrogeology and soil texture define the intrinsic suitability of a site to the use of spreading methods. As a result, the lack of clear objective at the initial stage of a MAR suitability analysis is a significant constraint to deal with most criteria without significantly increasing the subjectivity in the determination of criteria values and weights. The reliability of a suitability map including criteria that are related to a hypothetical MAR project is limited as it mainly reflects the developer's personal judgement, which can differ from the requirements of other users such as water authorities.

The most commonly used criteria for MAR suitability maps can be grouped into classes depending on which part of the problem they contribute to answer. For instance, MARSSSI focuses exclusively on the intrinsic properties of an area that will remain identical even if the study is repeated in a different country and in 100 years. These criteria (slope, hydrogeology and soil texture) define the primary

suitability of a site to enhance surface infiltration, independently from any concern of a potential MAR project. The other criteria will depend on the context and the current environment of the study area, which are subject to several constraints (budget, regulations…) that can be variable in time. From this observation, MARSSSI could be considered more as a primary level of mapping than a methodology to produce suitability maps.

This could appear clearly in the mapping methodology with a first level called 'Intrinsic suitability to MAR spreading methods' using the criteria and values of MARSSSI as a preliminary step to evaluate the potential of a site to enhanced surface infiltration. This stage would not require specific information on a potential MAR project and financial/legislative constraints. A second level of mapping could add information related to the source of water that would be used for a MAR project (river water, lake water, treated waste water...). Finally, a third level could include all the previous information to which criteria related to the constraints of a real project (distance to urban areas, distance to roads, water quality, infiltration and storage capacity...) can be added, resulting in a more reliable suitability map to MAR spreading methods.

More generally, the terminology used in the field of MAR suitability lacks clarity and uniform acceptance. An important task in future studies could be to provide clear definitions of the main terms involved in the development of a MAR project, some being suggested below:

➢ **Intrinsic MAR suitability**: suitability of a site to MAR defined by its intrinsic natural characteristics
➢ **MAR suitability**: suitability of a site to MAR according to specific requirements (objective, scale, and constraints) of the potential project to be implemented
➢ **MAR potential**: quantitative estimates of water volumes infiltrated, budget, water quality and infrastructure that would potentially be involved in a MAR project
➢ **MAR feasibility**: assessment of locations at which the implantation of a MAR site would be sustainable in terms of resources and capacities (land availability, desired source water, objective use of infiltrated water, water quality requirements, budget, infrastructures, regulations, site productivity…).

The case study of the Occitanie region gave promising results to add more understanding in the potential and limitations of using a standardization index for mapping the regional suitability to MAR spreading methods. The case study of the Occitanie region lead to the observation that suitability maps produced with no clear initial objective have a limited reliability. In these cases, only the criteria used in MARSSSI appear acceptable to reduce the subjectivity in the resulting map, to the condition that the term 'Intrinsic suitability' is clearly used to refer to the map. However, this index of intrinsic suitability is only applied to spreading methods, which are only one part of the possible MAR applications. The next step in this study is to apply a similar index to other techniques than spreading methods in order to assess the extent of MAR suitability in the Occitanie region.

4.4. Conclusion

The potential of MARSSSI to produce suitability maps for MAR spreading methods was assessed using the case study of the Occitanie region (South of France) in which a suitability map was developed for a hypothetical MAR project adapted to the context of the study area and compared to a map produced using the standardized index developed by INOWAS. The MARSSSI map gave good estimations of 'Highly suitable' and 'Suitable' areas from the original map. The similarity between the two maps decreased for lower suitability classes because of the constraints included in the suitability map. The limitations of suitability mapping are important when the analysis is performed without answering a clearly defined objective for a future MAR site, as most criteria require specific information on the scope of the project to be properly translated into MAR suitability. The criteria used in MARSSSI are the only ones that do not require a clear objective as they refer to intrinsic properties of the study area, defining the ability to infiltrate water from the surface and store it as groundwater.

From this observation, the term 'Standardized intrinsic suitability index for spreading methods (SISI-SM)' is suggested instead of MARSSSI and can be used to assess the intrinsic suitability to spreading methods, outside of the scope of a potential MAR project. To this state, this index is restricted to spreading methods but can be extended to other MAR techniques to assess the extent of MAR suitability in a study area.

5. Intrinsic suitability mapping for main MAR techniques

5.1. Method

MARSSSI showed a good ability to predict areas of high suitability using a standardized method based exclusively on intrinsic properties of the study area. This standardized index addresses the suitability for spreading methods, as this popular MAR technique can be characterized by surface datasets that are usually easily available. However, various other MAR techniques may also have a potential for application in the Occitanie region.

An index for intrinsic suitability similar to MARSSSI for spreading methods is applied for each class of MAR methods, described in 2.1.5. The suitability to one class of technique is assessed only from the natural intrinsic properties of an area, independently of the scope of a potential MAR project. This index measures the natural ability of the area to enhance aquifer recharge using a specific type of MAR techniques.

