TRANSNATIONAL DECISION SUPPORT TOOLBOX FOR DESIGNATING POTENTIAL MAR LOCATIONS IN CENTRAL EUROPE

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Version 1

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Terminology

CHECKLIST	A checklist is the summary of all selection criteria used to define a specific aspect of suitability. Checklists are created for three main suitability components: (i) climate exposure, (ii) hydrogeology/geology and (iii) sensitivity of MAR systems to extreme climate events.
CLIMATE EXPOSURE	Climate exposure is related to the exposure resulting from expected climatic changes, for which data can be extracted from climate models. Climate exposure is calculated based on the climatic water balance and is determined for a geographical area.
DECISION-SUPPORT TOOLBOX	The summary of all checklists in a chronological and methodological order.
EXTREME CLIMATE/ WEATHER EVENTS	An extreme climate event takes place at longer time scales. It can be the accumulation of several (extreme or non-extreme) weather events. For simplicity, in our project both extreme weather events and extreme climate events are referred to collectively as “climate extremes”.
GENERAL SELECTION CRITERION	A selection criterion is used during general screening, aimed at finding suitable areas for a specific type of MAR. This parameter has a Boolean characteristic defining suitable or unsuitable locations based on value ranges or category sets.
PARAMETER	The name of an aspect or physical property, such as aquifer lithology or land use, which is investigated for MAR site selection.
PILOT AREA	A pilot area is a smaller area (e.g. a catchment, waterbody or island) suitable for at least one specific MAR scheme. The pilot area is identified after the 2nd step of general screening from the set of suitable areas. It is the target of further investigation and specific screening to delineate highly suitable areas and the pilot site(s).
PILOT SITE	A pilot site is a potential construction site of a MAR scheme within the pilot area.
SELECTION CRITERION	The joint interpretation of the name, type, suitability range and dimension of a parameter.
SPECIFIC SELECTION CRITERION	A parameter that is used for the further evaluation of a suitable area, in order to characterize its actual suitability at a three-level scale (low, moderate, high).
SUITABLE AREA	A set of suitable areas per MAR type is indicated after the 2nd step of the general screening on a general (e.g. country) or regional level with the general parameters.

Foreword

This report was prepared by the consortium of the project DEEPWATER-CE – with the aim of developing an integrated implementation framework for Managed Aquifer Recharge solutions to facilitate the protection of Central European water resources endangered by climate change and user conflict. This project is funded by the European Regional Development Fund (ERDF) via the Interreg Central Europe programme. This reports reflects the authors' view and the funding authorities are not liable for any use that may be made of the information contained therein.

The chapters of this report containing climatological research were written by the Mining and Geological Survey of Hungary. The chapters dealing with hydrogeological and geological research on porous aquifers were written by Geogold Kárpátia Ltd and the Mining and Geological Survey of Hungary, while research concerning karst aquifers by the Croatian Geological Survey. Contributions to the topic of sensitivity analysis were written by the Water Research Institute (Slovakia). This handbook was edited by the Technical University of Munich.

1. Introduction

Managed Aquifer Recharge (MAR) refers to a suite of methods that are increasingly being used to maintain, enhance, and secure the balance of groundwater systems under stress. These methods apply processes by which excess surface water is intentionally directed into the subsurface. This can be done by spreading water on the surface, by using recharge wells, or by altering natural conditions to increase infiltration in order to replenish an aquifer and store water below the surface. MAR techniques offer promising solutions for water management, also with regard to tackling future climate change impacts. Therefore, MAR is receiving increasing attention among water retention measures (e.g. Dillon 2005, Casanova et al. 2016, Sprenger et al. 2017, Dillon et al. 2019). Within the DEEPWATER-CE project, we have reviewed practices and benchmark analyses on MAR solutions in the European Union (DW 2020). The following report provides a detailed description of principles, benefits, requirements, and objectives of MAR systems.

1.1 Structure of the decision-support toolbox

This handbook presents a **decision-support toolbox** for the evaluation of managed aquifer recharge (**MAR**) **suitability**. It includes three major components:

i. **Climatological selection criteria**, to find out where MAR schemes are needed or will be needed in the future
ii. **Geological and hydrogeological selection criteria**, to identify areas where MAR is possible
iii. The **sensitivity of MAR systems to** sequential and combined effects of **climate extremes**, to evaluate where and how MAR schemes can be applied if extreme climatic situations occur (such as dry or wet periods) as well as the identification of related potential risk

These selection criteria, aimed at identifying potential MAR sites, are portrayed in the form of **checklists** within a toolbox. By applying the selection criteria, suitability maps for MAR can be created. Those can be used prior to field investigations, in order to show the potential of an area or site for MAR schemes (e.g. Sallwey 2019). After a suitable area for MAR application has been identified, further aspects have to be analysed to evaluate the feasibility of MAR schemes. These aspects include, among others, water demand and supply, appropriate technical solutions, and costs and benefits – all of which will be subject of ongoing project work. Figure 1 indicates the contents and outputs of the decision-support toolbox.

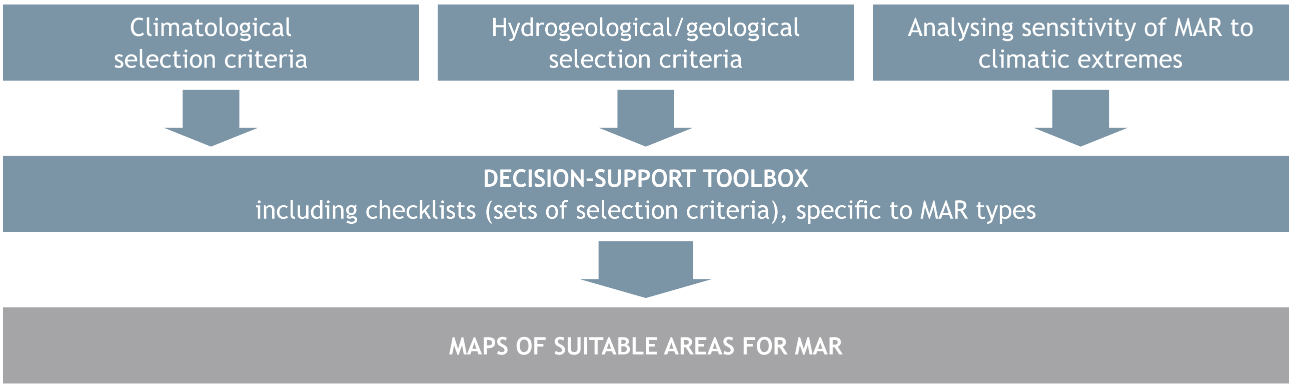


Figure 1: Structure of the decision-support toolbox and output (maps of suitable areas for MAR).

1.2 MAR type specification

As every MAR solution has its own specific requirements concerning the site, checklists containing the selection criteria are categorized by MAR types. For example, the implementation of an induced bank filtration MAR-scheme is possible only if a river or lake is in proximity. In contrast, well, shaft, or borehole recharge MAR schemes are practically independent of surface water. Since no general selection criteria for MAR can be defined, sets of selection criteria specific to MAR types are developed in this project. Based on common MAR application practice in Europe (e.g. Hannappel et al. 2014, BGR and UNESCO 2014, Sprenger et al. 2017) as well as local requirements identified for the project partner countries, **six promising MAR types** are selected for the evaluation:

1. Ditches (D)
2. Induced river and lake bank filtration (IBF)
3. Aquifer storage and recovery (ASR)
4. Infiltration ponds (IP)
5. Underground dam (UD)
6. Recharge dam (RD)

Detailed descriptions of the selected MAR types, and literature reviews that support this selection, are given in the public project report Collection of good practices and benchmark analysis on MAR solutions in the European Union (DW 2020).

1.3 Four-step evaluation of MAR suitability

The MAR site selection process proposed here is based on the assessment of geological and hydrogeological conditions, current and future (modelled) climate conditions, as well as exposure and sensitivity of different MAR types to climate extremes. In order to find suitable MAR sites in Central Europe, detailed information on geological, hydrogeological, and climatological criteria have to be collected and implemented within geographical information system (GIS) databases. Data availability strongly depends on available measurements from the participating countries, on both national and regional levels.

To meet requirements for data availability, and deal with possible restrictions, a four-step procedure is developed for the decision–support toolbox. This is indicated in Table 1. The specific steps relate to the scale, while investigations are based on the size of the screening area (different spatial resolution depending on data availability), the specific requirements of the selected MAR types, and the required order of investigations.

Table 1: The four-step procedure for the investigation of MAR suitability (highlighted in italics: not the subject of this handbook; this is part of ongoing project work).

	SELECTION CRITERIA	SCALE	MAR-SPECIFIC	AIMS
1ST STEP	Exposure to climate extremes	Central Europe	NO	Identify the need for MAR systems due to climate change and exposure to climate extremes.
2ND STEP	Geology and hydrogeology: general screening	Country or region	YES	Identify suitable areas for the implementation of the six selected MAR schemes.
3RD STEP	Geology and hydrogeology: specific screening (dependent on aquifer type)	Pilot area (sub-regional scale)	YES	Further evaluate the suitable areas by applying a three-level scale (low, moderate, and high suitability) and identify suitable pilot sites for MAR implementation.
4TH STEP	Sensitivity of MAR schemes to climate extremes *Costs and-benefits, regulatory framework* *Feasibility of technical solutions and acceptability of associated risks: field measurements and monitoring* *Water demand and supply*	Pilot site(s)	YES	Investigate and characterize the feasibility of the selected pilot site(s) for a specific MAR-scheme.

1.3.1 First step: Exposure to climate extremes

In the first step, the expected water demand due to climate change, based on climatological data and modelling, is investigated for Central Europe. Key climatological parameters for this analysis include temperature, precipitation, and potential evapotranspiration (PET). Based on these three parameters, the climatic water balance is determined, providing information about the water supply of the area. This is considered as the **climate exposure indicator** in the frame of this project. Based on the climatic water balance, four climate exposure categories – which are not MAR-specific – are defined to characterize the need for MAR systems.

Using **climate model data**, a set of **maps** is created which presents the expected change of annual mean temperature, precipitation, potential evapotranspiration, and climate exposure within the periods of 2021–2050 and 2071–2100, compared to the reference period of 1971-2000. From these maps, areas with a higher MAR potential, in terms of climate exposure, can be identified.

1.3.2 Second step: General screening with geological and hydrogeological selection criteria

Screening for a suitable geological and hydrogeological environment starts with an investigation area of country-wide or regional extent. At this level, general geological and hydrogeological selection criteria for MAR suitability are defined and arranged in checklists. Evaluation using these checklists results in maps that identify MAR-suitable areas. The maps help divide each MAR type into two categories: **suitable** and **unsuitable**.

1.3.3 Third step: Specific screening with geological and hydrogeological selection criteria

The output of the previous step, i.e. general level screening, indicates if a considered area is suitable or unsuitable for MAR. In the actual (third) step, suitable areas are further investigated with more specific selection criteria to characterize their actual suitability on a three-level scale (low, moderate, high), and to specify potential pilot areas for feasibility studies. These pilot areas include potential MAR pilot sites. In this step, relative weight of the selection criteria is also defined in the checklists to handle their uneven contribution to the final suitability.

MAR operation in karst areas is associated with relatively high uncertainties, operational costs, and risks of operation cessation (as e.g. reported by Rodriguez-Escales et al. 2018). Moreover, extensive monitoring efforts are required to ensure an adequate recovery rate and water quality. Therefore, specific screening for MAR-suitability should focus on priority areas. Priority areas are those where the demand for groundwater resources is high, and groundwater reserves are most exposed to over-abstraction, climate change, and seawater intrusion.

Based on local requirements identified for the Central European countries that are part of the project, this handbook focuses on porous and karst aquifers. Thus, the specific geological and hydrogeological selection criteria defined in this handbook refer to those two aquifer types. Fissured rock aquifers – another important group of aquifers for drinking water supply – may require additional considerations.

1.3.4 Fourth step: Feasibility study for selected pilot site(s)

In the fourth step, the feasibility of selected pilot site(s) for MAR-scheme implementation is investigated. Feasibility studies comprise:

i. Analysing the sensitivity of MAR schemes to climate extremes
ii. Setting up guidelines for assessing water demand and supply, before and after MAR implementation
iii. Setting up guidelines for selecting suitable technical solutions and risk management techniques for MAR schemes, including field measurements and monitoring
iv. Setting up guidelines for performing cost-benefit analyses and defining the Central European regulatory framework for MAR schemes

Feasibility studies are carried out at the pilot site scale and may include site-specific fieldwork. The pilot site scale is essentially the construction site scale of a MAR scheme. Feasibility studies are carried out for each final pilot site, where a MAR scheme which has been identified in the second and third steps is applied. Details of the sensitivity analysis (point i) are given in the following paragraph, while points ii-iv (guidelines) are not the subject of this handbook (but are part of ongoing project work).

In order to analyse the **sensitivity of MAR schemes to extreme climate events**, an impact chain approach is used. The **impact chain** considers **stimuli** (extreme climate events) that induce **hazardous events** (as a result of natural hazards combined with, or superimposed by, adverse anthropogenic impacts and influenced by the local surface and hydrogeological characteristics). Such hazardous events might cause specific **negative effects on MAR schemes**, which have to be dealt with using suitable precautionary **measures** for MAR systems. These measures are defined based on the results of the sensitivity analysis. The precautions for both climate extremes (wet and dry periods) relate to risks of temporary interruption in the operation of MAR systems, structural damage of MAR infrastructure, as well as water quality and water quantity problems specific to particular MAR types. The suggested precautionary measures should be taken into account when deciding on MAR-scheme implementation.

2. Background

2.1 Climate modelling

2.1.1 Introduction to climate modelling

Climate is a highly complex system consisting of five major components: The atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere. All of them are subject to complex interactions. Key drivers of the global climate system are incoming solar radiation, its atmospheric transfer (reflection, scattering, absorption), and its geographical distribution (Figure 2). The climate system evolves with time under the influence of its own internal dynamics; from external forcing such as volcanic eruptions and solar variations, to anthropogenic forcing such as changes in the atmospheric composition and in land use. The climate responds directly to such changes, as well as indirectly through a variety of feedback mechanisms such as ice-albedo feedback or cloud feedback. Climate models can provide us with projections on how the climate of the Earth may change in the future (Cubasch et al. 2013).

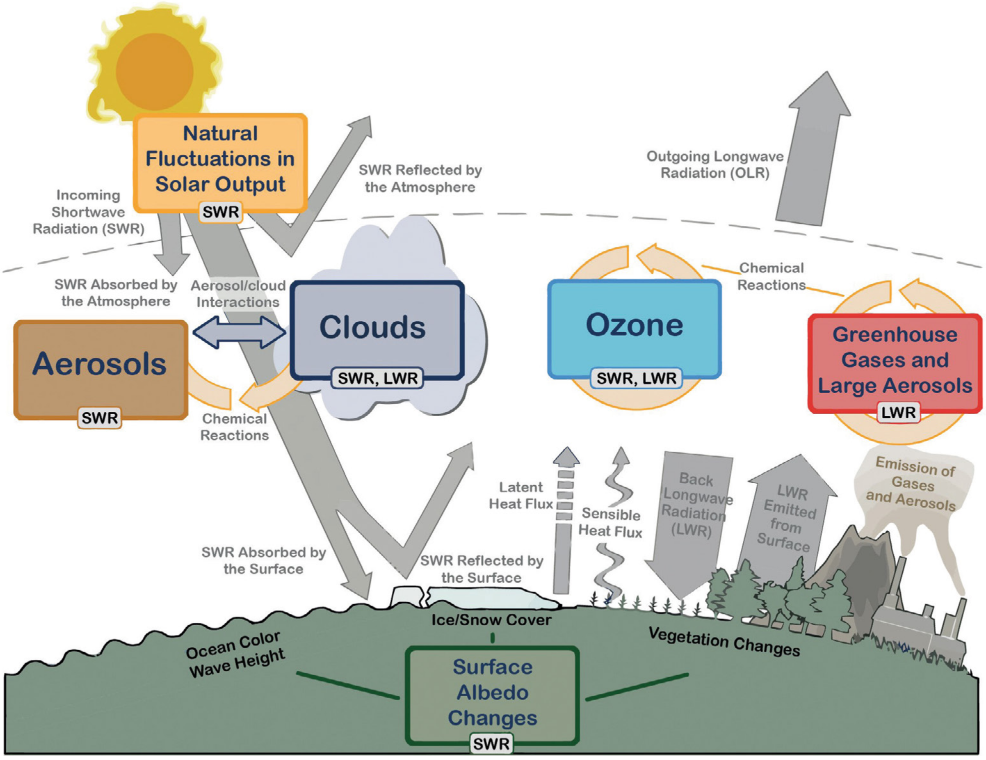


Figure 2: Main drivers of climate change (Cubasch et al. 2013). SWR and LWR: short- and long-wave radiation.

Climate modelling estimates the reaction of the climate system to the occurrence of a presumed radiation forcing. As for weather forecasting, numerical models are used to understand the expected climate change. These models are based on the description and parameterization of physical processes that determine the behaviour of the climate system. Climate models use mathematical equations to characterize how energy and matter interact in different parts of the ocean, atmosphere, and land. Over the past 35 years, climate models have been extensively developed, and their horizontal and vertical resolutions have been significantly increased. They were originally separated into atmospheric models and ocean models, yet nowadays coupled climate models exist which include the atmosphere, land surface, ocean and sea ice, aerosols, carbon cycle, dynamic vegetation, atmospheric chemistry, and land ice.

Global climate models (also known as general circulation models GCMs) are multi-modelling systems, that link surface, ocean, and atmospheric models. Hence, they can be used for a unitary analysis of the entire climate system. While global climate models can reliably be applied on a larger spatial scale, as the scale decreases, the uncertainty of the results increases. Climate models divide the Earth's surface into a three-dimensional grid of cells. More detailed models have more grid cells, so they need more computing power (Figure 3a). A GCM can provide reliable prediction information at a scale of ~1000 km by 1000 km, which can still include strongly differing landscapes (such as mountainous areas or flat coastal plains) with greatly varying potentials for floods, droughts, or other extreme events (e.g. Giorgi et al. 2009). Regional Climate Models (RCMs) and Empirical Statistical Downscaling (ESD), applied over a limited area and driven by GCMs, can provide information on much smaller scales (Figure 3b). RCMs provide projections with much greater detail and with more accurate representation of localised extreme events.

