COMMON METHODOLOGICAL GUIDANCE FOR DEEPWATER-CE MAR PILOT FEASIBILITY STUDIES

D.T3.2.5

Version 1

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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 (MAR) solutions to facilitate the protection of Central European water resources endangered by climate change and user conflict. Main author is the Technical University of Munich, with section contributions as well as inputs and revisions by the whole partnership (see contributors list).

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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 (Casanova et al., 2016; Dillon et al., 2019; Dillon, 2005; Sprenger et al., 2017).

Dillon et al., (2019) document an increase of MAR implementation of about 5 % per year since the 1960s, but this is not keeping up with increasing groundwater abstraction. In countries applying MAR technologies, about 2.4 % of the total groundwater abstraction is provided by these methods (or ~1 % worldwide). Even though geological and hydrogeological conditions are among the most predominant factors influencing MAR potential (determining the suitability of specific MAR methods), psychological and policy-related aspects are also important, as these are key factors in the acceptance of MAR schemes and their implementation. Such aspects were found to considerably contribute to the fact that potentials for using MAR are often far from being exploited (e.g. Dillon, 2005, Mankad et al., 2015). Leviston et al. (2006) found that the perception of human health risks is highly negatively correlated to trust in the MAR scheme. Alexander (2011) reports that public attention to technical and monitoring aspects of MAR facilities and related concerns were mostly about system management, treatment and the ability of scientists to advise on risks. In contrast, for scientists and engineers, it may often not be intuitive to engage stakeholders in the planning of MAR schemes (Richter et al., 2014). Page et al. (2012) state that aquifer treatment methods remain difficult to put in place, in comparison to common water treatment technologies, as it is not easy to identify the critical limits and control points of a MAR system. Human health and environmental risks can arise from the recharged water, and these risks are influenced (reduced or increased) by the fate of the infiltrated water within the subsurface. Among others, the complexity of reactive transport processes in the unsaturated zone can make it difficult to estimate relevant risks prior to MAR operation (e.g. Casanova et al., 2016, Juntunen et al., 2017).

Fernández Escalante et al. (2020) claim that the lack of regulatory frameworks often hinders the implementation of MAR schemes. Building trust in key regulating organisations, such as the state and drinking water agencies, has the potential to influence emotional responses and raise public acceptance for an organisation's risk estimation and MAR system proposals (Leviston et al., 2006; Mankad et al., 2015). Nandha et al. (2015) point out that a key step in promoting MAR would be to reduce uncertainties related to MAR implementation and operation. This could strengthen confidence in MAR technology, both for in the European Union in order to build up a **transnational knowledge base** (deliverable D.T1.2.1, DEEPWATER-CE, 2020a). We then developed in the second work package a transnational decision support toolbox on designating potentially suitable MAR locations in Central Europe (output O.T2.1, DEEPWATER-CE, 2020b), abbreviated **decision support toolbox** in the following. Based on this toolbox, pilot sites with applicable MAR types can be identified (deliverables D.T3.3-6.1-5). In the third work package, we aim to develop a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (deliverable D.T3.2.5), abbreviated **common methodological guidance** in the following. It is subject of the present report and includes the following main components, i.e. guidelines for (cf. Figure 1):

Within the DEEPWATER-CE project, we investigate the potential to implement MAR schemes in four partner countries: Hungary, Poland, Slovakia and Croatia considering these socio-economic, geological, hydrogeological, technical, regulatory and human health aspects. In the first of four work packages we have started to review common practices and conducted a benchmark analysis of MAR solutions in the European Union in order to build up a **transnational knowledge base** (deliverable D.T1.2.1, DEEPWATER-CE, 2020a). We then developed in the second work package a transnational decision support toolbox on designating potentially suitable MAR locations in Central Europe (output O.T2.1, DEEPWATER-CE, 2020b), abbreviated **decision support toolbox** in the following. Based on this toolbox, pilot sites with applicable MAR types can be identified (deliverables D.T3.3-6.1-5). In the third work package, we aim to develop a common methodological guidance for DEEPWATER-CE MAR pilot feasibility studies (deliverable D.T3.2.5), abbreviated **common methodological guidance** in the following. It is subject of the present report and includes the following main components, i.e. guidelines for (cf. Figure 1):

- **Consideration of the regulatory framework**
- **Desktop study of the pilot site**
- **Pilot site characterization, including the determination of water demand and supply**
- **Risk management related to MAR implementation and operation**
- **Cost-Benefit Analysis (CBA) of the MAR scheme**
- **Comparison of alternative solutions**

Several authors have intended to design guidelines on how to plan, design, implement and operate MAR sites, e.g. the American Society of Civil Engineering and Environmental and Water Research Insititute (ASCE and EWRI 2020), Salameh et al. (2019) and Rahman (2011). Building upon these guidelines, we have developed the **decision support toolbox**, which primarily addresses site selection and the guidance of MAR pilot feasibility studies (Figure 1). Firstly, a pilot site and an adequate MAR scheme is identified with the first three steps of the decision support toolbox. As another step, the decision support toolbox also incudes (i) analysing the sensitivity of MAR schemes to climate extremes, (ii) investigation of costs and benefits and the regulatory framework, (iii) investigating the feasibility of technical solutions and acceptability of associated risks, and (iv) investigating water demand and supply (DEEPWATER-CE, 2020b). Being part of the feasibility study, points (ii) to (iv) are also subject of the **common methodological guidance**, as described in the following. This guidance is addressing different components of the MAR scheme, as indicated in Figure 2.

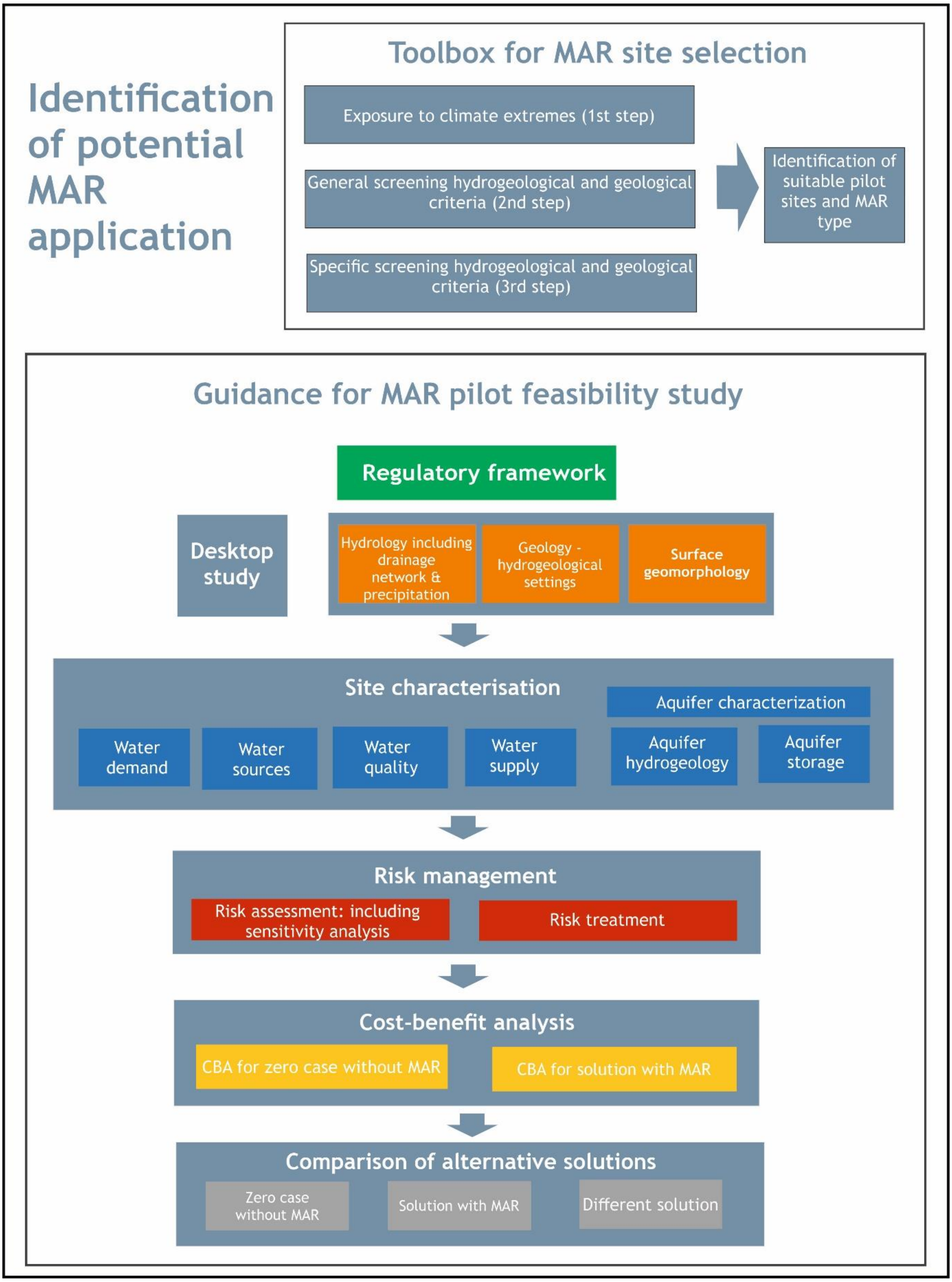

Figure 1: Procedure for the identification of potential MAR application, implementing the decision support toolbox for MAR site selection (on top) and the common methodological guidance for MAR pilot feasibility studies (bottom)

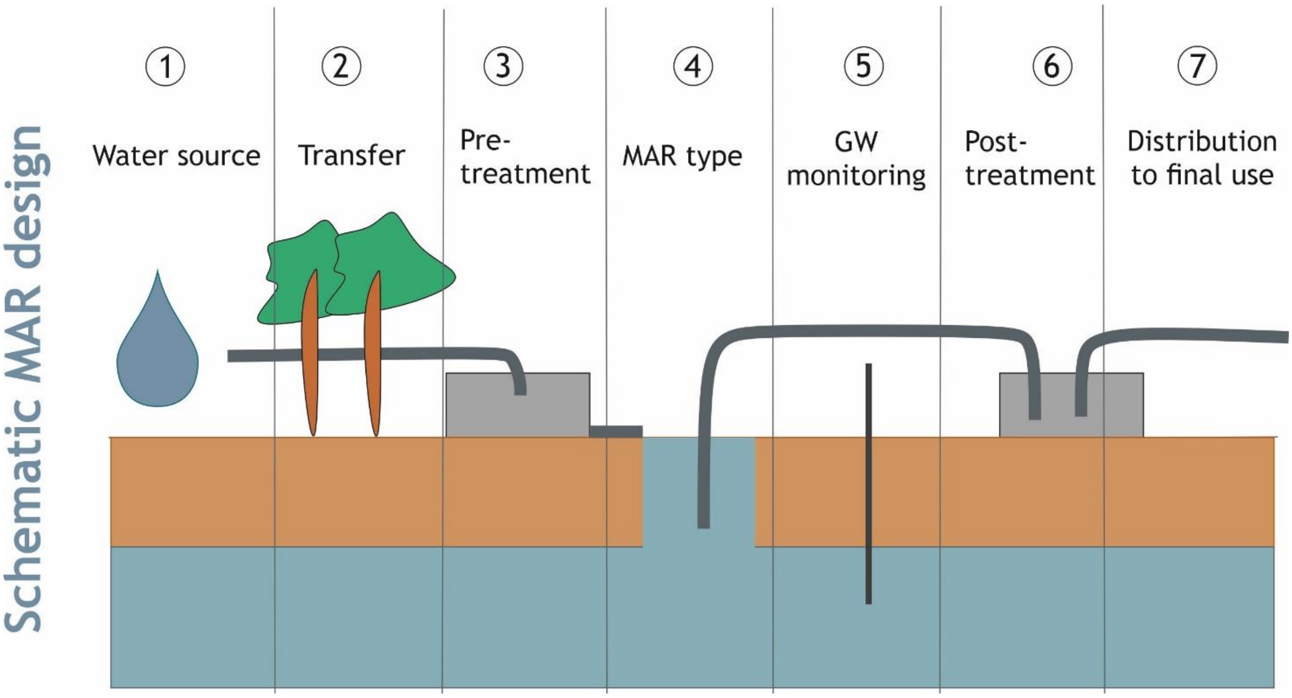

Figure 2: Schematic overview of a MAR scheme design indicating its major components

2. Regulatory framework

The national legislation of the four partner countries is in line with the European Union legislative framework for the implementation of MAR solutions. Core legal acts that are relevant to MAR schemes are the Water Framework Directive (WFD), Groundwater Directive (GWD) and Drinking Water Directive (DWD). These legislations do not include specific MAR regulations but their provisions shape broad regulatory frameworks for MAR systems.

The Water Framework Directive WFD (2000/60/CE), in particular Article 11(3) (f)), considers MAR schemes as a supplementary measure, which needs "*controls, including a requirement for prior authorization of artificial recharge or augmentation of groundwater bodies. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater. These controls shall be periodically reviewed and, where necessary, updated*" (European Parliament and European Council, 2000). Thus, the provisions of the WFD do not provide specific quality limits for recharged water but they are aimed to ensure that basic measures are in force to safeguard the application of MAR system, in order to avoid causing any harm to the qualitative status of the water bodies (European Council, 1998).

When it comes to the Groundwater Directive GWD (2006/118/EC), its core objective is the protection of groundwater against pollution through the requirement to identify the chemical status of groundwater. The GWD establishes limit values for nitrate and pesticides concentration and requires the member states to fix threshold values of As, Cd, Pb, Hg, NH_4^+, Cl^-, SO_4^{2-}, PCE, TCE and electrical conductivity. At the same time the GWD states in Article 6(3)(d) that particular exemptions from the established measures (including artificial recharge) are possible, since it might be technically infeasible to eliminate all inputs of hazardous substances, especially those that are environmentally insignificant and do not pose a danger to groundwater (European Parliament and of the Council, 2006).

Experts of MARSOL project (2017) emphasized that it is important to establish a common definition of the 'prevent and limit' requirements under the Water Framework and Groundwater Directives, without which lack of harmonization between the two directives in this regard can potentially give rise to interpretation conflicts.

Under the MARSOL project, the following MAR regulatory scheme was proposed (Figure 3):

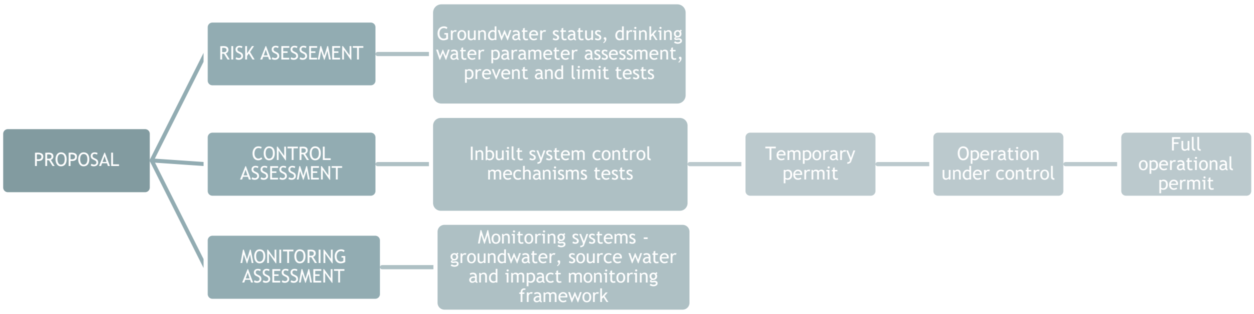

Figure 3: MAR regulatory scheme proposal (Leitão et al., 2017)

Among the three legal acts mentioned above, the Drinking Water Directive (98/83/EC) is the most restrictive, since it deals with human health protection, and serves as a reference in the majority of member states (European Council, 1998). This directive states mandatory target values for the majority of the contaminants and covers microbial, chemical and physical water characteristics (Table 1).

Table 1: Target values proposed for raw water for drinking water production (European Council, 1998)

Anthropogenic non-natural substances with known biological effects	Maximum permissible value (μg/L)
Pesticides and their metabolites per individual substance	$0.1^{*,a}$
Endocrine active substances per individual substance	0.1^{*}
Pharmaceuticals (including antibiotics) per individual substance	0.1^{*}
Biocides per individual substance	0.1^{*}
Other organic halogen compounds per individual substance	0.1^{*}
Substances with low biodegradability per individual substance	$0.1^{*,b}$
Synthetic complexing agents per individual substance	0.5^{c}

* Unless toxicological information necessitates a lower value, [a] Equal to drinking water standard, [b] If other non-natural organic substances have passed proper toxicological screening and are regulated as harmless, a target value of 1 μg/L is justified, similar to other official precaution targets. [c]: Only for complexing agents a temporary value of 5 μg/L is acceptable.

Since there are MAR schemes that envisage infiltration of treated wastewater into the aquifer (Rahman et al., 2014), provisions of the Urban Wastewater Treatment Directive (91/271/EEC) are also important for defining regulatory frameworks for such MAR systems. Protection of the environment from any negative effect caused by the discharge of wastewater is the core aim of the Urban Wastewater Treatment Directive, which gives estimates of the quality parameters of wastewater treatment plant effluents (Table 2) (European

Council, 1991). Legal acts that shape national regulatory framework in the project countries are presented in **Table 3**.

Table 2: Quality parameters of wastewater treatment plant effluents (EC, 1991)

Parameter	Concentration	Minimum percentage of reduction (%) [1]	Reference method of measurement
Requirements for the discharge of urban wastewater treatment plants, as subject to article 4 and 5 of the Urban Wastewater Treatment Directive (91/271/EEC), values for concentration or the percentage of reduction shall apply:			
Biochemical Oxygen Demand, BOD5 at 20° (without nitrification [2])	25 mg/l O_2	70-90 40 under article 4 [2]	Homogenized, unfiltered, undecanted sample. Determination of dissolved oxygen before and after five-day incubation at 20±1°C, in complete darkness. Addition of a nitrification inhibitor.
Chemical Oxygen Demand (COD)	125 mg/l O_2	75	Homogenized, unfiltered, undecanted sample, addition of potassium dichromate.
Total suspended solids	35 mg/l [3] 35 under article 4 [2] (> 10000 p.e.) [4] 60 under article 4 [2] (2000-10000 p.e.)	90 % [3] 90 under article 4 [2] (> 10000 p.e.) [4] 70 under article 4 [2] (2000-10000 p.e.)	Filtering of a representative sample through a 45 µm filter membrane. Drying at 105°C and weighing. Centrifuging of a representative sample (for at least five minutes), drying at 105°C and weighing.
Requirements for the discharge of urban wastewater treatment plans to sensitive areas that are subject to eutrophication, as described in Annex II.A (a). One or both parameters may be applied depending on the local situation. Values for concentration or the percentage of reduction shall apply (91/271/EEC, UWWTD):			
Total phosphorous	2 mg/l P (10000 - 100000 p.e.) [6] 1 mg/l P (> 100000 p.e.)	80	Molecular absorption spectrophotometry
Total nitrogen [5]	2 mg/l P (10000 - 100000 p.e.) [6] 1 mg/l P (more than 100000 p.e.)	70-80	Molecular absorption spectrophotometry

P.e.: population equivalent, [1] Reduction in relation to the load of the influent, [2] the parameter can be replaced by another parameter: TOC or TOD if a relationship can be established between BOD5 and the substitute parameter, [3] this requirement is optional, [4] One population equivalent (p.e.) means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day, [5] Total nitrogen: sum of total Kjeldahl-nitrogen (organic N + NH3), nitrate (NO3)-nitrogen and nitrite (NO2)-nitrogen, [6] One population equivalent (p.e.) means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day

Table 3: (following pages): Regulatory frameworks by pilot site country

Pilot country	Hungary	Croatia	Slovakia	Poland
Water regulation	Government Regulation 123/1997. (VII.18.) on the protection of vulnerable water supplies: This regulation concerns their protection measures and the criteria of water protection zones. Act LVII of 1995 on water management supports the recharge of underground aquifers by artificial recharge and reinjection. Accordingly, water users do not have to pay water supply contribution after the amount of water they recharge if the artificial recharge happens into the original water aquifer they withdrew from. The Government Regulation 219/2004. (VII.21.) on protection of groundwater regulates the artificial recharge and reinjection in order to preserve the quality and quantity of the underground water resources. This regulation also sets out conditions and makes it subject to official water protection authorization. 30/2004. (XII. 30.) KvVM Decree on rules of monitoring of groundwater regulates the monitoring of quality and quantity status of groundwater bodies.	Common implementation strategy for the Water Framework Directive: Guidance on Groundwater Monitoring	Water regulation in Slovakia is done in accordance with EC Directives, particularly the Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Nitrates Directive (91/676/EEC). The relevant water related legislation: Act No 364/2004 Coll (Water Act); Act No 7/2010 Coll. (on flood protection) and Government Regulation No 269/2010 Coll (on requirements to achieve good status of waters) Amendment 2.A provides the qualitative goals for surface water for drinking - https://www.aquaseco.sk/wp-content/uploads/2017/02/nv_269_2010.pdf Government Regulation No 167/2015 Coll (on environmental quality standards in the field of water policy), Government Regulation No 354/2006 Coll. (on drinking water standards).	- Water Law Act of 20 July 2017 (Journal of Laws 2017 item 1566) - Regulation of the Minister of Maritime Economy and Inland Navigation of 11 October 2019 on the criteria and method of evaluation of the state of groundwater bodies (Journal of Laws 2019, item 2148); - Ordinance of the Minister of Maritime Economy and Inland Navigation of 9 October 2019 on the forms and methods of monitoring surface water bodies and groundwater bodies (Journal of Laws 2019, item 2147)
Water for irrigation purposes	Groundwater utilization for irrigation purposes is limited by law (groundwater abstraction contingents are determined for irrigation) According to experiences, illegal wells are used very often for irrigation purposes. Only 1% of farmers have a water right permit for irrigation	Low on water services (OG no. 66/19) Water Act (OG no. 66/19) Regulation on special conditions for performing activities of water exploration works and other hydrogeological services, preventive flood defense activities and activities and measures of regular and extraordinary flood protection and maintenance of detailed buildings for drainage and irrigation (OG 26/20.)	Regulation 269/2010 Coll. which sets the requirements for reaching the good status of water, Amendment 2.B provides the qualitative goals for surface water for irrigation. The Slovak pilot site, i.e. recharge dam MAR type, is focused on irrigation purposes.	

