D.T4.2.1. TRANSNATIONAL GUIDELINES FOR BETTER MAR ADOPTION IN CE REGION LEGISLATION AND STRATEGY

D.T4.2.1 | Final version

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Date last release	December 2021

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1. Executive summary

The DEEPWATER-CE Central European Cooperation Project, led by the Mining and Geological Survey of Hungary, examines the applicability of various managed groundwater recharge and water storage technologies (Managed Aquifer Recharge - MAR, hereinafter MAR), with a special focus on the expected future effects of climate change.

The MAR method and technology have a strategic role in addressing the environmental changes and extreme weather events caused by climate change, overpopulation, pollution, and the challenges of growing global water scarcity. This method of water management has already been applied in many places and it aims to retain natural, seasonal or intermittent excess water or treated water by using various technical solutions and purposefully recharging it to aquifers to ensure subsequent recovery or environmental benefits (Dillon et al., 2019).

Due to climate change, increasing consumption and insufficient infrastructural conditions, sustainable and conscious management of water resources is often difficult to achieve. Therefore, the development, dissemination and increased use of MAR approaches and technologies are essential for the sustainable supply of water demands in all economic sectors.

The potential and predicted effects of climate change will cause shortage of rainfall in some parts of the Central European region, whereas there will be an increase in rainfall in other areas. The extreme temporal and spatial distribution of precipitation will be more common. Local, short-term, high intensity precipitation events can cause drastic changes in water recharge conditions. The collection of surface water surplus during such rainy periods and its storage in groundwater aquifers, followed by its utilization during increasingly frequent and prolonged periods of water scarcity, is of strategic importance for water management. We note that it is also possible to recycle used waters by using MAR, but this is not the subject of this document or the project.

The task of the fourth work package of the DEEPWATER-CE project is to frame and present policy recommendations for the application and dissemination of MAR systems in a general handbook format. The European Union's existing water regulations contain minimal recommendations for purposeful recharge of water to aquifers, which is also summarized in DEEPWATER-CE, 2021. However, recently, the Groundwater working group for the implementation of the WFD is preparing the MAR specific guidelines and regulations (EU WFD Working Group, 2021). Therefore, to promote the method widely among governing bodies, policy makers, professional organizations, users, and society in the CE countries, the beginning of this handbook provides a brief, comprehensive description of the systems developed so far and applied in many parts of the world.

Then the regulatory and legal environments developed in each country are presented. In the following, the handbook describes the complex and lengthy designing process of a managed aquifer recharge system and the aspects that are expected to present the most difficulties by providing summary of the technical, environmental, and regulatory challenges of the implementation.

This handbook concludes with proposals for the dissemination of the methodology and application of managed aquifer recharge, of which the following are highlighted:

- the revision of River Basin Management Plans should include an examination of the applicability of MAR as an important tool for integrated water resources management, especially in regions exposed to the effects of climate change and for water bodies at risk or in a poor condition;
- a detailed regulatory framework for MAR methods should be established;
- the need for MAR systems can be determined based on the environmental assessments of the River Basin Management Plans;

- these systems can be established on the basis of extensive, detailed examination of local conditions and pilot studies; and
- the operation of MAR systems requires the installation of monitoring systems prior to operation also for the planning phase. MAR systems can only be established based on the operation of these monitoring systems and constant evaluation of their data. These systems should cover all parts of MAR systems and monitor their planning and operation.

2. Necessity and applied practices of the utilisation of Managed Aquifer Recharge (MAR)

2.1. Needs and potentials of the applications of MAR systems

Due to climate change, overpopulation and pollution, water scarcity is not uncommon even in countries with abundant water resources. Although there may be a number of specific reasons for this – e.g., aging infrastructure and distribution systems, pollution, political/economic conflict or mismanagement of water resources – it is clear that climate change and the resulting deteriorating social factors are providing increasingly unfavourable conditions for the supply of clean drinking water for the population, for maintaining a balanced water management framework, and for providing the basis for a livable social environment. At the same time, the significant increase in water usage and wastage, and the concomitant water pollution, pose serious challenges to the developed world including the European Union. Therefore, strengthening the framework of prudent water management is a strategic need in the societies of the developed world.