It was discussed in the previous section that the methodology used in the suitability map for spreading methods in Occitanie can overestimate the suitability in certain areas if one of the factor criterion has a low score but all the others have a high score. For example, an area covered by unfractured volcanic rocks can still obtain the rank 'Suitable' if all the other criteria have a high score. This can occur since the sub-criterion 'Medium of hydrogeological entity' was considered as a factor rather than a constraint. Moreover, the interest of a decision-maker will be focused on areas with high suitability to MAR and will likely discard all other areas regardless of the degree of suitability. For these reasons, the intrinsic suitability for a specific type of MAR method is expressed in this section as a Boolean statement rather than varying degrees of suitability. The risk becomes in this case to exclude areas that might still be suitable but appear unsuitable because of the low resolution of one or several datasets or because of a suitability index designed as too restrictive. For that reason, the terms 'Suitable' and 'Unsuitable', too restrictive, are replaced in this section by the terms 'Favourable' and 'Unfavourable'.

For each type of MAR methods, the criteria describing the intrinsic suitability are defined from literature (IGRAC, 2007; Dillon *et al.*, 2009; DEMEAU, 2014; INOWAS, 2018b) and characterized as a Boolean value (1 = favourable; 0 = unfavourable). The distinction is made between MAR techniques that are applied to a land surface (Table 7) and techniques of channel modification (Table 8), as they will result in two types of output features (respectively polygons and lines). Moreover, each method included in the type 'Channel modification' is applicable for a specific context, unlike the other types of MAR methods, requiring an individual index of intrinsic suitability for each of them.

The criteria are aggregated to obtain the Boolean suitability score S (1 = favourable; 0 = unfavourable) using a modified version of the formula presented in 2.2.3, in which only constraint criteria are considered:

$$S = \prod c_j$$

Where:
S is the composite suitability score
c_j is the value of the constraint factor j
$\prod$ is the product of constraint criteria (1 = favourable; 0 = unfavourable).

Table 7: Criteria defining the intrinsic suitability to types of MAR methods for lands

Type of method	Criteria	1 (Favourable)	0 (Unfavourable)
Spreading methods: Diffuse land infiltration	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined
	Soil permeability	Fully permeable: gravel, sand	Partially permeable to impermeable: silt, loam, clay
	Slope	≤ 5%	> 5%
Spreading methods: Localized land infiltration	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined
	Soil permeability	Permeable: gravel, sand, silt, loam	Impermeable: clay
	Slope	≤ 5%	> 5%
Well, shaft and borehole recharge	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
Induced bank filtration	River or lake surroundings	≤ 500 m away from lake or river	> 500 m away from lake or river
	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined
	Soil permeability	Permeable: gravel, sand, silt	Low permeability to impermeable: loam, clay
Rainwater harvesting	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined

Table 8: List of criteria defining the intrinsic suitability to methods of MAR Channel modification

| Method name	Criteria	1 (Favourable)	0 (Unfavourable)
Channel spreading	Natural drainage channel	Natural permanent channel	Artificial channel, intermittent stream
	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined
Recharge dam	Intermittent stream	Natural intermittent channel	Artificial channel, permanent stream
	Aquifer nature	Porous, alluvial	Fractured, fissured, karstic, impermeable formation
	Aquifer state	Unconfined	Semi-confined, confined
	Soil permeability	Permeable: gravel, sand, silt	Low permeability to impermeable: loam, clay
Sand dam	Intermittent stream	Natural intermittent channel	Artificial channel, permanent stream
	Aquifer state	Confined	Semi-confined, unconfined
Subsurface dam	Intermittent stream	Natural intermittent channel	Artificial channel, permanent stream
	Shallow bedrock	Magmatic or metamorphic formations	Sedimentary, alluvial

5.2.   Results
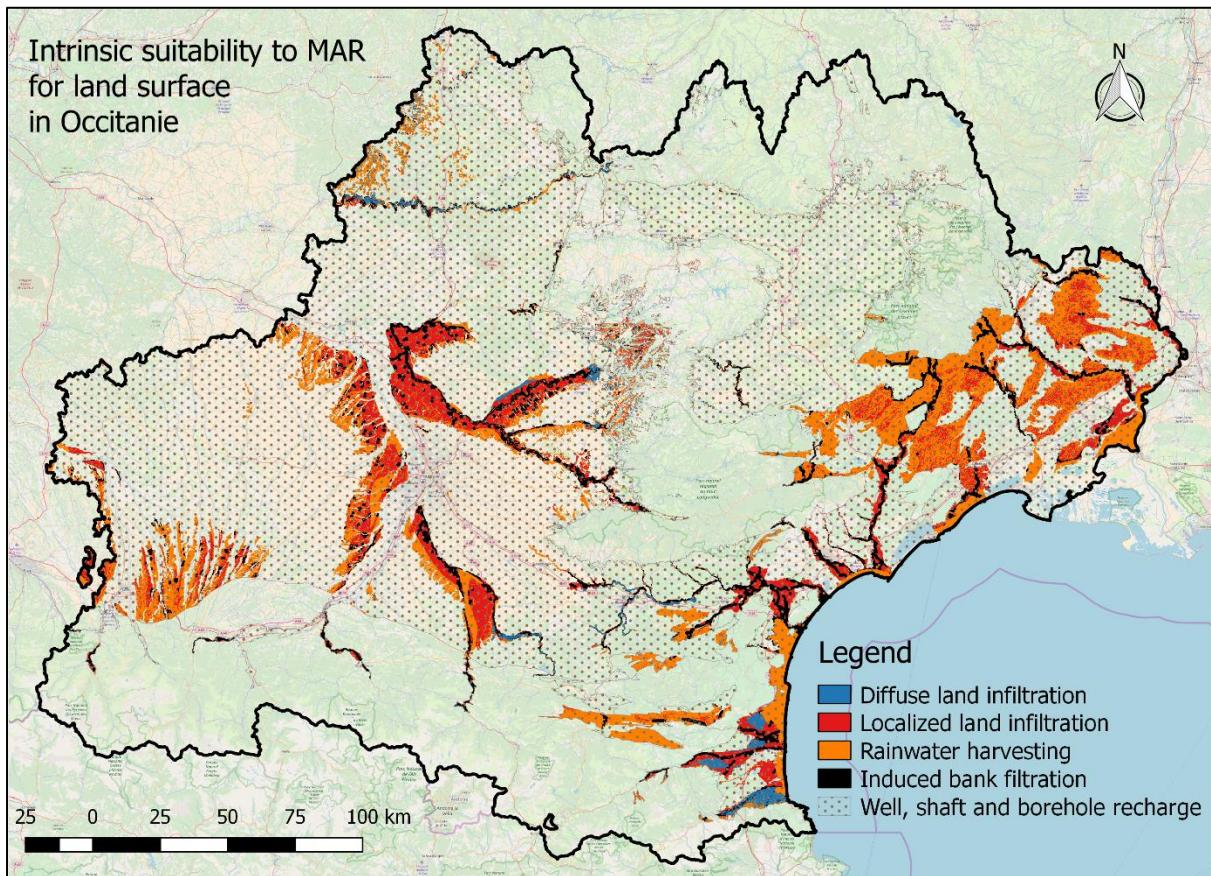
Figure 32: Result map of intrinsic suitability to MAR methods for land surface in Occitanie