Drinking water	201/2001. (X.25.) Government Regulation on the quality requirements of drinking water and regulation monitoring	Water quality in the Republic of Croatia is regulated by the Law on the water intended for human consumption ("Official Gazette" No.56/13, 65/15, 104/17), PROVISION OF COUNCIL DIRECTIVE 1998/83/ez of November 3rd, 1998, on the quality of water intended for human consumption, and Commission Directive (EU) 2015/1787 of October 6th, 2015, amending Annexes II and III to Council Directive 98/83/EZ (OJ L 260, 7/10/2015). Besides that, water for human consumption must conform to parameters for control of conformity of water for human consumption to standards defined by the Ordinance on conformity parameters analytical methods, monitoring and drinking water safety plans, and keeping a register of legal entities, which provide public water supply.	**Regulation 269/2010 Coll. which sets the requirements for reaching the good status of water, Amendment 2.A provides the qualitative goals for surface water for drinking - https://www.aquaseco.sk/wp-content/uploads/2017/02/nv_269_2010.pdf**	The new Regulation of the Minister of Health on the quality of water intended for human consumption, in force since 7 December 2017 Water Safety Plan
Specific MAR regulation	There is no specific regulation for MAR systems in Hungary	No specific regulations, but legislations have to be followed.	No specific regulations for MAR, but water-related legislation have to be followed.	In Poland, there are no separate, special regulations concerning operational monitoring for MAR

A specific regulatory framework for MAR does not exist in the partner countries. For a detailed overview of relevant regulations and guidelines for MAR on operation, at local national and international level, see e.g. Fernández Escalante et al. (2020), Bonfanti and Capone (2014) and Capone and Bonfanti (2015).

Similar to the approach of the MARSOL project, we consider it important that the regulatory framework is checked at several steps of the feasibility study:

- When having decided for a pilot site, regulations shall be considered on the regional level or on national level where MAR implementation is allowed.
- During the site characterization the regulations can help in the decision process on which parameters have to be measured or investigated.
- In the risk management step it is important to be amongst others aware of the regulations for human health regarding drinking water or environmental restrictions for irrigation water.
- For monitoring considerations, it is important to investigate amongst others which parameters have to be considered in the regulations and what are the limits for this parameter.
- For the cost benefit analysis, it is important to know how the regulatory framework can alter the benefits or the costs.

3. Desktop study of the pilot site

To start the initial assessment of MAR feasibility at the designated site, a collection of preliminary information about the pilot site is recommended. The scope of this step shall be to identify, with rudimentary and readily available information, the degree of difficulty of the project and the assessment if the pilot site is suitable for the intended scope under application of reasonable efforts. This shall be done with existing records in archives by the regional governments and also by field visits. Furthermore, the objective of MAR application can be addressed at this step, again, as already summarized in the good practice and benchmark report (DEEPWATER-CE, 2020a). It can also be helpful to interact with the general public and stakeholders to investigate their aims and objectives and hence reduce the risk of lack of public or political acceptance (Lyytimäki and Assmuth, 2014).

We suggest to collect information about:

- Climatology such as precipitation patterns, temperature, evapotranspiration
- Surface geomorphology, information on the geological history of the area
- Geological and hydrogeological settings
- Hydrological characteristics, such as the catchment area and the drainage network, shall be collected as well as existing water quality data.

The Australian guidelines on water recycling using MAR (NRMMC–EPHC–NHMRC, 2009) recommend to

- assess the conformity of the MAR scheme with aquifer and catchment management plans
- talk to the regulatory intuitions about the MAR project
- identify if sufficient management capabilities are available, such as knowledge of hydrogeology and water-quality management. Expertise on monitoring, reporting and water storage and treatment shall be made available for the next step.

Maliva, (2014) identified different logistical and infrastructure issues that are relevant for the construction, operation and maintenance of MAR systems. Therefore, it is recommended to analyse:

- Existing water supply infrastructure (water quantity and quality)
- Possible linkage with MAR (implement MAR to existing infrastructure)
- Land availability for MAR infrastructure
- Site accessibility
- Site security
- Proximity to water and wastewater distribution infrastructure
- Proximity to electrical power infrastructure.

Based on the collected information, a decision shall be taken about the commencement of the project, and the implementation of pilot site characterization has to be planned.

4. Site characterization

After having conducted a desktop study (among other including the collection of available data, the inquiry about regulatory requirements and the identification of expertise needed for the implementation of the MAR scheme) and having obtained a positive decision about the commencement of the project, further investigation for the planning and implementation of the MAR scheme shall be carried out in form of a site characterization process.

The objectives of the site characterization shall be to answer the question, if

- there are sufficient demand and supply possibilities for water
- the aquifer is suitable for storage and recovery of the required volume of water
- there is sufficient space available to capture and treat the water

The site characterization is followed by the determination of a specific MAR design and the validation of suitability and efficiency of this planned design with further investigations (i.e. extending information and data that have been gathered from the desktop study) (NRMMC–EPHC–NHMRC, 2009).

4.1 Objectives of site investigation for MAR schemes

To answer these questions and hence identify the feasibility of a site for MAR schemes, the following investigation objectives may be chosen:

- Aquifer delineation:
  Investigation of geological structures and identification of lithological or hydrostratigraphic units in the subsurface (e.g. layer boundaries, thickness of aquifers, etc.) in order to map the geometry of the target aquifer
- Characterization of aquifer properties:
  Determination of geohydraulic as well as geotechnical and/or petrophysical parameters (e.g. identification of preferential flow paths)
- Determination of groundwater dynamics:
  Measuring or modelling groundwater flow directions, recharge/discharge zones, groundwater abstractions and interaction between surface water and groundwater

- Determination of groundwater and source water quality:
  Investigating chemical composition, dissolved solids as well as geogenic and anthropogenic pollutions
- Identification of pollution sources:
  Delineation of pollutant sources (e.g. landfills or old deposits; detection of leakage in sealing systems), detection and identification of pollutants (what and where)
- Monitoring of the groundwater system:
  Monitoring of e.g. water levels, pollutant transport, water quality, etc., in order to identify and quantify temporal (e.g. seasonal) changes in the system

4.2 Methods of site characterization for a MAR scheme

A suite of different methods is most likely applied for the identification of parameters needed for site characterization. As identified in Figure 1, different aspects are targeted, such as:

- Water sources and water quality
- Hydrogeology, aquifer characteristics (including, e.g., storage properties)

In Table 4 an overview is given on potential methods that can be used to identify some parameters for site characterization. These methods were collected within the project partnership and with the help of literature (Fetter, 2001).

Table 4: Examples of available methods for site characterization, specific to different steps (according to criteria defined in the decision support toolbox); GW: groundwater

Parameter for site characterization	Suggested methods to identify these parameter (examples)
	Surface characteristics
Land use, hydrological soil type, topography, slope	Photogrammetry, Remote sensing, archive data processing (e.g. thematic maps such as CLC (CORINE Land Cover), aerial photos)
Lithology of the surface formation	Shallow drilling with a hand-held probe (e.g. Auger drilling); Processing of archived data (e.g. thematic maps, documentations, borehole logs, aerial photos)
	Aquifer characteristics
GW regime type, hydraulic gradient, GW flow direction, determination of watershed zones	Hydraulic head monitoring (e.g. piezometric observations, well tests); Tracer Tests; Hydrodynamic modelling (e.g. GW flow and tracer transport); developing a conceptual or numerical model of the subsurface in the pilot site; Processing of archived data (e.g. thematic maps, aerial photos)
Storage coefficient, storativity	Slug test, pumping test
GW level, aquifer confinement	Hydraulic head monitoring (e.g. piezometric observations)
Lithology of the aquifer	Electromagnetic surveys; Electrical resistivity tomography; Gravity and aeromagnetic methods; Speleological methods; Borehole drilling; Processing of archived data (e.g. hydrogeological maps and documentations, borehole logs)
Subsurface contamination	Ground penetrating radar; Magnetic surveys; Electromagnetic surveys; Electrical resistivity tomography; Induced polarization techniques;

	Soil or groundwater sampling and lab analysis (e.g. leaching test, groundwater monitoring)
Depth of the top of the aquifer (location), Thickness of the aquifer, Presence of subsurface structures providing storage or acting as barriers or channels	Electromagnetic conductivity surveys; Electrical resistivity tomography; Borehole geophysics & core analysis; Reflection/refraction seismic methods (P- or S wave); Ground penetrating radar
Characteristics of the water source	
Distance from the water source	Photogrammetry, remote sensing, geodesy, GIS data analysis
Water supply	Outflow and inflow analysis, recover efficiency (e.g. with EC measurements, Page et al., 2010)
Water quality	Groundwater sampling, (hydrogeo)chemical analysis
Water balance	Meteorology, hydrology data collection, climate model analysis, outflow and inflow analysis; hydrological and hydrogeological models

4.3 Sampling procedure for the characterisation of pilot sites

In order to characterize the pilot site with respect to water quality (precipitation, groundwater and surface water) and aquifer lithology, groundwater sampling and borehole analysis is done in order to derive the required parameters. The chemical composition of groundwater can also provide information on the groundwater flow system. In Table 4, possible methods (examples) are mentioned for identifying parameters that could be useful for MAR site characterization. Depending on the research question, the required sampling scheme and the quantity of required samples has to be determined. In order to obtain reliable and comparable results from the analysis of the samples it is important to stick to a defined sampling methodology.

In their field manual, the Texas Water Development Board has summarized eight aspects of groundwater sampling to be taken into consideration (Boghici, 2003). Several of these aspects can also be considered for precipitation and surface water sampling.

1. **Initial planning of groundwater sampling campaigns**

   Collect available data about your fieldwork location (e.g. well type, water use, aquifers or area, hydrogeology) and develop a sampling plan based on them (e.g. study criteria; monthly, seasonal or annual sampling schedule; sampling location). Before sampling: make sure, that you have the permission to take samples at the fieldwork location. It can also be helpful to visit the studied field site prior to the sampling campaign in order to determine if the location and sampling wells are accessible. Make sure to take clean and working devices and sampling bottles as well as a power supply for the devices. Among others, the following literature is suggested for setting up sampling strategies: Rivard et al. (2018), Jackson & Heagle (2016), Transdanubia (2004), Rein et al. (2011) or USGS (2006).

2. **Well purging procedure**

   Before sampling groundwater, the well has to be purged in order to stabilize the conditions and remove stagnant water. Water stagnating in a well is subject to various physicochemical processes that may have a negative impact on the representativeness of the water sample (Nielsen and Nielsen, 2007). Thus, as a rule for groundwater sampling often considered, at least twice the volume of water that is stagnating in the well should be removed (Witczak et al., 2013). However, there is no clear indication if this is adequate at every point within a well or piezometer, or if the removal of twice the volume is sufficient in every case (Dąbrowska et al., 2018). Other studies and sampling protocols propose that three water volumes should be purged, provided that the field parameters are stable (Qi et al., 2017). As another suggestion of Witczak et al. (2013), in case of piezometers, the purged water should at least cover twice the volume that corresponds to the well screen. An alternative method to the traditional “well volume” approach that is more commonly used is the low-flow method (Harte, 2017). The purpose of Low-Flow Purging and Sampling (LFPS) is to collect groundwater samples from monitoring wells that are representative of ambient groundwater conditions in the aquifer. This is accomplished by setting the intake velocity of the sampling pump to a flow rate that limits drawdown inside the well. LFPS has three primary benefits. First, it minimizes disturbance of sediment in the bottom of the well, thereby producing a sample with low turbidity. Second, LFPS minimizes aeration of the groundwater during sample collection. Third, the amount of groundwater purged from a well is usually reduced as compared to conventional groundwater purging and sampling methods (New Jersey Department of Environmental Protection, 2003).

3. <u>Determination of groundwater field parameters</u>

   Measure temperature, pH and specific conductivity until they have stabilized in the well. Alkalinity, oxidation/reduction potential and dissolved oxygen should be measured as well as they can change the chemical composition of the sample during holding times.

4. <u>Recording of field data</u>

   Field data shall be recorded during the field work. The data can be collected in prepared sheets. In order to avoid systematic errors, it can be helpful if two persons collect the data and the data is also stored in a digital data logger, if possible.

5. <u>Filtering of groundwater samples</u>

   For many analyses it is important to filter the samples prior to the measurement. Be informed about which pore size the filter shall have and which methodology of filtration can be applied. E.g. when analysing stable water isotopes, a filtration with 0,22 µm pore size of the sample is recommended, but not using a vacuum pump as it can change the isotopic composition of the sample. For some analyses, the filter itself has to be stored (dried and weighted).

6. <u>Routine sampling procedure</u>

   As every study and research question is different, it is important to carefully plan the fieldwork. It is recommended to be consistent with filling and labelling the used containers (recording the well number, sample type, date, etc.) in order to avoid errors and allow replicability of your study. It is important to apply routine procedures concerning sampling devices and analysis methods. Samples should be kept save during transport to the laboratory. Furthermore, samples may have to be stored cool.

7. <u>Health and safety issues</u>

   Exposure to chemicals must be avoided. Also weather conditions shall be taken into account (consideration of sun and rain/snow protection).

The following ISO norms can help with developing a sampling strategy, and selecting suited methods, for surface water, groundwater and soil sampling:

- Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 1: Technical principles for execution (ISO 22475-1:2006); German version EN ISO 22475-1:2006

- Geotechnical investigation and testing - Sampling of soil, rock and groundwater - Part 1: Technical principles (ISO/DIS 22475-1.2:2019); German and English version prEN ISO 22475-1:2019-NORMENTWURF
- Water quality - Sampling - Part 1: Guidance on the design of sampling programmes and sampling techniques (ISO/DIS 5667-1:2019); German and English version prEN ISO 5667-1:2019
- Water quality - Sampling - Part 14: Guidance on quality assurance and quality control of environmental water sampling and handling (ISO 5667-14:2014); German version EN ISO 5667-14:2016
- Water quality - Sampling - Part 6; Guidance on sampling of rivers and streams (ISO 5667-6:2014)
- Water quality - Sampling - Part 11: Guidance on sampling of groundwaters (ISO 5667-11:2009)

4.4 Water demand

Water demand determination in the context of Managed Aquifer Recharge (MAR) is not widely discussed in literature, to date. As no case studies on the determination of water demand specific to MAR have been found, as a starting point, we have considered the suggestions provided by the Environmental and Water Resources Institute and the American Society of Civil Engineering in their standard guidelines for artificial recharge of groundwater (ASCE American Society of Civil Engineering EWRI Environmental and Water Research Insititute, 2020). As national guidelines for water demand determination are diverse in different Central European countries, it has been found that they cannot be described with a common methodology. Based on input of project partners, several possibilities for water demand determination in Central Europe have been collected and described in Appendix A.

Key aspects from national guidelines and publications related to the determination of water demand, in general (not specifically related to MAR), are summarized in the following (sections 4.4.1-3.). These sections provide input on how the task of water demand determination can be approached, independent of the existence of specific national regulations on water demand.

4.4.1 Current water demand

Termes et al. (2015) have shown in a review of water demand models that water demand estimation studies often used household, census tract and aggregated data. Household level data estimates are expected to be consistent over time but are difficult to obtain. To overcome such lacks, several studies used the same dataset (e.g. Worthington and Hoffman 2008), gathered samples through surveys (e.g. Domene and Sauri 2006, Olmstead et al. 2007) or studied residential water demand at census tract level, water utility or municipality level (e.g. Ouyang et al. 2014, Worthington and Hoffman 2008). Concerning the type of data, pooled time series (panel data) have mostly been used to estimate water demand, but also cross-section time-series are considered for water forecasting (Termes et al., 2015; Worthington and Hoffman, 2008). The uncertainty of water consumption data can be high, among others due to unauthorized and/or unregistered wells for drinking or irrigation water abstraction.

Input data to assess the water demand, based on DVGW (2008) and EWRI/ASCE (2001):

- Past and present water consumption
- Past and present water quality
- Past and present regulations and water rights issues

Output data from the evaluation of water demand:

- Average water demand, annually or daily

- Peak day demand
- Ratios of maximum day to average annual demand, maximum week to average annual demand, and monthly demand as a percentage of average annual demand
- Monthly variability of water demand
- Trends of past and present data

4.4.2 Prediction of water demand

Based on evaluations of collected data with respect to the current water demand, predictions on future demands can be made. E.g. based on German guidelines, the prediction time should be between 10 and 30 years in order to be in an acceptable uncertainty range (DVGW, 2008). It should also be mentioned that with an increasing scale of the area, the uncertainty of the prediction will increase, as well.

The Australian guidelines for water recycling state that the water demand is likely to increase in the future due to climate change (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009). Within the partnership of the DEEPWATER-CE project, no general conclusions could be drawn if the future water demand is expected to increase or decrease. It is important to consider several different aspects, in order to make prediction on a local scale. Termes et al. (2015) have summarized specific aspects, based on which water demand predictions can be considered. They have categorized explanatory variables in five criteria groups, as described in the following.

<u>Economic criteria</u>

Regarding economic variables, factors affecting water demand are the price and the income (Termes et al., 2015). The demand of water is price-inelastic, which means that a change in price of 1 % is expected to cause a change in demand between 0 and 1 % (e.g. Fenrick et al., 2012; Martínez-Espiñeira, 2007; Martínez-Espiñeira and Nauges, 2004; Polycarpou and Zachariadis, 2013). This can be explained by small participation in household expenditure and the lack of water substitutes for most of its uses (Arbue and Barberán, 2004). However, with different applications of water, the elasticity was found to vary. Indoor uses of water have a vital role, whereas outdoor applications are more related to leisure, which increases the elasticity of the price-demand function (e.g. Hansen, 1996; Renwick and Green, 2000).

To measure the impact of household income on water consumption, different studies have used different variables as a proxy for income, including for example the value of property, education level and mean income at census tract (Arbue and Barberán, 2004; Dandy et al., 1997; Hewitt and Hanemann, 2015). Some studies did not find income to be a variable affecting water consumption (House-Peters et al., 2010; Musolesi and Nosvelli, 2010), however many studies suggested a positive correlation (e.g. Hung and Chie, 2013; Lyman, 1992; Martínez-Espiñeira and Nauges, 2004; Polycarpou and Zachariadis, 2013). This can be explained by the access to outdoor spaces and the fact that, with a higher income, the part of the water bill is little, which decreases the awareness for the scarcity of water (Arbués et al., 2003). The different use cases of water also play an important role regarding the seasonal effects influencing water demand. Indoor uses are mostly not influenced by seasonal changes compared to outdoor uses (Makki et al., 2011). This leads to high-income households being more sensitive to climate variations (Balling Jr. and Gober, 2006).