According to the reports of the United Nations (UN-Water, 2021), the following findings can be made about the current global situation:

- four billion people – almost two-thirds of the world's population – suffer from severe water shortages for at least one month a year;
- more than two billion people live in countries with inadequate water supplies;
- by 2025, half of the world's population may live in water-scarce areas;
- by 2030, some 700 million people may be forced to leave their homes due to intense water shortages; and
- by 2040, roughly one in four children worldwide will live in an area hit by extreme water shortages.

Due to the challenges outlined above, a new paradigm for sustainable water management has begun to develop in recent years. Some strategic approaches, most importantly water-use efficiency, water recovery and water reuse and recycling aim to meet current water needs without compromising future water resources and supply (UN-Water, 2021; Wintgens et al, 2009). Managed water recovery in accordance with such principles provides an excellent opportunity to use the recovered water for agricultural, industrial, or even domestic purposes. The widespread application of the above strategies could lead to great progress in the development of a more sustainable water management framework.

Based on the principles of water recovery and recycling, the methodology and technology of MAR are of strategic importance in addressing the challenges posed by climate change, overpopulation, pollution, and global water scarcity (Szabó and Mádlné, 2018). Aquifer is recharged by the managed infiltration or injection (via injection wells) of rainwater, surface water, recovered water, treated wastewater or water from other aquifers for later recovery or for environmental benefits (Dillon et al., 2019).

This technical solution is in accordance with the circular economy approach regarding water usage and provides the most favourable environmental and cost-benefit conditions for environmentally conscious water management (Declan et al., 2018).

The growing demand for MAR systems is well illustrated by the fact that since the first Scottish infiltrators were built around 1870, the number of MAR systems has begun to explode especially from the 1960s, as shown by Figure 1**Hiba! A hivatkozási forrás nem található.**. As a result, the national authorities had set up about 30 new MAR sites a year in Europe by the 2000s, which clearly demonstrates an increase in the value of the technology.

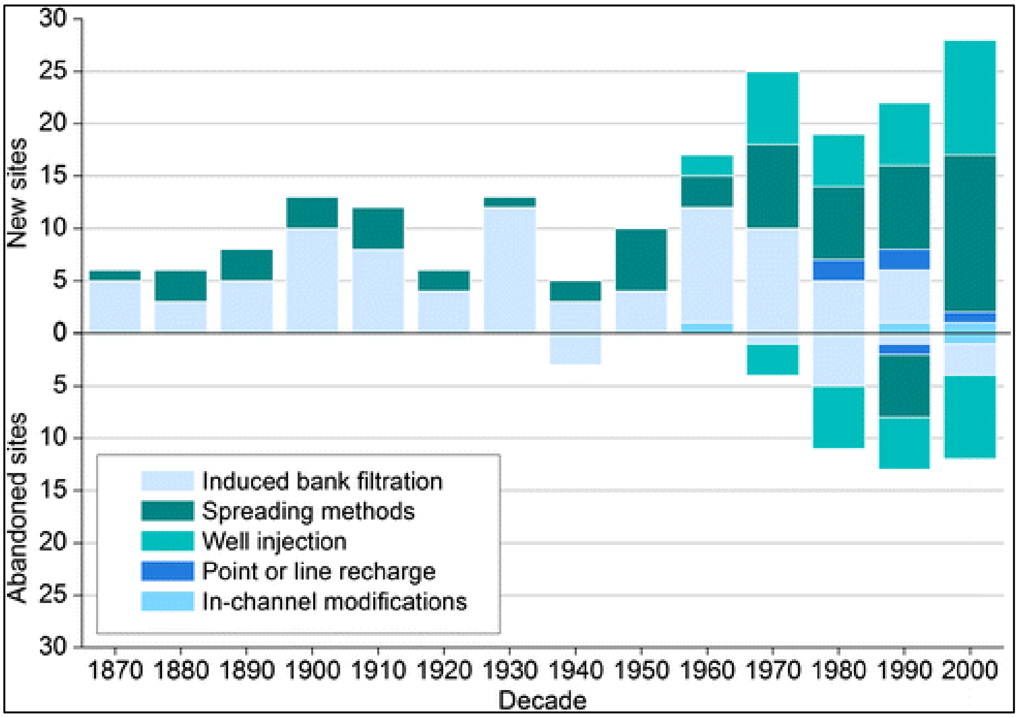

Figure 1: Change in the number of new MAR sites created per year in Europe (Sprenger et al., 2017)

The number of MAR sites in Europe increased to a total of 224 facilities in 23 countries by 2013 with a significant proportion in Germany (64 sites), the Netherlands (41 sites) and, to a lesser extent, France (21 sites) (Figure 2) (Sprenger et al., 2017). The most recent data can be found on the IGRAC MAR Portal (https://ggis.un-igrac.org/maps/1233).