The suitability map for techniques applied to land surface resulting from the methodology introduced in the previous section (5.1) is shown in Figure 32. It should be noted that the layers appearing in the legend from top to bottom are presented on top of each other on the map, as several layers cover a similar area, the maps presenting each layer individually are presented in Appendix C. The specific MAR type covering the largest favourable area is 'Well, shaft and borehole recharge', as it was considered applicable in terms of intrinsic suitability at the unique condition that a porous aquifer (alluvial or sedimentary) is present. The suitability for other types of MAR techniques becomes more restricted with more numerous and restrictive criteria. As a result, MAR types showing the highest potential of application in Occitanie based on intrinsic properties are 'Well, shaft and borehole recharge', 'Rainwater harvesting' and 'Localized land infiltration'.

In addition, it can be observed that the resulting favourable area for spreading methods ('Diffuse land infiltration' and 'Localized land infiltration') using a Boolean statement is more restricted than the area obtained when using varying degrees of suitability (Figure 26 and Figure 28). This can be observed especially with the exclusion of the areas located in the direct vicinity of the Garonne River, which results from the area being characterized by a mix of confined and unconfined aquifer units, setting the criterion 'Aquifer state' (Table 7) as 'Unfavourable. However, despite the high requirements of the methodology used to obtain a 'Favourable' area, this figure shows the wide potential of application of other MAR techniques on land surface, underlining the interest of not limiting a suitability analysis to spreading methods only.
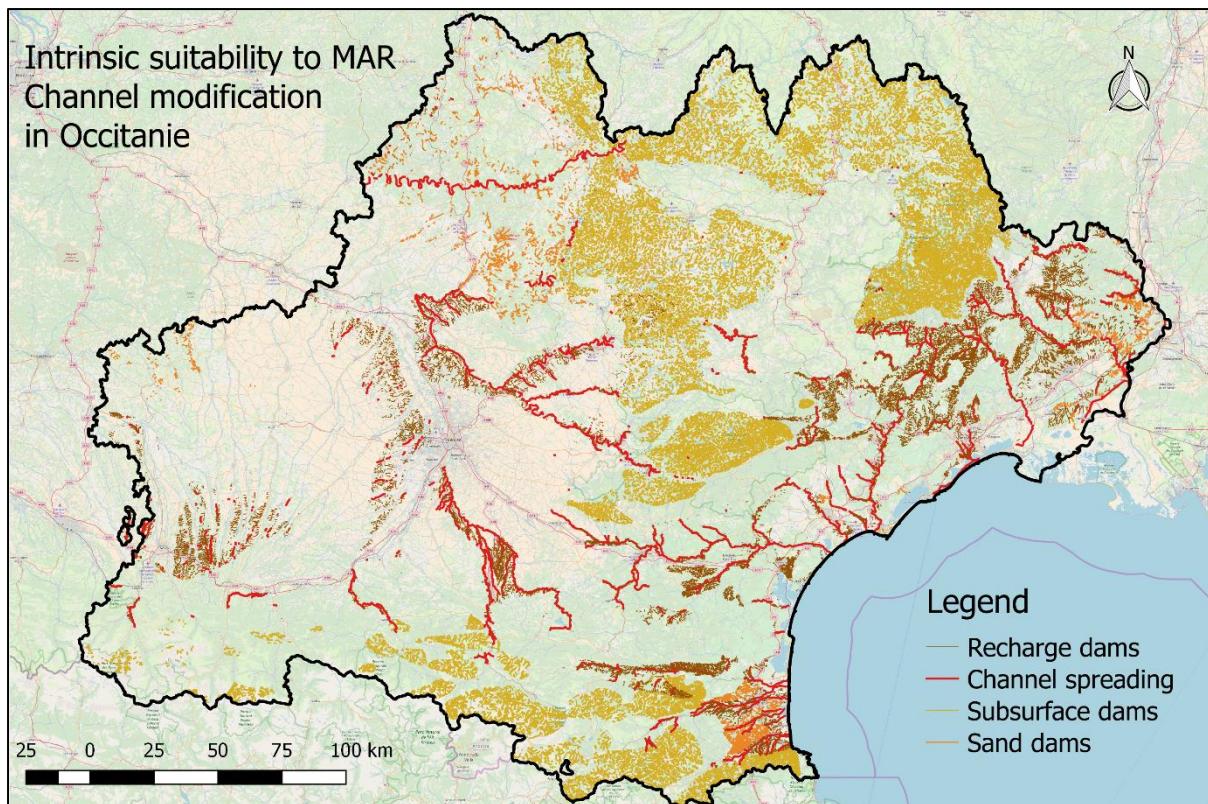
Figure 33: Result map of intrinsic suitability to MAR methods for channel modification