<u>Socio-demographic criteria</u>

The effect of socio-demographic factors, such as age distribution, has only infrequently been assessed in regard to water demand (Termes et al., 2015). However, some studies suggest the household size to positively contribute to water consumption (e.g. Arbués et al., 2003; Kenney et al., 2008). In per capita terms, the water consumption decreases due to economies of scale with the increment in members of the household (Schleich and Hillenbrand, 2009). Children were clearly found to increase water demand (e.g.

Makki et al., 2011; Nauges and Thomas, 2000), whereas the results for elderly people were conflicting. On the one hand, it was implied that they have a higher water demand because of more time spend at home (e.g. Schleich and Hillenbrand, 2009). On the other hand, studies suggested elderly people to have water saving attitudes (e.g. March et al., 2012; Nauges and Thomas, 2000). Furthermore, the influence of employment status, foreign vs. native population and the educational level on the water consumption was assessed (e.g. Binet et al., 2014; Gaudin, 2006; March et al., 2012; Pfeffer and Stycos, 2002).

Physical characteristics

Physical characteristics cover for example property type, house size, outdoor size and garden (e.g. Domene and Saurı, 2006; House-Peters et al., 2010; Wentz and Gober, 2007). In this regard, the influence of the number of bedrooms or the house size was not consistently proven to be significant. Some studies suggested a positive correlation with the water demand (e.g. Fox et al., 2009; Wentz and Gober, 2007) while others did not propose any influence (Domene and Saurı, 2006). Characteristics associated with outdoor activities, such as a swimming pool, were always found to be significant and positively related (e.g. Domene and Saurı, 2006; Wentz and Gober, 2007).

Climate characteristics

For the assessment of climatic influences, Termes et al. (2015) found rainfall and temperature to be the most repeated variables in literature. Rainfall on the one hand with a direct impact on outdoor applications, and on the other hand temperature, affecting both indoor and outdoor usages (Ouyang et al., 2014). To measure rainfall, different approaches have been listed in literature, such as considering precipitation frequency, the amount of rainfall and psychological effects resulting from rainfall (e.g. Jain et al., 2001; Martínez-Espiñeira, 2002; Schleich and Hillenbrand, 2009; Zhou et al., 2000). A useful tool for the prediction of influences of climate change on water availability could be the coupled climatological and hydrogeological model developed in the NAGiS project (NAGis, 2016). The Hydrologic Evaluation of Landfill Performance (HELP) model developed by the US EPA is used in combination with climatological input data created from varying predictive climate conditions based on different global climate models. This approach provides a quantitative link between the climate and hydrogeological conditions at larger regional flow systems. It considers pressures on water supply that originate from water abstraction for drinking water, irrigation water, or other purposes (Toth et al., 2019).

Other criteria

Regulatory, non-pricing measures, which are mainly established during droughts were found to reduce water consumption (Termes et al., 2015). The effectiveness of these measures was detected to be influenced e.g. by its timing (Berk et al., 1980), the number of programs for saving water introduced (Michelsen et al., 1999), the level of information and enforcement efforts of the program (Halilch and Stephenson, 2009) or the implementation of a mixed policy (Kenney et al., 2008). For instance, measures implemented before the drought were proven to be less significant than measures applied during the drought (Berk et al., 1980).

4.4.3 Mathematical estimation methods

Functional forms to describe water demand can e.g. cover linear functions, semi-log, log-log and Stone-Geary formulations. The selection of a suitable functional form is dependent on the research question, as all functions have their own strengths and weaknesses (Termes et al., 2015). Another approach could be to predict the water demand based on the consumption during a dry and during a wet year, which is defined based on historical data.

Water demand equations most often involve the Ordinary Least Squares (OLS) technique, followed by the methods of Generalized Least Squares (GLS) and Instrumental Variables (IV). Another approach often used for water demand estimation is the Discrete-Continuous Choice (DCC) approach. More details can e.g. be obtained from Chicoine et al. (1986), Olmstead (2009) or Sateth and Dinar (1997).

5. Risk management

Contents of this section, as well as section 5.1., are part of a manuscript recently submitted to *Water* (Imig et al., n.d.) In the context of risk management, harm can describe an injury or damage to human health, as well as damage to property or the environment. Hazard is the potential source of harm, which can e.g. be a biological, chemical, physical or radioactive agent, and a hazardous event is an event that can cause harm. The combination of probabilities for the identified hazard to occur in a specific time frame and the magnitude of its harm is termed risk (ISO/IEC International Organization for Standardization; International Electrotechnical Commission, 2014; NRMMC-EPHC-AHMC, 2006).

The International Organization of Standardization (ISO) proposes an iterative process for risk management (ISO, 2018) as summarized in Figure 4. After establishing the scope and context of the evaluation, risk assessment is carried out followed by risk treatment. The risk assessment procedure consists of three steps, i.e. risk identification, risk analysis and risk evaluation. Risk identification is conducted in order to identify and describe hazards that aid or prevent the achievement of an aim. Factors such as tangible and intangible risks, threats and opportunities as well as consequences and their impact on the aims should be taken into account. Risk analysis describes the likelihood of a hazard or hazardous event by taking into consideration the consequences and sensitivities of these consequences. Risk evaluation intends to identify risks for which actions have to be undertaken such as further analysis, maintenance of existing control structures or risk treatment options (ISO/IEC International Organization for Standardization; International Electrotechnical Commission, 2014; ISO International Organization for Standardization, 2018).

Risk assessment is a step of risk management. Findings of the risk assessment are subsequently used to derive proactive measures in order to handle or reduce risks (risk treatment) within the scope of risk management schemes (EC, 2015; UNISDR, 2009). Risk treatment measures aim to reduce present risks to an acceptable level. Risk treatment options for MAR can comprise pre- and post-treatment of recharge water, adaption of the MAR system design in order to deliver the required functions, the selection of sites that are better suited, an adequate maintenance and operation of the infrastructure or the development of suitable responses to unplanned incidents (NRMMC-EPHC-AHMC, 2006; Pedretti et al., 2012a, 2011). By applying monitoring programs, the effectiveness of the risk management system and preventive measures can be ensured (NRMMC-EPHC-AHMC, 2006).

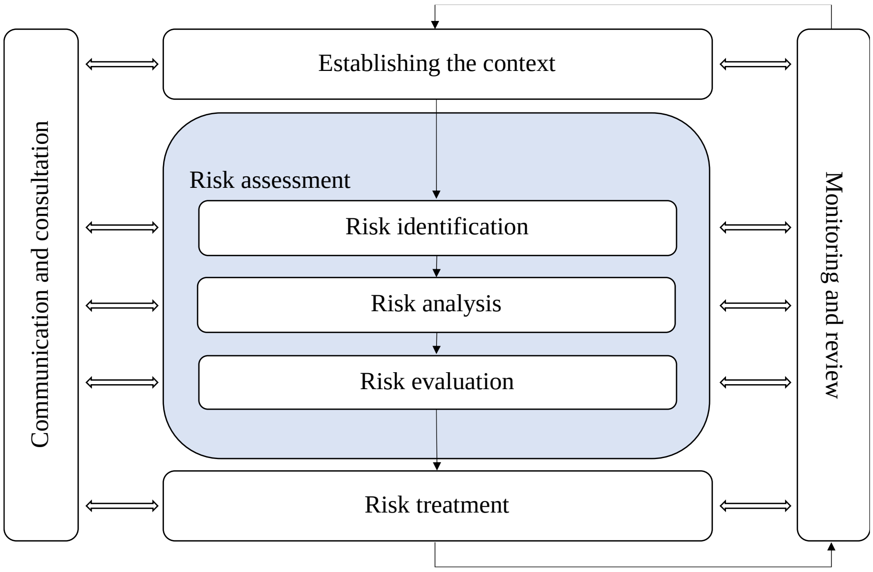

Figure 4: Risk management process (after ISO International Organization for Standardization, 2018)

In Appendix B, regulations for MAR risk assessment and management are summarized for the four different partner countries with pilot sites. The partners from Poland and Hungary documented that national guidelines recommend the development of a Water Safety Plan (WSP) for risk management. The risk assessment as well as the risk treatment processes identified in the following can be incorporated in the WSP.

5.1 Risk assessment

As described above and displayed in Figure 4, the first step of risk assessment in order to develop a risk management plan is a central part. Several risk assessment guidelines and methodologies applied for MAR schemes were collected and are summarized in the following (chapter 5.1.1 and 5.1.2). In Table 5 and Table 6 their strengths and weaknesses are identified. Some of the risk assessment approaches described in this section are involving two international frameworks that have been developed for risk assessment in general (without specific attention to MAR): (i) the framework of hazard analysis and critical control points (HACCP) and (ii) the framework of water safety plans (WSP) suggested by the WHO.

Hazard analysis and critical control points. The HACCP framework has been proposed by the European Union in particular for application within the food and feed sector (e.g. EC, 2005; EC, 2004). Application of the HACCP framework is compulsory in EU countries where water utilities fall under the provision of food safety (EC European Commission, 2015). The HACCP framework was developed in the 1960s as a universal, scientifically based approach for food safety. Among others, the Pillsbury Company (Minnesota, USA), the National Aeronautics and Space Administration (NASA) and the U.S. Army Laboratories at Natick (Massachusetts, USA) have contributed to its development (Havelaar, 1994; WHO World Health Organization, 1997; WHO World Health Organization and FAO Food and Agriculture Organization of the United Nations, 2006). In a twelve-step procedure, a control system is established by identifying hazards and their critical control points. A critical control point is defined as a step in the procedure where control can be applied and can lead to hazard prevention, hazard elimination or the reduction of a hazard to an acceptable level. An effective HACCP plan also focuses on prevention, by defining precautions for preventing hazards (EC European Commission, 2015).

Water safety plans. The WHO has published the so-called Stockholm Framework in which it was agreed that future guidelines for drinking-water, wastewater and recreational water should include risk assessment and risk management (Bartram et al., 2001). Based on this, the setup of Water Safety Plans (WSP) was proposed in 2004 (WHO World Health Organization, 2004).WSPs are partly based on principles of the HACCP framework but are tailored for the water industry (Page et al., 2012). Human health risks related to drinking water use (potentially arising from microbial, radiological and chemical hazards) are assessed for the whole process of providing drinking water ("from the catchment to the consumer"). This risk assessment forms the basis for decision-making in order to target the health risks of the system on a multi-barrier principle (WHO World Health Organization, 2006). Operational monitoring and control measures are defined within the WSPs, as well, since those are important for ensuring that the health-based targets are met. Water safety plans (WSP) and hazard assessment and critical control points (HACCP) methods comprise the development of a risk management plan as well.

5.1.1 Frameworks for MAR risk assessment

In this section, risk assessment guidelines related to MAR are described, which include detailed instructions. To the best knowledge of the authors, detailed guidelines on MAR risk assessment possessing official status are available only for Australia (named "Australian guidelines" in the following). For India, guidelines have been developed based upon the Australian guideline as well as the sanitary survey to produce a water safety plan with the WHO drinking water guidelines have, however, no official status but are intended as a recommendation (WHO World Health Organization, 2004). Aside from Australia and India, there are also other countries that published guidelines on MAR implementation and operation: these guidelines acknowledge that risk assessment shall be conducted, however they do not propose specific methodologies (therefore we did not mention them above in section 4.1). Such guidelines we found, amongst others, for the Netherlands, USA, Italy, Mexico and Chile (ASCE American Society of Civil Engineering EWRI Environmental and Water Research Insititute, 2020; Minister van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer, 1993; Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2016; MOP Ministerio de Obras Públicas, 2014a; SEMARNAT Secretaría del Medio Ambiente y Recursos Naturales, 2009). For South Africa, a guideline for planning and authorizing MAR schemes is available that includes questionnaires for risk identification but no specific methods for risk analysis or evaluation (Ravenscroft and Murray, 2010). Fernández-Escales et al. (2020) have highlighted that policies and legal frameworks applicable to MAR are scarce and at an early stage, especially when looking at developing countries where WHO guidelines are widely implemented. For tailoring of MAR guidelines, Fernández-Escales et al. (2020) propose to include risk assessment as well. Pindoria-Nandha (2016) observed that water companies are not keen on spending money for desk analyses or pilot sites for MAR schemes, if there is considerable uncertainty to the legislative requirements. Both guidelines are described in detail in this chapter, and their reported strengths and weaknesses (together with references for application examples) are summarized in Table 5: Overview of repeated strengths and weaknesses of risk assessment guidelines related to MAR, as well as references for application examples..

Australian guidelines for MAR risk assessment. Australia has recommended specific risk assessment methodologies for MAR, as laid down in national guidelines for water recycling (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC–NHMRC, 2009). These guidelines aim at developing a MAR risk management plan including twelve steps, and they address the use of storm water, recycled water originating from wastewater treatment plants, surface water, groundwater and water originating from drinking water distribution systems. These guidelines can be applied for all aquifer types, and water reuse can involve drinking water supply, irrigation, industrial use or environmental purposes (e.g. restoration of the aquifer to its ambient environmental values or stabilizing ecosystems such as wetlands). The risk assessment framework incorporated within the Australian guidelines has four iterative stages for identifying human health and environmental risks: (i) entry-level assessment, (ii) assessment of maximal risks, (iii) assessment of residual risks for MAR pre-commissioning, and (iv) assessment of residual risks for the operational phase of MAR. In the first stage of the risk assessment process, an entry-level assessment should be conducted. This is based on existing information (e.g. is there sufficient water demand, is there an appropriate water source, is there sufficient space available for a MAR site) to give an outlook on MAR viability and the degree of difficulty, which may be related to the MAR project. Aims are also to inform about the extent of investigations needed in the following stages and to support the decision-making process in this regard. Such investigations are more extensive and connected to higher costs and should therefore be evaluated carefully. Then, risks are assessed at two levels: maximal risks (including unmitigated or inherent risks) in stage (ii) (as mentioned above) and resulting residual risks (for MAR pre-commissioning) in stage (iii), after having considered preventive measures that could minimize the determined maximal risks. The pre-commissioning assessment (stage iii) aims at indicating the safety and sustainability of the planned MAR project through estimating the residual risks that are expected at the related MAR site. In case of high residual risks, preventive measures are again needed until risks have been reduced to an acceptable level. In case this reveals impossible, the project is considered unviable. However, if in the earlier stage (ii) the maximal risk is assessed to be low for every hazard, the project can proceed to construction, without the need for stage (iii). In stage (iv), the residual risk for the operational phase of MAR is assessed. This is supported by data collected through the monitoring of project trials.

For twelve potential hazards to human health and the environment related to MAR implementation and operation, the Australian guidelines give advices on adequate management. This includes possible preventive measures, monitoring strategies (validation, verification and operational monitoring) and acceptance criteria for the four risk assessment stages. If acceptance criteria given in the guidelines are met in one stage, the next stage can follow. Methods suggested by the Australian guideline to evaluate acceptable risks are based on qualitative risk assessment for environmental risks, and quantitative risk assessment for human health risks. In case sufficient data is available, a quantitative risk assessment can also be applied for addressing environmental risks. Details on the methodologies of qualitative and quantitative risk assessment are given in Chapter 5.1.2.

Indian guidelines for MAR risk assessment. Dillon et al. (2014) developed a water quality guide related to the implementation of managed aquifer recharge in India. This guide (named “Indian guidelines” in the following) is structured by a sequence of steps, including the first stage from the Australian guidelines, entry-level risk assessment and sanitary surveys proposed by the WHO (WHO World Health Organization, 2017). The steps guide the risk assessment, which is often done in the form of specific questions, which are intended to be answered by the user. The Indian guidelines propose risk assessment based on low availability of data (Dillon et al., 2014; Dillon et al., 2020). The first step includes an entry-level risk assessment, as proposed by the Australian guidelines (NRMMC–EPHC–NHMRC, 2009). If risks to public health and the environment, identified at this level, are sufficiently low, no evaluations at a higher level of detail are required. This can e.g. be the case if the aquifer intended for MAR is not used for drinking water supply and the water being recharged to this aquifer can be assumed to be of an adequate quality (such as low risks of pollution, e.g. arising from the infiltration of collected rainwater). If the entry-level assessment reveals relevant risks, the next step of the proposed procedure is to carry out a viability assessment, where the water demand and supply as well as hydrological, hydrogeological and logistical aspects for the foreseen MAR scheme are evaluated. If the chosen site and intended MAR scheme is evaluated to be viable, the next step evaluates the inherent risk. If the inherent risk is low (e.g. recharging water is not sewage effluent, or the aquifer is unpolluted) risk assessment can be conducted based on sanitary surveys, otherwise more data has to be collected and the successive stages of the Australian guidelines shall be followed (cf. previous section). With the sanitary surveys, potential contaminations are identified with the help of questionnaires (e.g., animal faeces or sewage is considered indicative of a microbiological hazard). The questionnaires are based upon recommendations given along with the WHO drinking water guidelines (WHO World Health Organization, 2017, 2012). The next step includes an assessment of aquifer characteristics to be done at a higher level of detail as compared to the viability assessment. For this task, the Indian guidelines contain a set of questions, to be answered by the user, concerning water quality, storage capacity and other (hydro)geological aspects. Based on the outcome, in the last step, a water safety plan and protective measures for risk treatment are developed for the foreseen MAR scheme, as recommended by the WHO (WHO World Health Organization, 2004).

Table 5: Overview of repeated strengths and weaknesses of risk assessment guidelines related to MAR, as well as references for application examples.

Risk assessment guidelines	Weaknesses	Strengths	Examples for guideline application (references)
Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC-NHMRC, 2009)	Detailed input data needed (Dillon et al., 2020)	Tailored to specific MAR-related hazards with detailed indications of acceptable risks	(Bartak et al., 2015; Gibert et al., 2015; D Page et al., 2010; D. Page et al., 2010c, 2010a, 2010b; Page et al., 2013, 2009; Seis et al., 2015; Vanderzalm et al., 2011)
Water safety plans (WHO World Health Organization, 2004)	Precautious approach might indicate many hazards at high risk (e.g. when likelihood data is limited)	Comprehensive approach from catchment to customer	Dominguez-Chicas and Scrimshaw (2010); Davison et al. (2005)
Hazard analysis and critical control points (HACCP) framework (e.g. EC, 2015; Havelaar, 1994; WHO, 2006, 1997)	Hazard identification is subjective; critical control point identification for MAR is more difficult than existing water treatment options because MAR is a complex system failures and risks are not quantified	Not limited to specific hazards	Dewettinck et al. (2001); Page et al. (2009, 2008); Swierc et al. (2005)
Indian guidelines (Dillon et al., 2014)	(approach was not validated to date)	Low data need (however, approach was not validated to date)	(no application documented to date)

5.1.2 Methodologies for MAR risk assessment

In this chapter, risk assessment methodologies are described that are frequently applied for MAR-related risk assessment. Reported strengths and weaknesses of these methodologies, together with references for application examples, are summarized in Table 6.

In the **decision support toolbox**, a method to identify **the sensitivity of MAR schemes to climate extremes** was developed. With this methodology risks related to extreme climate events such as floods, flash floods, hydrological drought, groundwater drought and soil drought for six different MAR types can be investigated. Details of the methodology can be found in the toolbox (DEEPWATER-CE, 2020b).

Qualitative risk assessment. As described above, the Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC–NHMRC, 2009) propose a qualitative risk assessment for MAR. The likelihood of a hazard to occur is identified by the expected recurrence of the hazard (indicated in units of years), and this likelihood is expressed by using a five-step scale. A hazard recurrence interval of 100 years is defined as "rare" (lowest scale) and a recurrence of several times per year is defined as "almost certain" (highest scale). The consequence of the hazard is thereafter assessed with a further five-step scale. According to this scale, a "catastrophic impact" (highest scale) has to be expected e.g. if the human health of a large population is threatened by the hazard, the integrity of regional ecosystems or the life of plant/animal species are endangered. The lowest scale defines an insignificant (or even non-detectable) impact. If both the likelihood and the consequence of the hazard are ranked high, the resulting risk is identified to be very high (Figure 5). Swierc et al. (2005) applied qualitative risk assessment to define measures for prioritized pollution prevention and to set up a HACCP framework. Earlier, the WHO has proposed a qualitative human health risk assessment related to drinking water use (Bartram et al., 2001). Following this methodology, which is known as the Stockholm Framework, risks are estimated from the likelihood of adverse effects resulting from drinking water use and the severity of human health consequences (ranked in a five-step scale).