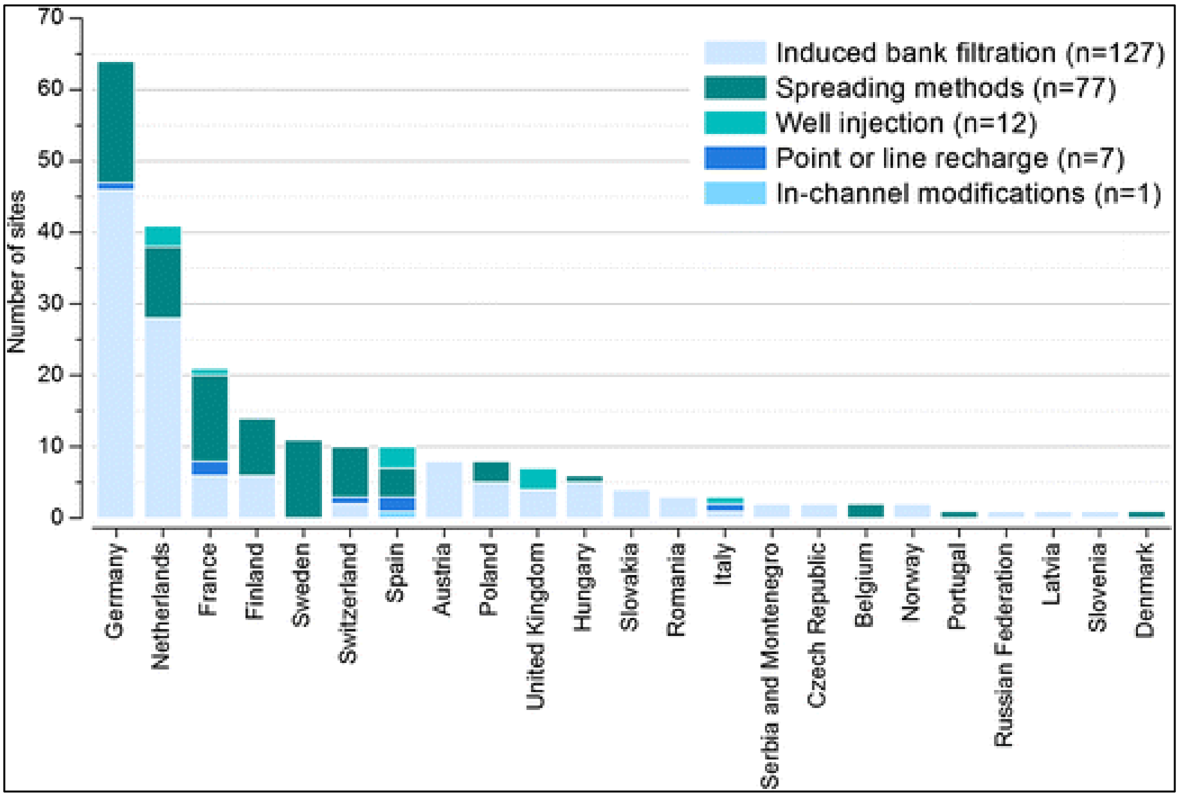

Figure 2: Distribution of MAR sites among individual EU member states in 2013 (Sprenger et al., 2017)

The most common MAR technologies in Europe are the methods based on induced bank filtration and direct surface infiltration via spreading methods, as shown in Figure 3. The former is the most widely used in the regions of Central and Western Europe, whereas the latter is mainly applied by Western and Northern Europe and the Mediterranean. Groundwater resources are limited in Scandinavia and due to the small extent of good permeability and porosity aquifers, thus surface infiltration plays a significant role in replenishing groundwater resources. In Spain and in Portugal, mainly surface spreading methods are used for the replenishment of heavily exploited groundwater reserves (Sprenger et al., 2017).