The suitability map for techniques involving channel modification resulting from the methodology introduced in the previous section (5.1) is shown in Figure 33. The map shows the wider potential of channel modification to enhance aquifer recharge compared to land surface methods, as possible applications include permanent as well as ephemeral streams, confined and unconfined aquifers and in environments characterised by sedimentary deposits as well as bedrock formations.

In the case of the MAR types 'Channel spreading' and 'Recharge dams', the requirement to have an unconfined porous aquifer to infiltrate water results in favourable areas covering similar locations than land surface techniques. The potential of application of 'Sand dams' and 'Subsurface dams' presents the interest to cover areas in which most MAR techniques are not applicable, for instance in mountainous areas like the Pyrenees and the Massif Central. These two types of MAR techniques, applied exclusively to ephemeral streams to collect storm water runoff, can provide ways to locally store water for dry periods.

For more visual representation, the results from Figure 32 and Figure 33 were combined to observe how many MAR methods presented a potential for application based on intrinsic properties at each location in Occitanie.
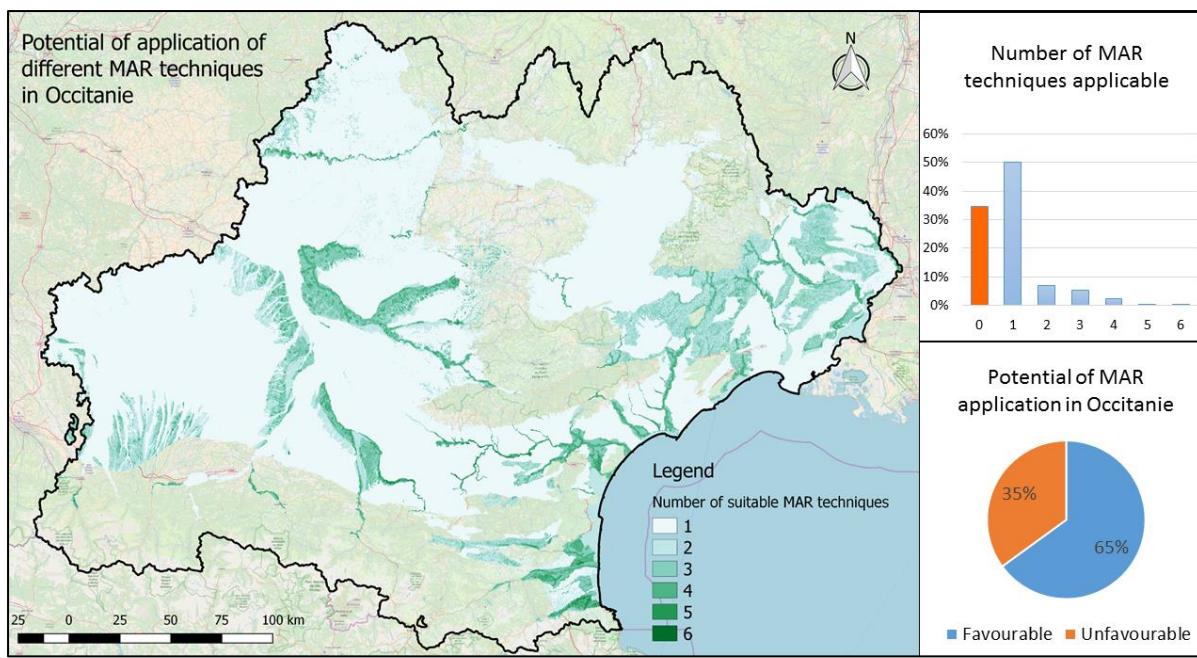
Figure 34 Result map showing the number of applicable MAR techniques in Occitanie (left) with the percentage of region cover corresponding to each class (top right) and the pie chart showing the percentage of region cover where the application of any MAR method

Figure 34 shows that some locations are favourable to up to 6 MAR applications out of the 9 types of methods investigated. Only 35% of the region cover was ranked as not favourable to any type of MAR method, 50% of the region cover being favourable to one MAR application, mainly 'Well, shaft and borehole recharge' as this type was the least restrictive in terms of intrinsic suitability, therefore resulting in the largest coverage. This shows that in a region presenting a great diversity of geomorphology and landscape like the Occitanie, MAR could potentially be successfully applied in more than half of the area in terms of intrinsic properties.