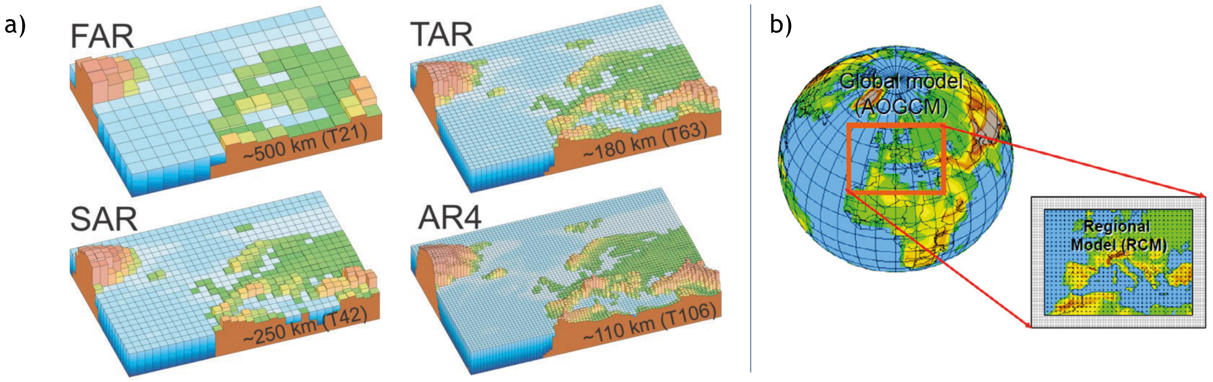
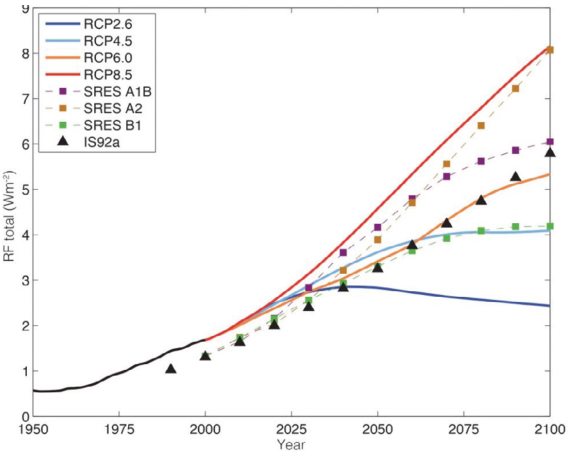


Figure 3: a) Increase in the spatial resolution of climate models, reflecting advances in model development between 1990 and 2007 (Le Treut et al. 2007), b) Global and regional model resolutions (WCRP 2018).

2.1.2 Emission scenarios

Climate models are subject to uncertainties, which, for regional climate projections, include the model configuration, greenhouse gas emission and concentration scenarios, RCM and GCM internal variability, non-linearities in the climate system and regional climate downscaling for the region of interest (Giorgi et al. 2009). One of the main uncertainty factors is the anthropogenic activity, the climate impact of which is described in different scenarios. Common scenarios have been defined in the Special Report on Emission Scenarios SRES as part of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007). These scenarios predict potential future trends in emissions, economic and social changes, however they do not take into account the possible mitigation of climate change effects. In the Fifth Assessment Report of IPCC (AR5), further scenarios have been selected in order to meet more recent requirements of professional and non-professional users. These scenarios are referred to as next-generation RCP (Representative Concentration Pathways) scenarios (IPCC 2014).

Depending on the level and trajectory of the radiation forcing, four types of scenarios were identified assuming different levels of total radiation forcing for the year 2100: (i) 8.5 W/m², (ii) 6 W/m², (iii) 4.5 W/m² and (iv) 2.6 W/m² (IPCC 2014). Radiation forcing indicates the change in the net radiation energy absorbed by the troposphere. According to the RCP scenarios, components of radiation forcing include greenhouse gases, aerosol molecules, chemically active gases and land use characteristics (van Vuuren et al. 2011). Each single RCP scenario is based on different sets of internally consistent socioeconomic assumptions, i.e. different combinations of predicted economic, technological, demographic, political, and institutional conditions/developments (Figure 4; IPCC 2014).



SCENARIO	DESCRIPTION
RCP2.6	Peak in radiative forcing at ~3 W/m^2 before 2100, with subsequent decline
RCP4.5	Stabilization of radiative forcing (without overshoot pathway) at ~4.5 W/m^2 shortly after 2100
RCP6.0	Stabilization of radiative forcing (without overshoot pathway) at ~6 W/m^2 after 2100
RCP8.5	Increasing radiative forcing pathway, with ~8.5 W/m^2 in 2100

Figure 4: Projections of radiation forcing until the year 2100, considering SRES and RCP scenarios (IPCC 2014).

Specific emission scenarios, differences of the models and methods, as well as the overall internal variability characteristic of the climate system are contributing to simulations. The more climate simulations with different starting conditions or with different models and methods are taken into consideration, the better the uncertainty of the simulation results can be reduced.

2.1.3 Climate modelling database

In order to select the most appropriate area for MAR solutions, we need to use downscaled regional climate model data to determine expected changes for the future climate. CORDEX is a freely available database containing numerous climate model simulations. The goal of the CORDEX (Coordinated Downscaling Experiment) initiative was to give a framework for regional climate modelling, which enables the development and evaluation of climate models, and defining uncertainty of results more accurately. The European Domain is EURO-CORDEX, which covers the European continent (Jacob et al. 2014; Figure 5a).

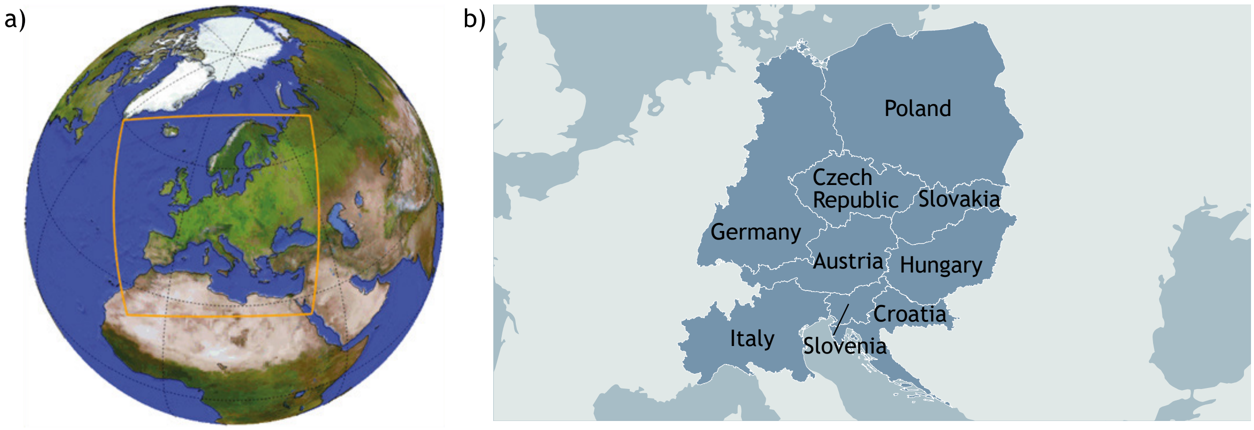


Figure 5: a) The EURO-CORDEX region (WCRP-CORDEX, 2015), b) the Interreg Central Europe Program area.

Within this project, climate modelling results are represented in the form of maps for the Central European area. The respective areas covers the Interreg Central Europe Program area, as indicated in Figure 5b.

The spatial extent considered by the EURO-CORDEX database makes it possible to examine areas of any size (limited by the grid resolution) within the European area by using the available simulations and parameters. Climate-related information and simulation results can be extracted for a given target area under investigation (such as the Central Europe region, country scale, regional scale). Figure 6 gives information on available grids, geographic positions and resolution.

In the present assessment for the Central European area, four climate simulations available in the CORDEX system are considered. These four simulations have been carried out with the RCA4 regional climate model, using data from the CNRM-CM5 and EC-EARTH global models as threshold conditions. The simulations are based on two types of scenarios, RCP4.5 and RCP8.5 (Table 2), the considered spatial resolution was 0.11°.

	EURO-CORDEX DOMAIN	CENTRAL EUROPEAN REGION
LONGITUDE	-44.60° to 64.96°	2.55° to 25.73°
LATITUDE	21.99° to 72.58°	41.30° to 55.53°
NUMBER OF GRID POINTS	174688 (424 x 412)	15128 (122 x 124)
GRID RESOLUTION	0.11°	0.11°

Figure 6: Grid resolution of the EURO-CORDEX domain (shown in the map) and the Central European region.

Table 2: Applied climate simulations separated in global and regional model, as well as considered scenarios.

GLOBAL MODEL	REGIONAL MODEL	SCENARIO
CNRM-CM5	RCA4	RCP4.5
CNRM-CM5	RCA4	RCP8.5
EC-EARTH	RCA4	RCP4.5
EC-EARTH	RCA4	RCP8.5

2.2 Suitability mapping

The analysis of MAR suitability is usually based on intrinsic factors related to geology/hydrogeology, soil type, land-use and climate, which control the groundwater recharge process (e.g. Sallwey et al. 2019). Geographic information system (GIS)–based multi criteria decision analysis (MCDA) is frequently applied to identify MAR-suitable sites (e.g. INOWAS 2019). GIS-MCDA covers a set of different tools, which can be selected in order to design, evaluate and prioritize (e.g. Malczewski and Rinner 2015). However, there is no common understanding on criteria, weights and methods to be used for suitability mapping (e.g. Sallwey et al. 2019). Therefore, in most cases, a specific methodology needs to be developed for the investigated target area and MAR types. In this project, we propose the following procedure for suitability mapping (as suggested by Rahman et al. 2012):

- defining the problem; in our project: screening for the six MAR schemes selected for the Central European region (cf. Section 1.2)
- constraint mapping (screening of suitable areas); in our project: general screening or screening with general selection criteria (2nd step screening)
- suitability mapping, classification of thematic layers or criteria, standardization, weighting and layers overlying, sensitivity analysis; in our project: 3rd step screening with specific selection criteria

By constraint mapping, it is possible to exclude areas that are not suitable for MAR application (e.g. Valverde et al. 2016). This occurs in the 2nd step, i.e. **general screening with geological and hydrogeological selection criteria** (Table 1, Section 1.3.2). Detailed suitability mapping, and ranking the suitability of potential areas, are done in the 3rd step, i.e. **specific screening with geological and hydrogeological selection criteria** (Section 1.3.3). By weighting the different criteria in this step, the relative importance of one specific criterion within the whole criteria set can be described. This process can be verified by a sensitivity analysis (e.g. Sallwey et al. 2019).

Suitability mapping seeks to consider all relevant criteria that can affect a site's suitability for MAR implementation. These criteria can be clustered by defining main criteria (such as surface characteristics) that include a set of sub-criteria (such as geomorphology or land use) for further specification. Each sub-criterion can include individual criteria (such as slope). The criteria are represented by different types of maps, such as a classified map (e.g. for land use) or a value map (e.g. slope, infiltration). The values and classes should be standardized, by assigning weights to each criterion. The result is a final suitability map, which is the outcome of the different overlying criteria maps (Kazner et al. 2012).

In their review, Sallwey et al. (2019) identified a total number of 467 criteria, which they grouped into five main criteria (Level 1) and different sub-criteria (Level 2), as shown in Table 3. Geomorphology is the most used sub-criterion for surface characteristics, and includes the most overall used individual criterion: the slope. Soil is also an important sub-criterion for all MAR types, with land use being the second most used individual criterion.

Following the surface criteria group, aquifer characteristics form the second-most used main criterion. Parameters in this group mainly focus on the storage capacity, which is indicated by individual criteria such as the aquifer thickness or groundwater level. The most used criterion in this group is general information on geology and lithology. The water quality main criterion focuses on the quality of groundwater to be recharged, primarily in terms of groundwater salinity or the assessment of chloride and nitrate concentrations.

Table 3: Main criteria (Level 1) and sub-criteria (Level 2), as well as numbers of sub-criteria per specific MAR method (Sallwey et al., 2019).

NUMBER OF CRITERIA PER SPECIFIC MAR CRITERIA CATEGORY

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

NOTE: One study can have more than one criterion that falls into a specific category; the number of regarded studies is given in brackets. MAR, managed aquifer recharge; SM, surface spreading methods; IM, in-channel modifications; WSB, well, shaft, and borehole recharge: RWH, rainwater harvesting methods; Unsp., unspecified.

It turned out that frequently used criteria often don’t have the highest weight. E.g. “slope” was used the most but “geology” and “hydrological soil type” was weighted the highest. Data availability is also an important factor. Remote sensing data such as on land use, slope or soil type are accessible for many regions worldwide but aquifer-related data are often unavailable on a larger scale. When subsurface data were available this was ranked as one of the most important criteria (Sallwey et al. 2019).

In the following, three case studies are compared regarding the methodology used and the selection criteria chosen for the geology and hydrogeology (Table 4). Concerning the MAR technology, two of these studies consider only the spreading method, while a third considers both the spreading method and in-channel modification. GIS-MCDA is used for the identification of suitable MAR sites, however there are some noticeable differences between these studies in terms of their geological/hydrogeological selection criteria. Table 4 summarizes the criteria defined in each of the studies. The studies consider four to nine parameters each, relating to geology, hydrogeology, as well as additional parameters like drainage network density or the distance to users.

Table 4: Criteria defined in three case studies concerning the suitability of two different MAR technologies.

CASE STUDIES

VALVERDE ET AL. (2016)	DUPONT (2018)	FUENTES AND VERVOORT (2020)
CRITERIA DEFINED IN THREE CASE STUDIES		
Hydrogeological aptitude Terrain slope Top soil texture Drainage network density	Slope Land cover Soil texture Distance to source water Hydrogeology Groundwater contamination (nitrate)	Surface (slope) Distance to rivers Distance to users Drainage density Aquifer characteristics (hydrogeological unit, hydraulic conductivity) Aquifer yield Aquifer salinity Groundwater depth Soil saturated hydraulic conductivity
MAR TECHNOLOGY		
Spreading method	Spreading method	Spreading method and in-channel modification

The parameters can be sorted into **three main selection criteria groups**, which are: the (i) **aquifer-related characteristics** (red in Table 4), (ii) **surface characteristics** (green) and (iii) **characteristics of the water source** (blue). For the compilation of the hydrogeological parameter set and selection criteria in this project, these three main criteria groups are used. The most important parameters are associated with these three main criteria groups, as presented in the following paragraph. As seen from Table 4, the number of surface-related parameters is higher than the number of parameters related to aquifer and water source characteristics, which corresponds to the findings of Sallwey et al. (2019).

In another study, Wang et al. (2016) investigated induced river bank filtration (RBF). With the aim of finding suitable areas for future development of an RBF system, the authors used a multi-criteria system consisting of different indices to evaluate the suitability of bank filtration along the Second Songhua River in China. This multi-criteria system was integrated into GIS to complete the evaluation of the various indicators. First, the authors focused on *natural geographical conditions* like plain areas and the extent of *hydraulic connections* between river and groundwater. The RBF evaluation index system is based on water quantity, water quality, development and utilization conditions of groundwater resources, and the interaction intensity between surface water and groundwater (Wang et al. 2016).

Table 5 shows the evaluation suitability index system used in their work. The development of this system is based on a detailed analysis of the physical geography and geological/hydrogeological conditions (the main influential factors of RBF), as well as on the analysis of water demand and the development and utilization of water resources.

Although their work is mainly related to the Second Songhua River catchment, the primary evaluation principle and the index system can still be used as a scientific reference for the selection of RBF at other sites (Wang et al. 2016).

Table 5: Suitability evaluation for induced river bank filtration (Wang et al. 2016).

CATEGORY OF EVALUATION INDEX		EVALUATION INDEX (X)	INDEX WEIGHT (W)	
Water quantity	groundwater	hydraulic conductivity (K)	0.10	0.30
		aquifer thickness (M)	0.10	
	surface water	runoff in cross-section (Q)	0.10	
Water quality	groundwater	status of groundwater quality (G)	0.15	0.30
	surface water	status of surface water quality (S)	0.15	
Interaction intensity between surface water and groundwater		groundwater hydraulic gradient (I)	0.05	0.30
		possible influence zone width of surface water under the condition of groundwater exploitation (L)	0.15	
		permeability of riverbed layer (R)	0.10	
The exploitation condition of groundwater resource		groundwater depth (D)	0.10	0.10

Based on the literature research summarized above, it is clear that suitability mapping has a strong potential for locating promising MAR sites. Therefore, we include **suitability mapping** as a tool in our decision-support toolbox. Furthermore, we consider the weighting of the selection criteria as being important, similar to the authors in the aforementioned studies. Selection criteria are highly various and can differ between countries and MAR types.

Due to specific characteristics, including a very high heterogeneity, karst aquifers require selection criteria that differ in some aspects to those for non-karstified aquifers. Details on this topic are discussed below, and an overview on karst characteristics is given in the appendix.

2.3 Sensitivity analysis for extreme climate events

The implementation of MAR requires analysing the sensitivity of intended MAR schemes to extreme climate/weather events (primarily different kinds of floods and droughts). In this context, the sensitivity analysis investigates the vulnerability of MAR schemes. Thus, in this project, the term “sensitivity analysis” is used in a different context than in other cases, where it is often related to mathematical modelling (the sensitivity of a model results to input parameters).

Here, the main objective of the sensitivity analysis is to look into the (potential) impacts of climate extremes on MAR schemes. This is done by analysing impact chains (cf. Section 1.3.4). Criteria are identified that can be used to determine potential impacts. These sets of criteria show if the MAR-scheme is sensitive to extreme climate (weather) events, as well as the consequences of such events. The selection criteria are compiled within checklists as part of the decision support toolbox. They are then used to facilitate the decision-making process, where, as a next step, potential threats to MAR systems and appropriate precautionary measures can be evaluated (also as part of the hazard/risk assessment procedure).

Due to their high complexity, there is no “commonly used methodology” for evaluating the input parameters and selection criteria, which in the end define how vulnerable an area is to extreme climate events. Increasing attention is being given to issues of vulnerability, capacity, and resilience in disaster management. There is a growing amount of literature seeking to expand the theoretical understanding of disaster resilience and vulnerability, as well as to measure them empirically (Beccari, 2016).