Risk Factor Matrix — Likelihood of occurance / Severity of consequences	Insignificant *rating: 1*	Minor *rating: 2*	Moderate *rating: 3*	Major *rating: 4*	Catastrophic *rating: 5*
Rare *rating: 1*	low	low	moderate	high	high
Unlikely *rating: 2*	low	low	moderate	high	very high
Possible *rating: 3*	low	moderate	high	very high	very high
Likely *rating: 4*	moderate	high	high	very high	very high
Almost certain *rating: 5*	moderate	high	very high	very high	very high

Figure 5: Risk factor score matrix for qualitative risk assessment, relating the likelihood of hazards to the severity of consequences (after Swierc et al. 2005)

Quantitative risk assessment. The Australian guidelines (cf. above) propose a methodology for quantitative risk assessment (QRA) for MAR, which is based on chemical risk assessment procedures that have been developed by the US Environmental Protection Agency (US EPA United States Environmental Protection Agency, 2002, 1998, 1987). This methodology compares e.g. chemical concentrations in an environmental matrix (such as groundwater) to reference values (such as drinking water limits, e.g. US EPA, 2002, 1998, 1987; WHO, 2017). Four steps are considered as shown in Figure 6 for quantitative human health risk assessment. Firstly, the hazard, together with its variability, and related impacts are identified. Secondly, the dose-response relationship is quantified, which describes how the likelihood and severity of adverse human health effects (the responses) are related to the amount and condition of exposure to an agent (the dose provided) (see also US EPA, 2002, 1998, 1987). Subsequently, the size and nature of the exposed population to the hazard is identified, including an assessment of the amount (such as contaminant intake), the exposure route (such as the ingestion of contaminated drinking water) and the duration of exposure. In the last step, obtained information is combined in order to characterise the risk, i.e. to predict the probability of adverse health effects, where not only the magnitude, but also variabilities and uncertainties are determined (e.g. Haas et al., 1999; NRMMC-EPHC-AHMC, 2006). Several studies have coupled QRA with stochastic (Monte Carlo-based) simulations to provide a sensitivity analysis for the identified risks. Model inputs are described with a probability distribution function to describe the uncertainty (Page et al., 2010 a, 2009, 2008). Methodologies of QRA can also be applied to other aspects, such as for quantifying risks related to the technical operation. In field tests, Sultana and Ahmed (2016) identified and analysed factors that influence the probability for the clogging of drinking water wells. Findings can be used for the quantification of related risks.

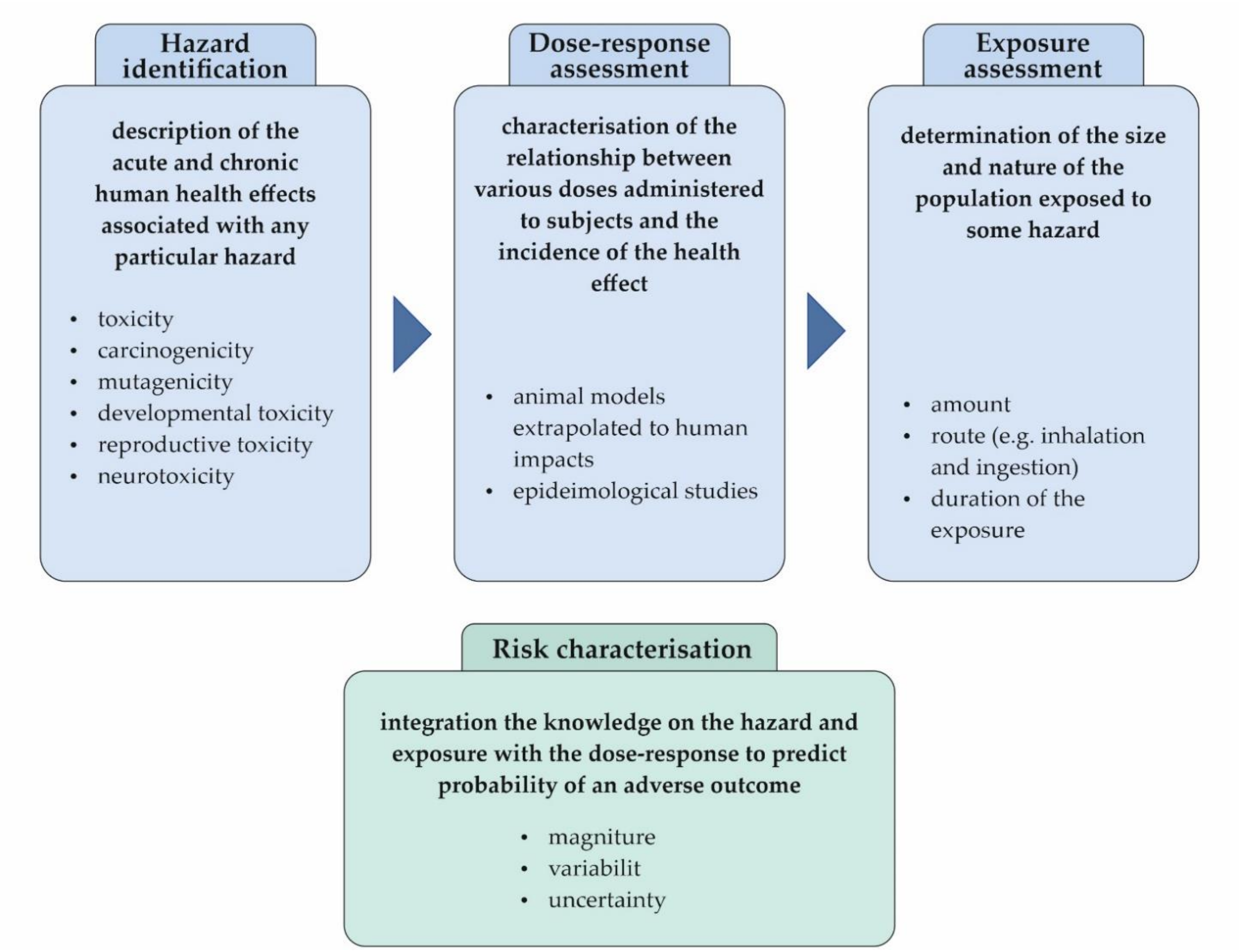

Figure 6: Steps of quantitative risk assessment addressing human health risks arising from chemicals (adopted from Haas et al., 1999).

Quantitative microbial risk assessment. Quantitative microbial risk assessment (QMRA) follows the same steps as above for QRA, but focuses on the quantification of human health risks arising from indicator microorganisms in water (Haas et al., 1999). Source water can contain a variety of microbial pathogens, however it may be difficult, with reasonable efforts, to determine concentrations, dose-response relationships and related impacts for all potentially relevant pathogens at an investigated site. Therefore, in practice, often an indicator or reference pathogens are assessed as recommended by the WHO in their guidelines for the safe use of wastewater and greywater (WHO World Health Organization, 2006) and the

Australian guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009) also for the context of MAR. The latter recommends the assessment of a selection of reference pathogens in order to represent major groups of bacteria, viruses, protozoa and helminths. A focus is given on pathogens that show a high occurrence, relevant concentrations in MAR source water and low removal rates in MAR water treatment as well as a long environmental persistence (NRMMC-EPHC-AHMC, 2006). In the first step of the proposed QMRA procedure, pathogen-related hazards posing potential risks to human health are identified. Then, the likelihood of illness (for a given population) is calculated using dose-response curves of the reference pathogens. As a next step, taking into account a certain number of exposure events per year, the daily probability of infection is transformed into a probability of infection occurring per year. In the last step, information from the previous steps is integrated in order to determine and evaluate the magnitude of risks. Both guidelines mentioned above (WHO 2006 and the Australian guidelines) refer to the disability-adjusted life years (DALYs) method for risk evaluation. This method describes the disease burden by calculating accumulated years of life that are lived with disability and/or are lost due to an early death. A metric is included in order to assess international disease burdens where health impacts are weighted in terms of severity by assigning a number between zero (no health impact) and one (death). The number is then multiplied by duration of the health impact and the number of people that are affected. The WHO recommends a tolerable median risk of 10^{-6} DALYs per person and year (WHO World Health Organization, 2006). Applying this methodology for MAR, e.g. Ayuso-Gabella et al. (2011), Page et al. (2012) considered rotavirus, as well as *Cryptosporidium* and *Campylobacter* strains as reference pathogens, whereas focused Toze et al. (2010) on rotavirus, *Cryptosporidium* spp. and *Salmonella typhimurium*. QRA and QMRA can advance the HACCP framework for determining chemical and microbiological risks (Page et al., 2009).

Integrated human health risk framework for MAR. Assmuth et al. (2016) have developed a methodology for regional-level human health risk assessment of chemical and microbiological water contamination. This methodology aims at aiding water management, and it also incorporates socio-economic aspects of health risks. A model of risk and its impact chain is proposed, combining the related social and economic aspects, as well as factors related to the eco- and techno system. In the first phase, input data for evaluating risks and their adverse impacts are collected. Health risks related to pathogens are proposed to be quantified by QMRA, determining disability-adjusted life years (DALYs) or quality-adjusted life years (QALYs). Information on chemicals that may threaten human health is proposed to be obtained from modelling of environmental transport and fate of contaminants in the system, where the application of equilibrium model approaches is suggested for socio-economic analysis. Obtained data should then be used for a structural integrated risks analysis, considering pollutant sources, release mechanisms, environmental transport and fate pathways, exposures routes, health effects and resulting socio-economic impacts, as well as management responses. In this way, a multidimensional view on risks is taken (instead of limiting the analysis to single system parts, only).

Pollutant release and transfer register. Ji and Lee (2016a, 2016b, 2017) proposed the use of a pollutant release and transfer register (PRTR) together with deterministic and stochastic methods in order to assess potential chemical risks for a MAR site. A PRTR provides data to determine (i) the quantity of emitted chemicals (discharged to water systems, soil and the atmosphere) and (ii) the transfer of these chemicals (from their source to the MAR facilities) as a function of time. Potential accumulated chemical risks are proposed to be determined from the toxicity of the chemicals, the distance from the source to the MAR site and the total quantity of chemical to be transferred from the source over time. When recorded data are lacking or predictions for future developments are intended, Ji and Lee (2016b, 2017) propose the application of PRTR in combination with a stochastic approach for estimating potential risks. PRTRs can be used for carrying out a risk assessment as part of the HACCP procedure and/or the setup of water safety plans, as e.g. done by Ji and Lee (2017) for two different MAR sites.

Probabilistic risk assessment based on fault trees. Rodríguez-Escales et al. (2018) developed a probabilistic risk assessment methodology for the operational phase of MAR based on fault trees, which considers a series of quasi-independent events that contribute to total risk. This subdivision aims at simplifying the risk assessment process, i.e. the events can be managed individually: probabilities are computed for the occurrence of these individual events, and these probabilities are systematically recombined to assess overall risk for the MAR system. For applying this approach, the open-source application MAR-RISKAPP is available (Rodríguez-Escales et al. 2018). A fault tree is evaluated by the user that includes 65 basic events that potentially can lead to MAR failure (these basic events were assumed to be potentially relevant, based upon a literature review considering 47 different MAR sites). Probabilities of the individual events and the resulting probability for the failure of the global system are determined, forming the basis for the next step: risk treatment should then be conducted for the events identified as most significant.

Public health and economic risk assessment. Juntunen et al. (2017) proposed a risk assessment methodology for MAR with the aim of decreasing the uncertainty of risk prediction and in order to enable more accurate decision making for the mitigation of adverse effects. The authors combine methods for economic, environmental and health assessment with different computational techniques. Their proposed methodology is composed of four steps. First, flow and (reactive) transport models are applied to predict contaminant and pathogen transport and related potential risks for the use of MAR. The second and third steps include the prediction of public health risks, where QMRA for the determination of human health risks (related to pathogens causing diarrheal diseases) was combined with chemical risk assessment using acceptable daily intake (ADI) levels, as proposed by the (WHO World Health Organization, 2010). In the final step, regional economic effects resulting from the assessed health impacts are investigated, including the illness probability (and related change in labour productivity) estimated by using a computable general equilibrium (CGE) model. Juntunen et al. (2017) have applied this methodology for different probable scenarios (e.g. flood, pre-treatment failure, wastewater spill at the intake site) to assess their impacts on health risks stemming from the MAR scheme.

Screening-level assessment of human health risks arising from micropollutants. (Rodriguez et al., 2007b, 2007a) propose a methodology for human health risk assessment at the screening level, for evaluating potential risks to MAR arising from contamination with micropollutants. These studies concentrate on micropollutants, as chemicals of concern for indirect potable reuse schemes. In order to calculate health risks arising from a chosen chemical, the risk quotient is calculated by relating measured chemical concentration in the recovered water to a benchmark (non-effect) concentration. Such benchmark values are available for regulated compounds, e.g. defined by the accepted maximum level of the compound in drinking water. For unregulated compounds with existing toxicity information, benchmark values can e.g. be calculated based on the health-based screening level (HBSL) approach developed by Toccalino et al. (2003) and applied by Toccalino et al. (2004) on a large (state) scale. In the HBSL approach it is important to subdivide between non-carcinogenic and carcinogenic compounds. For compounds, which are neither regulated nor subject to available toxicity information, the threshold of toxicological concern (TTC) has been proposed as a benchmark value (Kroes et al., 2004 and 2005). The risk quotient can then be used to evaluate the potential health risks from upon defined chemicals of concern and enable policy-makers to include them in specific guidelines.

Table 6: Overview of reported strengths and weaknesses of risk assessment methodologies related to MAR, as well as references for application examples.

Risk assessment methodologies	Weaknesses	Strengths	Examples for methodology application (references)
Qualitative risk assessment	Detailed processes cannot be highlighted	Low data need	(Sultana and Ahmed, 2016; Swierc et al., 2005)
Quantitative microbial risk Assessment	Detailed input data needed	Precise predictions possible	(Ayuso-Gabella et al., 2011; Bekele et al., 2008; Bloetscher, 2001; D. Page et al., 2010a, 2010b; Page et al., 2016, 2015b, 2015a,

			2013, 2012b; Toze et al., 2010)
Quantitative risk assessment	Detailed input data needed	Precise predictions possible	(Page et al., 2009; Page et al., 2008)
Integrated human health risk frameworks for MAR	Detailed input data needed; Limited to human health risks	Multidimensionality of a risk	(Assmuth et al., 2016)
Pollutant release and transfer register (PRTR)	Limited to chemical hazards; Detailed input data needed	Low data need for risk quantification; Objectivity in hazard identification is made sure	(Ji and Lee, 2016a, 2017)
Probabilistic risk assessment based on fault trees	Probability determination based on MAR operator judgements: methodology suited for existing structures	Integrated approach: technical and non-technical risks are incorporated	(Rodríguez-Escales et al., 2018)
Screening-level assessment of human health risks arising from micropollutants	Health based benchmark are conservative and might lead to overestimation of risks	Unregulated contaminants can be incorporated	(Rodriguez, Cook, et al., 2007; Rodriguez, Weinstein, et al., 2007)
Public health and economic risk assessment	Input data for scenarios underlie uncertainty	Consideration of environmental, economic and human health risks; Different steps do not rely on each other's output as input data	(Juntunen et al., 2017)
Assessment of economic risks arising from well clogging	high amount of input data (e.g. pilot studies)	Economic viability can be assessed	(Dillon et al., 2016)

Risk identification

The first step in risk assessment is the identification of the hazard or hazardous event that can pose a risk. Through the review of 40 papers and two guidelines, risks of MAR were clustered in 5 categories: (i) health, (ii) environment, (iii), technical, (iv) socio-economic, (v) governance and legislation. Nandha et al. (2015) suggest that the hazard identification should be conducted by identifying the risk at every step of the implementation and operation of a MAR scheme. So we further categorized hazards to MAR implementation and operation phases ((i) planning, (ii) assessment of the MAR catchment or water source, (iii) MAR operation and management, (iv) water distribution and final use). Examples for aspects frequently reported in literature are given (including possible hazards and related processes, as well as objectives and aims of risk assessment), Figure 7. Another support to identify risks could be to assess the different components of the MAR scheme, Figure 2. In Appendix C the summary of hazards and potential risks are given clustered in the 5 categories (i) health, (ii) environment, (iii), technical, (iv) socio-economic, (v) governance and legislation.

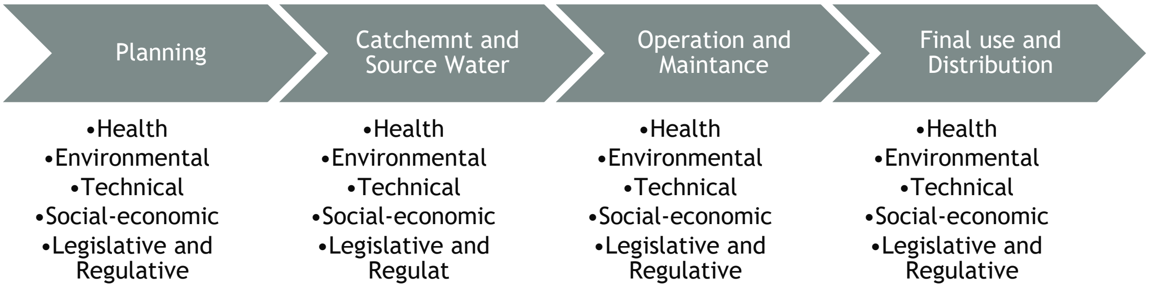

Figure 7: Risk identification for every step of the implementation and operation of a MAR scheme.

Hazard identification can also be conducted with a modelling software. Pindoria-Nandha (2016) proposes in her Strategic Planning Tool for Aquifer Storage and Recovery (ASR) MAR schemes the application of modelling tools such as PHREEQC for hydrogeochemical assessment of clogging and to investigate potential reactions between recharge water, groundwater and aquifer matrix. Song et al. (2019) used the program THOUGHREACT to determine the contamination risk of pollutants.

5.2 Risk treatment

After having identified hazards (applicable hazards summarized in **Fehler! Verweisquelle konnte nicht g efunden werden.** and others if needed) their likelihood of occurrence is analysed (risk analysis). In the risk assessment methods listed above risk analysis is included. For the risk evaluation process, an educated evaluation of the importance of the risk to the system has to be made. It should be possible to decide if the risk has to be minimized to an acceptable level. This can be done with risk treatment options. In the next chapters (5.2.1 to 5.2.5), a summary for the possible treatment of the above identified hazards and the related risk is given.

5.2.1 Environmental and health risks

The aspect of water quality changes due to infiltration or injection into the aquifer has to be evaluated for a MAR scheme. The water quality of the recharge water and the change of it during recharge have also operational effects on a MAR site (Hartog and Stuyfzand, 2017). In Table 4 water quality aspects of MAR schemes to be considered before and during recharge are summarized. In Table 7 environmental and health risks are described and respective risk treatment options are given.

Table 7: Environmental and health risks description and risk treatment aspects

Environmental and health risks	Description	Risk treatment
Transit Time (MOP Ministerio de Obras Públicas, 2014b)	Water quality is affected by the amount of time that the water is stored in the aquifer.	With longer transit time, water quality can improve as a significant mixing with the groundwater has occurred, as well as pathogens could be eliminated.
Salinization and Sodicity	Use of MAR schemes to counteract the salinization caused by overexploitation (Stuyfzand et al., 2017).	Recharge of sweet water into the aquifer to create a hydraulic barrier.