The applicability of MAR depends highly on the abundance of water resources of the respective country or region, the purpose and extent of water uses, the hydrographic conditions (most MAR systems in Europe consist of a series of bank-filtered wells installed along large rivers), the available financial resources and public acceptance.

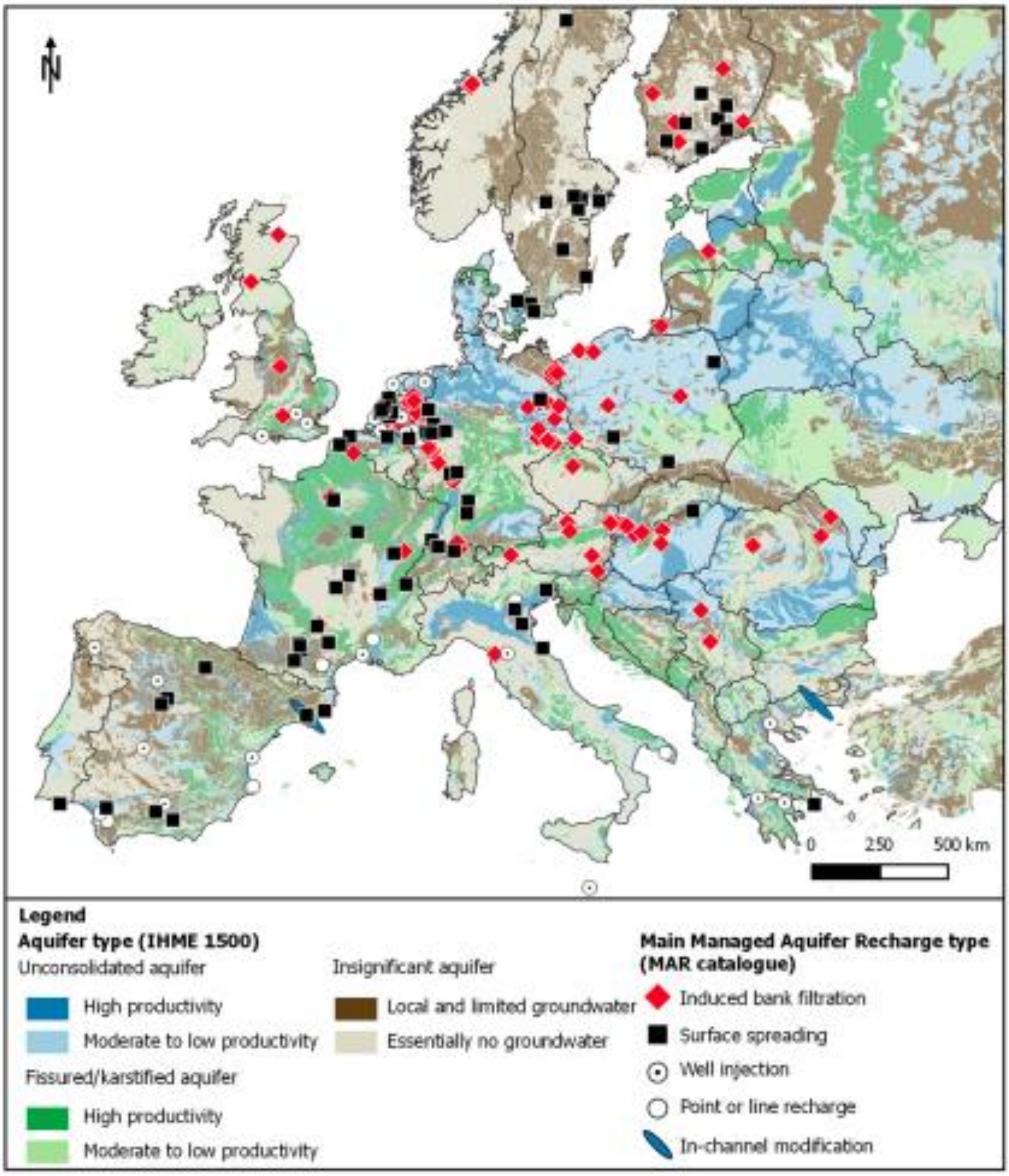

Figure 3: Location of MAR sites in some European countries in 2013 (Sprenger et al., 2017)

The widespread adaptation of MAR, both on the European and global scale, is hampered by the fact that during their infrastructural developments, countries have not developed comprehensive water management solutions that are able to renew groundwater resources while keeping pace with increasing water consumption. It can be concluded that because of the climate change (IPCC, 2007), increasing consumption and insufficient infrastructural conditions, sustainable management of water resources is currently only provided in a very narrow geographical environment. Therefore, the development, dissemination and increased use of MAR approaches and technologies are essential for the global sustainability of water resources.