5.3. Discussion

The application of an 'Standardized intrinsic suitability index for spreading methods (SISI-SM)' to the main types of MAR techniques available showed the broad range of suitability offered by MAR in Occitanie, which is generally restricted in studies to only one type of techniques such as spreading methods. The methodology used is more restrictive than in chapter 4.1 as no varying degrees of suitability are considered by using exclusively constraint criteria in order to optimize the application of an index to 9 types of MAR techniques. Despite these restrictions, the results showed that 65% of the region cover is ranked favourable for at least one type of MAR method, with some areas being favourable to up to 6 types of methods, showing a wider potential of application than when only considering spreading methods.

The simplification of the methodology by using a Boolean statement instead of varying degrees of gave different results for spreading methods. Indeed, some areas considered as highly suitable using MARSSSI are excluded using this methodology of intrinsic suitability mapping (*e.g.* direct vicinity of the Garonne River). This observation emphasizes the variability that exists in the field of suitability mapping, where changes in the methodology design can lead to major differences in results.

Even though the suggested index only assesses the suitability to MAR based on intrinsic properties, it shows that in a region comprising two mountain ranges and a high variability of geomorphology, 65% of the area is potentially suitable to at least one MAR technique. This is the first time that a simple methodology using easily available data is suggested to spatially represent the full potential of MAR

on a regional scale. This visual representation can contribute to encourage decision-makers to consider MAR more often in their water management plans by showing the wide application potential of various techniques. The case study of the Occitanie highlights that the suitability for MAR should not be restricted to one particular technique such as spreading methods, as it appeared that the wide range of possible MAR schemes offers the possibility to apply at least one technique in 65% of the region.

5.4.   Conclusion

This section suggested a simple methodology to assess the suitability to different types of MAR techniques almost only based on intrinsic properties of the study area. The chosen methodology differs from MARSSSI by the use of a Boolean statement instead of varying degrees of suitability, which caused differences in the resulting suitable area for spreading methods in the new map. This variability of results emphasizes the high variability existing in the domain of suitability mapping due to the choice of methodology based on the developer's personal judgement.

The resulting maps showed the broad potential of application of various MAR schemes in the Occitanie region, despite the use of a restrictive methodology in a study area where obvious limits to MAR suitability (two mountain ranges; high variability of geomorphology) are observed. Showing that MAR could be applied in 65% of the study area, the map underlines that including several types of MAR method has more value when assessing the regional suitability to MAR than most studies only considering one type of methods. This simple methodology could be used in the future as an efficient visual tool to raise awareness on the wide applicability of MAR and encourage water authorities to consider MAR more often for water resources management strategies.

6. Main findings on MAR suitability mapping

The work performed during this 4-months internship at IGRAC lead to an extensive reflexion on regional mapping of MAR suitability and its future potential to advocate MAR as a promising adaptation measure to increase the availability of freshwater and resilience to climate change. The main findings that resulted from the assessment of the potential of MARSSSI as a tool to produce MAR suitability maps using a unified method are summarized below:

- **MARSSSI uses criteria related to intrinsic properties of the study area which play a major role in the preliminary assessment of MAR suitability**

The criteria used in MARSSSI are slope, hydrogeology and soil texture, which have the advantage to play a major role in defining the suitability of the study area to the use of spreading methods, independently from specific requirements for implementing a MAR site. These criteria are related to intrinsic properties defining the ability of water to infiltrate from the surface and be stored as groundwater into an underlying unconfined aquifer. Without surprise, these criteria have been considered by most of previous spreading methods suitability mapping studies.

- **MARSSSI can produce overestimations of intrinsic suitability to spreading methods.**

MARSSSI does not use constraint criteria in its methodology design. It means that an area with no underlying aquifer or with an underlying confined aquifer can result in a suitability index up to 65% (suitable area) if the soil is highly permeable and the terrain is flat.

- **MAR suitability maps cannot be validated with existing MAR sites**

Given the high subjectivity of MAR suitability maps produced so far, some authors have used the presence of exiting MAR sites to try to validate their maps. They assumed that suitability maps can be validated if they indicate a good or high suitability near existing MAR sites. However, a good suitability map must highlight the suitable zones but also the unsuitable ones. We could imagine a map that predicts a high suitability everywhere. Such map would indicate a high suitability near existing MAR sites and therefore be validated, following the reasoning above. This example clearly shows that existing MAR sites can be used to confront MAR suitability maps but cannot be used as a validation process.

- **MARSSSI should be called differently to acknowledge the fact that it assesses the intrinsic suitability for spreading methods**

MARSSSI stands for MAR Site Selection Standardized Index. Due to the limited number of criteria (Soil – Hydrogeology – Slope), it is highly unlikely that a MAR site will be selected on this sole basis. The 3 criteria only give an idea of the intrinsic suitability of a region to spreading methods. This index must be understood as a preliminary step to locate potentially suitable areas where more in-depth studies could be considered in view of the implementation of a MAR site using spreading methods. It is also misleading to refer to MAR while the method only investigated the suitability to spreading methods, a subgroup of MAR techniques. Instead of MARSSSI, another name could be found that is more explicit as of the use of the method. Something like 'Standardized intrinsic suitability index for spreading methods (SISI-SM)' is considered a more adequate term.