Mobilized Ions During Recharge	Mobilized iron, chromium or manganese, oxidation of ions (due to oxic surface water infiltration) during the MAR scheme.	Insight on what determines the mobilization e.g. hydrogeochemical models (e.g. Ganot et al., 2017; Niinikoski et al., 2016)(Ringleb et al., 2016) ; Postreatment
Water contaminants	Recharging water or effluent water does not meet water quality standards. Contamination can stem from agricultural production or industrial (nutrients, organic pollution, pesticides, etc.). Pathogen or organic contamination can be related to waste water/farming effluents in the source water. (Illegal) Release of waste water into catchment of source water. Chemical accidents, contaminant mitigation; aquifer dissolution and stability. Seasonal changes causing anaerobic conditions on the bottom of lakes and rivers	Monitoring, laboratory measurements (e.g. redox conditions), understanding of hydrogeochemical processes; Using purification potential of the MAR scheme to enhance water quality, e.g. removal of pathogens, pharmaceutical or emerging compounds (e.g. Donn et al., 2020; Regnery et al., 2017, 2015; Schmidt et al., 2007; Valhondo et al., 2018)(Ringleb et al., 2016); Pre- and posttreatment; Exclude water for recharge that does not meet the water quality needs; Fence the buffer zone around the recovery wells.
Impacts of MAR scheme On GW dependent ecosystem	Groundwater level, pressure, volumes, flow rates changes can affect the groundwater ecosystem.	Monitoring of groundwater ecosystem; Operation on a steady state scheme to maintain groundwater ecosystem (NRMMC–EPHC–NHMRC, 2009)
Energy and greenhouse gas considerations	Pollution of the environment due to energy consumption and greenhouse gas production by operation of the MAR scheme.	Reduction of energy consumption by appropriate design of the system; Implementation of low consumption pumps, green energy solutions
Aquifer Dissolution	Aquifer dissolution can lead to collapse of wells, production of turbid water or water containing a lot of sand , mobilisation of clay particles	Monitor wells, choose different well locations

5.2.2 Technical risk

Appropriate risk treatment strategies for technical risks can be taken into account after having assessed which technical risks are leading to failure or malfunctioning of a MAR scheme. In Table 8, Table 7technical risks are described and respective risk treatment options are given.

Table 8: Technical risks description and risk treatment aspects (clogging as described by ASCE and EWRI, 2020)

Technical risks	Description	Risk treatment
Chemical clogging	Precipitation of chemical compounds on and within the	Recharge sediment and water source have to be investigated, with field monitoring e.g. with

	recharge sediments such as calcium carbonate, iron and manganese.	isotopes to assess the contribution in mixed source MAR systems (Negev et al., 2017).This has to be done in order to avoid chemical clogging in the aquifer. Precipitation can be also addressed in the post-treatment with filtration.
Biological clogging	Microorganisms grow on the recharge surface and form biofilms that clog the soil.	Preventing conditions that enhance biological growths, such as warmer temperatures, sunlight, nutrients. Pre-treatment such as disinfection of recharge water (Barry et al., 2017)
Physical Clogging	Accumulation of suspended solids on the surface.	Reducing suspended solids concentration in the recharge water. Use coagulants for flocculation of suspended solids.
Flood	Inundation of the MAR scheme, damage of MAR scheme	Building of flood protection system (channels, reservoirs or dams)
Drought	Not sufficient water available to meet water demand	Safety reservoir
Low infiltration rate	Not sufficient water available to meet water demand	Safety reservoir, prevent clogging which result in low infiltration rate
Missing aquifer storage capacity	Not sufficient water available to meet water demand	Lower water supply predictions
Slope stability	Landslides, damage of MAR scheme	Safety reservoir, protection measures for slope instability (installing inclinometer for monitoring)
Lack of land	The MAR scheme cannot be implemented at the suitable declared site	Site selection must be conducted again, Regulation by the government (expropriations)
Water demand and supply changes	Fluctuations in water demand and supply can be caused by changing precipitation patterns, seasons with more water demand due to tourism or weather conditions	Predicting water demand and supply by checking historical data and taking into account changes (socio-demographic, climatological data)
Reliability of technology	Malfunctioning of technical equipment (pre-and post-treatment, pumps, monitoring scheme..)	Maintaining of technical equipment, ensuring interoperability between hardware and software, redundant pipes, pumps, etc.
Missing (trained) operating personal / technical knowledge	-	rely on consulting companies, educate the staff, set incentives with higher salaries

5.2.3 Social risk

Appropriate risk treatment strategies for social risks can be taken into account after having assessed which social risks are leading to problems in the planning, operation stage of a MAR scheme. In Table 9 risks are described and respective risk treatment options are given.

Table 9: Socio-economic risks and risk treatment options

Socio-economic risks	Risk description	Risk treatment
lack of funding / financial support, business case		Incorporate educated staff
Unplanned costs (maintenance, installation etc.)		Account for economic flexibility
Changing standards for end-user	The recovered water is bind to changing standards	Post-treatment/pre-treatment processes need to be adapted
Communication and risk perception	Risk perception of the public and policy makers is often different to risk perception of scientists	Work on informing and winning the acceptance and trust of the public and policy makers (e.g. webinars, workshops, leaflets)
Acceptance and trust of public		engage the public and the policy makers

5.2.4 Governance and legislation risks

Appropriate risk treatment strategies for governance and legislative risks can be taken into account after having assessed, which social risks are leading to problems in the planning, operation stage of a MAR scheme. In Table 10, Table 7governance and legislative risks are described and respective risk treatment options are given.

Table 10: Governance and legislative risks and risk treatment options

Governance and legislative risks	Risk treatment
The environment could be polluted, e.g. by infrastructure development; or the environmental conditions can be improved, e.g. by conservation measures or remediation policies	Adjustment of concept and project design for avoiding adverse environmental effects, according to existing changing regulations
No access to land/missing land rights	Try to acquire access
Legislative requirements; regulatory risk	Be aware of the latest version of legislative regulations

5.2.5 Operational Monitoring

Managed aquifer recharge and aquifer recharge are distinguished from each other by the application of monitoring. If managed aquifer recharge is applied, water quality and/or quantity aspects have to be monitored (e.g. Dillon et al., 2014; Zhang et al., 2020). Monitoring continuously supports and improves risk assessment by generating necessary data (NRMMC-EPHC-AHMC, 2006; NRMMC–EPHC–NHMRC, 2009). NRMMC-EPHC-NHMRC (2009) provides four types of monitoring specifically for MAR projects: baseline monitoring, validation monitoring, operational monitoring and verification monitoring.

Baseline monitoring is conducted before the implementation of the MAR system, and it is used to answer the question “where are we now in terms of water quality/quantity?” (NRMMC-EPHC-AHMC, 2006). It therefore determines the state of the system before commissioning the MAR project.

Validation monitoring is only undertaken once for each new system configuration, in order to measure the treatment efficiency. It answers the question “will it work” (NRMMC-EPHC-AHMC, 2006) and is essential when there is a reliance on the treatment capacity.

Operational monitoring answers the question "is it still working?" (NRMMC-EPHC-AHMC, 2006). The majority of respective monitoring is conducted throughout the daily operation of the system, in order to set appropriate limits and manage the facility accordingly.

Verification monitoring is used to answer the question "did it work?" (NRMMC-EPHC-AHMC, 2006). It can be used on a compliance basis to confirm that the system works as anticipated (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC-NHMRC, 2009).

According to the Australian MAR guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC–NHMRC, 2009), operational monitoring needs to assess the efficiency of preventive actions through observations and measurements. This requires the development of monitoring plans "from source to use" of recharged water, identification of the parameters that are used to measure the operational effectiveness and continuous review to confirm operational performance. The results of these monitoring programs should be reported frequently and timely to allow preventive actions to be taken before the use of unsafe recycled water (NRMMC-EPHC-AHMC, 2006). In Appendix D, regulations for MAR monitoring are summarized for the four different partner countries with pilot sites.

The following examples of operational monitoring practices for each MAR step are given by the Australian guidelines (Table 11):

Table 11: Examples of subsurface operational monitoring and supporting programs for managing human health risks, environmental risks and risks related to clogging (NRMMC-EPHC-NHMRC, 2009)

Process step to be monitored	Operational monitoring	Supporting programs
Subsurface storage and water travel time, groundwater mixing processes	E.g. online electrical conductivity; Other parameters that can provide evidence of hydraulic short circuits	Instrument calibration Maintenance (changing batteries, replacing parts, cleaning, etc.)
Arsenic dissolution	Redox potential; Dissolved oxygen	Instrument calibration Maintenance (changing batteries, replacing parts, cleaning, etc.)
Clogging	Recharge rate Head loss (in injection well and nearby wells, in the infiltration basin and in tensiometers beneath the bottom of the infiltration basin) Turbidity and nutrient level in the recharge water	Online instrument calibration Periodic pump testing Infiltration rate testing

However, as the following examples show, operational monitoring systems are not homogenized throughout current MAR schemes.

Ganot et al. (2016), for example, assessed differences between infiltration and groundwater recharge of MAR with desalinated seawater. To assess the dynamics of the involved processes, the applied monitoring system included observation wells, soil sensors and infiltration rings. On the one hand, they used groundwater observation wells with a depth of 30 m. These were monitored by loggers measuring the hydraulic pressure head and electrical conductivity (EC). On the other hand, they used 8 soil sensors for the shallow unsaturated zone for measuring volumetric water content (WC) and bulk EC. The monitoring system was continuously operated and measurements were obtained regularly every 15–30 min and at a finer resolution of 1–5 min during MAR or infiltration tests.

O'Leary et al. (2015) evaluated sources of high-chloride water and the impact of MAR on groundwater levels and movement of groundwater to wells. For this reason, they measured groundwater levels periodically at all of the multiple-well sites and obtained data on water chemistry (including pH and concentrations of chloride, dissolved oxygen and arsenic) and stable isotopes of oxygen and hydrogen, and tritium.

Valhondo et al. (2018) analysed how a reactive barrier that consisted of vegetable compost, iron oxide and clay was able to enhance the removal of emerging organic compounds in the recharge water. To detect potential effluents, they measured electrical conductivity, temperature and flow rates of the infiltrating water. Additionally, they monitored water upstream as representative for local groundwater and investigated the evolution of groundwater along the MAR procedure. Monitoring points were usually sampled weekly during infiltration periods. Recharge water was sampled every 2–3 days. A conductivity-temperature-depth (CTD)-Diver was installed within each piezometer during most of the infiltration experiments to continuously measure temperature, hydraulic head and electrical conductivity.

Regnery et al. (2015) evaluated the long-term performance of a MAR system through assessing the annual and seasonal concentrations of chemicals, such as dissolved organic carbon (DOC), ultraviolet absorbance at 254 nm, nitrate, phosphate and trace organic chemicals (TOrC).

Zuurbier et al. (2014) investigated how multiple partially penetrating wells improve the freshwater recovery of coastal ASR (aquifer storage and recovery) MAR-systems. They have installed monitoring wells, conducted a sediment analysis, monitored groundwater quality, logged boreholes, and monitored the ASR operation and target aquifer. The data are logged with a 30 min interval, including ASR cycle registration, injected volumes per well, recovered volumes per well, the EC of recovered water per well and the total operation period per pump. In Table 12, different monitoring parameters with their aims and references to related literature are given.

Table 12: Monitoring aims and parameters (examples)

Aim	Parameter	Reference
Determine physical and hydrochemical properties of groundwater, as well as contaminant concentrations	E.g. pH, temperature, electrical conductivity, dissolved oxygen concentration, chloride concentration; flow rate of infiltrating water; arsenic concentration	(O'Leary et al., 2015; Regnery et al., 2015; Zuurbier et al., 2014)
Detection of potential effluents in source water	pH, electrical conductivity; flow rate of infiltrating water	(Valhondo et al., 2018)
Detection of salinization	Sodium, chloride, sulphate, total dissolved solids in groundwater, recharging water and recovered water, electrical conductivity	(Pindoria-Nandha, 2016)
Measure leachable metals and metalloids	Arsenic, uranium, molybdenum, nickel, zinc, cobalt in groundwater, recharging water and recovered water, polarization and electrical conductivity	(Pindoria-Nandha, 2016)
Assessment of infiltration and groundwater recharge dynamics to detect potential lag between infiltration and groundwater recharge	Pressure head, electrical conductivity of bulk soil and water, volumetric water content	(Ganot et al., 2016)
Assessment of chemical concentration of groundwater	Dissolved organic carbon (DOC), ultraviolet absorbance at 254 nm,	(O'Leary et al., 2015; Regnery et al., 2015; Zuurbier et al., 2014)

(determination of potential long-term attenuation within the aquifer)	nitrate, phosphate, trace organic chemicals	
Assessment of clogging potentials	Entrained air in recharge water, dissolved oxygen (DO), temperature, microbial activity, total suspended solids, biodegradable dissolved organic carbon (BDOC), redox potential (EH), pH, Total dissolved solids (TDS)	(Ganot et al., 2016; Pindoria-Nandha, 2016)
Measure metals and ions	DO, pH, Eh, alkalinity, Cl^-, Na^+, nitrate, phosphate, ammonia, total organic carbon (TOC)	(Pindoria-Nandha, 2016)
Measure disinfection by-products	E.g. Trihalomethanes (THMs), haloacetic acids (HAAs)	(Pindoria-Nandha, 2016)
Measure redox mineral reaction	Iron, manganese, EH, dissolved oxygen, dissolved sulphide, redox couple	(Pindoria-Nandha, 2016)
Measure silicate minerals and miscellaneous parameters	Dissolved silica, potassium, fluoride, barium	(Pindoria-Nandha, 2016)
Measure carbonate mineral equilibrium	Calcium, magnesium, bicarbonate, pH	(Pindoria-Nandha, 2016)

6. Cost-benefit analysis

6.1 Literature review economic feasibility assessment

An economic evaluation of water projects in most cases aims to determine whether their benefits justify anticipated costs and/or compare alternative options (Rashid and Hayes, 2011). The first objective is supported by economic efficiency analysis (mainly cost-benefit analysis), while analysis of cost-effectiveness is used to meet the second objective.

The latest approach is based on the establishment of the minimum investment for the best possible performance among the number of alternative options/improvements (Rashid and Hayes, 2011). Cost-effectiveness analysis is mainly used in cases where the reliable estimation of benefits is infeasible. However, its core limitation is that all alternatives can be ranked without affirmation that any of them are actually worth implementation (Maliva, 2014).

Among other data-driven methods that are used to prioritize alternative projects is multiple criteria analysis (Rashid and Hayes, 2011). The multi-criteria approach is based on quantification in dimensionless units of a broad range of criteria. In the case of water projects, these factors include health, environmental, social and economic aspects. The impact is assessed through the comparison of the project with a baseline strategy (without the implementation of MAR scheme, so-called “zero case”). Main steps of the analysis are a selection of criteria, their weighting and quantification. Among economic criteria included in the above approach is affordability to pay (quantified using survey data), and net present costs and benefits are commonly used (Rahman et al., 2014). This approach incorporates cost-benefit analysis (CBA) within one of its steps.

Multi-criteria decision analysis (MCDA) implemented within geographical information systems (GIS), named GIS-MCDA, is a widely applied method for suitability mapping and MAR site selection (Sallwey et al., 2019). This technique comprises the evaluation of spatial alternatives based on the decision-makers’ goals and preferences. The basic components of a GIS-MCDA are: criterion value scaling, criteria set weights and the decision rule (Sallwey et al., 2019). Among the groups of criteria commonly used in the GIS-MCDA studies are aquifer characteristics, surface characteristics, water quality, hydrometeorology and management criteria. Maréchal et al. (2020) carried out a review of GIS-MCDA for suitability mapping of MAR schemes. The authors state that the cost is rarely included in such an analysis. They propose a methodology for the assessment of the levelised cost, which should be incorporated within a more classical GIS-MCDA.

Cost-benefit analysis (CBA) is one of the most frequently used approaches for assessing the economic feasibility of MAR projects. CBA is a method for measuring the economic profitability of investment by comparing all benefits and costs (private and social, direct and indirect, tangible and intangible) resulting from it. The criteria for approval of MAR system construction under CBA is the total economic value of benefits that exceeds the total costs. Environmental CBA that is applied in assessing the feasibility of water projects has special features and includes issues of water quality and supply (Maliva, 2014).

Case studies that apply the afore mentioned methods to assess the economic feasibility of MAR schemes are presented in Table 13, while the strengths and limitations of each method are outlined in Table 14.

Table 13: Assessment of economic feasibility of MAR

Reference	Area	Methodology
Cost-benefit Analysis (CBA)		
Arshad et al., (2014)	South-eastern Australia	Net present values (NPV) of farm benefits are compared to identify whether MAR is financially superior to surface storage; break-even analysis of cross-over points is performed
Rupérez-Moreno et al., (2017)	Southern Spain	Private benefits calculated as a difference between market revenues and costs; Socio-environmental benefits are quantified through a contingent valuation (CV) approach
Perrone and Rohde, (2016)	California	Bond-funding applications used; Geospatial analysis performed
Damigos et al., (2016)	Italy	The CV method was applied to get a monetary estimate of MAR's total economic value; Factors influencing people's perception and WTP for MAR were investigated
Niazi et al., (2014)	Sirik region of Iran	CBA was coupled with a systems' dynamics model and a finite difference model of the groundwater management system
Cost-effectiveness analysis		
Missimer et al., (2014)	Kingdom of Saudi Arabia	Costs of MAR's construction and operation were compared to costs of three alternative methods that provide water-supply solution
Maréchal et al., (2020)	Southern France	The cost function was built to compute the capital and operating costs of a MAR scheme, then costs' mapping method was applied
Multicriteria Decision Analysis (MCDA)		
Rahman et al., (2014)	Northern Gaza (Palestine)	Selection of criteria and their weighting scheme. Economic criteria included, among others, the affordability to pay, as well as net present costs and benefits

Table 14: Overview of strengths and limitations of methods used to assess the economic feasibility of MAR, as well as references for application examples

Method	Strengths	Limitations	References
Cost-benefit analysis (CBA)	- allows measuring the economic feasibility and profitability of current and future investments by comparing all benefits and	- challenging to estimate accurate values of benefits as they should incorporate non-use values - data-intensive method	(Arshad et al., 2014; Damigos et al., 2016; Niazi et al., 2014; Perrone and Rohde,

	costs (private and social, direct and indirect, tangible and intangible)	- mainly used for infrastructure and large projects	2016; Rupérez-Moreno et al., 2017)
Cost-effectiveness analysis	- can be applied in the case where a reliable estimation of benefits is not feasible - less data demanding	- can only consider options that provide the same benefit or set of benefits - alternative projects could be ranked based on the cost analysis but no affirmation can be made whether it is actually worth implementing them	(Maréchal et al., 2020; Missimer et al., 2014)
Multi-criteria decision analysis (MCDA)	- incorporation of a broad range of criteria: health, environmental, social and economic aspects - considers both quantitative and qualitative information	- comparison of MAR management strategies may be substantially affected by assigned weights, which are based on expert opinions - data-intensive method - mainly applied for regional level analysis	(Rahman et al., 2014)

6.2 Cost-benefit analysis of MAR schemes

6.2.1 Identifying the costs of MAR

Main groups of costs associated with managed aquifer recharge sites are presented in Table 15.

Table 15: Main groups of MAR cost (based on Maliva, 2014)

Initial investment: Capital costs	Costs of land purchase Construction costs Testing costs Authorization costs Costs related to regulatory testing requirements during construction and operational testing Costs of consulting services for the design and supervision of the construction (if applicable)
Storage costs	Costs of the acquisition of water Costs of the conveyance of water to the storage facility Costs of the storage of water at the storage facility
Other operation and maintenance costs	Groundwater exploitation operating costs Labour costs Electricity costs Water quality testing costs Maintenance costs Pre-treatment costs Post-treatment costs

It is also important to account for environmental costs resulting from aquifer overexploitation. These are monetarized using the stated preference approach (unlike abovementioned costs), for which the accounting approach is applied (Rupérez-Moreno et al., 2017). These costs are summarized in Table 16.

Table 16: Costing methods for MAR schemes (based on (Ross and Hasnain, 2018))

Levelised costs	Defined as the constant level of annual revenue needed to recover all capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply. An effective tool to compare the costs of water from alternative projects was developed by Dillon et al. (2009).
Water supply security insurance costs	Used when MAR schemes are primarily intended to supply water during a drought, emergency or highly seasonal need (water storage for water supply reliability). These costs can be calculated by dividing the capital cost of the project by the daily supply capacity ($/m^3 per day).