Accordingly, in Europe, especially in the Mediterranean basin, measures such as aiming at a more efficient water use, as well as the recycling of water, and its managed recharge to aquifers are of strategic importance. Replenishing water back into aquifers may improve local water supply and may help to alleviates water scarcity (Bouwer, 2002).

The application of MAR technology can be used to achieve e. g. the following water management objectives:

- expanding limited water resources through water retention and groundwater storage;
- providing water storage and water treatment capacities for residential, industrial, environmental and agricultural purposes;
- restoring groundwater resources quality damaged by seawater/pollutant inflows; and
- installing an artificial barrier against the inflow of seawater/pollutants.

Accordingly, the application of MAR can provide key benefits such as the followings:

- irrigation water supply for agriculture without further exploitation of natural water resources;
- utilisation of rainwater for industrial purposes;
- water purification and long-term water storage; and
- addressing seasonal peak water demand induced by e.g. tourism activities.

The application of MAR can fulfil both the environmental/sustainability, as well as, economic needs. The environmental benefits of MAR application are mainly related to potential water recharge and water quality improvements. The purpose of MAR systems is often to manage better hydraulically connected habitats and groundwater systems and, in some cases, the infiltration of treated waste water through geological media for aquifer storage and groundwater augmentation.

In addition to environmental considerations, the economic aspects of MAR also have significant positive benefits, which are related to the cost benefits of managed aquifer recharge and recovery (DEEPWATER-CE, 2020b). Compared to the costs of traditional methods of wastewater treatment and stormwater drainage, the use of MAR can be economically viable alternative overall. The application of any form of MAR directly contributes to water savings, therefore, it has the potential to significantly reduce or even eliminate investments in new surface water infrastructures (e.g., reservoirs, dams). Managed recharge and reuse of water is in most cases a viable alternative to the long-term, conventional exploitation, storage, and treatment of fresh water (e.g., deep water abstraction, seawater desalination, distillation, dam system construction, stormwater, and treated water release into waters) from a financial point of view (Yuan, 2016).

2.2. Application possibilities of MAR systems in Central Europe

The design of an appropriate MAR system can take place in several ways, depending on the geographical characteristics of the location, the type of water available for recharge, the method of recharge, the type of water treatment system and the utilisation of recovered water (Figure 4). Several types of potential and installed MAR systems are reported in the literature (Dillon et al., 2009b).

The MAR methods can be classified into the following main groups: managed surface infiltration; induced bank filtration; recharge through a well, shaft or borehole; modification of bed morphology; collection and utilisation of rainwater and surface runoff.

The most commonly used technologies are:

- **Aquifer storage and recovery (ASR)**: ASR technology is the direct recharge of surface water into an aquifer for later recovery and use. The injection and extraction are done by using the same well. This type of MAR method can be cost-effective and has relatively low environmental impact. The application of ASR technology proved to be very useful for saline aquifers, as managed recharge can reduce the salinity of groundwater (e.g., the Netherlands). One of the main purposes of the use of ASR technology is the storage of water in aquifers for later use as drinking water. The operation of these systems in the United States can be considered as best practice. The technology is also successfully used in Australia for the utilization of treated wastewater in agriculture or the storage of urban stormwater (Dillon, 2009a).

- **Aquifer storage transfer and recovery (ASTR)**: ASTR technology is the recharge of water into a well for storage and recovery from a different well. This method is a more specific version of ASR, and it is often used to achieve better water quality by extending its residence time in the aquifer. The further purification of recharged water through aquifer deposits, which efficiently removes pathogens and micro-contaminants, provides an adequate technical solution for urban drinking water supply.

- **Application of shallow (vadose zone) wells**: these types of shallow, near-surface wells (located in a vadose zone) are also called dry wells, of the relatively large space between the topographic surface and the groundwater saturated zone. This method is often used for instance, in rainwater seepage to facilitate the drainage in mountainous regions, to reduce soil erosion and to recover the accumulated rainwater.