Other authors such as Hagenlocher et al. (2019) note that reducing the social, environmental, and economic impacts of droughts, and identifying pathways towards drought resilient societies, remains a global priority. A common understanding of the drivers of drought risk, and ways in which drought impacts occur, is crucial for improved assessments, and for the identification and (spatial) planning of targeted drought risk reduction and adaptation options. Over the past two decades, there has been an increase in drought risk assessments across spatial and temporal scales, drawing on a multitude of conceptual foundations and methodological approaches. Recognizing the diversity of approaches in science and practice, as well as the associated opportunities and challenges, the aforementioned authors present the outcomes of a systematic literature review. This includes state-of-the-art human-addressed drought vulnerability, risk conceptualization and assessments, and identifying persisting gaps.

3. Methods

3.1 Climate selection criteria

3.1.1 Climate indicators

Climate is usually characterized by statistical quantities of the meteorological variables along multi-decadal periods (e.g. 30-year mean temperature, frequency of extreme events). For long-term projections of the climate system, the expected future changes are usually compared to a baseline period (e.g. IPCC TAR 2001). In the decision support toolbox, climate-related selection criteria are defined based on different climate indicators which consist of daily temperature, maximum temperature, and precipitation data. These indicators have to be derived in order to determine where MAR schemes will most likely be necessary in view of expected future climate changes. Thirty-year averages are calculated from sets of daily data for “climate windows” covering the periods 1971-2000, 2021-2050 and 2071-2100. To show the direction and extent of expected changes, differences between future climate windows can be calculated relative to the base period 1971-2000. The indicators given in Table 6 are considered to be the most relevant for assessing future climate change and its related potential impacts on MAR systems. Most of them are used as input parameters for the sensitivity analysis, to identify climate extremes (e.g. extremely warm or dry year) that are triggering factors of extreme events (e.g.extremely hot period, drought).

Table 6: Description of derived climatological indicators. ET: evapotranspiration. Max.: maximum.

BASIC INDICATORS	DERIVED INDICATORS	TEMPORAL RESOLUTION	DEFINITION
BASED ON DAILY MEAN TEMPERATURE DATA	Mean temperature	Yearly Seasonal Monthly	Projected changes in mean temperature for the future climate windows 2021-2050 and 2071-2100 compared to the reference period 1971-2000. Averaged values for every grid point within the Central European region, based on climate simulation data. *This is abbreviated as "changes" in the following.*
	Potential ET	Yearly	Amount of ET that would occur if a sufficient water source were available. Potential ET was calculated according to a modification of the modified Thornthwaite method.
BASED ON DAILY MAXIMUM TEMPERATURE DATA	Number of summer days	Seasonal	Changes in mean number of summer days (summer day if daily max. temperature > 25°C)
	Number of hot days	Seasonal	Changes in mean number of hot days (daily max. temperature ≥ 30°C)
	Number of extremely hot days	Seasonal	Changes in mean number of extremely hot days (daily max. temperature ≥ 35°C)
BASED ON DAILY PRECIPITATION DATA	Amount of precipitation	Yearly Seasonal Monthly	Changes in mean precipitation
	Number of rainy days	Monthly	Changes in mean number of rainy days (rainy day if daily amount of precipitation ≥1 mm)
	Number of days with precipitation above 10 mm	Monthly	Changes in number of days with precipitation >10 mm
	Number of days with precipitation above 20 mm	Monthly	Changes in number of days with precipitation >20 mm
	Number of days with precipitation above 30 mm	Monthly	Changes in number of days with precipitation >30 mm
	Number of dry days	Monthly	Changes in number of dry days (daily sum of precipitation <1 mm)
	Maximum numbers of consecutive dry days	Monthly	Changes in max. number of consecutive dry days.
	Climatic water balance	Yearly	Changes in mean climatic water balance (Climatic water balance defined as difference between annual sum of precipitation and annual sum of potential ET; potential ET calculated by Thornthwaite method)

3.1.2 Climate exposure categories

In order to understand the effects of climate change on a regional level, climate exposure of the investigated area has to be examined. Exposure is related to climate and the expected climatic changes, for which data can be extracted from climate models, and is characteristic of a specific geographical location. Within this project, data are extracted from climate simulations available at the EURO-CORDEX database (cf. Section 2.1.3). Four simulation scenarios are considered: two projections of the RCA4 regional climate model (driven by EC-EARTH and CRNM-CM5 global models) with (i) the relatively optimistic climate change scenario RCP4.5 and (ii) the pessimistic scenario RCP8.5 (Section 2.1.2, Table 2). The area of investigation is the Central European region (Figure 6), and data from climate simulations are extracted for each grid point. According to the available spatial resolution, one grid point corresponds to an area of 12.5 km x 12.5 km. The considered Central European region includes 15128 grid points (Figure 6).

For MAR suitability and sensitivity studies, annual mean temperature, precipitation, and potential evapotranspiration (PET) are considered as key climatological parameters to analyse the expected climate of the region, because these parameters are the components of climatic water balance. (Homolya et al. 2017). PET is calculated by using a modified Thornthwaite method (e.g. Dingman 2015, Ács and Breuer 2013, Szász et al. 2007), which is based on daily mean temperature data from the climate simulations. The climatic water balance is then derived as the difference between the annual sum of precipitation and the annual sum of PET. Positive or negative values are obtained from the climatic water balance, which indicate climate-induced surpluses or deficits in the water budget. Areas with an increasing or decreasing water supply can be identified, accordingly, and information on their regional distribution can be obtained.

Climate exposure categories are defined based on the climatic water balance. **For each grid point** (area of 12.5 km x 12.5 km), **30-year averages** are determined for the climatic water balance. These averages correspond to the simulated future climate windows (2021-2050 and 2071-2100) and the reference period (1971-2000; cf. Table 6). Furthermore, **differences** of these averages between the future climate windows and the reference period are obtained for each grid point. In order to analyse the spatial variation within the whole Central European region, quartiles are determined for whole datasets (all grid points, n = 15128) of 30-year averages and differences. The quartiles reflect frequencies of the **30-year averages** and the differences. This aims at determining a lower probability (25th percentile), the median (50th percentile) and a higher probability (75th percentile) for a given value (30-year average or difference) to occur within the Central European region (e.g. Schau-Noppel et al. 2020, Anandhi et al. 2011). At each grid point, given values (30-year averages and differences) are compared to the quartiles. Scores (1-4 points) are assigned for each grid point, depending on the quartile range in which given values are positioned, as indicated in Table 7. This is done both for the 30-year averages and the differences. Scores for the 30-year averages are then multiplied with scores for the differences in order to yield final scores, which indicate the **exposure category**. Four exposure categories are defined: slightly, moderately, highly and extremely exposed (Table 8).

As an example, if at a given grid point the 30-year average value is less than the 25th percentile, 4 points are assigned as a score. This value is rather “exceptional” (relatively low probability) for the whole Central European region, thus the high score. If, at this grid point, the difference value (indicating climatic change) is higher than the 75th percentile, 1 point is assigned as a low score: the value is rather "common" (relatively high probability). By multiplying the two scores (4x1), the final score is 4, which means that this grid point is within the "slightly exposed" category.

Maps are created for the Central European region (at a resolution of 12.5 km x 12.5 km) for indicating the exposure category as well as temperature, precipitation and potential evapotranspiration changes.

Table 7: Scoring scheme for climate exposure categorisation. p: percentile.

CLIMATIC WATER BALANCE 30-YEAR AVERAGE FOR CLIMATE WINDOW	30-YEAR AVERAGE SCORE	DIFFERENCE OF 30-YEAR AVERAGE BETWEEN CLIMATE WINDOW AND REFERENCE PERIOD	DIFFERENCE SCORE
> 75th p	1	> 75th p	1
50th p - 75th p	2	50th p - 75th p	2
25th p - 50th p	3	25th p - 50th p	3
< 25th p	4	< 25th p	4

Table 8: Climate exposure categories with final score values.

FINAL SCORE	EXPOSURE CATEGORY
1-4	Slightly exposed
5-8	Moderately exposed
9-12	Highly exposed
13-16	Extremely exposed

3.2 General and specific screening with geological and hydrogeological selection criteria

As the suitability conditions of the various MAR technologies are quite different, no system of criteria was found which could be applicable for every MAR type at once (Sallwey et al., 2019).

We propose to set up MAR suitability maps on two different levels: (i) **general screening** and (ii) **specific screening** (Figure 7). As proposed by Rahman et al. (2012) and Sallwey et al. (2019), constraint mapping is done at a larger scale (in our case *general screening*) with two ranges of parameters: suitable and unsuitable. A second step of suitability mapping is done at the sub-regional scale (in our case, *specific screening*) with three ranges of parameters: high, low, and moderate suitability. The final product comprises two sets of maps, making it possible to distinguish between MAR types.

Groups of suitability parameters for the general and specific screening, as well as the resulting maps, are compiled for the six jointly selected MAR technologies (cf. Section 1.2). Different selection criteria are needed at the two levels, since different information is derived from the resulting maps.

Key aspects during the selection of these parameters are:

- parameters are displayed on maps
- parameters are categorized, assigned to ranges
- parameters are available at the Central European level (at partner countries)

To specify or classify these parameters, the following dimensions (attributes) are used: Boolean data type (yes/no), numeric value (e.g. the distance is 100 m), category (e.g. gravel, sand, clay, etc.).

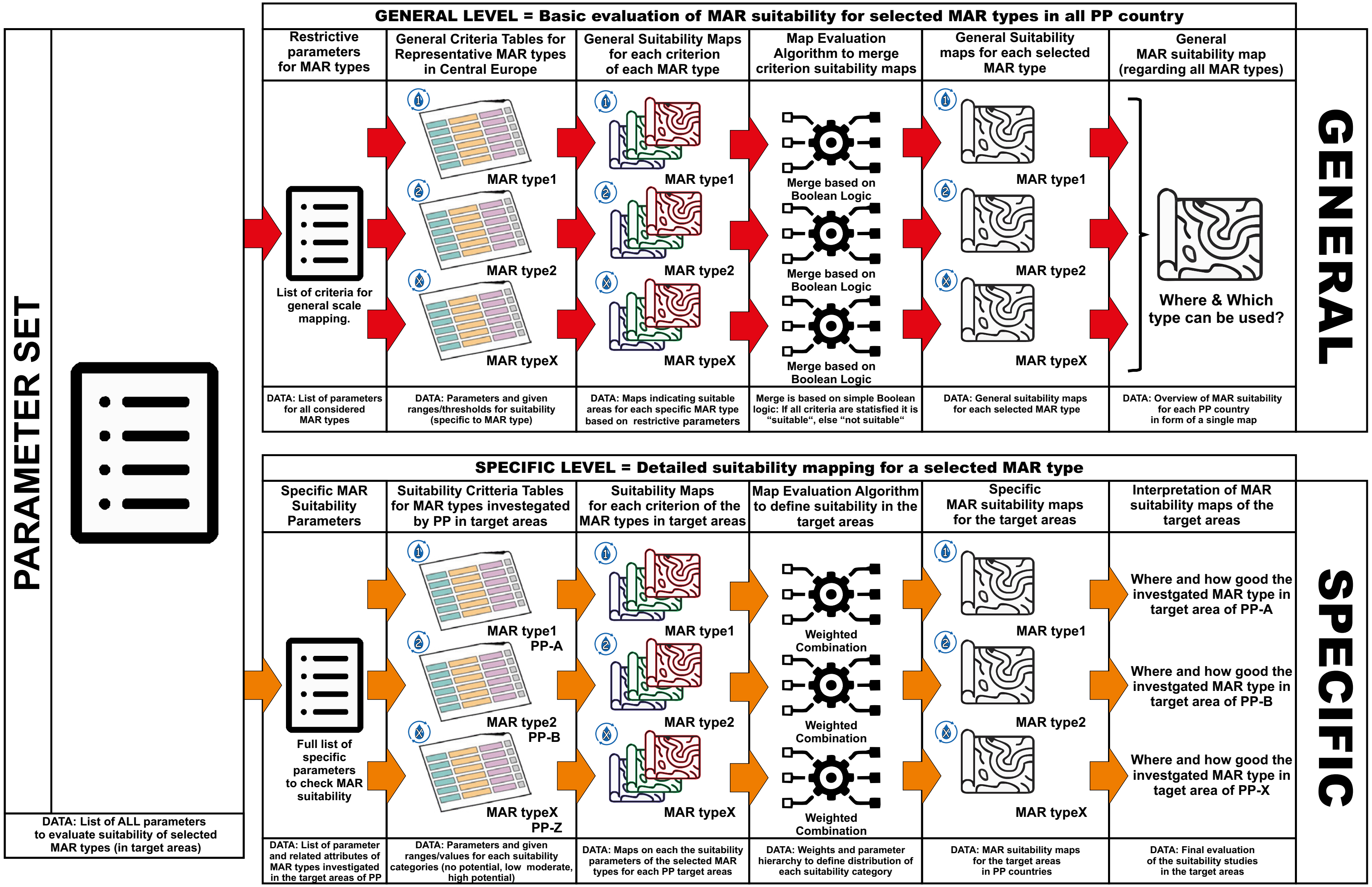


Figure 7: Scheme for general screening (general level, top) and specific screening (specific level, bottom).

In the evaluation process, general screening (with general parameters) takes place on the country or region level (e.g. the whole area of Hungary, or the Split-Dalmatia County of Croatia), while specific screening occurs on sub-regional levels, such as for parts of a river catchment or water body, or an island (e.g. the Podunajska lowland, or the island of Vis) (Figure 7).

With these parameters we can get information for important MAR-related questions, including, among others: what can be used as a water source for MAR (surface water or groundwater); if the quality and quantity of the water source is sufficient; what the main characteristics of the geological setting are.

Figure 8: Scheme for defining general and specific selection criteria.

- The general parameters (Figure 8, Table 9 below) are MAR restriction parameters. By the mapping/spatial analysis of these parameters, areas unsuitable for establishing the selected six MAR types (one by one) can be excluded on a country (or sub-country, regional) level as the first step of the MAR location selection process. The resulting maps from this work show unsuitable areas at a general level.
- The specific parameters (Figure 8, Table 10 below) are MAR suitability parameters. Based on these parameters we are able to examine to what extent the previously screened areas are suitable (high/moderate/low) for installing the six selected MAR types (Table 10). This screening needs to be done separately for each MAR type for the suitable areas. The specific-level studies can provide information to regional water management authorities and experts.

In the next step, threshold values and defined categories are specified for both the set of general parameters and the set of specific parameters. This results in the geology/hydrogeology-based **selection criteria** that are defined based on literature data and professional experience.

Due to the restrictive nature of general parameters, these need to show two possibilities: if an area is *suitable* or *unsuitable* for a certain MAR technology. Categories have to be determined for each general parameter in order to define a threshold or interval(s) for suitability, or they have to be ordered within two sets: one for suitable and another for unsuitable values. For example, underground dams are only suitable in areas which have a slope angle lower than 8°. Hence, anything steeper than that is not suitable for underground dams, and those MAR schemes are removed from further processing. Areas with slope angles below 8° are considered to be suitable and move forward to specific screening. This restrictive screening step has to be carried out for each MAR technology. The intersection of the unrestricted areas contour the areas suitable for the given MAR technology, following the Boolean logic; if the answer for all general parameters is “suitable”, then the area is considered suitable and is worth being examined at the specific level (3rd step).

The territories which are considered to be suitable on a general level (2nd step) are further sub-divided into smaller areas of high, moderate, and low suitability, using the specific selection criteria (3rd step). This procedure aims at identifying areas that are most promising for the given MAR technology. In order to rank the areas based on their suitability, possible specific parameter values are assigned to suitability ranges or sets. As an example for range allocation, underground dams are considered highly suitable on flat areas (slope of 0-2°), moderately suitable on slightly undulating surfaces (2-4°), and have a low suitability on quasi-steep areas (4-8°). Such ranges have to be given for every parameter of each MAR type, although the level of importance of the different factors is not equal. Since parameters have a different effect on suitability, a weight has to be assigned to each of them. E.g. for the case of aquifer storage and recovery (ASR), the aquifer transmissivity plays a more significant role than the slope, and therefore has a higher weight. In our study, the Multi Influencing Factor (MIF) technique is used for weighting, as described by e.g. Shaban et al. (2006) and Magesh et al. (2012).

The MIF technique investigates the influence of each criterion to the others, and based on the degree of correlation, a factor is assigned to each relationship. A factor of 1 is assigned if the criterion has a major influence on the other one, 0.5 if it has only a minor impact, and 0 if it has no significant impact. In general, determining the influences between parameter pairs is done based on professional experience (in the current project, by the respective experts within the project consortium). After the relationships of the considered factors have been defined, the relative importance of each criterion can be calculated. To do so, parameter values have to be standardized. Parameter ranges are defined and min and max values are assigned to each of them. The higher the suitability, the higher the value. Moderate suitability, as well as non-indicative ranges (which can play either a positive or negative role), are both defined by assigning half of the maximum value (0.5). After each criterion has been given a suitability category number, it is multiplied with the sum of the factors from the relationships. The final weight of a criterion is given by the sum of its multiplied suitability values divided by the sum of the multiplied suitability values for all criteria, expressed in percentage.

3.2.1 Parameters for selection criteria

The following parameter sets (Table 9 and Table 10) form the basis for developing geological and hydrogeological selection criteria. For geological and hydrogeological aspects, the aforementioned two groups (**general and specific parameters**) have three subgroups of parameters. These take into consideration the **characteristics of the water source**, the **surface characteristics** which define infiltration, and the **aquifer characteristics** which define, among others, the water storage capacity. While land use is neither a geological nor a hydrogeological parameter, it should still be considered a component of surface characteristics as it affects other important parameters (e.g. infiltration, depth of the groundwater table). At the same time, it also determines the possibility of using an area for different MAR technologies (e.g. urban areas or natural reserves are unsuitable areas for MAR systems).

Table 9: General parameter set for geological and hydrogeological MAR restriction parameters.