- **A simple index is developed to identify the intrinsic suitability of a region to the main MAR techniques, not only spreading methods.**

Most studies refer to 'MAR suitability' when in reality they restrict their analysis to one type of techniques such as spreading methods, which might lead to a confusion for users and to a significant underestimation of the potential of MAR as a whole on a regional scale such as in Occitanie. The 'Intrinsic suitability index' discussed earlier was adapted to the main types of MAR techniques available. It is based on 8 easily available criteria and makes use of constraints to limit the risk of overestimating intrinsic suitability.

- **This new index can be used as an efficient visual tool to promote MAR to decision-makers**

The new index is applied over the Occitanie region. Despite a more restrictive methodology and a study area presenting two mountain ranges and a high variability of geomorphology, 65% of the region was ranked potentially suitable to at least one MAR technique. This methodology underlines that MAR offers a wide potential of application, therefore should not be restricted to one specific type of methods. Even if this index must be understood as a preliminary step before more in-depth investigations, it could be used as an efficient visual tool to raise awareness on the wide applicability of MAR. The application of the intrinsic suitability index to semi-arid regions where there is a need to secure water resources for the dry season would contribute to encourage water authorities to consider MAR more often for water resources management strategies.

References

Casanova J., Cagnimel M., Devau N., Pettenati M., Stollsteiner P., 2013. Recharge artificielle des eaux souterraines : état de l'art et perspectives. BRGM. 227 p.

Chowdhury A., Jha M.K., Chowdary V.M., 2010. Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. Environmental Earth Sciences; Vol. 59; p. 1209-1222

Department of Water Affairs (DWA), 2010. Strategy and Guideline Development for National Groundwater Planning Requirements. Water Banking: A practical guide to using Artificial Groundwater Recharge. 26 p.

Dillon P., Pavelic P., Page D., Beringen H., Ward J., 2009. Managed Aquifer Recharge: An Introduction. Australian Government: National Water Commission; 76 p.

Dillon P., Toze S., Page J., Vanderzalm J., Bekele E., Sidhu J., Rinck-Pfeiffer S., 2010. Managed aquifer recharge: rediscovering nature as a leading edge technology. Water Science and Technology; Vol. 62; No. 10; 9 p.

Eastman J. R., Jin W. G., Kyem P., Toledano J., 1995. Raster procedures for multicriteria multiobjective decisions. Photogrammetric Engineering and Remote Sensing, 61(5), 539–547.

Eastman J.R., 2005. Multi-criteria evaluation and GIS. *In*: New Developments in Geographical Information Systems: Principles, Techniques, Management and Applications; Vol. 1; Chapter 35; p. 493-502

Estoque R.C., 2011. GIS-based Multi-Criteria Decision Analysis in Natural Resource Management. University of Tsubuka, Division of Spatial Information Science. 24 p.

Gale, 2005. Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas. UNESCO IHP. 33 p.

Greene R., Devillers R., Luther J.E., Eddy B.G., 2011. GIS-Based Multiple-Criteria Decision Analysis. Geography Compass; Vol. 5; p. 412-432

Hannapel S., Scheibler F., Huber A., Sprenger C., 2014. Recommendations for further data generation. EU Project 'Demonstration of promising technologies to address emerging pollutants in water and waste water' (DEMEAU). 36 p.

Hillel D., 1998. Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations. Academic Press, Waltham. 771 p.

INOWAS, 2018a. Managed Aquifer Recharge: Definitions, methodologies, objectives and benefits of managed aquifer recharge. TU Dresden. Accessed 06/09/2018. < https://inowas.hydro.tu-dresden.de/managed-aquifer-recharge/>

INOWAS, 2018b. Database for GIS-based Suitability Mapping. TU Dresden. Accessed 06/09/2018. < https://inowas.hydro.tu-dresden.de/tools/t04a-database-for-gis-based-suitability-mapping/>

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Keeney, R. L., 1992. Value-focused thinking: A path to creative decision making. Cambridge: Harvard University Press.

Keller A., Sakthivadivel R., Seckler D., 2000. Water scarcity and the role of storage in development. Colombo Sri Lanka: International Water Management Institute (IWMI), vii, 20p. (Research report 39)

Kruseman G.P., de Ridder N.A., 1994. Analysis and Evaluation of Pumping Test Data, Second Edition. Vol. 47 of International Institute for Land Reclamation and Improvement (ILRI) publication. 377 p.

Malczewski J., 2006. GIS-based multicriteria decision analysis: a survey of the literature; International Journal of Geographical Information Science; Vol. 20; No. 7; p. 703-726

Malczewski J., Rinner C., 2015. Multicriteria Decision Analysis in Geographic Information Science. Advances in Geographic Information Science; *Eds*: Springer; 331 p.

Rahman M.A., Rusteberg B., Gogu R.C., Lobo Ferreira J.P., Sauter M., 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. Journal of Environmental Management; Vol. 99; p. 61-75

Région Occitanie/Pyrénées – Méditerranée, 2017. État des lieux sur les ressources et les milieux aquatiques : Document de synthèse. 28 p.