The most influential factors affecting the costs are the MAR type and the water source (Ross and Hasnain, 2018). In particular, infiltration basin and spreading basin schemes have lower costs per cubic meter of recharge compared to MAR implementing recharge wells. Usually, as recycled water often needs additional treatment to meet water quality standards, MAR types that use recycled water have much higher costs that schemes using natural water.

6.2.2 Monetarizing MAR benefits

The value of environmental goods is not only derived from their direct use but also their indirect use, as well as non-use values (support of ecosystems, scenic beauty, bequest value). Thus, it is exceptionally important to consider the total economic value of benefits in CBA of MAR projects:

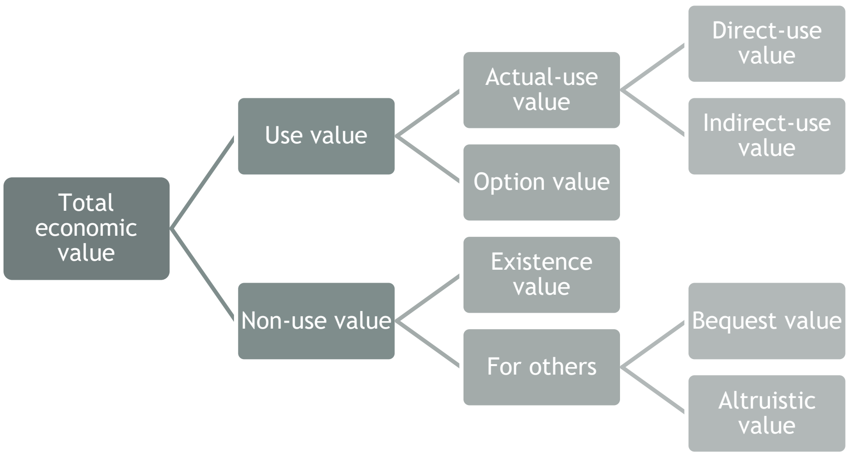

Figure 8: Total economic values and its main categories

Among the direct-use values of MAR schemes, there are an increased supply of water for irrigation and drinking. This can be enabled by making use of periodic excess surface water supplies and recycled water, or the preservation or improvement of water quality. An indirect-use value of MAR systems is given by their effect as a buffer against droughts and a variable climate. Option values are reflecting a willingness to pay for conserving the option of making use of the water even though no current use is made of it. Finally, non-use values reflect a willingness to pay for the water in a conserved or sustainable use state, but the willingness to pay is unrelated to the current or planned use of the water.

The beneficial value of water stored or treated by MAR systems can be evaluated using different valuation approaches, including market-based methods (considering costs of replacements, damage avoidance, substitutes and productivity changes), the revealed-preference approach (travel cost method, random utility modelling, hedonic pricing method) and the stated-preferences approach (contingent valuation method and attribute-based choice modelling) (Maliva, 2014). However, only stated-preference techniques allow to capture non-use values and are suitable for ex-ante valuations, where the contingent valuation method is widely used to estimate the benefits of MAR schemes (Damigos et al., 2017). The application of benefit valuation methods depends strongly on the scope of the MAR scheme and its primary objective.

While MAR schemes may target both socio-economic and environmental (i.e. ecosystems) benefits, for the purpose of this project we are focusing only on socio-economic aspects. Table 17 outlines objectives for the MAR pilot sites considered in this project.

Table 17: Possible benefit valuation techniques (Ross and Hasnain, 2018)

The main objective of a MAR scheme	Method	Comments
Additional water supply	The volume of water recovered or supplied multiplied by the price of water.	Best way to estimate the value of additional water, theoretically. However in practice, water is often supplied at rates that do not reflect its full economic value.
	The costs of recovering or supplying an equivalent amount of water of similar quality by the next cheapest supply option.	Alternative costs of production or the avoided cost of production approach.
	The net benefit of additional production made possible by the additional water supply.	In case of water for agricultural or industrial use.
Improvement in water quality	The benefit can be valued by the costs of the next cheapest water treatment facility.	Other water treatment facilities, such as desalination plants.

Among profitability measures, the most commonly applied methods in water resource management are the net present value (NPV) and internal rate of return (IRR). As non-use values should be incorporated in the cost-benefit analysis, a differentiated NPV has to be used: future private benefits are discounted at a market rate, and the socio-environmental benefits at an ecological rate (Rupérez-Moreno et al., 2017).

Cost-benefit analysis (CBA) is a widely applied tool in the assessment of the economic feasibility of water projects. However, this approach has some limitations: a difficult and typically expensive process of gathering needed data, concealed degree of uncertainty and/or inaccuracy (Rashid and Hayes, 2011). To address the latter drawback of the CBA approach and come up with unbiased upwardly expected benefits of MAR implementation, it is important to incorporate uncertainty in the analysis.

Among different ways to address uncertainty within the CBA, there are the expected value analysis and the calculation of crossover points. The expected value analysis is based on the identification of each potential contingency and weighting it by a probability assigned to its occurrence (Maliva, 2014). These probabilities are based on historical data or expert opinions. Crossover points are thresholds where the NPV of MAR is equal to the NPV of surface storage. Crossover points they serve as a minimum requirement beyond which investment in MAR may be worthless (Arshad et al., 2014).

6.3 Main steps of the cost-benefit analysis

6.3.1 Identifying main stakeholders

Increased supply of irrigation and drinking water constitute two of the core benefits associated with the implementation of MAR schemes. Consequently, agricultural producers, regional water supply entities and the local population are three of the groups in society whose behaviour may directly be affected by MAR schemes. Agricultural producers benefit from reliable water supply during dry years that secures agricultural production under unfavourable weather conditions. When MAR schemes target drinking water facilities, the users of drinking water benefit directly from improved water quality and reliable drinking water quantity.

Except for the direct impacts of MAR schemes, their implementation is also connected with indirect impacts, such as support of ecosystems, scenic beauty and bequest value, which are non-use values that should be included in the total economic value of MAR scheme.

6.3.2 Assessment of MAR costs

Data acquisition

CBA requires the collection of a substantial group of technical and financial parameters that should be considered to evaluate the economic feasibility of MAR schemes. Among the approaches for acquiring needed data, documentary studies are carried out on the hydrogeological characteristics of the different aquifers, among others aimed at obtaining information on representative wells (Rupérez-Moreno et al., 2017).

Another approach is to estimate itemized costs by combining current market rates of earthworks, services and materials for water infrastructure projects in a particular relevant country and then adjust to the local conditions in the area of MAR site (Arshad et al., 2014). In case of availability of such an option, an efficient way can be to request data on construction dates and costs of the recharge structures and maintenance costs from local watershed and irrigation departments (Dashora et al., 2019).

Assumptions

In case of data scarcity, in particular if the CBA is performed for MAR schemes serving as future investments, a number of plausible assumptions have to be made, e.g. including the infiltration rate or water loss during MAR operation (Arshad et al., 2014) or the weir discharge coefficient (Dashora et al., 2019).

Estimation of MAR-related costs

Capital costs. Basically, capital costs are initial investments that include different components depending on the MAR scheme. For MAR intended for irrigation water supply, such components may e.g. cover well construction, pump installations, irrigation ponds and localised irrigation systems (Rupérez-Moreno et al., 2017). Amortization annuities should also be calculated considering the interest rate (with 5 % standard value) and amortization periods for different components. As a suited approach, the annualized present value of construction costs can be obtained from multiplying the present value of the capital costs by the capital cost recovery factor (Dashora et al., 2019):

$$AC = PVC \times r(1 + r)^L / [(1 + r)^L - 1] \tag{1}$$

where AC indicates the annualized construction costs, PVC the present value of construction costs, r the discount rate. L indicates the assumed economic life (in years) of the recharge structure for the level of provided maintenance.

Operating and maintenance costs. Rupérez-Moreno et al. (2017) proposed an approach to calculate the exploitation costs of MAR systems, *CE*, as follows:

$$CE = 0.004 \times V \times h_m \times e + c_m \tag{2}$$

where *V* is the annual volume of extracted water (m^3), h_m is the pump head (m), *e* is the energy price and c_m indicates the maintenance costs (3% of the total investment for considered case study). A factor of 0.004 was found by Rupérez-Moreno et al. (2017) to be adequate for their investigated aquifer.

Levelized costs. Levelized costs are among the most frequently used measures of total costs in CBA of MAR schemes (Arshad et al., 2014). Levelized costs are obtained as the sum of costs (operation, maintenance and management costs, annualized capital costs) divided by the annual volume of water supply by the MAR system.

6.3.3 Assessment of MAR benefits

Agricultural water MAR scheme

Data acquisition. Agricultural data needed for estimation of MAR scheme's benefit can e.g. be requested from official regional statistics or obtained through farm surveys (Dashora et al., 2019).

Assumptions. When MAR benefits are quantified for agricultural producers, then an assumption that can be made is that all the recharge from the MAR system contributes to additional agricultural production. However, it would also be assumed here that the MAR recharge is used to cover the water needs of farmers in the case of adverse weather conditions, thus protecting farmers for agricultural losses due to reduced agricultural productivity (Dashora et al., 2019).

Estimation of MAR benefits. One of the approaches to quantify benefits of MAR systems for agricultural producers is to use a partial measure of productivity which is defined as the ratio of the agricultural gross margin (or profit) with respect to the irrigation returns (Arshad et al., 2014). In this case, irrigation productivity can be calculated as of the ratio of the gross value of crop (total crop revenue minus variable costs) to the total absorbed volume of irrigation water by the plant (after transfer losses and runoff). To obtain another proxy of the market revenues generated by the exploitation of the aquifer, it should be estimated what percent of the final agricultural production is related to their spending on irrigation water, i.e. divide agricultural revenue by the irrigation cost (Rupérez-Moreno et al., 2017).

Dashora et al. (2019) proposed a methodology for the calculation of MAR benefits for agricultural activities that requires data on the average yield of each crop type in the MAR area (Y_i), the average price for each crop type (P_i), the average production cost for each crop type (C_i), average irrigation water use of each crop type (U_i), the average proportion of the cropped area of each crop type (f_i). Annual benefit per unit of water volume attributed to MAR-recharge, *BR*, can be calculated as:

$$BR = g \times \frac{\sum_i f_i (Y_i P_i - C_i)}{\sum_i f_i U_i} \tag{3}$$

where g is the proportion of recharge from MAR that results in additional agricultural production

Drinking water MAR scheme. Among important use benefits of MAR schemes are the supplementary potable water supplies in times of water scarcity. To quantify these benefits, it is important to obtain data on the price of water and expected drinking water demand. As in the majority of cases there is no free market with respect to water, it is the estimation of water value that poses a core challenge for quantifying economic benefits of MAR projects. For example, Maliva (2014) provides a systematic overview of common methods to calculate or estimate the value of water that might be supplied or treated by MAR scheme (Table 18Table 18).

Table 18: Methods used to estimate the value of water (Maliva, 2014)

Method	Description
Market prices	Value of water is determined by actual prices set by willing buyers and sellers in a competitive market.
Alternative cost	Value of water storage or treatment is determined from the cost of the least expensive alternative that provides comparable benefits.
Value marginal product	The value of water is quantified from the marginal productivity of water, i.e., the extra value of output that can be obtained from additional applications of water.
Contingent value	Survey-based methods to determine an individual's willingness to pay or to accept compensation for a good or service.
Hedonic property value	Value of water is inferred from market transactions (e.g. real estate sales) that are linked to the value of water.
Defensive behaviour	Value of a safe and reliable water supply can be estimated from expenditures to avoid exposure to unsafe water.
Damage cost	Value of water is estimated from damage costs avoided, such as health impacts or drought damage.
In-situ groundwater value	MAR system value is estimated from costs avoided resulting from groundwater being in place, such as pumping and land subsidence costs.

Since only stated preference techniques allow to capture non-use values and ex-ante valuations, the contingent valuation method (CVM) is widely used to estimate the benefits of MAR schemes and will be described in more detail in the next section.

The percent of MAR water of total household water consumption during the dry season is strongly affected by the person's subjective perception of his/her risk of contracting a disease from drinking MAR water (Hasan et al., 2019). Thus, it is exceptionally important to consider health and social risks while assessing the benefits of MAR with respect to drinking water.

Required data for the determination of drinking water demand as well as estimation methods that can be used to predict water demand are described in detail in section 2.

Non-use benefits

Data acquisition. Since it is important to account for non-use values in the estimation of MAR benefits for the local population, stated preference techniques are widely used in studies revealing the economic value of MAR systems (Damigos et al., 2017; Rupérez-Moreno et al., 2017). In particular, the contingent valuation method (CVM) allows capturing non-use values and ex-ante valuations. This is a survey-based method, i.e. data on statements of persons regarding their willingness to pay (WTP) is acquired via conducting surveys (an example of a questionnaire is provided in Appendix E).

Assumptions. When it comes to indirect positive environmental impacts of MAR, one of the main assumptions related to MAR benefits' estimation is that they are stated by the local population's willingness to pay (WTP), which can later be converted into the actual payment obligation.

Estimation of MAR benefits. To estimate socio-environmental benefits, a representative sample of the local population can be surveyed on the maximum amount of money that they are willing to pay in their water bill over one year to improve the ecological status of the water bodies and ensure the sustainability of agricultural production in their area. The obtained mean value of WTP (with implied variables such as income level, employment status and green commitment) multiplied by the target population serves as an annual estimate of socio-environmental benefits (Rupérez-Moreno et al., 2017).

Conducted surveys mainly provide interval data points, so that nonparametric and parametric approaches can be applied to estimate mean and median WTP values (Damigos et al., 2017). Within parametric estimation, the conditional relation of WTP and different respondents' demographic, socioeconomic, and behavioural characteristics are revealed. This approach requires assumptions on the distribution of WTP, unlike the nonparametric approach. However, the latter does not provide evidence on the effect of respondents' characteristics on their WTP for non-use benefits of the MAR scheme (Bateman et al., 2013).

6.3.4 Fixing the discount rate and project lifespan

For the evaluation of water projects, CBA that accounts for social aspects needs to be performed to assess both the economic and social profitability of the water investment, with the financial and social discount rates being pre-defined and distinguished. The financial discount rate (FDR) reflects the opportunity costs of capital investment and is used to calculate the present value of future cash flows. While the social discount rate (SDR) reflects the social view on how future benefits and costs should be valued against present ones (EC European Commission, 2014).

The CBA guide of the European Commission (EC) provides a summary of different approaches for calculation of FDR and empirical estimation of SDR (EC European Commission, 2014). The EC benchmark of FDR is 4% in real terms for a 30-year reference period from water supply projects. When it comes to SDR, EC's benchmark for major projects in Cohesion countries is 5 %, while it reduces to 3 % for all the other member states. The empirical literature suggests considering 5.5 % market discount rate for investment types such as MAR schemes (Rupérez-Moreno et al., 2017), while for projects with a time horizon up to 30 years a lower environmental rate of 3.5 % is suggested (Almansa and Martínez-Paz, 2011). Some papers apply higher financial discount rates in CBA of MAR schemes: 6 % as propose by Perrone and Rohde (2016), 6.67 % by Ross and Hasnain (2018), 7% by Arschad et al. (2014) and 8 % by Dashora et al. (2019). When it comes to project lifespan, a 30-years horizon for the assessment is frequently used in MAR case studies (Arshad et al., 2014; Dashora et al., 2019; Ross and Hasnain, 2018).

6.3.5 Selection of profitability indicators

The most commonly applied profitability indicator assessing economic feasibility of MAR schemes is the net present value NPV (Rupérez-Moreno et al., 2017; Arschad et al. 2014; Maliva, 2014). It is the sum of private and socio-environmental net cash flows:

$$\boldsymbol{NPV = -k + \sum_{t=1}^{t} \frac{NCF_p}{(1+r)^t} + \sum_{t=1}^{t} \frac{NCF_e}{(1+r_e)^t}} \qquad (4)$$

where k is initial investment cost, t is time, NCF_p is the private net cash flow, NCF_e the socio-environmental net cash flow, r the market discount rate and r_e the ecological discount rate. The NPV can also be seen as the difference between the present value of benefits and the present value of costs over a selected time horizon.

6.3.6 Uncertainty incorporation in CBA

For a comprehensive assessment of economic feasibility of a MAR scheme it is important to account for risk and uncertainty while conducting CBA. Among possible ways to address uncertainty, a break-even analysis of cross-over points can be performed. In particular for key variables characterized by high levels of uncertainty, thresholds are provided that denote points where MAR and surface storage have equal financial returns (Arshad et al., 2014). For MAR schemes with an additional supply of irrigation water as primary objective, uncertainty can be incorporated by calculation of NPV values under different scenarios of climate change and varying irrigation demand conditions (Rupérez-Moreno et al., 2017).

Sensitivity analyses can be carried out in order to investigate if the decision regarding the economic feasibility of a MAR scheme is sensitive to substantial but plausible variations in critical parameters (such as WTP). The Monte Carlo method is often implemented within the probabilistic risk analysis to simulate the uncertainty that affects the value of the critical parameters (Damigos et al., 2016).

In Appendix F an overview of a survey design (contingent valuation method for revealing the willingness to pay) is given.

7. Comparison of alternative solutions

In order to objectively assess the feasibility of a MAR scheme it can be helpful to compare the intended MAR scheme to other technical solutions (e.g. water treatment plants, desalination plants, changed irrigation schemes) that might lead to the same goal. Also the comparison to a solution without any technical implementation (zero case) can be useful. Technical, social and economic aspects, as well as environmental aspects can be considered for allowing such a comparison.

7.1 Technical aspects

Technical aspects may comprise the evaluation of water supply reliability of the MAR scheme or other options. Subject of investigation is also the durability and sustainability of the technical solution for the design period.

This section deals with methods for the reliability assessment of water demand and supply, related to MAR schemes. In order to assess water supply reliability for covering present and future water demands, the following scenarios can be investigated for MAR: (i) the **"Zero Solution"**, for the scenario without MAR implementation and (ii) the **"A Solution"**, for the scenario with implementation a specific MAR system.

The following goals can be set for the reliability assessment:

- estimate or measure annual enhanced recharge and recovery volumes of the MAR site
- estimate recover efficiency (such as based on EC measurements, e.g. Page et al. 2010)
- estimate seasonal influence on enhanced recharge and recovery volumes
- determine water demand fluctuations (peak hour, peak day, average demand)
- determine if existing infrastructure in the area can supply the demand (sufficiently dimensioned pumps and pipes)

Based on these information, decisions on the reliability of the water supply for meeting the water demand can be made. In the following, possible options for water demand and supply determination are described. In literature, often models are applied for setting up water supply scenarios. Hydrological models can be used to assess the supply reliability of MAR projects under consideration of current and future conditions (e.g. Clark et al. 2015, Lindhe et al. 2020). Runoff, recharge and recovery can be simulated in different scenarios in order to estimate the probability of water shortages and evaluate if sufficient amounts of water can be supplied.

Two hydrological models that have been identified in the literature for this task are, e.g., the Water Supply Security Model WSSM (Lindhe et al., 2020) and the WaterCress model (Clark, 2015). The WSSM is as an easily accessible spreadsheet model, which can be applied without expert knowledge on modelling. It uses a statistically generated time series of the availability of source water in combination with storage dynamics in dams and aquifers. Subsequently, the potential supply can be compared to water demands in order to simulate the magnitude and probability of water supply shortages. Additionally, Monte Carlo simulations are used to consider uncertainties in input data and results (Lindhe et al. 2020).

The WaterCress model divides the water supply system into a network of interconnected knots including catchments, water storages, diversions and losses, water treatments, customer demands and waste flows. It is used iteratively to simulate runoff, recharge and recovery for different scenarios of varying rainfall, operational and catchment scenarios in order to determine water supply reliability (Clark, 2015). Further details can be obtained from Clark et al. (2015) and Ringleb et al. (2016).

7.2 Social and economic aspects

With the developed CBA (section 6) the costs and benefits of the intended MAR solution ("A Solution") can be compared to the case without technical implementations ("Zero Solution"). Furthermore, the developed CBA can be applied to compare different MAR types (such as ditches or river bank filtration).

In order to assess the costs and benefits of different solutions (such as desalination, membrane filter plant or a water supply dam), specific methodologies for the assessment have to be developed. Social acceptability should always be incorporated into the assessment processes.

7.3 Environmental aspects

Furthermore, the consideration of environmental aspects might be required for the comparison of different alternative solutions. Environmental impact assessment guidelines are e.g. available from the European Parliament and European Council Directive 2011/92/EU (European Parliament and European Council, 2011).