GENERAL PARAMETER SET / MAR RESTRICTION PARAMETERS

MAIN PARAMETER CATEGORY	NAME OF THE PARAMETER(S)	TYPE OF THE PARAMETER(S)	DIMENSION	EXPLANATION
CHARACTERISTICS OF THE WATER SOURCE	distance from surface water source	numeric value	number/ category	The distance of the surface water source can define its suitability. A long distance entails higher costs, due to the need for hydraulic infrastructure to transport the water.
SURFACE CHARACTERISTICS	lithology of the surface formations	category	category	The lithology of the surface formations is an important geological and hydrogeological parameter that influences hydraulic and biogeochemical processes, such as infiltration and aquifer recharge.
	slope	numeric value	number/ category	Many processes related to the land surface depend on the slope. Some MAR types require specific slope categories. Areas with a high relief are not optimal for various MAR types, due to the resulting surface water runoff characteristics (high runoff rates). In contrast, in areas with a very low relief, recharge might be lower compared to hilly landscapes, such that these areas might not be well suited as a water source. Sites with low slopes show comparatively low surface water runoff and still enable comparatively high infiltration. However, on steep slopes it is possible to slow/prevent parts of the runoff by constructing recharge dams, which can facilitate infiltration.
AQUIFER CHARACTERISTICS	depth of the top of the aquifer (location)	numeric value	number/ category	The top of the aquifer has to be located within an acceptable range in view of related MAR operational costs. It specifies suited technological solutions for some MAR types (e.g. well injection). Deeper aquifers require different MAR systems than shallow aquifers.
	lithology of the aquifer	category	major rock types	The lithology of the aquifer is an important geological and hydrogeological parameter that influences hydraulic and biogeochemical processes in the subsurface, such as groundwater flow, storage properties, as well as fate and transport of groundwater pollutants.
	depth of the groundwater table	numeric value	number/ category	Provides information on water storage capacity and availability. Deeper aquifers need different MAR systems than shallow aquifers. A very shallow groundwater table usually leads to unsuitable conditions for MAR systems. For each MAR scheme there are optimal ranges for the groundwater table in order ensure an efficient use of MAR.

Table 10: Specific parameter set for geological and hydrogeological MAR suitability parameters.

SPECIFIC PARAMETER SET / MAR SUITABILITY PARAMETERS

MAIN PARAMETER CATEGORY	NAME OF THE PARAMETER(S)	TYPE OF THE PARAMETER(S)	DIMENSION	EXPLANATION
CHARACTERISTIC OF THE WATER SOURCE	distance from surface water source	numeric value	number/category	The distance of the surface water source can define its suitability. A long distance implies higher costs for the realization due to the need for hydraulic infrastructure to transport the water. Exceeding a threshold value for the distance of the surface water source can be a constraint parameter for certain MAR types.
SURFACE CHARACTERISTICS	lithology of the surface formations	category	category	As described in Table 9.
	(hydrologic) soil type	category	texture class (sand, silty clay loam, loam, clay, etc.) and/or hydrologic soil group	Soils can be classified into four hydrologic soil groups based on the soil's runoff potential (USDA, 2009): Group A sand, loamy sand, or sandy loam Group B silt loam or loam Group C sandy clay loam Group D clay loam, silty clay loam, sandy clay, silty clay, or clay
	land use	category	e.g. pasture, agricultural terrain (arable land), forest, surface water, urban areas, industry	The land use affects important parameters such as infiltration, depth, and gradient of the groundwater table, or the suitability of an area for MAR (e.g. urban areas or nature reserves are usually not optimal areas for MAR systems).
	slope	numeric value	number/category	As described in Table 9.
AQUIFER CHARACTERISTICS	confinement of the aquifer	category	confined/semi-confined/unconfined	It defines e.g. hydraulic pressure conditions of the aquifer and recharge mechanisms/pathways. Confined aquifers may be recharged (replenished) by precipitation or stream water infiltrating at considerable lateral distance.
	thickness of the aquifer	numeric value	number/category	Some parameters depend on the thickness of the aquifer, such as transmissivity or aquifer storage.
	depth of the top of the aquifer (location)	numeric value	number/category	The top of the aquifer has to be located within an acceptable range in view of related MAR operational costs. It specifies suited technological solutions for some MAR types (e.g. well injection). Deeper aquifers require different MAR systems than shallow aquifers.
	depth of the aquifer base (location)	numeric value	number/category	The aquifer base (impermeable layer below the aquifer) has to be in an acceptable range regarding MAR operational costs. It specifies technological solutions e.g. for underground dams.
	lithology of the aquifer	category	major rock types	As described in Table 9.
	depth of the groundwater table	numeric value	number/category	As described in Table 9.
	regime type of the groundwater flow system	category	recharge/transition/discharge area	Recharge and transition areas can be used for different MAR types. That said, regional recharge and discharge areas are not optimal due to dominant vertical groundwater flow components.
	Presence of subsurface structures providing storage or acting as barriers or channels	Boolean	yes/no	Subsurface structures (heterogeneities) can act as channels or barriers that guide or restrict groundwater flow locally. They can also form geological traps providing prosperous water storage potentials (such as buried riverbeds, alluvial fans in piedmont zones, buried anticlines and synclines, tectonic traps).
	Storage coefficient	numeric value	number/category	It is used to characterize the aquifer storage and is also important for determining MAR potentials and expected performance and limitations (among others).

3.2.2 Data processing

After collecting geological and hydrogeological information, a GIS-based analysis must be performed to create the suitability maps. GIS software can be used for the creation of maps related to the defined geological and hydrogeological selection criteria.

3.2.3 Selection of potential MAR locations in karst areas

Methodologies for MAR suitability mapping in karst areas are based on the proposed geological and hydrogeological selection criteria, as described above. Significant discrepancies exist in the consideration of processing the geological and hydrogeological data, namely, their resolution and scale of mapping. After many trials to develop water resources in karst terrains, it was found that pre-existing methods which are used for other geological environments must be modified. Some of these are simply not applicable for karst environments, whatsoever (e.g. Milanović, 2018). Due to the extreme complexity and heterogeneity of karst systems, extensive research is required to provide geological and hydrogeological parameters that can be considered adequate for suitability mapping.

3.3 Analysing the sensitivity of MAR systems to climate-induced extreme situations

3.3.1 Impact Chains

To understand the concept of analysing the sensitivity of MAR systems to extreme climate events, it is necessary to characterise the inputs, outputs, and interconnection among parameters. A methodological approach via **impact chains** considers the combination of different processes that lead to hazardous events which have a potential adverse impact on MAR schemes (as e.g. applied by Fritzsche et al., 2014; Briche et al., 2018; Chapman et al., 2018). This is indicated in Figure 9, and the used terms are explained further below.

Analysing the sensitivity of particular MAR schemes to extreme climate events includes a process of evaluation (first row in Figure 9) comprising effects that originate from stimuli/triggers (i.e. climate/ weather extreme events). Extreme climate situations, might cause hazardous events as the result of several combined impacts. These include natural hazards and anthropogenic impacts, the influence of specific local surface characteristics (e.g. soil hydraulic properties), and hydrogeological conditions (Figure 9). Such hazardous events can have adverse effects on MAR schemes. By analysing the sensitivity of MAR systems to these effects, specific precautions, i.e. precautionary measures, can be defined for MAR systems (as described below). These help ensure an adequate and safe technological design, implementation, and operation.

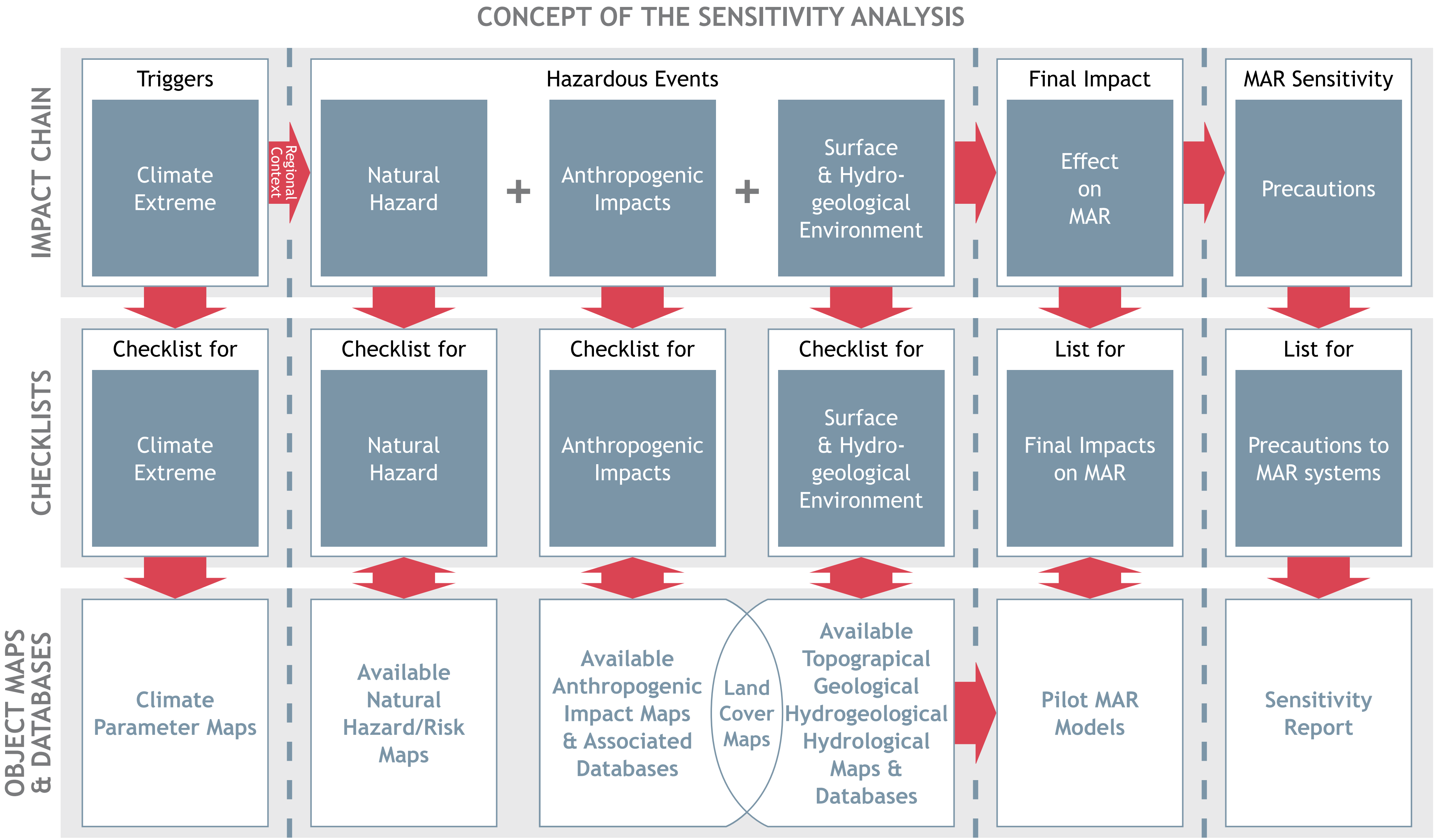


Figure 9: Proposed methodology of analysing the sensitivity of MAR systems to climate extreme events.

In each impact chain category, **checklists** are created (cf. second row in Figure 9) for the six selected MAR types (as specified in Section 1.2). The checklists comprise triggers of climate extremes that result in hazardous events (natural hazards and anthropogenic impacts, influenced by the surface and hydrogeological environment) and also aim at describing the final impacts on selected MAR schemes. This is followed by specifying precautions for MAR systems, shown in another checklist. The information provided in the checklists can be used by potential MAR users as a basis for developing thematic maps, databases, or models for MAR sites at the site-specific level (cf. third row in Figure 9).

At the first level of detail, checklists for analysing the sensitivity of MAR to extreme climate events are compiled. These are named **general checklists** (Section 3.3.1.7). At the second level of detail, **checklists specific to** all six **selected MAR types** are compiled (part of Chapter 4).

These checklists can contribute to the task of drafting recommendations for the planning and implementation of future MAR systems. Terms within the checklists which are used for the methodological concepts, are explained in the following sections. Most of them originate from the Intergovernmental Panel on Climate Change (IPCC, 2012). The final section contains a general checklist for the climate-related sensitivity analysis.

3.3.1.1 Triggers

Climate extremes (extreme weather) refer to climatic conditions which diverge from given threshold values (above/below). These are defined based on long-term weather and climate observations (IPCC, 2012). An extreme *weather* event is typically associated with changing weather patterns on time scales of less than a day and up to a few weeks. An extreme *climate* event occurs on longer time scales; it can be the accumulation of several (extreme or non-extreme) weather events. For simplicity, in our project both extreme weather events and extreme climate events are referred to collectively as “climate extremes”. In this project, climate extremes cover extreme precipitation events that result in water abundances or shortages, as well as related natural hazards. They are also influenced by other atmospheric and surface conditions.

Climate extreme events trigger hazards to the environment and human systems (e.g. urban areas, energy grid, industry), including MAR operations. According to the terminology of the United Nations Office for Disaster Risk Reduction (UNDRR, 2020), a hazard can be a process, phenomenon, or human activity that may cause losses, health impacts, property damage, social and economic disruption, or environmental degradation. Hazards may be single, sequential, or combined in their origin and effects. Each hazard is characterized by its location, intensity or magnitude, frequency, and probability.

The characteristics of extreme climate events are generally related to temperature and precipitation. In the case of MAR systems, precipitation is an important factor (the abundance or lack of). Triggers that cause climate extremes can be initiated by: (i) a short period of extremely large amounts of precipitation; (ii) an extremely long period of precipitation; (iii) an extremely high frequency of precipitation events; and/or (iv) extremely high amounts of snow accumulation. All of these conditions can cause natural hazards such as floods (flash floods, floods, increased surface runoff, or excess inland water). In the case of a lack of precipitation, the trigger parameters are: (i) an extremely low amount of precipitation; (ii) extremely high temperatures and evapotranspiration; (iii) an extremely low amount of snow accumulation; and/or (iv) extremely low temperatures. The latter four conditions can cause soil droughts, surface water droughts, and groundwater droughts.

Wet and dry periods can be determined by the following climate-related indicators, which originate from climate model data (Table 6). **Wet periods:** Intensity of precipitation, number of days with precipitation above 10, 20, or 30 mm (case-specific), number of consecutive rainy days. **Dry periods:** maximum number of consecutive dry days, potential evapotranspiration, number of days when the daily maximum temperature exceeds 25, 30, or 35°C.

Examples of how climate extremes, as trigger parameters, can result in natural hazards are given in Figure 10 for wet and dry conditions.

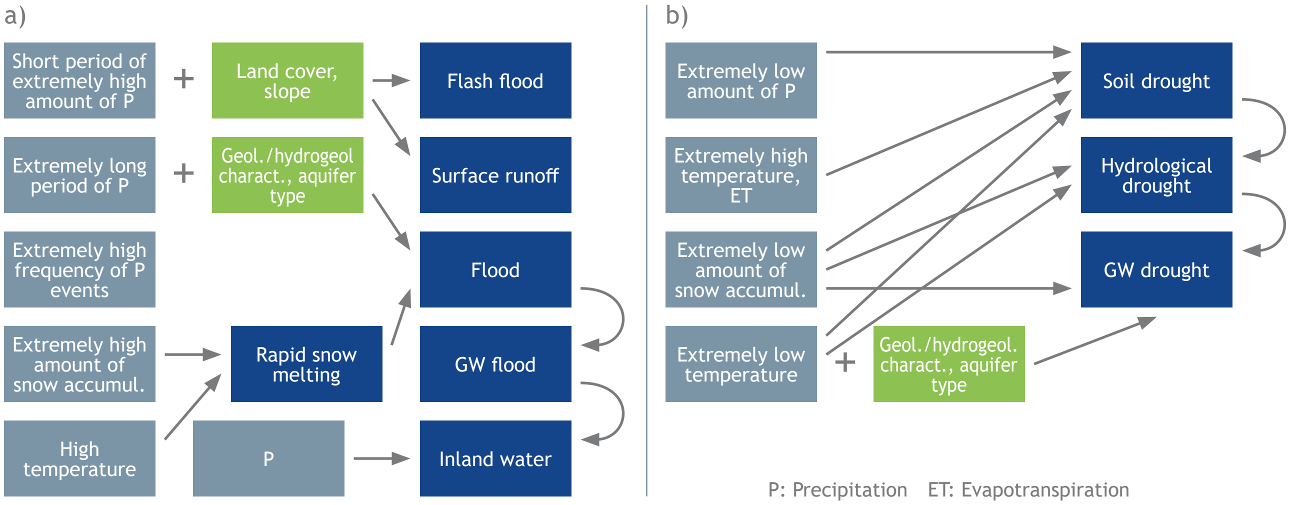


Figure 10: Trigger parameters causing natural hazards a) in wet periods, b) in dry periods (examples).

3.3.1.2 Hazardous events – natural hazards and anthropogenic impacts

In general, **natural hazards** are naturally occurring physical phenomena caused either by a rapid or slow onset of events. They include geophysical or geological events (earthquakes, landslides, volcanic activities), hydrological events (avalanches, floods), climatological events (extreme temperatures, drought, wildfires), meteorological events (cyclones, storms), or biological events (disease epidemics, insect plagues) (e.g. UNDRR 2020, IFRC 2020). The following section describes natural hazards in more detail, and lists the expected ones for the Central European region.

A **drought** is an event of prolonged shortage in water supply, which includes atmospheric water, surface water, and groundwater (NOAA, 2006). A **hydrological drought** refers to the lack of water in a hydrological system. This can result in abnormally low river streamflow and low water levels in lakes, reservoirs, and groundwater (Van Loon, 2015). The duration and periodicity of such conditions have to be analysed. Threshold values of hydrological droughts are commonly based on certain percentiles of the flow-duration curve (Tallaksen et al., 1997), such as Q80 discharge of the surface watercourse. The Q80 discharge is the flowrate value that is exceeded by 80 percent of recorded flow events within an observation period. The duration of this period should be at least one year, yet more often longer time periods (several years or decades) are used for calculating the Q80 value. The duration and intensity of a hydrological drought can be expressed by the Streamflow Drought Index (SDI). The SDI calculation is based on average monthly discharge values and essentially follows the calculation of the Standardized Precipitation Index (SPI) index (e.g. Nalbantis and Tsakiris 2009). Positive SDI values reflect wet conditions, while negative values indicate a hydrological drought.