Saaty T.L., 1980. The Analytic Hierarchy Process. McGraw-Hill, New York

Singh P.K., Kainthola A., Singh R., Gupte S.S., Maji V., Singh T.N., 2013. Estimation of critical parameters for slope instability in an in-pit mine dump. SGAT Bulletin; Vol. 14; No. 1; p. 34-44

Sprenger C., Hartog N, Hernández M., Vilanova E., Grützmacher G., Scheibler F., Hannappel S., 2017. Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives. Hydrogeology Journal; 14 p.

Stefan C., Ansems N., 2017. Web-based global inventory of managed aquifer recharge applications. Sustainable Water Resources Management; 10 p.

Tuinhof A., Heederik J.P., 2002. Management of Aquifer Recharge and Subsurface storage: Making Better Use of our Largest Reservoirs. Seminar, Wageningen, 18-19 December 2002. Secretariat National Committee IAH. 106 p.

van Engelen V.W.P., Wen T.T. 1995. Global and national soils and terrain databases (SOTER). Procedures manual. Revised ed. Wageningen: UNEP-ISSS-ISRIC-FAO (also published as World Soil Resources Report 74 Rev. 1); 125 p.

Vasquez López F., 2017. MAR site selection in Western Europe and comparison with other suitability maps by means of the MAR index (Unpublished thesis dissertation). Dresden University of Technology; 103 p.

Appendix A: Overview of existing MAR techniques

Main MAR methods	Specific MAR methods	Scheme	Advantages	Constraints	Suitable environment
Techniques referring primarily to getting water infiltrated	Spreading methods	**Infiltration ponds**	Infiltration of large quantities of water at relatively low cost, maintenance and anti-clogging procedures relatively simple, organic contaminants in source water filtered out in soil	Requires large flat permeable surface area, potential for surface water related breading of disease vectors, potential for water pollution, potential for high evaporation	Flat of gently sloped terrains underlined by an unconfined aquifer composed of permeable sedimentary rocks and fractured crystalline rocks with permeable soils
		Flooding	Infiltration of large quantities of water at relatively low cost		Flat of gently sloped terrains close to rivers, underlined by an unconfined aquifer composed of permeable sedimentary rocks and soils
		Ditches and furrows Linear structures that allow for the recharge water to infiltrate to the aquifer underneath. They are usually shallow, flat-bottomed and closely spaced structures that are excavated	In case of reversed drainage, structures can be installed underground, and therefore do not interfere with land use	Requires large permeable surface area, potential for surface water related breading of disease vectors	Flat or gently sloped terrains close to rivers, underlined by an unconfined aquifer composed of permeable sedimentary rocks and soils
		Excess irrigation Excess water is spread over the area during dormant or non-irrigated seasons to allow for aquifer recharge	limited costs due to use existing facilities		
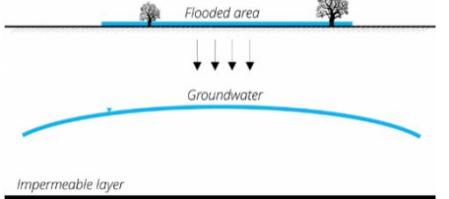
Induced bank filtration	River/lake bank infiltration		Large quantities of good quality water can be withdrawn, organic contaminants in source water filtered out in soil	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging	Floodplains or lake banks underlined by an unconfined aquifer with coarse soils (sand, gravel)
	Dune filtration		Large quantities of water can be withdrawn and pollutants contained in source water may be removed by filtration process	Intensive monitoring of system performance is required with high potential of clogging	Dunes underlined by an unconfined aquifer with coarse soils (sand, gravel)
Well, shaft and borehole recharge	ASR		Clogging partially removed during recovery cycle, infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high quality requirements of source water	Confined or unconfined aquifers composed of unconsolidated rocks
	ASTR		Infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging, high quality requirements of source water	
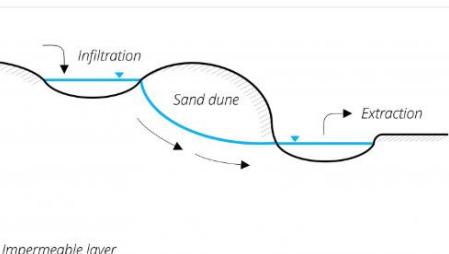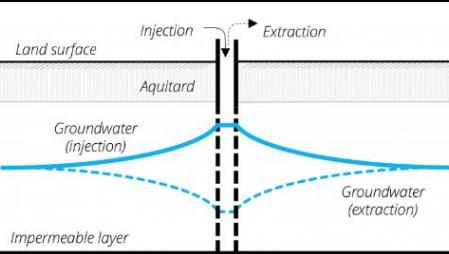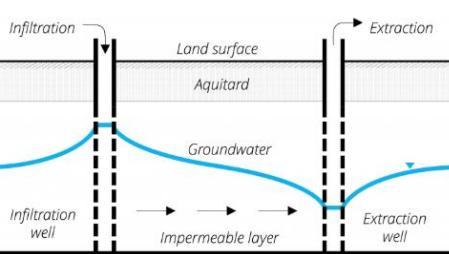
Techniques referring primarily to intercepting the water	In-channel modifications	Shallow well/shaft/pit infiltration		Use of existing facilities reduces costs, recovery from same structure reduces clogging	High quality requirements of source water	Unconfined aquifers composed of unconsolidated sediments with a low permeability surface layer
		Recharge dams		Structures are installed in streambeds, and therefore do not interfere with land use	Breached structures may result in significant damage downstream	Intermittent or ephemeral streams underlined by an unconfined aquifer and a permeable river bed
		Subsurface dams		Low cost structures, community based, low maintenance, structures are installed in streambeds, and therefore do not interfere with land use	Potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water, quality control of the structure difficult	Intermittent or ephemeral streams underlined by an unconfined aquifer with an impermeable layer located a few meters below the surface
		Sand dams			Potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water	Intermittent or ephemeral streams with sandy river beds
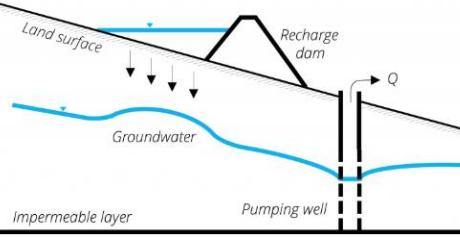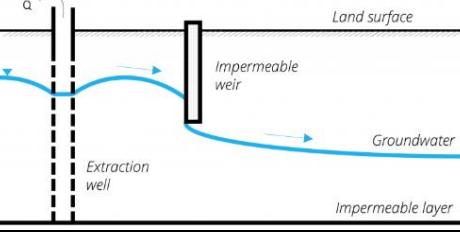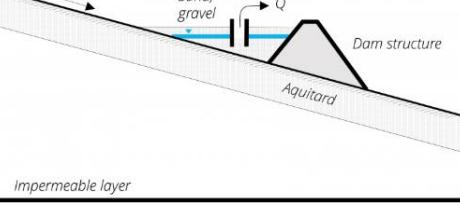
		Channel spreading		Low cost technique, structures are installed in streambeds, and therefore do not interfere with land use	Structures are easily breached during high runoff	Natural drainage channels underlined by an unconfined aquifer with a permeable river bed
	Runoff harvesting	Rooftop rainwater harvesting		Use of already existing structures; storage of rain events mitigating floods	Water quality might be problematic	Urban areas underlined by an unconfined aquifer with sandy soils
		Barriers and bounds		Low cost technique, simple design, simple construction, simple operation and maintenance, prevents soil erosion as well as recharging the groundwater	Infiltration of relatively small quantities of water	Gently sloping rural areas underlined by an unconfined aquifer with sandy soils
		Trenches				
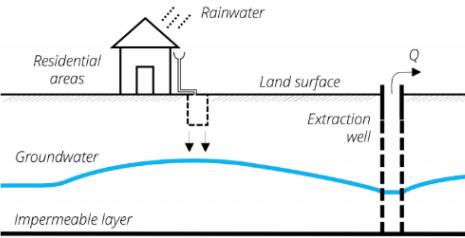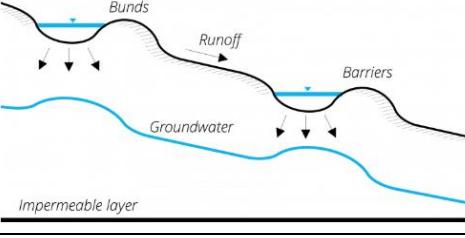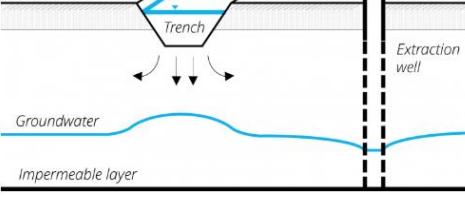
Appendix B: Overview of datasets used for suitability mapping in Occitanie