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Appendix A - Water demand determination in partner countries with pilot sites

Hungary

A) Irrigation water

Concerning the water demand of irrigation water, only data on authorized amounts and rough estimations of illegal abstractions exist. To predict the present use of groundwater, the authorized amount of abstractions can be used. According to an estimation of the Hungarian Chamber of Agriculture (2019), the number of groundwater wells used for irrigation is ranging between 10 000 and 100 000. Only ~1 % of the farmers are reported to have a water right permit for irrigation, despite the fact that the costs of using water for irrigation are negligible for farmers (the Ministry of the Interior estimates an average of 5000 HUF (~15 €) per hectare and year). According to the data provided by the General Directorate of Water Management in 2013 (the most recent available data), a volume of 8.867 million m^3 groundwater was withdrawn and used for irrigation purposes in agriculture and another 21.601 million m^3 for other agricultural purposes.

In the future, the Ministry of Agriculture will handle the authorization procedure instead of the Ministry of Interior. Then the water permit allowing the use of groundwater wells for agricultural purposes will be taken over by a new institution, the National Land Centre. This transformation is currently in progress.

There are quota for groundwater abstractions in special regions. These quota (limits) are determined on the basis of the quantity status of groundwater bodies.

B) Drinking water

Drinking water demand will be estimated within the framework of the River Basin Management Plan 3, Hungary, based on different scenario estimations. The current authorized quantities can be found in the registers of the Directorate of Water Management and in that of the National Disaster Management. According to the data of the General Directorate of the Water Management in 2013 (which is the most recent data) a volume of 580.129 million m^3 groundwater was withdrawn and used as drinking water in the country.

The average daily water demand is only relevant to interpret for drinking water, otherwise these data are not available. In Hungary, only daily water consumption data are available, however no data on water needs. Daily water consumption data can be obtained from regional waterworks or the Hungarian Central Statistical Office.

Poland

There is currently no legal act in Poland that would directly refer to the forecast for water demand from the national economy and water supply of the population. However, there is a Regulation of the Minister of Infrastructure (from 14 January 2002) on the determination of average water consumption standards. This document consists of 9 tables which calculate the average water consumption standards for particular groups of recipients, such as households, home gardens and agricultural crops, services, farms and livestock facilities, motor vehicles, agricultural machinery and workshops, agricultural product processing plants, construction work, chemical plant protection, military facilities of the ministries of defence and internal affairs (www-2).

A) Irrigation and other agricultural and forestry-related purposes

According to the official data, based on the Statistical Information Centre, agriculture and forestry consumed nearly 10% of the total volume of water in 2019 (www-1). The water consumption in agriculture and forestry in Poland is steadily decreasing and amounted to 847.407 million m^3 in 2019, which is about 25% less than 10 years ago.

The demand for water in agriculture can be forecasted based on the Ordinance of the Minister of Infrastructure of 14 January 2002 on the determination of average water consumption standards. In this document, average amounts of used water are given for (www-2):

- Watering house gardens and agricultural crops,
- Farms and livestock facilities,
- Operation of agricultural machinery
- Food processing plants,
- Chemical plant protection.

Based on the existing River Basin Management Plans that take into account climate change predictions, it is expected that water demand in agriculture will increase as a consequence of a longer growing season. Currently, agricultural land is drying up due to climate desertification. For this reason, legislative measures are taken to increase retention as well as the access to groundwater for agriculture.

B) Industrial use

The largest part in water consumption by the national economy is associated with industry (whose share in water consumption was more than 70 % in 2019). The major source of water in industry is surface water. Only 3 % of the groundwater is used by this sector of economy. The greatest annual demand for water was in the energy sector, which uses considerable amounts of water for cooling purposes. In 2018, the processes of production and supply of electricity, gas, steam and hot water consumed 6033 million m^3 of water (89 % of total industrial water consumption). The second section of business activity in terms of water consumption was industrial processing, where water consumption was 666 million m^3 (about 10 % of industrial consumption). Within industrial processing, the largest amounts of water were used in the production of chemicals and chemical products (318 million m^3).

4 % of the water used for production purposes in Poland was used in closed circuits, i.e. in a system in which water once used is not discharged but returned to the point of direct water supply for reuse.

C) Drinking water supply and demand

In 2019, about 19 % of the water consumed by the national economy and population was provided by the water supply network. 77% of this water was consumed by households. For many years (2003-2019), household water consumption in Poland has been stable, ranging from 85 to 92 litters per capita per day (92 in 2019). In 2019, households used 1292 million m^3 of tap water.

The technical condition of the water supply networks has a fundamental influence on water losses from the network. Water supply networks are constantly modernized and renovated, which helps to reduce the losses. Networks are particularly vulnerable to damage in mining areas. In Poland, losses up to 30 % or more were estimated for several water supply networks. Official statistics for the country in this respect are not kept. In recent years, there has been a clear downward trend in overall water consumption, which is mainly associated with lower industrial demand. In 2019, the total water demand was 8 816 million m^3, which corresponds to 0.629 m^3 per capita and day (www-1).

Surface water abstraction amounted to 7400 million m^3 in 2019 and covered 80% of the needs. It is used mainly for production purposes in industry. Groundwater abstraction amounted to 1800 million m^3 and was similar to the volume abstracted in 2018. Groundwater is the main source of water used for drinking purposes in Poland.

Croatia

The amount of water per inhabitant places the Republic of Croatia among best positioned countries in Europe. The average volume of the country's own available waters is 5880 m^3 per inhabitant and year (www-3). The average daily water in Croatia is 328 L per inhabitant and day for all purposes. This includes all types of water consumption and water losses (losses are currently very high, they are estimated to account for ~47 % of the water volume provided by public water supply systems). The average daily water demand for human consumption is 126 L per inhabitant per day.

Croatia belongs to a group of countries for which water issues are not a limiting factor of development. The main water consumers in Croatia are private households, agriculture and tourism. As the population was decreasing within last three decades, this does not affect future water demands. Due to a weak growth of agriculture and the introduction of new irrigation technologies, water consumption is currently decreasing in the agricultural sector, as well, where only ~2.5 % of the agricultural area in Croatia is irrigated. So the only water consumption that rapidly increases is for touristic demands, and the attractive position of touristic facilities in the Adriatic region worsens the future situation for water demand. As the Adriatic region is completely depending on karst aquifers, some problems occur during warm summer periods when precipitation is generally low, natural discharge is small, groundwater levels are low, and water demand increases due to tourism. Water policy is the responsibility of the ministry responsible for water management (Water Management Administration) that proposes laws and regulations. It adopts by-laws in the field of water management, performs administration and inspection and establishes international cooperation. Croatian Waters is an executive body responsible for water management and the implementation and coordination of the implementation of state policy in the field of water, including the development of River Basin Management Plan in the draft and all its elements. Furthermore, Croatian Waters is competent for all activities related to the use of water, they give permission for the use of water, determine the conditions and limits for its use. Based on available data, in 2012 about 953 million m^3 of water for different purposes (without hydropower) was extracted. Groundwater makes up about 41 %, springs 17 % and the remaining 42 % are obtained from surface water. Almost half of the extracted water (460.8 million m^3 per year) is used for public water supply (derived by ~49 % from groundwater, ~16.4% from surface water (rivers, accumulations and lakes) and ~35 % from springs). The remaining 492.5 million m^3 per year are used for technological purposes, agriculture (irrigation, livestock), freshwater aquaculture, recreation, health and the production of electricity. Figure 2 gives an overview on water use in Croatia for different sectors.

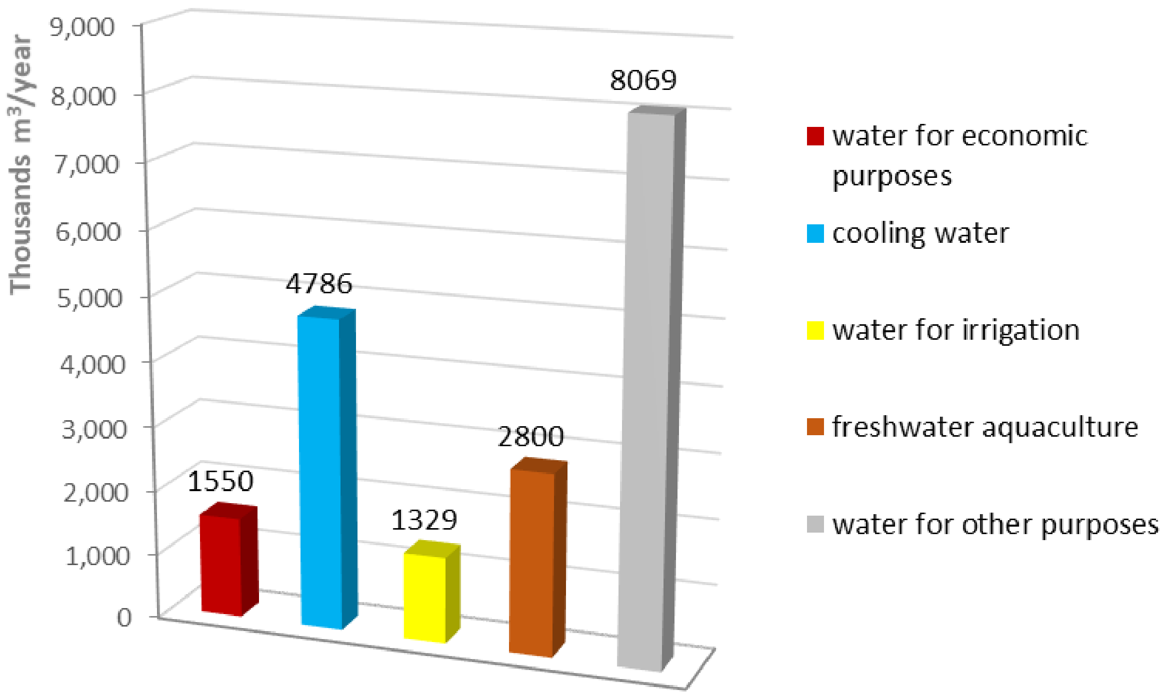

Figure A1: Water use in Croatia for different sectors (River Basin Management Plan 2016-2021)

Slovakia

In Slovakia, §2, item 2 of the Decree 684/2006 Coll. refers to perspective water consumption. An increase of 10 % was estimated for the future water demand in Slovakia (considering a 30-years period after 2018). This estimation was subject to considerable uncertainty, among others related to the population trend and water demands for agricultural and industrial purposes (www-4).

A) Irrigation and other agricultural purposes

Decree 397/2003 Coll. of the Ministry of Environment of the Slovak Republic relates to basic water consumption, water supply by public networks and discharged water, as well as the amount of waste water and surface runoff water. In this decree, Amendment 1 provides the average water demand for various uses. Part IX deals with farm animals, where identified average demands per animal and year are e.g. 22 m^3 for milk cows, 3.7 m^3 for pigs, 14.6 m^3 for horses, 0.13 m^3 for chicken and 0.44 m^3 for ducks and geese.

In 2018, water consumption for agriculture in Slovakia was covered by surface water and groundwater that contributed with volumes of 12.97 and 10.56 million m^3, respectively. An increase of 10 % was predicted to occur within a 30-years period (leading to volumes of 14.26 and 11.62 million m^3 from surface water and groundwater, respectively) (www-5). Uncertainties associated to this prediction are also related to agricultural practices of crop growing and stock farming.

B) Drinking water supply

Based on present demographic data there is a slightly increasing trend (+ 0,05 % year, www-6), therefore the water consumption is also expected to increase slightly. Since it is currently very low (below hygienic minimum), it is anticipated that it would not get lower, anymore. In Slovakia, the current specific water consumption is about 165 L per capita per day and the specific drinking water consumption in households is about 78 L per capita per day. A reason for the relatively low and constant specific drinking water consumption is the relatively high price of water. Therefore, it is expected that drinking water consumption will be relatively stable or increase slightly, as mentioned above. Actually, the available drinking water capacity of water resources (32 800 m^3/s) is exploited by 12 800 m^3/s, which is a little bit more than one third of the total existing capacity. Drinking water consumption was decreasing between 2000 and 2018, in total from 257 to 165 L per capita per day and for households from 120 to 78 L per capita per day. For 2018, the percentage of water losses in pipeline networks was estimated to be 24.1 % (Blue Report issued for the Ministry of Environment of the Slovak Republic; report in Slovak). Water losses by leaking networks were higher in cities with older (and more leaking) networks. Above mentioned statistics consider averages for Slovakia.

[www-1] https://bdl.stat.gov.pl/BDL/start

[www-2] http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20020080070/O/D20020070.pdf

[www-3] https://www.climatechangepost.com/croatia/climate-change/

[www-4] https://www.epi.sk/zz/2006-684

[www-5] https://www.enviroportal.sk/indicator/detail?id=721

[www-6] https://www.worldometers.info/demographics/slovakia-demographics/

[www-7] https://www.enviroportal.sk/indicator/detail?id=721

Appendix B – MAR-related regulations that are in place for risk assessment and management (per country)

Hungary

There are only general regulations on risk assessment and management, and only for drinking water in Hungary, in general: *201/2001. (X.25.) Government Regulation*. Annex 6 contains descriptions of risk assessment and management requirements. It was modified by *65/2009. (III. 31.) Decree*.

Furthermore, there is the guideline *Water safety plan manual* (prepared by the National Public Health and Medical Officer Service of Hungary, ÁNTSZ, 2013), which is based on WHO recommendation ((Nandha et al., 2015)

Poland

In Poland there are no regulations directly related to risk assessment and management in the context of MAR. However, there are regulations (Water Law, Journal of Laws 2017, item 1566) which impose an obligation to perform risk analysis by the owners of the wellfield for the purpose of assessment of health hazards, taking into account factors negatively influencing the quality of the intake. The risk analysis is carried out on the basis of hydrogeological or hydrological analyses and hydrogeological or hydrological documentation, the analysis of identification of sources of danger resulting from the land use, as well as the results of the examination of the quality of the intake water (http://www.hydrogeolodzy.pl/wordpress/wp-content/uploads/2019/09/Hydrog-Z2-55-58-Czop.pdf).

The second document is the Water Safety Plan (WSP). It contains recommendations developed by the World Health Organization (WHO), translated into Polish and published as a Manual for developing water safety plans. Step-by-step risk management - instruction for drinking water suppliers (https://www.who.int/water_sanitation_health/water_safety_plan_2009_pol.pdf?ua=1).

The main goal of the WSP is to ensure effective control of the entire drinking water supply system in the right quantity and quality. Closely linked to the WHO Water Safety Plan is the standard *PN-EN 15975-2:2013-12 Safety drinking water sup*ply. *Crisis and risk management guidelines. Part 2: risk management*.

In Poland, the implementation of WSP is in a very early phase due to lack of legal obligation. There are single examples of waterworks in Poland, that have implemented the WSP recommendations themselves in their companies (https://igwp.org.pl/index.php/nasza-aktywnosc/eureau/270-plany-bezpieczenstwa-wody).

The new Regulation of the Minister of Health on the quality of water intended for human consumption, in force since 7 December 2017, recommends taking into account, among others, risk assessment. The risk analysis requires taking into account, among other things, the characteristics of the intake, water treatment plant and distribution network, which allows to establish more effective monitoring of water quality while minimizing costs. The identification and characterization of the individual risks that may affect the quality of water directly in the tap at the customer's site is a key element in maintaining the stability of the parameters of the water supply and thus maintaining consumer health security (https://www.infor.pl/akt-prawny/DZU.2017.240.0002294,rozporzadzenie-ministra-zdrowia-w-sprawie-jakosci-wody-przeznaczonej-do-spozycia-przez-ludzi.html).

According to the act on sharing information on the environment and its protection, public participation in environmental protection and on environmental impact assessments (Journal of Laws 2008 No. 199, item 1227) the local competent authority for environmental protection may commission an environmental impact assessment report for MAR site. Within the framework of the environmental impact assessment, a project is identified, analysed and evaluated: 1) direct and indirect impact of the project on: a) environment and population, including human health and living conditions, b) material goods, c) monuments, ca) landscape, including cultural landscape, d) interaction between the elements referred to in points a-ca, e) availability of mineral deposits, 1a) risk of serious accidents and natural and construction disasters, 2) possibilities and ways of preventing and reducing the negative impact of the project on the environment, 3) required scope of monitoring.

This assessment should include the probability of occurrence of risk to human health or threat to the environment, risk of serious accidents or natural and construction disasters, taking into account the substances and technologies used, including the risk related to climate change (http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20081991227/U/D20081227Lj.pdf).

Croatia

Not available

Slovakia

Although, in Slovakia, there are no direct MAR related risk assessment or management regulations in place, there are binding legislative documents reflecting these issues.

Related to risk assessment, the Guidelines No.1/2015-7. issued by Ministry of Environment of the Slovak Republic are dealing with an elaboration of the risk analysis of polluted areas (https://www.minzp.sk/files/sekcia-geologie-prirodnych-zdrojov/ar_smernica_final.pdf). This document is also focused on soil pollution due to using land for agricultural purposes. Also several authors were dealing with risk assessment, e.g. Chriaštel et al. (2004) (http://www.sah-podzemnavoda.sk/cms/request.php?316) or Holubec (2006) (http://www.vuvh.sk/rsv2/download/02_Dokumenty/11_Seminare_konferencie/03_Seminar_RSV_stav_implementacie/12_Holubec.pdf)

Management regulations for different climate extremes are mentioned in Act. No 7/2010 Coll. dealing with flood protection where the management structure to tackle the flood events is defined.

In 2018, the Slovak Government approved the document *Value is Water – Action Plan* tackling water scarcity and droughts where the concept of management during drought periods is described.