- **Rainwater harvesting**: during the application of this MAR technology, rainwater is diverted to a well and then allowed to seep into the groundwater from where it can be extracted by pumping. This process provides an efficient solution for the natural filtration of rainwater therefore it facilitates the balanced hydrological cycle of urban areas.

- **Bank filtration**: this technique can be applied along the banks of rivers and lakes, and it aims to induce infiltration of surface water into the related coastal or floodplain aquifers by pumping. The filtration process generally improves the quality of the extracted water; therefore, its application provides a suitable technological solution primarily in the drinking water supply of riverside settlements, as exemplified by the practice of Germany, the Netherlands and Hungary, Poland.

- **Infiltration ditches, channels**: During its application, water is infiltrated through bottom of the ditches. The great advantage of the method is that it requires much less area compared to infiltrating basins (see below), and the chance of clogging may be significantly lower due to the low level of algal bloom and higher permeability of the channel deposits relative to quiet-water sediments.

- **Infiltration basins**: the accumulated rainwater is recharged to the aquifer via artificially created catchment basins. This technique has good pollution removal capacity and can be considered as an effective tool for rapid replenishment of groundwater. The technology, however, requires a significant amount of space due to the construction of the lakes, in addition clogging decreases the efficiency of the technology, and periodic dredging is generally necessary.

- **Dune filtration**: During the application of this technique surface water is infiltrated to a shallow depth through adjacent drilled wells (e.g., the Netherlands) of constructed lakes within the coastal dunes. This infiltration method can be used primarily for water purification and for achieving suitable drinking water supply. Belgium's water treatment practice, besides that of the Netherlands, can be considered as best practice.

- **Leaky dams**: typically, low-head dams are built on intermittent - mainly mountainous - streams, which facilitates the infiltration of water into the aquifers while reducing seasonal floods and slowing down the flow rate of the stream.

- **Sand storage dam**: dams are constructed in the bed of intermittent mountain streams and smaller watercourses. The natural accumulation of sediments takes place behind the dam (it can also be done artificially). This allows rainwater retention by avoiding or reducing evaporation. The water stored in the alluvium can be used for the recharge of groundwater but can also be used to improve the supply of drinking or other water utilisation along the river.