Dataset	Year	Source	Resolution	Available at	Derived product
European soil database	2004	European Commission - European Soil Data Centre (ESDAC)	1/1000000 and 1/20000000	https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data	Soil texture
Corine Land Cover Occitanie	2012	Ministère de l'écologie, du développement durable et de l'énergie	Mapping unit of 25 hectare	http://www.statistiques.developpement-durable.gouv.fr/clc/fichiers/	Land use
Water network France	2016	Institut Géographique National (IGN)	Shapefile (1/25000)	http://professionnels.ign.fr/bdtopo-hydrographie	Intermittent streams
Hydrogeological map of France	2011	Service d'Administration Nationale des Données et Référentiels sur l'Eau (SANDRE) - BRGM	1/50000	https://www.data.gouv.fr/fr/datasets/referentiel-hydrogeologique-francais-bdrhfv1/	Hydrogeology
Digital Elevation model	2014	Space Shuttle Topography Mission (SRTM)	30 meters	https://earthexplorer.usgs.gov/	Slope
Vulnerable areas to nitrate pollution	2015	Geo.data.gouv.fr	Shapefile	https://geo.data.gouv.fr/fr/datasets/11ba3cbd980e1f0307e089054a9f91548ec40912	Groundwater-Nitrates
Water bodies - River	2010	Data.gouv.fr	Shapefile	https://www.data.gouv.fr/fr/datasets/masses-deau-cours-deau-metropole-version-rapportage-2010/	Proximity to water source

Appendix C: Detailed intrinsic suitability maps for MAR techniques applied to land surface

Intrinsic suitability to MAR
Well, shaft and borehole recharge
in Occitanie

Legend

Well, shaft and borehole recharge

25 0 25 50 75 100 km

Intrinsic suitability to MAR
Runoff harvesting
in Occitanie

Legend

Runoff harvesting

25 0 25 50 75 100 km