Appendix C – Hazards for different risk categories

Table C1: Examples of hazards for different risk categories

Hazard	Example references
Potential hazards for human health	
Pathogens	(Ayuso-Gabella et al., 2011; Bartak et al., 2015; Bekele et al., 2008; Bugan et al., 2016; Casanova et al., 2016; Donn et al., 2020; Gibert et al., 2015; Gonzalez et al., 2015; Ji and Lee, 2016b, 2017; Lee and Ji, 2016; NRMMC-EPHC-NHMRC, 2009; Page et al., 2016, 2015b, 2015a, 2013, 2012b, 2009, 2008; D Page et al., 2010; D. Page et al., 2010c, 2010a, 2010b; Seis et al., 2015; Swierc et al., 2005; Vanderzalm et al., 2011)
Inorganic and/or organic chemicals	(Bartak et al., 2015; Bekele et al., 2008; Bugan et al., 2016; Gibert et al., 2015; Ji and Lee, 2016a, 2017; Juntunen et al., 2017; Lee and Ji, 2016; NRMMC-EPHC-NHMRC, 2009; Page et al., 2016, 2013, 2009, 2008; D. Page et al., 2010b, 2010c; Rodríguez-Escales et al., 2018; Rodriguez et al., 2007a; Seis et al., 2015; Toze et al., 2010; Vanderzalm et al., 2011)
Salinity and sodicity	(Bartak et al., 2015; Bugan et al., 2016; Gibert et al., 2015; Gonzalez et al., 2015; NRMMC-EPHC-NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2016, 2013, 2009; Seis et al., 2015; Vanderzalm et al., 2011)
Nutrients	(Bartak et al., 2015; Bugan et al., 2016; Casanova et al., 2016; Gibert et al., 2015; Lee and Ji, 2016; NRMMC-EPHC-NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2016, 2013; Rodríguez-Escales et al., 2018; Seis et al., 2015; Vanderzalm et al., 2011)

Turbidity and particulates	(Bartak et al., 2015; Bekele et al., 2008; Bugan et al., 2016; Gibert et al., 2015; Lee and Ji, 2016; NRMMC–EPHC–NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2013, 2009; Rodríguez-Escales et al., 2018; Seis et al., 2015; Sultana and Ahmed, 2016; Swierc et al., 2005; Vanderzalm et al., 2011)
Radionuclides	(Gibert et al., 2015; NRMMC–EPHC–NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2016, 2013, 2009; Rodríguez-Escales et al., 2018; Seis et al., 2015; Vanderzalm et al., 2011)
Adverse land use	(Bartak et al., 2015; Lee and Ji, 2016; Swierc et al., 2005; Vanderzalm et al., 2011)
Disinfection by-products (CBPs)	(Lee and Ji, 2016; Pavelic et al., 2005)
Potential hazards for the environment	
Chemical accidents (e.g. industry, road/train/planes, household pesticides, nuclear radiation), sabotage	(Assmuth et al., 2016; Bartak et al., 2015; Bouwer et al., 2008; Bugan et al., 2016; Lee and Ji, 2016; NRMMC–EPHC–NHMRC, 2009; D. Page et al., 2010b; Page et al., 2013; Swierc et al., 2005; Vanderzalm et al., 2011)
(Illegal) release of waste and wastewater, sewer overflow, (illegal) livestock, contamination by birds	(Bugan et al., 2016; Juntunen et al., 2017; Lee and Ji, 2016; Swierc et al., 2005)
Impacts of MAR scheme on GW-dependent ecosystem, e.g. due to changing water levels, quality, pressure, volumes and flow rates leading e.g. to the mobilization and migration of contaminants, dissolution of minerals	(Assmuth et al., 2016; Bartak et al., 2015; Dillon et al., 2009a; Gibert et al., 2015; Nandha et al., 2015; NRMMC–EPHC–NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2013, 2009; Pasini et al., 2012; Seis et al., 2015; Swierc et al., 2005; Vanderzalm et al., 2011)
Energy consumption and greenhouse gas emissions	(Bartak et al., 2015; Gibert et al., 2015; NRMMC–EPHC–NHMRC, 2009; D. Page et al., 2010b, 2010c; Page et al., 2013, 2009; Seis et al., 2015; Vanderzalm et al., 2011)
Potential technical hazards	
Flood, heavy rainfalls (such as monsoon rainfall)	(Bartak et al., 2015; Bugan et al., 2016; Juntunen et al., 2017; Lee and Ji, 2016; NRMMC–EPHC–NHMRC, 2009; Rodríguez-Escales et al., 2018; Swierc et al., 2005)
Clogging	(Bartak et al., 2015; Bekele et al., 2008; Bugan et al., 2016; Lee and Ji, 2016; Nandha et al., 2015; NRMMC–EPHC–NHMRC, 2009; D Page et al., 2010; D. Page et al., 2010b, 2010c; Pedretti et al., 2012b; Rodríguez-Escales et al., 2018; Song et al., 2019; Sultana and Ahmed, 2016)
Drought	(Juntunen et al., 2017; Lee and Ji, 2016; Nandha et al., 2015; NRMMC–EPHC–NHMRC, 2009; Rodríguez-Escales et al., 2018; Swierc et al., 2005)
Reduced/elevated infiltration rate	(Bartak et al., 2015; de los Cobos, 2018; Rodríguez-Escales et al., 2018)
Slope instability, erosion	(Rodríguez-Escales et al., 2016; Swierc et al., 2005)
Lack of land	(Rodríguez-Escales et al., 2018)
Water demand and supply changes	(Lindhe et al., 2020; Nandha et al., 2015; NRMMC–EPHC–NHMRC, 2009)
Reliability of technology, malfunctioning or failure of technical equipment or infrastructure (including e.g. pre and post treatment, pumps, pipes, monitoring schemes), fires, computer hacking, terrorism	(Bartak et al., 2015; Bouwer et al., 2008; Bugan et al., 2016; Juntunen et al., 2017; Lee and Ji, 2016; Nandha et al., 2015; Rodríguez-Escales et al., 2018; Swierc et al., 2005)
Missing trained operating absence of required staff / technical knowledge, resulting mistakes in operation	(Assmuth et al., 2016; Peter Dillon, Fernández Escalante, et al., 2020; Rodríguez-Escales et al., 2018; Swierc et al., 2005)
Bacterial regrowth, biofilm in distribution system and storage tanks	(Bugan et al., 2016)
Potential socio-economic hazards	
Lack of funding /financial support, business case	(Maliva, 2014; Pindoria-Nandha, 2016; Rodríguez-Escales et al., 2018; Shah et al., 2013)
Unplanned costs (maintenance, installation etc.)	(Rodríguez-Escales et al., 2018)
Changing standards for end-user	(Nandha et al., 2015)
Insufficient communication and negative risk perception of the public	(Alexander, 2011; ASCE American Society of Civil Engineering EWRI Environmental and Water Research Insititute, 2020; Bartak et al., 2015; Bekele et al., 2008; Juntunen et al., 2017; Le Corre et al., 2012)
Economic losses if performance objectives cannot be met	(Blood and Spagat, 2013; Dillon et al., 2016; Maliva, 2014; Nandha et al., 2015)

Behaviour of public that affects groundwater quality around the MAR scheme (e.g. washing/bathing near to wells, absence of buffer zone or groundwater protection zone for recreational purposes)	(Bartak et al., 2015; Bugan et al., 2016)
Negative economic effects due to illness originating from poor water quality	(Assmuth et al., 2016; Juntunen et al., 2017)
Missing acceptance and trust of public	(Alexander, 2011; Leviston et al., 2006; Mankad et al., 2015)
Missing commitment of stakeholders	(Casanova et al., 2016)
Benefits are lower than anticipated, e.g. if the actual willingness-to-pay is lower than declared; or if there is an insufficient demand (e.g. for irrigation water under different climate change scenarios)	(Maliva, 2014; Rupérez-Moreno et al., 2017)
Potential hazards related to legislation and governance	
Subsidies can lead to inefficient water consumption by population	(Maliva, 2014)
Missing land rights	(Bartak et al., 2015; Rodríguez-Escales et al., 2018)
Legislative requirements; regulatory risks such as environmental conservation policies, water quality regulations	(Bartak et al., 2015; Casanova et al., 2016; de los Cobos, 2018, 2015; Fernández Escalante et al., 2020; Lee and Ji, 2016; Nandha et al., 2015; Rodríguez-Escales et al., 2018)

Appendix D - MAR-related regulations that are in place for monitoring (per country)

Slovakia

In Slovakia, there are no special regulations in place concerning operational monitoring of MAR systems. Surface water and groundwater monitoring is done under EC Directives, particularly the Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Nitrates Directive (91/676/EEC).

Surface water monitoring is performed in accordance with Act No 364/2004 Coll (Water Act); Act No 201/2009 Coll. (on state hydrological service and state meteorological service); Act No 7/2010 Coll., (on flood protection) and Government Regulation No 269/2010 Coll (on requirements to achieve good status of waters), Government Regulation No 167/2015 Coll (on environmental quality standards in the field of water policy), Government Regulation No 201/2011 Coll. (on technical specifications concerning chemical analyses and monitoring of water), Government Regulation No 354/2006 Coll. (on drinking water standards) in accordance with Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic (on occurrence, monitoring and assessment of quantity and quality of surface water and groundwater).

Groundwater monitoring relates to item 4 of Collection of Slovak Republic, Act No 364/2004 Coll (Water Act), Act No 201/2009 Coll. (on state hydrological service and state meteorological service), Act No 569/2007 Coll. (Geological Act), Act No 7/2010 Coll. (on flood protection), Government Regulation No 416/2011 Coll (on the assessment of chemical status of groundwater body) and Decree No 418/2010 Coll. of the Ministry of Agriculture, Environment and Regional Development of the Slovak Republic.

Surface water and groundwater monitoring data are stored in the Slovak Hydrometeorological Institute. Surface water monitoring is partially performed by the Slovak Water Management Enterprise and Water Research Institute, other monitoring activities are covered by Slovak Hydrometeorological Institute. Within the River Basin Plan of Slovakia, framework programmes of water monitoring covering 5 years are prepared. The framework programme of water monitoring in Slovakia for the period 2016 – 2021 can be found at:

http://www.vuvh.sk/RSV2/download/02_Dokumenty/26_Ramcovy_program_monitorovania_vod/RPM_2016_2021.pdf.

Croatia

Since there are no active MAR sites in Croatia, operational monitoring is performed on groundwater bodies that are characterized by a deteriorated chemical status or are at risk of achieving a deteriorated status, in accordance with Water Framework Directive (WFD) objectives. However, operational monitoring could be used in terms of MAR to distinguish impacts from different pressure types, to assess the spatial extent of impacts and to determine contaminant fate and transport between the source and the receptor. Furthermore, operational monitoring could be used in the risk assessment process and also provide an answer to whether MAR operation is efficient or not. More details on operational monitoring in Croatia can be found at: https://www.voda.hr/sites/default/files/15_-_guidance_on_groundwater_monitoring_-_eng.pdf.

Poland

In Poland, there are no separate, special regulations concerning operational monitoring for MAR. Groundwater monitoring is carried out by the Polish Geological Institute (in accordance with Article 349(8) of the Water Law Act) on behalf of the Chief Inspectorate of Environmental Protection (based on Article 385(3)(4) of the Water Law Act), which also covers areas where MAR is applied.

The organisation and scope of groundwater monitoring in Poland was adapted to comply with European Community directives, particularly the Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Nitrates Directive (91/676/EEC), in accordance with its specific features resulting from the unique geological structure and hydrogeological conditions in Poland.

The general conditions to be met when carrying out monitoring and assessment of the condition of groundwater are set out in the regulations of Polish law, including the following legal acts:

- Water Law Act of 20 July 2017 (Journal of Laws 2017 item 1566) (https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20170001566/U/D20171566Lj.pdf).

- Regulation of the Minister of Maritime Economy and Inland Navigation of 11 October 2019 on the criteria and methods of evaluation of the state of groundwater bodies (Journal of Laws 2019, item 2148) (https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20190002148/O/D20192148.pdf).

- Ordinance of the Minister of Maritime Economy and Inland Navigation of 9 October 2019 on the forms and methods of monitoring surface water bodies and groundwater bodies (Journal of Laws 2019, item 2147); (https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20190002148/O/D20192148.pdf).

In order to determine the state of the JCWPd (groundwater bodies) in Poland, the methodology presented in the guidelines developed by the European Commission experts are applied, e.g:

Guidance Document No. 1. Statistical aspects of the identification of groundwater pollution trends, and aggregation of monitoring results. European Communities, 2001.

Guidance Document No. 7. Monitoring under the Water Framework Directive. European Communities, 2008.

Guidance Document No. 15. Guidance on Groundwater Monitoring. European Communities, 2007.

Guidance Document No. 16. Guidance on Groundwater in Drinking Water Protected Areas. European Communities, 2007.

Guidance Document No. 18. Guidance on groundwater status and trend assessment. European Communities, 2009. (Wytyczne w sprawie stanu wód podziemnych oraz oceny tendencji).

Guidance document No. 26. Guidance on risk assessment and the use of conceptual models for groundwater. European Communities, 2010.

The methodologies presented in the manuals developed by the experts of the European Commission have been adapted to take into account the requirements of the Polish law and the studies carried out in Poland to support the interpretation of monitoring results (https://mjwp.gios.gov.pl/art_metodyka/o-metodyce.html).

Hungary

There is no specific regulation for MAR systems in Hungary, but there are some general regulations about groundwater protection, groundwater management and monitoring activity:

Government Regulation 123/1997. (VII.18.) on the protection of vulnerable water supplies. This regulation concerns their protection measures and the criteria of water protection zones.

The **Act LVII of 1995 on water management** regulates the recharge of aquifers by artificial recharge and reinjection. Accordingly, water users do not have to pay water supply contribution after the amount of water they recharge if artificial recharge is done into the original aquifer from which water was withdrawn.

The **Government Regulation 219/2004. (VII.21.) on protection of groundwater** regulates the artificial recharge and reinjection in order to preserve the quality and quantity of the underground water resources. This regulation also sets out conditions and makes it subject to official water protection authorization.

The **30/2004. (XII. 30.) KvVM Decree on rules of monitoring of groundwater** regulates the monitoring of quality and quantity status of groundwater bodies.

The **201/2001. (X.25.) Government Regulation** has a focus on quality requirements of drinking water and regulates respective monitoring.

Authorities can determine further monitoring requirements in their permissions.

Appendix E - Data requirements for CBA related to MAR

1. Identification of MAR scheme
    a. MAR type (e.g. infiltration, recharge wells, water bank infiltration, etc.)
    b. Water source for MAR (e.g. natural/recycled water, fluvial, sewage, etc.)

c. Objective of the MAR scheme (e.g. irrigation, drinking water, ecosystems, multi-purpose, municipal use, industrial use, etc.)

2. Contextual information of the MAR scheme and the associated aquifer
   a. Site name
   b. Country
   c. City
   d. Latitude/Longitude
   e. Expected construction duration
   f. Expected lifespan
   g. Recharging rate
   h. Influent source
   i. Effluent final use
   j. Expected average annual influent volume
   k. Expected annual extracted volume

3. Physical/hydrogeological characteristics
   a. Land area (ha)
   b. Number of wells
   c. Well capacity
   d. Well water quality (we can identify different measures here based on the need of the case study) – very important for drinking water

4. CBA
   a. Cost Analysis
      i. Cost of extraction (i.e. well construction or maintenance, pump installation)
      ii. Cost of distribution (i.e. piping)
      iii. Groundwater exploitation costs: investment and operating costs of installations for pumping and
         1. Irrigation piping infrastructure
         2. transfer to drinking water distribution facility/ to water treatment plant)
      iv. Raw water costs, if any.
      v. Cost of land purchase
      vi. Cost of construction
      vii. Regulatory requirements related costs
      viii. Environmental cost/damage from aquifer overexploitation (these will be analysed using contingent valuation method/surveys)
      ix. Expected annual expenses (i.e., energy, maintenance, employees) – this part can be simulated by us, if the information cannot be available.

   b. Benefit Analysis
      (water being available in times of scarcity, improvement in water quality, or a combination of both)
      i. Private/market benefits
         1. Revenues of drinking water facilities – more straightforward as there is a market for drinking water most of the time.
         2. Revenues from charging irrigation water or calculation of marginal productivity of water (in that case the amount of water used and the amount of output produced is needed).
      ii. Socio/environmental benefits (i.e. ecological sustainability of the aquifer)
         1. willingness to pay (WTP) for:
            the environmental improvement of the aquifer
            the sustainability of agriculture

the safety of drinking water
(very simple few questions that can be answered by local stakeholders through email, post, in person)

2. Damage avoidance
Value of water is estimated from damage costs avoided, such as health impacts or drought damage. In economics, we have damage value modelling approaches for estimations like that.

c. Risk and Uncertainty Assessment

Most often, feasibility studies using CBA conduct an extra step that is important for policy decision making: risk and uncertainty. This part can be incorporated by considering any of the following:

- Recharge may not result in anticipated changes in aquifer water levels;
- Unexpected water quantity and quality changes (e.g., leaching into stored water, drought, floods, extreme weather events);
- Anticipated demand for water (and associated revenues) may not be realized.

Appendix F – Survey design example

In the following, a brief overview of a survey design is given (contingent valuation method, revealing the willingness to pay), based on Damigos et al. (2017).

Target group

Individuals, 18 years of age or older (local population)

Proposed approach toward estimating and decomposing the non-use values by means of the CV method is not to split the sample into a user and a nonuser group, but ask respondents including users to partition their total WTP into various use and nonuse categories

Main groups of questions

"The approach that has been generally accepted as more efficient in CV applications, which is also reflected in recent CV surveys, starts with general questions on the state of the environment. Gradually, the questions become more specialized and focused to the valued good; they are supplemented by valuation questions; and they end with demographic questions."

<u>First part: Current local environmental conditions and existing problems</u>

1. Have you used groundwater in your locality in the past or in the present?
   - Yes, in the past
   - Yes, in the present
   - No
2. Have you heard about any groundwater issues (from any type of media)?
   - Yes, a few times
   - Yes, rather frequently
   - Never heard
3. Please, rate your knowledge of groundwater issue
   - Poor
   - Fair
   - Good
   - Excellent

4. Have you heard of problems related to groundwater quality or quantity?
    - Yes, a few times
    - Yes, rather frequently
    - Never heard
5. Please, select your main concern in regard to groundwater problems among the following:
    - natural pollution
    - over-pumping
    - pollution from industrial wastewater
    - pollution from pesticides and fertilizers
    - other (please, specify) ______________________________
6. What are the main reasons behind groundwater degradation to your point of view (please, select up to two):
    - poor implementation of existing legislation
    - lack of public awareness
    - lack of appropriate legislation'
    - other (please, specify) ______________________________
7. To what extent it is important for the competent authorities (agencies) to protect or preserve groundwater?
    - Very important
    - Somewhat important
    - Not important
8. Do you think that these authorities have the necessary capacity to fulfil this obligation?
    - Yes
    - No
    - Not sure
9. To what extent it is important for public (individuals) to protect or preserve groundwater?
    - Very important
    - Somewhat important
    - Not important
10. Do your household have impact on groundwater quality and/or quantity?
    - Yes, we impact groundwater as much as the other households
    - Yes, but we impact groundwater more than the other households
    - Yes, but we impact groundwater less than the other households
    - No impact
11. Please, select prevailing pressures on groundwater among the following:
    - wasting of water
    - municipal wastewater discharge
    - inappropriate municipal waste management
    - other (please, specify) ______________________________
12. Do you believe that there should be a protection and preservation plan for groundwater?
    - Yes
    - No
    - Not sure
13. Do you feel some responsibility for paying for it?
    - Yes
    - No
    - Not sure

<u>Second part: Revealing willingness to pay</u>

- Description of the project with clear explanation of expected results of its implementation and benefits from MAR

Example (based on Damigos et al., 2017):

‘‘Suppose a management plan was proposed for groundwater for the next 5 years that tried to balance the needs of users of groundwater, such as farmers, industries, and citizens, with the goals of preserving and protecting groundwater quality and quantity, as well as groundwater-dependent ecosystems. The plan would include a number of actions. More importantly, the proposed plan would implement a structured program of artificial aquifer recharge projects. The main objective of artificial aquifer recharge is to store excess water and thus to increase available reserves of groundwater for later use, while improving water quality. In addition, artificial aquifer recharge may promote recovery of overexploited aquifers, prevent sea-water intrusion, reduce groundwater salinity, etc. However, if this plan was adopted, it would cost money. Assuming that economic activities, such as industry, agriculture, etc., would pay the cost of reducing the impacts that come from them, citizens would also be asked to financially contribute to this plan.’’

What is your preferred way of funding the proposed policy?

- through municipal taxes
- through water bills
- through high-income taxes
- other way (please, specify) ____________________

If you were given the choice to make a monetary contribution, through your preferred way of donation, toward supporting the groundwater preservation and protection plan, what is the MAXIMUM amount you would be willing to pay per month over a 5-year period?

- 0 Euro
- 1 Euro
- 2 Euro
- 5 Euro
- 10 Euro
- 15 Euro
- 20 Euro
- 25 Euro
- 30 Euro
- 35 Euro
- 40 Euro
- 50 Euro
- more than 50 Euro (please specify exact amount)

If your answer is zero in the previous question, please, choose the reason for your decision:

- I already pay enough municipal/income taxes
- I cannot afford it
- It is the government’s responsibility
- The proposed plan is not feasible, good enough, convincing, etc.
- Industries, farmers, etc. should pay
- I don’t care much about preserving and protecting groundwater
- Other reason (please, specify) _________________________

If your answer is non-zero in the previous question, please, distribute the amount of your financial support according to the following distinct categories:

1. Fraction A: Use of groundwater by the members of their household
2. Fraction B: Use of groundwater by other members of the local community
3. Fraction C: Use of groundwater by future generations
4. Fraction D: Use of groundwater by groundwater-dependent ecosystems

Third part: Demographic questions

What gender do you identify as?

- Male
- Female
- ________ (Short Answer Space)
- Prefer not to answer.

What is your age?

- 0 - 15 years old
- 15 - 30 years old
- 30 - 45 years old
- 45+
- Prefer not to answer

What is the highest degree or level of education you have completed?

- High School
- Bachelor's Degree
- Master's Degree
- Ph.D. or higher
- Prefer not to say

What is your annual household income?

- Less than $25,000
- $25,000 - $50,000
- $50,000 - $100,000
- $100,000 - $200,000
- More than $200,000
- Prefer not to say

What is your current employment status?"

- Employed Full-Time
- Employed Part-Time
- Seeking opportunities
- Retired
- Prefer not to say

How many children do you have?"

- None
- 1
- 2
- 3
- More than 3
- Prefer not to say

Survey pretest stage is important (pilot study to reveal potential problems with the survey, questions that might be misunderstood)