A **Groundwater drought** refers to low groundwater levels (daily or monthly values) and the duration of such conditions compared to long-term averages of the groundwater level. This consequently leads to lower water flows to groundwater-fed rivers and wetlands. Threshold values, such as the groundwater level showing an exceedance of 80 % within the entire evaluated period (GWL80), are calculated the same way as the values of Q80 flow for surface watercourses. The Standardised Groundwater Level Index SGI (e.g. Bloomfield and Marchand, 2013) can be used to express the duration and intensity of droughts. The SGI index is built on the SPI approach, similar to the SDI index.

A **Soil drought** (physiological) is the state of soil water at which the plant biomass production decreases to below its maximum (potential) rate. This occurs when a plant's transpiration rate becomes lower than the rate of potential transpiration. The soil water content (SWC) at the start of a (physiological) soil drought is approximately twice that of the wilting point (WP), and half the SWC of saturated soil saturated. During a (physiological) soil drought, groundwater recharge is minimized or interrupted (Novák and van Genuchten, 2008).

As defined by Article 2.1 of Directive 2007/60/EC on the assessment and management of flood risks (EC 2007), a "'**flood**' is the temporary covering of (usually dry) land by water. This includes floods from rivers, mountain torrents, Mediterranean ephemeral water courses, as well as coastal flooding, and may exclude floods from sewerage systems". Inland floods are caused by abundant precipitation. Moreover, the intensity and periodicity of a flood are important factors, which can be defined by the n-year-flood discharge (e.g. n = 20 years, 50 years, 80 years, and 100 years).

Storm water runoff / flash floods tend to occur due to intensive precipitation. Depending on the geomorphology of the area, torrential precipitation can cause flash floods in hilly and mountainous terrains and surface runoff (with lower flow rates than flash floods) on more gradual slopes. Particularly strong impacts can often be seen in small catchments, based on empirical data (e.g. in an area up to 100 km^2, a precipitation event lasting up to three hours can amount in ~100 mm of rainfall).

Inland excess water refers to ponding on the surface of undrained areas. The water can originate from precipitation, ascending groundwater (groundwater flooding), incoming water from other areas, or seepage through (or below) embankments.

Land use involves the management and modification of a natural environment or wilderness into a built environment. These may include settlements or semi-natural habitats like arable fields, pastures, or managed woods. Land use influences the suitability of MAR schemes, by e.g. changing specific recharge properties of the subsurface or polluting groundwater.

Groundwater overexploitation occurs due to intensive water abstraction – i.e. when the average abstraction rate from an aquifer is greater than, or close to, its average recharge rate. This results in a significant reduction in groundwater levels. Overexploitation has a significant impact on water supplies, even under normal climatic conditions. During droughts, i.e. when the water demand is high (such as for drinking water use or irrigation), water stress considerably increases, leading to intensified conflicts between water users.

A **diffuse pollution source** refers to areal pollution – from e.g. agricultural origin (such as plant protection products and fertilisers) or contaminants from the atmosphere – that leach into surface waters or groundwater.

A **point pollution source** refers to a concentrated pollution source (e.g. waste landfills, fuel spills, wastewater treatment plants, the leakage of untreated urban water via sewer systems).

Mining activities – which entail, for example, pumping of groundwater and pond construction – can cause various negative environmental impacts, affecting both water quality and water quantity.

3.3.1.3 Surface and hydrogeological environment

Land cover refers to the structure and characteristics of the Earth's surface, such as vegetation (e.g. agricultural land, grass land, trees and forests, impacts by deforestation) or ground sealing (settlements, pavements).

The **slope and geomorphology** of an area influence the suitability for MAR systems. For example, steep slopes are prone to landslides, and therefore flat terrains are most suitable for many MAR types.

Surface water sources (such as rivers, lakes, dams, wetlands) in a sufficient quantity and quality are crucial for many MAR types. MAR schemes which utilize surface water are usually located in proximity to surface water bodies. Thus, floods can lead to the inundation of MAR infrastructure (such as water treatment plants or rainwater collecting systems) and to the pollution of groundwater by infiltrated contaminated surface water.

Soil hydraulic properties of an area surrounding MAR schemes influence infiltration and thus aquifer recharge.

The **aquifer type** – with respect to rock type (porous, fractured, karst) and hydraulic conditions (confined, unconfined, semi-confined) – also influences the MAR scheme selection. Unconfined aquifers are characterized by a free groundwater table, fed by infiltration from areas located above it. Confined aquifers are bounded at their top and bottom by impermeable, or very low-permeable, layers that prevent infiltration from areas located directly above. For the semi-confined aquifer, the condition (confined or unconfined) can change locally (due to heterogeneities) or temporally (unconfined if the groundwater table is located below the top impermeable layer). Porous aquifers consist of loose sediments with water-saturated pores (such as alluvial plains), and fractured aquifers of solid rocks (such as sandstone with water-filled fractures). Karst aquifers are formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. They have highly heterogeneous porosities (water filled pores up to water-filled conduits and caves). Specific characteristics of karst aquifers are summarized in Appendix A2.

The term **aquifer characteristics** summarizes key properties for water recharge, transmission, and storage in the subsurface (such as porosity, transmissivity, storage coefficient).

Groundwater quality can be influenced by, for example, changes in groundwater chemistry (leading to different contents of dissolved ions) or the intrusion of polluted water (e.g. induced by changed hydraulic conditions).

The **position in the groundwater flow system** includes lateral points (e.g. recharge, transitional or discharge area) and vertical points (e.g. order of aquifers in vertical position, aquifer depth and thickness).

The **geological structure** includes, among others, inhomogeneities such as layering, intercalation, fractures, or faults. These can influence infiltration and recharge, as well as groundwater flow.

Coastal areas are especially sensitive to sea water intrusions.

3.3.1.4 Effects on MAR systems

Various combinations of natural hazards and anthropogenic impacts, which occur within environments of different surface and hydrogeological characteristics, can have adverse effects on MAR schemes. These effects differ for (extremely) wet and (extremely) dry periods.

During **wet periods**, possible outcomes include landscape erosion, landslides (if slopes are instable), the flooding of infrastructure (e.g. water treatment or desalination plants, rainwater collecting systems), the clogging of streambeds and streambanks (preventing water filtration for groundwater recharge), groundwater overflow, increased water residence times in ponds during floods (which can cause e.g. eutrophication), the contamination of (shallow) aquifers by infiltration of polluted flood water, the mobilization or dissolution of contaminants (biological, chemical, or physical processes), the intrusion of polluted (or saline) groundwater from other aquifers (due to changed hydraulic potentials during floods), or sea water intrusion.

During **dry periods**, the following adverse effects on MAR systems can occur: A reduction of water storage in ponds due to sedimentation, the depletion of surface water sources, lower groundwater levels (due to low groundwater recharge), an increase in pollutant concentration (due to a lower volume of water), the eutrophication of surface water sources, and the intrusion of polluted water or salt water into freshwater sources (due to changed hydraulic conditions).

3.3.1.5 Precautions for MAR systems

In order to avoid or mitigate adverse effects to MAR systems, precautionary and protective measures are required. In the context of this work, the term **“precaution”** refers to the prevention of adverse effects. Such precautions should be considered for the implementation of MAR schemes. For both extreme periods (wet and dry), the required precautions are specific to the MAR scheme. In general, precautions address temporary interruptions in the operation of the MAR system, structural damage to MAR infrastructure, as well as water quantity and water quality problems.

3.3.1.6 General checklist for analysing MAR sensitivity to extreme climate events

Table 11 presents a general **checklist for MAR sensitivity**, including criteria (potential aspects) of climate-related stimuli, hazards/impacts, and precaution targets. Specific aspects for the six selected MAR schemes (cf. Section 1.2) are given in Section 4.4 (**MAR-specific general checklists**). There are numerous possible combinations of these criteria, and realistic (expected) combinations for a potential MAR site depend on site conditions and characteristics, as well as on the intended MAR scheme. For this task, the elaboration of site-specific impact chains is recommended (for concrete cases, based upon site-specific information and data). Within the DEEPWATER-CE project, this is done as part of site-specific feasibility analyses for four MAR pilot sites (to be implemented in Hungary, Croatia, Poland and Slovakia; as part of work package WP T3).

Table 11: Overall checklist for analysing the sensitivity of MAR to extreme events. P: precipitation, GW: groundwater, SW: surface water.

TRIGGER/STIMULUS		HAZARDOUS EVENTS				FINAL IMPACT	SENSITIVITY TO MAR
	CLIMATE EXTREMES		NATURAL HAZARDS	ANTHROPOGENIC IMPACTS	SURFACE & HYDROGEOLOGICAL ENVIRONMENT	EFFECT ON MAR	PRECAUTION TARGETS
WET PERIOD	Short period of extremely high P amount Extremely long period of P Extremely high frequency of P events Extremely high amount of snow accumulation	FLASH FLOOD	Flash flood Extreme run-off	**Overexploitation of GW** (changes in GW dynamics) **Land use impacts** (urban, industrial, agricultural) leading to water overexploitation **Diffuse pollution** (e.g. agriculture-related soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) **Point pollution** (e.g. waste landfills, fuel spills, wastewater treatment plants, untreated urban water) **Mining activity** (intensive drainage of SW and GW; leaching of pollutants)	**Land cover** (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) **Slope** (e.g. influence of infiltration) **SW source** (e.g. surface water level dynamics) **Soil hydraulic properties** **Aquifer type** (unconfined, confined, porous, fractured, karst, etc.) **Aquifer characteristics** (e.g. porosity, transmissivity, properties related to pollutant transport & fate) **Connection between aquifers** **GW quality** (e.g. dissolved mineral content, changes in GW chemistry) **Position in the GW flow system** (recharge, transitional or discharge area; order of aquifers in vertical position; aquifer depth & thickness) **Geological structure** (fractures, faults, other in-homogeneities) Coastal area	**Slope instabilities** (e.g. landslides) **Erosion** **Flooding of infrastructure** (e.g. of treatment/desalinization plant, rainwater collecting system) **Decrease of water storage in SW bodies** due to sedimentation **Increased residence time in SW bodies** Eutrophication **Overflowing GW Clogging** (by fine particles or biogeochemical processes) **Contamination of (shallow) aquifers** (infiltration, influx from surface water; salt water intrusion from ocean) **Mobilization or dissolution of contaminants** (biological, chemical, physical) **SW sources or GW production wells drying out** **Reduction in GW well yield** (due to GW table depression, decrease of GW level, decrease of GW recharge)	**Temporary interruption in MAR operation** **Structural damage in MAR infrastructure & related effects** (specific to MAR type & technology) **Water quantity problems & related effects** (specific to MAR type & technology) **Water quality problems & related effects** (specific to MAR type & technology)
		FLOOD	Flood (high P) Rapid snow melting Extremely high GW table ("GW flooding") Inland excess water				
DRY PERIOD	Extremely low P amount Extremely high temperature/ET Extremely low amount of snow accumulation Extremely low temperature/ET	HYD. DROUGHT	Low surface water level for extremely long time durations Drought (lack of physical P)				
		GW DROUGHT	GW table depression				
		SOIL DROUGHT	Decrease of soil moisture and GW recharge				

4. Implementation of the decision-support toolbox

In this chapter, the decision-support toolbox is presented. This toolbox aims at supporting the decision process for implementing MAR systems, with a focus on the region of Central Europe. It consists of the proposed four-step procedure (Table 1), and includes checklists and maps that were developed based on the previously described methodologies.

4.1 First step: Climate-related selection criteria

The first step of the proposed procedure evaluates (future) climatic conditions. It aims at answering the question "where is MAR needed", primarily in light of climate change. This evaluation is made at a regional (Central European) scale, and thus it is not site specific. The available spatial resolution is 12.5 km x 12.5 km. This allows for investigations above the standard scales typically used to evaluate selection criteria related to geology/hydrogeology and checklists for sensitivity analysis to extreme events (cf. Table 1). The first step in this process is selecting areas based on climate-related criteria.

Mean annual values for temperature, precipitation, and evapotranspiration are used in order to calculate the climatological water balance. The latter indicates water deficit or surplus, from which related **climate exposure** is derived: this is essentially the **selection criterion**. Related data are derived from simulations using different climatological models (cf. Methods section), and maps are created (presented later in this chapter). The described changes exhibit different scenarios: (i) a "relatively optimistic scenario" (RCP4.5) and (ii) a "pessimistic scenario" (RCP8.5). Changes between the chosen reference period (1971-2000) and two future periods (2021-2050 and 2071-2100) are compared (cf. Methods section).

The simulated temperature changes indicate a clear future warming of the region. This warming appears more moderate in relatively optimistic scenario (Figure 11), and stronger in the pessimistic scenario (Figure 12). For the first half of the 21st century, climate models indicate a 0.5–2.5 °C warming, while by the end of this century, a possible temperature increase of up to 6.5 °C could occur for some areas (pessimistic scenario). It can also be seen that particularly high temperatures are expected for the Alpine region.

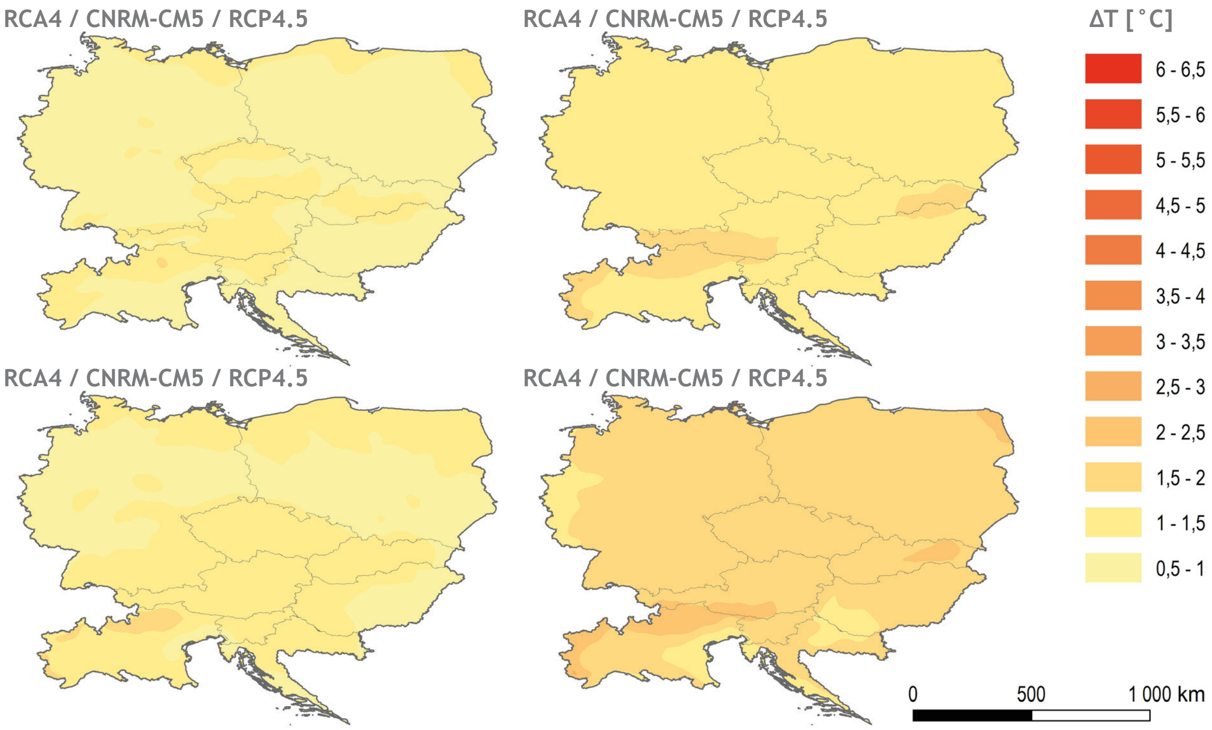


Figure 11: Simulated mean temperature change for 2021-2050 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

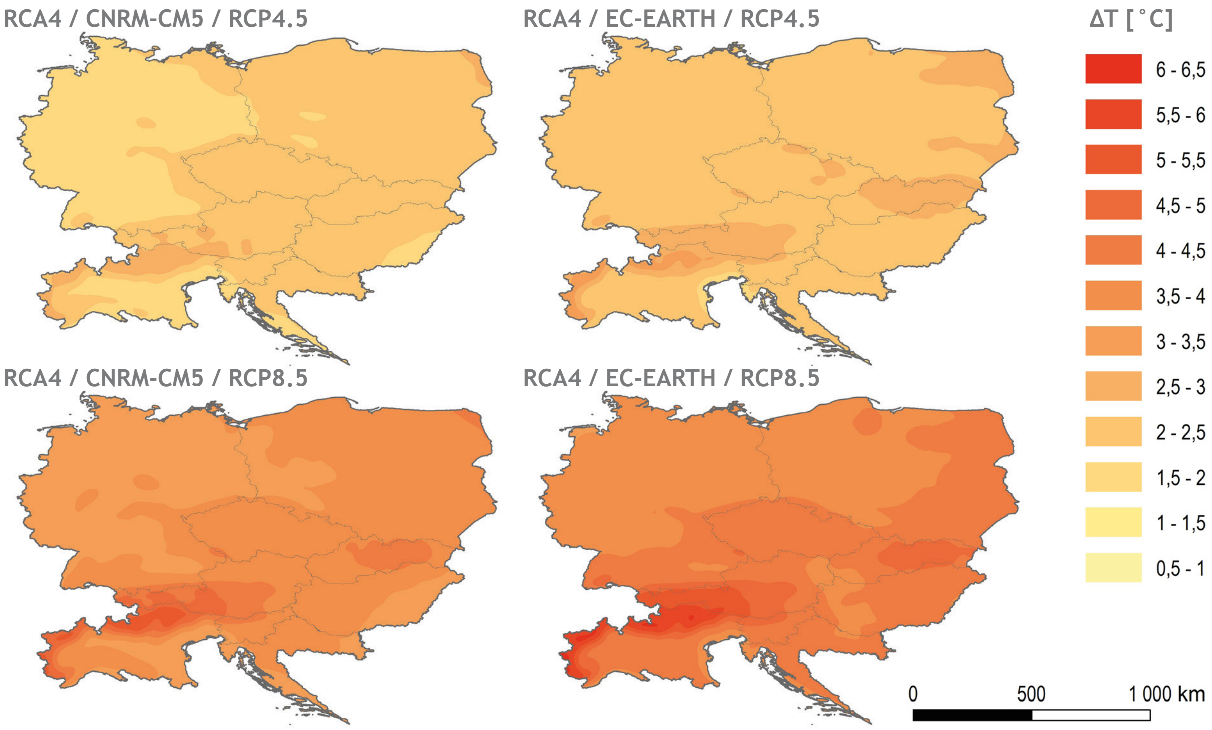


Figure 12: Simulated mean temperature change for 2071-2100 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

There is a higher uncertainty regarding the annual precipitation change (Figure 13 and 14), which shows greater variability. Both increasing and decreasing trends are plausible, yet these highly depend on the simulation run, as well as the time period and the location chosen. Based on these projections, expected precipitation changes could be between -200 mm to +300 mm, relative to the reference period. Pessimistic climate model scenarios project even greater changes, both positive and negative.

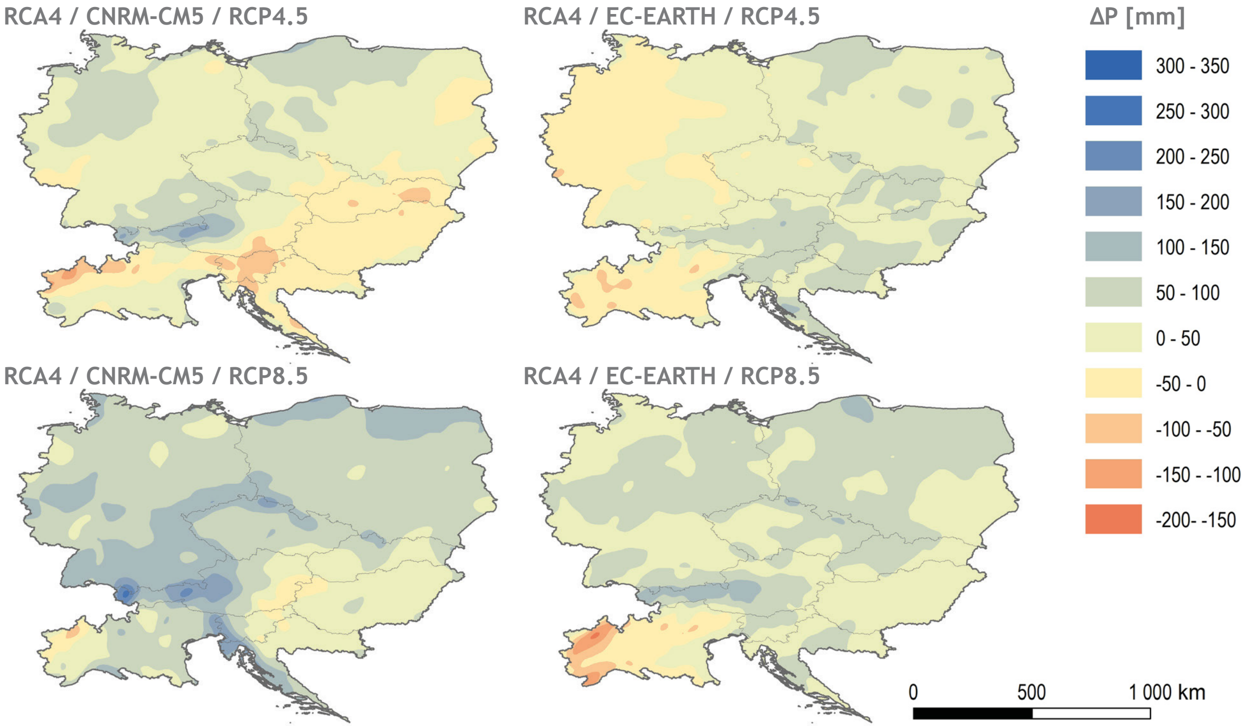


Figure 13: Simulated mean precipitation change for 2021-2050 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

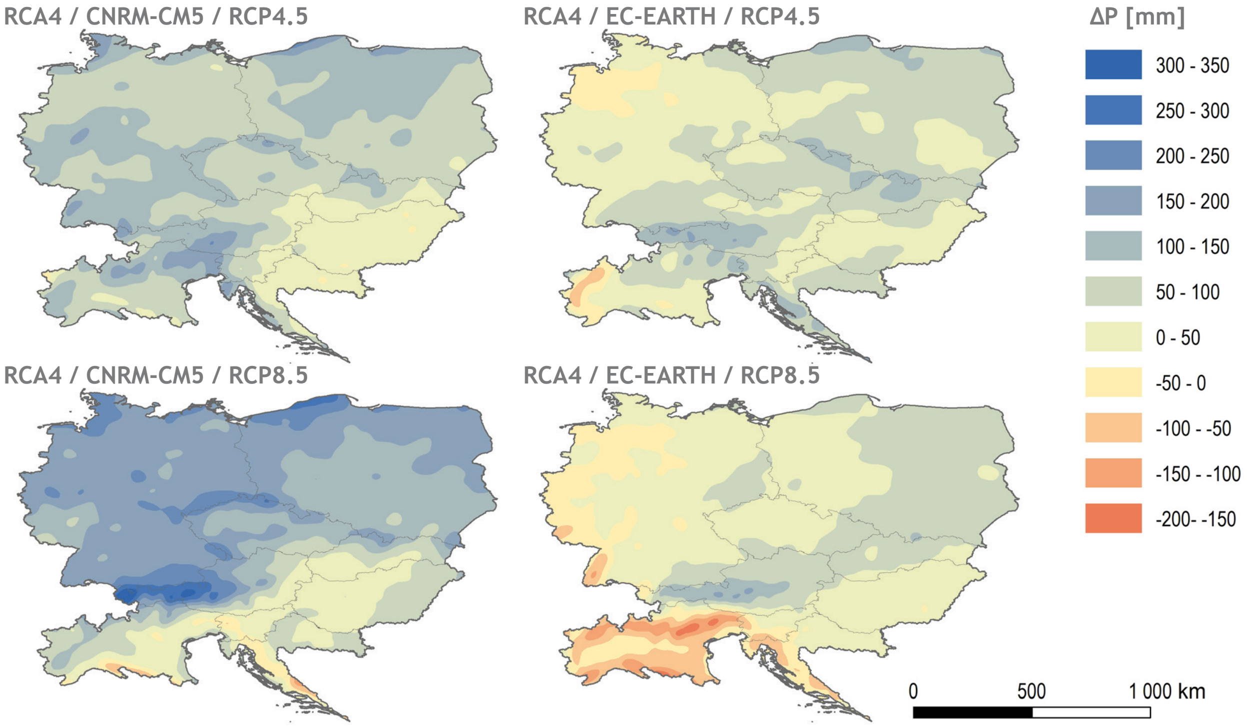


Figure 14: Simulated mean precipitation change for 2071-2100 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

Based on climate modelling results, we can conclude that the expected annual potential evapotranspiration will mainly increase (Figure 15 and 16). In the first half of the 21st century, simulations project an increase of 5-75 mm. However, by the end of the 21st century the increase may reach 250 mm. This is particularly true for the pessimistic scenario (RCP8.5) which projects an even higher increase in the southern part of the CE region.

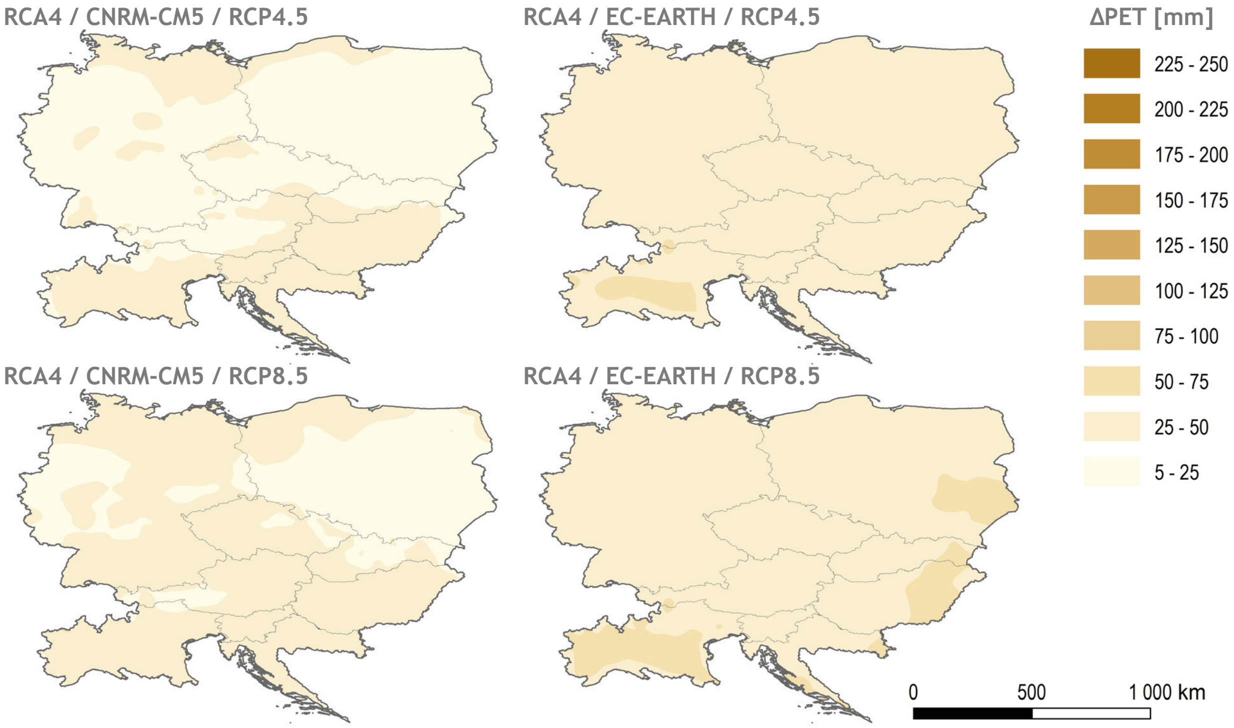


Figure 15: Simulated change of potential evapotranspiration (PET) for 2021-2050 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

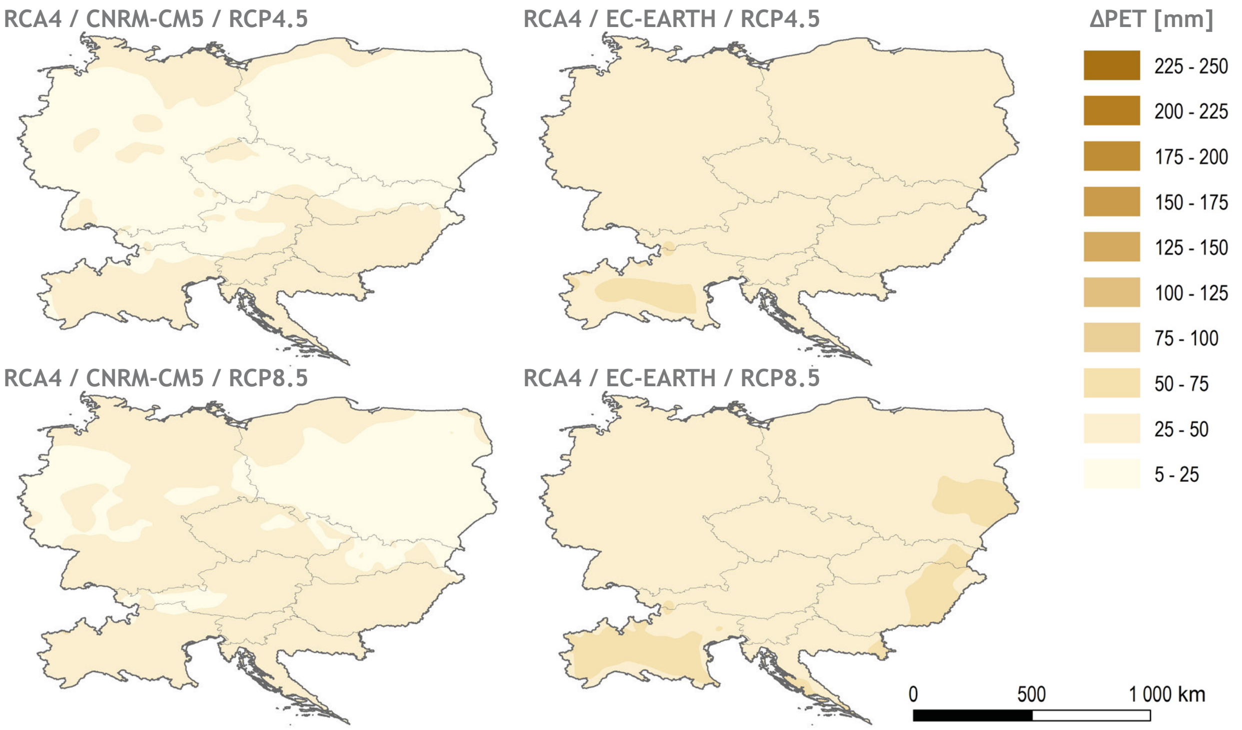


Figure 16: Simulated change of potential evapotranspiration (PET) for 2071-2100 (versus reference period 1971-2000). Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

Simulation results for the change of temperature, precipitation and potential evapotranspiration (presented in Figures 11-16) are used to calculate the climatic water balance, which is evaluated for climate exposure (cf. Methods section). Exposure evaluation is done using four climate exposure categories: (i) slightly exposed, (ii) moderately exposed, (iii) highly exposed, or (iv) extremely exposed to climate change (cf. Table 8).

Exposure maps obtained from simulations are shown in the following section. For the first half of the 21st century, moderate climate exposure is expected for many areas (Figure 17). Approximately two-thirds of the modelled Central European region is expected to be slightly or moderately exposed. However, in some areas (such as the Carpathian Basin), high or even extreme climate exposure is projected for the near future. Moreover, towards the end of the 21st century, a higher climate exposure is expected for most of the considered Central European region (Figure 18). In particular, the EC-EARTH projection (maps on the right-hand side) shows a large number of areas for which a high or extreme climate exposure is expected. This can be seen not only in the “pessimistic scenario” (RCP8.5), but also in the “relatively optimistic scenario” (RCP4.5). It affects all considered Central European countries.

Climate modelling results, and the analysis of the derived climate exposure indicators, strongly suggest that Central European countries should prepare for the effects of climate change. For that, the results shown here can help identify those areas where MAR technologies might be most needed in the near future.

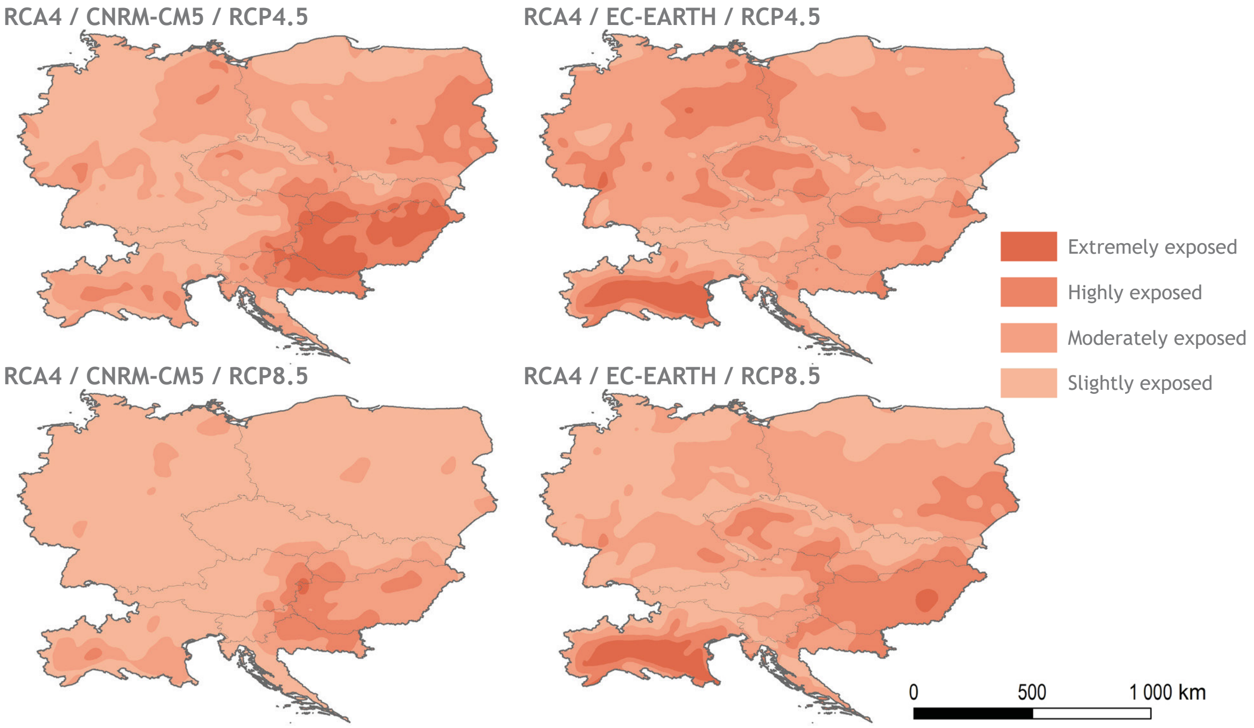


Figure 17: Simulated exposure due to climate change (based on climatic water balance) for 2021-2050. Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

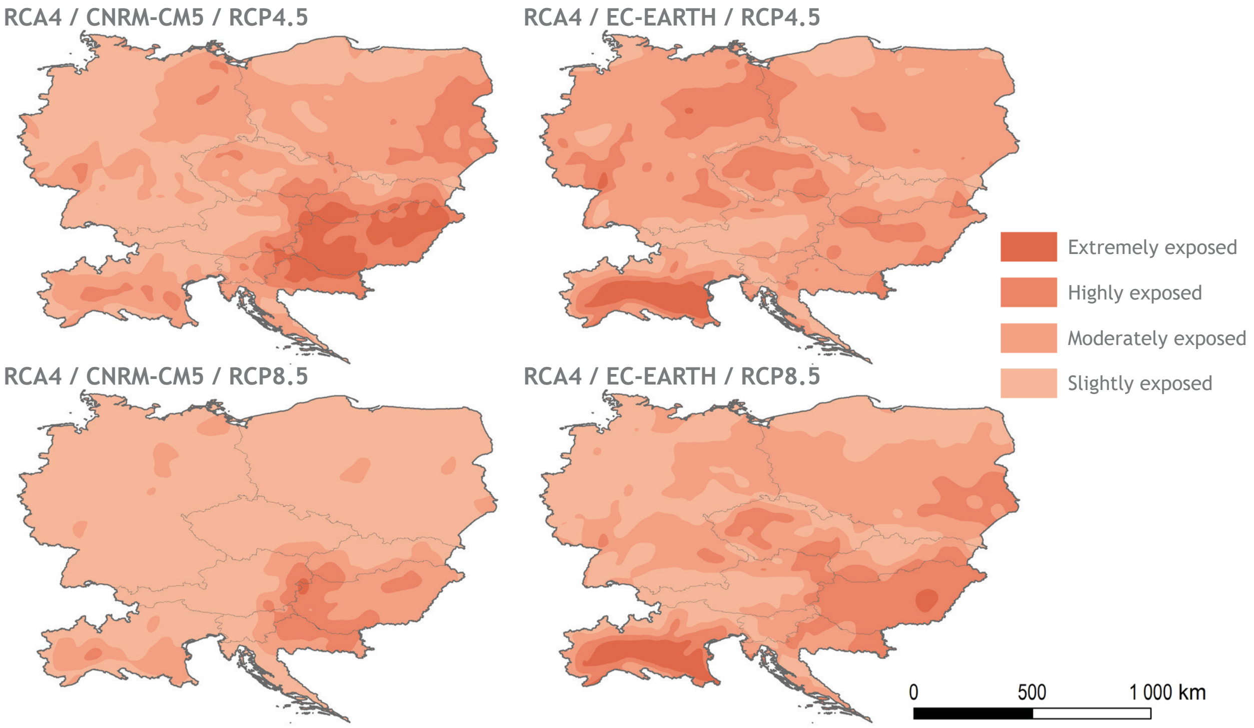


Figure 18: Simulated exposure due to climate change (based on climatic water balance) for 2071-2100. Two simulations for the relatively optimistic scenario (RCP4.5) and the pessimistic scenario (RCP8.5), respectively.

4.2 Second step: General screening with geological and hydrogeological selection criteria (MAR type specific)

The second step for evaluating MAR suitability refers to general screening, carried out at the national or regional level (cf. Table 1). Each selection criterion consists of the parameter category, its relevant parameter(s) and suitability thresholds for these parameter(s). Using these selection criteria, screening on the national or regional level can be done in order to distinguish between **suitable and unsuitable areas for MAR application** – it is therefore a restrictive screening (Table 1).

The parameters and their suitability thresholds can be mapped, and the maps can be used as a decision support tool for the selection of suitable pilot areas (for the next evaluation step, Section 4.3). In the following, the general selection criteria are summarized specifically for the six selected MAR types (Table 12-17).

Table 12: Selection criteria for general screening.

MAR type: **DITCHES**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	<15 m or >1500 m	15 to 1500 m
SURFACE CHARACTERISTICS	Lithology of the surface formations	slightly fractured igneous rocks, volcanic rocks, metamorphic rocks, fine-grained sediments	coarse-grained sediments and sedimentary rocks, moderately to highly fractured and karstified rocks
AQUIFER CHARACTERISTICS	Depth of the groundwater table	<2 m or >20 m	2 to 20 m
	Lithology of the aquifer	fine-grained sediments and sedimentary rocks, slightly fractured igneous and metamorphic rocks, non-karstified and slightly fractured carbonate rocks	coarse-grained sediments and sedimentary rocks, moderately to highly fractured and karstified rocks

Table 13: Selection criteria for general screening.

MAR type: **INDUCED RIVER AND LAKE BANK FILTRATION**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	<15 m or >1000 m	15 to 1000 m
AQUIFER CHARACTERISTICS	Lithology of the aquifer	fine-grained sediments and sedimentary rocks, igneous and metamorphic rocks, carbonate rocks	coarse-grained sediments

Table 14: Selection criteria for general screening.

MAR type: **AQUIFER STORAGE AND RECOVERY**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
AQUIFER CHARACTERISTICS	Depth of the top of the aquifer	<5 m or >1000 m	5 to 1000 m
	Depth of the groundwater table	<5 m	≥5 m
	Lithology of the aquifer	fine-grained sediments and sedimentary rocks, unfractured igneous and metamorphic rocks, carbonate rocks	gravel, sand, karstified and/or fractured rocks

Table 15: Selection criteria for general screening.

MAR type: **INFILTRATION POND**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
SURFACE CHARACTERISTICS	Lithology of the surface formations	Unfractured or slightly fractured igneous and metamorphic rocks, fine-grained sediments and sedimentary rocks	coarse-grained sediments and sedimentary rocks, moderately to highly fractured and karstified rocks
	Slope	>10°	≤10°
AQUIFER CHARACTERISTICS	Depth of the groundwater table	<5 m	≥5 m

Table 16: Selection criteria for general screening.

MAR type: **UNDERGROUND DAM**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
SURFACE CHARACTERISTICS	Slope	>8°	≤8°
AQUIFER CHARACTERISTICS	Depth of the groundwater table	>20 m	≤20 m
	Lithology of the aquifer	igneous rocks, volcanic rocks, metamorphic rocks, fine grained sediments	alluvial deposits, porous sediments (mainly sand), carbonates (karstic or fractured)

Table 17: Selection criteria for general screening.

MAR type: **RECHARGE DAM**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	SUITABILITY THRESHOLD	
		NOT SUITABLE	SUITABLE
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	>0 m	0 m
AQUIFER CHARACTERISTICS	Depth of the groundwater table	<30 m	≥30 m
	Lithology of the aquifer	igneous rocks, volcanic rocks, metamorphic rocks, fine-grained sediments	alluvial deposits, porous sediments (mainly sand), carbonates (karstic or fractured)

4.3 Third step: Specific screening with geological and hydrogeological selection criteria

The third step, i.e. **specific screening**, requires more specific selection criteria for the evaluation of areas found “suitable” in the second step (previous section). Here, a differentiation between karstic and porous aquifer is necessary (cf. Section 3.2.3 and Appendix A1 and A2).

In contrast to the more robust general selection criteria defined in the previous section, the specific selection criteria allow to evaluate potential areas (and suitability) for MAR in more detail. In order to sort them into **low**, **moderate**, and **high suitability** categories, detailed geological and hydrogeological characteristics have to examined, which often differ in their level of importance for each MAR scheme. As an example, for the aquifer storage and recovery (ASR) technology, the surface slope is not as important as the lithology of the aquifer, since the slope does not affect MAR applicability to much extent. To deal with this unbalanced nature of the parameters, and to handle possible correlations between them, weighting must be applied. More significant/dominant values have higher weights than less important ones and thus contribute more to the suitability of a MAR technology. In our study, we used the **Multi Influencing Factor** (MIF) technique for weighting (cf. Methods section). Table 18-23 summarize specific selection criteria, with respect to geology and hydrogeology, for the six selected MAR types.

Table 18: Selection criteria for specific screening.

MAR type: **DITCHES**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY			PARAMETER WEIGHT
		Low suitability	Moderate suitability	High suitability	
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	300-1500 m	100-300 m	15-100 m	20%
SURFACE CHARACTERISTICS	Lithology of the surface formations	low permeability sediments (e.g. sandy loam, silty sand), moderately fractured rocks	moderate permeability sediments (e.g., fine sand, sand with lenses of silt or clay), highly fractured and karstic rocks	high permeability sediments (e.g. coarse sand, gravel)	16%
	Land use	artificial surfaces	agricultural areas	forest and semi-natural areas	12%
	Slope	>5°	3°-5°	<3°	8%
AQUIFER CHARACTERISTICS	Thickness of the aquifer	<5 m	5-50 m	>50 m	4%
	Depth of the top of the aquifer	2-5 m	1-2 m	0-1 m	12%
	Lithology of the aquifer	silty sand, clayey sand	fine and unsorted sand	coarse sand, gravel, pebbles, karstic rock	12%
	Depth of the groundwater table	2-5 m	5-10 m	10-20 m	16%

Table 19: Selection criteria for specific screening.

MAR type: **INDUCED RIVER OR LAKE BANK FILTRATION**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY			PARAMETER WEIGHT
		Low suitability	Moderate suitability	High suitability	
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	300-1000 m	100-300 m	15-100 m	28%
SURFACE CHARACTERISTICS	Lithology of the surface formations	low permeability sediments (e.g. sandy loam, silty sand)	moderate permeability sediments (e.g. fine sand, sand with lenses of smaller fraction)	high permeability sediments (e.g. coarse sand, gravel)	20%
	Land use	artificial surfaces, wetlands	agricultural areas	forest and semi natural areas	12%
AQUIFER CHARACTERISTICS	Confinement of the aquifer	confined	semi-confined	unconfined	6%
	Lithology of the aquifer	silty sand, clayey sand	fine and unsorted sand	coarse sand, gravel, pebbles	28%
	Depth of the groundwater table	>10 m	5-10 m	0-5 m	6%

Table 20: Selection criteria for specific screening.

MAR type: **AQUIFER STORAGE AND RECOVERY**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY			PARAMETER WEIGHT
		Low suitability	Moderate suitability	High suitability	
SURFACE CHARACTERISTICS	Slope	>10°	5-10°	0-5°	14%
AQUIFER CHARACTERISTICS	Confinement of the aquifer	confined	semi-confined	unconfined	18%
	Depth of the groundwater table	5-10 m	>200 m	10-200 m	18%
	Storage coefficient	<10-6	10-6 - 0.1	>0.1	25%
	Lithology of the aquifer	fractured igneous and metamorphic rocks	fine sand, non-karstified fractured carbonates, coarse grained sedimentary rocks	sandy gravel, gravel, sand, alluvial sediments, highly fractured and karstic rocks	25%

Table 21: Selection criteria for specific screening.

MAR type: **INFILTRATION POND**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY			PARAMETER WEIGHT
		Low suitability	Moderate suitability	High suitability	
CHARACTERISTICS OF THE WATER SOURCE	Distance from surface water source	>1000 m	100-1000 m	0-100 m	5%
SURFACE CHARACTERISTICS	Lithology of the surface formations	low permeability sediments (e.g. sandy loam, silty sand)	moderate permeability sediments (e.g., fine sand, sand with lenses of silt or clay), moderately fractured non-karstifed carbonates, igneous and metamorphic rocks	high permeability sediments (e.g. coarse sand, gravel), highly fractured and karstified carbonates	15%
	Land use	industrial or urban areas (artificial surfaces), wetlands	forests, agricultural terrains	pastures, barren land, open spaces with little or no vegetation, natural vegetation, shrub and/or herbaceous vegetation associations	3%
	Slope	>5°	3-5°	<3°	17%
AQUIFER CHARACTERISTICS	Thickness of the aquifer	<5 m	5-70 m	>70 m	10%
	Depth of the top of the aquifer	>15 m	10-15 m	5-10 m	20%
	Lithology of the aquifer	clayey/silty sand, moderately fractured carbonate and igneous rocks	fine sand, moderately to highly fractured carbonate, volcanic and sedimentary rocks	sandy gravel, gravel, sand, alluvial sediments, highly fractured carbonates and karstic rocks	10%
	Depth of the groundwater table	>15 m	10-15 m	5-10 m	20%

Table 22: Selection criteria for specific screening.

MAR type: **UNDERGROUND DAM**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY Low suitability	Moderate suitability	High suitability	PARAMETER WEIGHT
SURFACE CHARACTERISTICS	Slope	<1° or 6-8°	4-6°	1-4°	12%
AQUIFER CHARACTERISTICS	Confinement of the aquifer	confined	semi-confined	unconfined	9%
	Thickness of the aquifer	<2 m	2-10 m	>10 m	17%
	Depth of the impermeable layer under the aquifer	<5 m or >17 m	12-17 m	5-12 m	18%
	Depth of the groundwater table	<2 m or 7-20 m	5-7 m	2-5 m	8%
	Regime type of the groundwater flow system	discharge	transitional	recharge	5%
	Presence of subsurface structures providing storage or acting as barriers or channels	low amount of buried paleo-riverbed segments	moderate amount of buried paleo-riverbed segments	high amount of buried paleo-riverbed segments	22%
	Lithology of the aquifer	clayey/silty sand moderately fractured carbonates	fine sand, highly fractured/ karstic carbonates	gravel, sand, porous conglomerates, porous sandstones	9%

Table 23: Selection criteria for specific screening.

MAR type: **RECHARGE DAM**

MAIN PARAMETER CATEGORY	NAME OF PARAMETER(S)	LEVEL OF SUITABILITY			PARAMETER WEIGHT
		Low suitability	Moderate suitability	High suitability	
SURFACE CHARACTERISTICS	Lithology of the surface formations	low permeability sediments (e.g. sandy loam, silty sand), slightly fractured carbonates	moderate permeability sediments (e.g., fine sand, sand with lenses of silt or clay), moderately fractured carbonates, igneous and metamorphic rocks	high permeability sediments (e.g. coarse sand, gravel), highly fractured and karstified carbonates, porous conglomerates, porous sandstones	25%
	Hydrologic soil type	group D	group B and C	group A	15%
	Land use	industrial or urban areas (artificial surfaces), wetlands	forests, agricultural terrains	pastures, barren land, open spaces with little or no vegetation, natural vegetation, shrub and/or herbaceous vegetation associations	10%
AQUIFER CHARACTERISTICS	Thickness of the aquifer	<5 m	5-20 m	>20 m	10%
	Lithology of the aquifer	clayey/silty sand, slightly fractured carbonate	fine and very fine sand, moderately fractured carbonates	gravel, very coarse, coarse and medium sand, porous conglomerates, porous sandstones, highly fractured/karstic carbonates	12%
	Depth of the top of the aquifer	>10 m	5-10 m	<5 m	10%
	Depth of the groundwater table	<5 m or 20-30 m	10-20 m	5-10 m	12%
	Regime type of the groundwater flow system	discharge	transitional	recharge	6%

4.3.1 MAR site selection for karst aquifers

Considering the relatively high uncertainties regarding MAR operation in karst areas, the high costs of operation, the high risks for operation disruptions (as can e.g. be seen in Rodriguez-Escales et al. 2018), as well as extensive monitoring efforts (recovery rate and adequate water quality), it is necessary that research efforts focus on priority areas. **Priority areas** are those where the demand for groundwater resources is high and groundwater reserves are most exposed to over-abstraction, climate change, and seawater intrusion. At these sites, small scale (local) site characterization is necessary in order to determine potential MAR site suitability. Often, important hydrogeological parameters for specific screening (3rd step, specific screening) may either be missing or unavailable. In such cases, it is recommended to substitute a missing parameter with the most similar one available (in a hydrogeological sense). Additional parameters can enhance the precision of suitability mapping and decrease the risks of operation by reducing uncertainty in the planning phase. Examples of additional criteria to be considered during suitability mapping include:

- Using data from past research that are available at the time of the planning phase, such as data from water supply companies, pumping tests, catchment delineation, or tracer tests
- Lateral confinement of the aquifer
- Karst characteristics (presence of karstic forms such as channels, conduits, springs, sinkholes)
- Connectivity to the sea, aquifer outflow
- Groundwater residence time
- Effective infiltration

4.4 Fourth step: Feasibility study - Characterization of selected pilot site

The impact chain approach (cf. Methods section) was used for analysing the sensitivity of MAR schemes to climate extremes. The following tables (Table 24-30) present the checklists, related to MAR sensitivity, for the six selected MAR schemes. The identified criteria should be taken into consideration for the evaluation of sequential and combined effects of extreme climate events on MAR systems, as well as for the identification of related potential risks.

The next steps within the DEEPWATER-CE project include feasibility studies for the planned pilot sites. More detailed, site-specific impact chains will be formulated and incorporated, so that checklists are further developed. Analysing the sensitivity of MAR schemes to climate extremes (the subject of this section) is the first part of the 4th step, i.e. of the feasibility study. The other three parts will comprise (i) a cost-benefit analysis and regulatory framework, (ii) feasibility of technical solutions and acceptability of associated risks and (iii) investigation of water demand and supply (Table 1), as part of ongoing project work.

Table 24: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **DITCHES**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amount of precipitation Extremely high temperature/evapotranspiration Extremely low temperature	Short period of extremely high amount of precipitation Extremely high amount of snow accumulation Long period of extremely high amount of precipitation Extremely long duration of precipitation
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	Soil drought Hydrological drought GW drought	Flash flood Flood
		Hazard types	Decrease of soil moisture and GW recharge, salt precipitation in soil Decrease in surface water levels & flow rates Lowering of GW table Freezing of water, e.g. to the bottom of ditches where water levels are very low (limiting or even stopping infiltration, lowering of GW table)	Flash flood Extreme runoff Rapid snow melting Flood (high precipitation) Extremely high GW table (“GW flooding”) Excess inland water
	ANTHROPOGENIC IMPACTS		Land use (urban/industrial/agricultural) Overexploitation of water for various uses (e.g. changes in GW dynamics) Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)	Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness) GW quality (e.g. high dissolved mineral content, changes in GW chemistry)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Reduction in GW well yield or depletion of GW production wells due to GW level decrease Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Contamination of (shallow) aquifers (infiltration, influx from surface water; salt water intrusion from the sea)	Erosion Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Infiltration of contaminants from surface water
MAR SENSITIVITY	PRECAUTION TARGETS		Temporary interruption in the operation of the MAR system (clogging or geochemical processes) Water quantity problems (clogging or geochemical processes; reduction in GW well yield or depletion of GW production wells due to GW table decrease; depletion of surface water sources) Water quality problems (contamination of shallow aquifers; infiltration of contaminants from surface water)	Structural damage in MAR infrastructure (e.g. clogging or geochemical processes; erosion) Water quantity problems (clogging or geochemical processes) Water quality problems (infiltration of contaminants from surface water)

Table 25: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **INFILTRATION POND**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely high temperature/evapotranspiration Extremely low amount of precipitation	Long period of extremely high amount of precipitation Short period of extremely high amount of precipitation
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	Soil drought Hydrological drought	Flash flood Flood
		Hazard types	Drought (lack of physical precipitation)	Flash flood Extreme run-off Flood (high precipitation) Excess inland water
	ANTHROPOGENIC IMPACTS		Land use (urban/industrial/agricultural) Overexploitation of water for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)	Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Surface water source (e.g. surface water level dynamics) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Slope (e.g. influence of infiltration) Surface water source (e.g. surface water level dynamics) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Reduction in GW well yield or depletion of GW production wells due to GW level decrease Decrease of water storage in ponds due to sedimentation Increased residence time in surface water bodies Eutrophication Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification)	Erosion Eutrophication Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Infiltration of contaminants from surface water
MAR SENSITIVITY	PRECAUTION TARGETS		Water quantity problems (clogging or geochemical processes; increased residence time in surface water bodies; decrease of water storage in ponds due to sedimentation; reduction of GW well yield or depletion of GW production wells due to GW table decrease; drying-up of surface water sources) Water quality problems (eutrophication)	Water quality problems (infiltration of contaminants from surface water) Water quantity problems (clogging or geochemical processes)

Table 26: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **INDUCED RIVER OR LAKE BANK FILTRATION**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amount of precipitation Extremely low amount of snow accumulation Extremely high temperature/evapotranspiration (together with low amount of precipitation) Extremely low temperature (mountainous area)	Short period of extremely high amounts of precipitation Extremely long period of precipitation Long period of extremely high amounts of precipitation Extremely high amount of snow accumulation Extremely high frequency of precipitation events
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	Hydrological drought GW drought	Flash flood Flood
		Hazard types	Low water level for an extremely long time period Drought (lack of physical precipitation) GW table depression Decrease of soil moisture and GW recharge	Flash flood Extreme runoff High precipitation Rapid snow melting Extremely high GW table (“GW flooding”) Excess inland water
	ANTHROPOGENIC IMPACTS		Overexploitation of water for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)	Land use (urban, industrial, agricultural) Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Surface water source (e.g. surface water level dynamics) Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Vertical groundwater flow between different aquifers) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Slope (e.g. influence of water infiltration) Surface water source (e.g. surface water level dynamics) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Infiltration of contaminants from surface water Reduction in GW well yield or depletion of GW production wells due to GW level decrease Eutrophication	Slope instabilities (e.g. landslides) Erosion Flooding of infrastructure (e.g. treatment/desalinization plant, rainwater collecting system) Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Infiltration of contaminants from surface water Intrusion of polluted GW or sea water (salt water)
MAR SENSITIVITY	PRECAUTION TARGETS		Water quantity problems (depletion of surface water sources; reduction in GW well yield or depletion of GW production wells due to GW level decrease) Water quality problems (infiltration of contaminants from surface water, eutrophication)	Temporary interruption in the operation of the MAR system (clogging or geochemical processes) Structural damage in MAR infrastructure (e.g. clogging or geochemical processes; erosion) Water quantity problems (clogging or geochemical processes) Water quality problems (infiltration of contaminants from surface water, intrusion of polluted GW or sea water (salt water))

Table 27: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **AQUIFER STORAGE AND RECOVERY**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amounts of precipitation Extremely high temperature/evapotranspiration	Short period of extremely high amounts of precipitation Extremely long period of precipitation Long period of extremely high amounts of precipitation
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	GW drought Hydrological drought	Flood
		Hazard types	GW table depression Drought (lack of physical precipitation)	Extreme runoff Rapid snow melting Flood (high precipitation) Excess inland water Extremely high GW table (“GW flooding”)
	ANTHROPOGENIC IMPACTS		Overexploitation of water for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)	Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) GW quality (e.g. high dissolved mineral content, changes in groundwater chemistry) Coastal area (intrusion of sea water)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Slope (e.g. influence of water infiltration) Aquifer type (porous, fractured, karst) and hydraulic conditions (confined, unconfined, semi-confined) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Reduction in GW well yield or depletion of GW production wells due to GW level decrease Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Intrusion of polluted GW or sea water (salt water)	Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Infiltration of contaminants from surface water Intrusion of polluted GW or sea water (salt water) Mobilization or dissolution of contaminants (biological, chemical, physical)
MAR SENSITIVITY	PRECAUTION TARGETS		Temporary interruption in the operation of the MAR system (reduction in GW well yield or depletion of GW production wells due to GW level decrease; clogging or geochemical processes) Water quantity problems (reduction in GW well yield or depletion of GW production wells due to GW level decrease; clogging or geochemical processes; depletion of surface water sources) Water quality problems (intrusion of polluted GW or sea water (salt water))	Temporary interruption in the operation of the MAR system (infiltration of contaminants from surface water) Water quality problems (infiltration of contaminants from surface water, mobilization or dissolution of contaminants; intrusion of polluted GW or sea water (salt water))

Table 28: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **INFILTRATION POND**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amounts of precipitation Extremely low amount of snow accumulation Extremely high temperature/evapotranspiration (together with low amount of precipitation) Extremely low temperature (mountainous area)	Short period of extremely high amounts of precipitation Extremely long period of precipitation Long period of extremely high amounts of precipitation Extremely high amount of snow accumulation Extremely high frequency of precipitation events
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	Hydrological drought GW drought	Flash flood Flood
		Hazard types	Low water level for an extremely long time period Drought (lack of physical precipitation) GW table depression Decrease of soil moisture and GW recharge	Flash flood Extreme runoff High precipitation Rapid snow melting Extremely high GW table (“GW flooding”) Excess inland water
	ANTHROPOGENIC IMPACTS		Overexploitation of water for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)	Land use (urban, industrial, agricultural) Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Surface water source (e.g. surface water level dynamics) Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Vertical groundwater flow between different aquifers Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Slope (e.g. influence of water infiltration) Surface water source (e.g. surface water level dynamics) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Infiltration of contaminants from surface water Reduction in GW well yield or depletion of GW production wells due to GW level decrease Eutrophication	Slope instabilities (e.g. landslides) Erosion Flooding of surface infrastructure (e.g. treatment/desalinization plant, rainwater collecting system) Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Infiltration of contaminants from surface water Intrusion of polluted GW or sea water (salt water)
MAR SENSITIVITY	PRECAUTION TARGETS		Water quantity problems (depletion of surface water sources; reduction in GW well yield or depletion of GW production wells due to GW level decrease) Water quality problems (infiltration of contaminants from surface water, eutrophication)	Temporary interruption in the operation of the MAR system (clogging or geochemical processes) Structural damage in MAR infrastructure (e.g. clogging or geochemical processes; erosion) Water quantity problems (clogging or geochemical processes) Water quality problems (infiltration of contaminants from surface water, intrusion of polluted GW or sea water (salt water))

Table 29: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **UNDERGROUND DAM**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amount of precipitation Extremely high temperature/evapotranspiration	Long period of extremely high amount of precipitation
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	GW drought	Flood
		Hazard types	GW table depression	Inland excess water Extremely high GW table ("GW flooding")
	ANTHROPOGENIC IMPACTS		Land use (urban, industrial, agricultural) Water overexploitation for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)	Land use (urban, industrial, agricultural) Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Soil hydraulic properties (if soil is more permeable, the transpiration rate is higher and can influence GW recharge) Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness) GW quality (e.g. high dissolved mineral content, changes in groundwater chemistry) Coastal area (intrusion of sea water)	Soil hydraulic properties (if soil is impermeable, the flood is quicker (no possibility for water infiltration in a large area) and therefore more dangerous for infrastructure) Aquifer type (porous, fractured, karst) and hydraulic conditions (confined, unconfined, semi-confined) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)
FINAL IMPACT	EFFECTS ON MAR		GW well yield reduction or drying-up of GW production wells due to GW level decrease Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification) Intrusion of polluted GW or sea water (salt water)	Overflowing GW Infiltration of contaminants from surface water Intrusion of polluted GW or sea water (salt water) Mobilization or dissolution of contaminants (biological, chemical, physical)
MAR SENSITIVITY	CAUTION TARGETS		Temporary interruption in the operation of the MAR system (clogging or geochemical processes; intrusion of polluted GW or sea water (salt water)) Water quantity problems (clogging or geochemical processes; GW well yield reduction or drying-up of GW production wells due to GW level decrease) Water quality problems (intrusion of polluted GW or sea water (salt water))	Temporary interruption in the operation of the MAR system (infiltration of contaminants from surface water; overflowing GW; intrusion of polluted GW or sea water (salt water)) Water quality problems (infiltration of contaminants from surface water, mobilization or dissolution of contaminants; intrusion of polluted GW or sea water (salt water))

Table 30: Checklist on sensitivity analysis of MAR types to extreme situation cases (GW: groundwater).

MAR type: **RECHARGE DAM**

			DRY PERIOD	WET PERIOD
TRIGGER/STIMULUS	CLIMATE EXTREMES		Extremely low amounts of precipitation Extremely high temperature/evapotranspiration Extremely low amount of snow accumulation Extremely low temperature	Short period of extremely high amounts of precipitation Extremely long period of precipitation Extremely high frequency of precipitation events Long period of extremely high amounts of precipitation Extremely high amount of snow accumulation
HAZARDOUS EVENTS	NATURAL HAZARDS	Hazard groups	Soil drought Hydrological drought GW drought	Flash flood Flood
		Hazard types	Decrease of soil moisture and GW recharge Low water level for an extremely long time period Drought (lack of physical precipitation) GW table depression	Flash flood Extreme runoff Flood (high precipitation, long periods, high frequency) Rapid snow melting
	ANTHROPOGENIC IMPACTS		Land use (urban, industrial, agricultural) Water overexploitation for various uses (e.g. changes in GW dynamics) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)	Land use Diffuse pollution (e.g. agricultural soil pollution by plant protection products, fertilisers; atmospheric input of contaminants) Point pollution (e.g. waste landfills, fuel spills, waste water treatment plants, untreated urban water) Mining activity (intensive drainage of surface water and GW; leaching of pollutants)
	SURFACE & HYDROGEOLOGICAL ENVIRONMENT		Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Surface water source (e.g. surface water level dynamics) Soil hydraulic properties Aquifer characteristics (e.g. porosity, transmissivity facilitating infiltration of water and/or pollutants) Vertical groundwater flow between different aquifers Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)	Land cover (e.g. grass, trees/forest (or deforestation), asphalt, agricultural crops) Slope (e.g. influence of water infiltration) Aquifer characteristics (e.g. porosity, transmissivity, properties related to pollutant transport & fate) Position in the GW flow system (recharge, transitional or discharge area; order of aquifer in vertical position, aquifer depth and thickness)
FINAL IMPACT	EFFECTS ON MAR		Depletion of surface water sources Decrease of GW level (interruption or decrease in GW recharge) Eutrophication Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification)	Slope instabilities (e.g. landslides) Erosion Flooding of surface infrastructure (e.g. treatment/desalinization plant, rainwater collecting system) Eutrophication Clogging (by fine particles or biogeochemical processes such as evaporation, scaling/calcification)
MAR SENSITIVITY	PRECAUTION TARGETS		Water quantity problems (depletion of surface water sources; clogging or geochemical processes; decrease of GW level) Water quality problems (eutrophication)	Temporary interruption in the operation of the MAR system (flooding of surface infrastructure) Structural damage to MAR infrastructure (flooding of surface infrastructure; slope instabilities) Water quantity problems (erosion; clogging or geochemical processes) Water quality problems (eutrophication)

Appendix

A1 Specification of hydrogeological criteria for karst aquifers

The number of examples for MAR in karstic environments is small compared to those in porous media (Daher et al. 2011). While simple MAR techniques, such as sand dams, recharge release dams or ditches have the advantage of relatively low implementation costs and simple maintenance, they are only useful for replenishing shallow phreatic aquifers (Rolf, 2017). The application of induced river bank and lake bank filtration MAR schemes in karst aquifer is limited, whereas aquifer storage and recovery (ASR) and infiltration methods are often considered suitable for application in karst terrains (e.g. Pavelic et al. 2006, Page et al. 2010).

According to Rolf (2017) and Xanke (2017), main challenges of successful MAR application in karst areas are:

- extreme heterogeneity of karst flow patterns (including injected water)
- high flow rates of conduits and/or insufficient permeability of limestone matrix
- quality of the source water
- disruption of the chemical balance between rapidly infiltrating source water and the ambient groundwater in aquifer
- difficult installation of abstraction or injection wells due to a complex, hardly explorable conduit network

A2 Special characteristics of karst aquifers

Karst is a complex geological feature formed by the dissolution of soluble rocks, such as limestones, dolomites, gypsum or halite. Rock types that are susceptible to karstification are widely distributed throughout the world (Milanović, 2018). According to Maksimovič (1969), one quarter of Earth’s land-mass area consists of soluble and primarily carbonate rock. According to an often-cited estimation by Ford and Williams (2007), approximately 20–25% of the global population depends largely or entirely on groundwater obtained from karst aquifers, while in some regions such as the Dinaric region (Europe), karst water contributes 50% or more to regional freshwater supplies (Hartmann et al., 2014). Figure A1 gives an overview on the presence of karst aquifers within Europe.

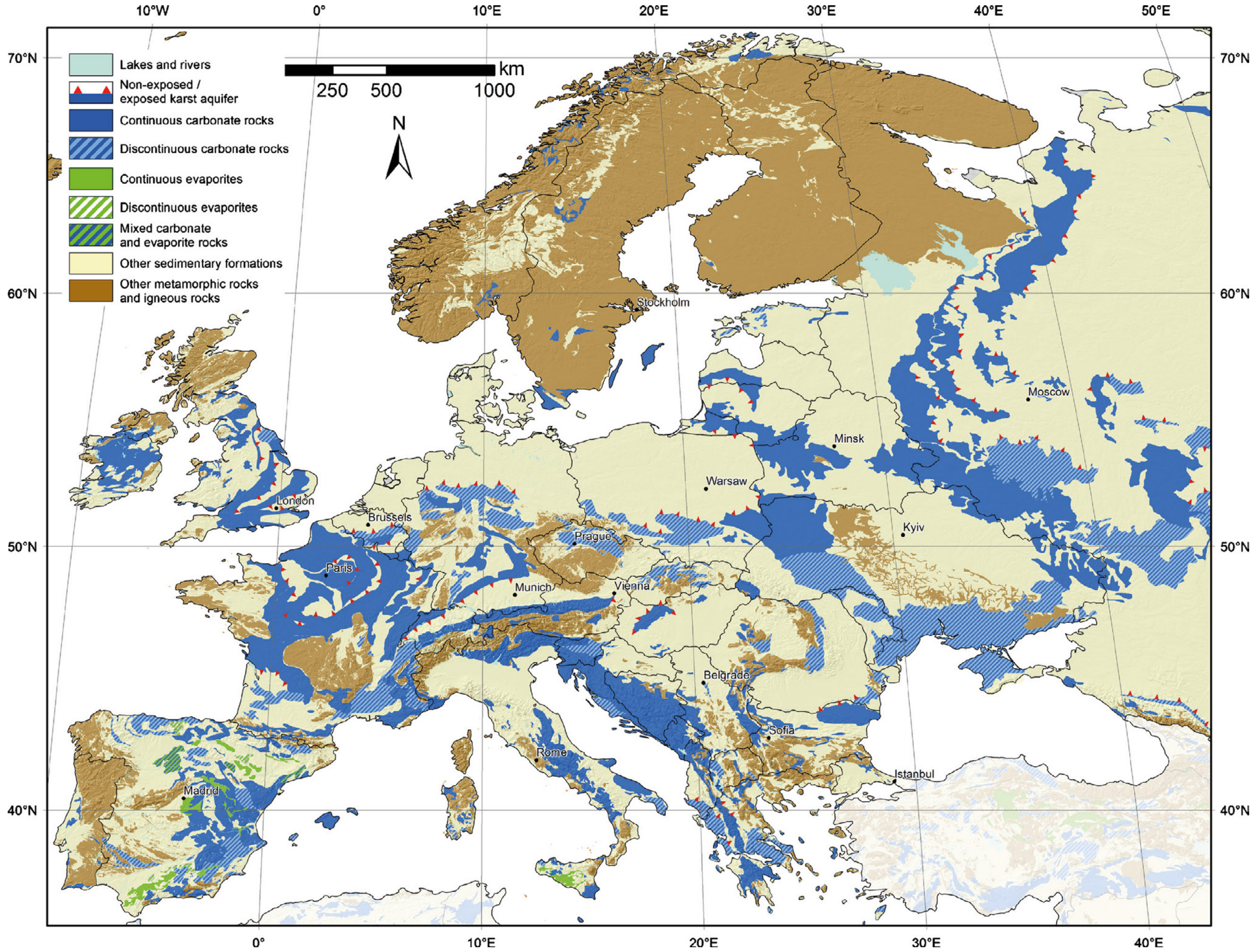


Figure A1: Overview on the presence of karst aquifers in Europe (Chen et al. 2017)

Karst aquifers are very unique compared to uniformly porous (Darcian) aquifers, since the process of carbonate rock dissolution (karstification) generates a distinct heterogeneity and anisotropy, observable in the characteristic duality of discharge patterns (Bakalowicz, 2005; Goldscheider and Drew 2007; Ford and Williams 2007). The distinctive duality of discharge pattern is attributed to the triple porosity character of karst aquifers, where intergranular porosity (primary porosity), fracture porosity (secondary porosity) and conduit porosity (tertiary porosity) coexist (Ford and Williams 2007; Hartmann et al. 2014). Depending on the hydraulic interconnectivity of the fracture network, water progressively dissolves the rock and enlarges the fractures to channels, conduits or caves. Since this combined process of water flow, rock dissolution and widening of the fractures is self-reinforcing, it often develops directions of preferential flow within the bedrock (Goldscheider and Drew 2007; Kresic 2013). Hydraulic conductivity in karst aquifers can span many orders of magnitude as a result of the different types of porosities. Diffuse groundwater flow through the matrix porosity may reveal flow velocities of a few centimetres a day, whereas concentrated flow through channels and conduits can reach velocities of several hundred meters per hour (Teutsch and Sauter 1991; Kresic et al. 1992; Ford and Williams 2007; Goldscheider and Drew 2007). The mechanism of groundwater recharge in karstic environments is driven by two different types of infiltration: diffuse infiltration and point infiltration (Goldscheider and Drew 2007).

The unique character in terms of storage and drainage pattern poses a particular challenge for the management of karst aquifers (Worthingthon, 2013). Spring discharge usually responds rapidly to rainfall events with a high discharge and is also often associated with water quality deterioration through turbidity or bacteriological contamination (Goldscheider and Drew 2007), whereas discharge rates during dry periods are often not sufficient to cover the increasing water demand.

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