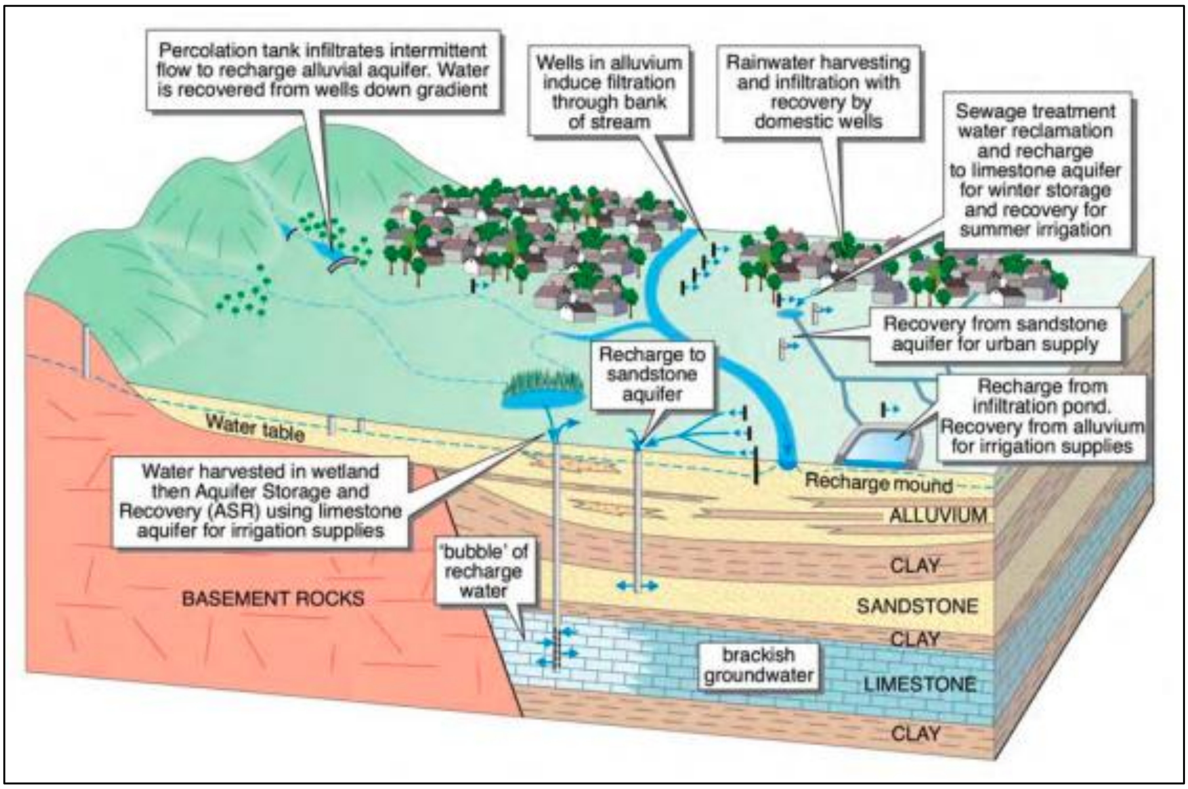

Figure 4: Illustration of chosen MAR technologies as a function of geographical, geological and hydrogeological conditions (Dillon et al., 2009b)

In the DEEPWATER-CE project we assumed that for CE the most promising are the 6 methods for which the toolbox was created (DEEPWATER-CE, 2020a).

3. Regulatory Background of MAR

In order to, enhance the European adaptation of MAR, the applied MAR technologies must not jeopardise the water protection objectives set out in European and national legislation (Mariona et al., 2012). Therefore, it is particularly important to understand the relevant EU legal environment, which also sets out the framework for the applicability of MAR technologies. It should be emphasized that the current EU water directives do not address specifically the design and operation of MAR systems, rather provide a broad framework for adapting MAR technologies. Moreover, in legal terms, for the implementation of the EU directives guidance documents are provided to EU member states (Szabó and Tahy, 2020). Consequently, the development of MAR-related and specific national legislation (e.g., protection of human health, environment protection, water resources, defining thresholds, etc.) should be a national competence.

The EU directives and the examples of regulations developed in some EU member states, provide the foundations of a coordinated European and national legislative environment for the implementation of MAR technologies. The following key issues are well represented in legislation, so far:

- quality of the water used for recharge;
- quality of groundwater;
- utilisation of recovered water (it is necessary to satisfy different end-use requirements); and
- environmental impacts (e.g. protection of groundwater-dependent ecosystems).

This chapter of the handbook provides an overview of EU directives related to the application of MAR technologies and relevant national law from which conclusions and recommendations can be drawn to support the wider utilisation of MAR systems.

3.1. The Water Framework Directive (2000/60/EC)

The EU Water Framework Directive (WFD) defines the objectives to ensure good water quality status for all water bodies (including sea water that is up to one nautical mile from the coast) by 2015 to prevent their further pollution and deterioration for the Member States. The Water Framework Directive applies an integrated and coordinated approach consisting of different steps and proposals, which is an important step towards the flexibility of European water management. In order to coordinate and rationalise national water protection legislation, the WFD has set the following objectives in Article 1:

- preventing further deterioration of aquatic ecosystems and associated aqueous habitats and to protect and improve their condition;
- promoting sustainable water usage through the long-term protection of available water resources;
- increasing protection and improvement of the surface water environment;
- gradually reducing of groundwater pollution, the prevention of further pollution, and
- mitigating of the effects of floods and droughts.

The methodology of the Directive aims to apply a holistic approach in water management considering water, as it flows through watersheds of lakes and rivers, as well as through aquifer to estuaries and finally to the seas and oceans. In this respect, the quality and quantity of surface water and groundwater should be treated in an integrated way (Jakeman et al., 2016). As an important innovation, the WFD requires EU Member States to prepare River Basin Management Plans for the coherent international management of surface and groundwater resources. The EU and its member states have divided their river basins and coastal areas into 110 river basin districts. Forty of the river basin districts are international and transboundary areas, which cover about 60% of the EU. Under the legislation of the WFD, Member States were required to prepare River Basin Management Plans for the ecological protection of the 110 river basin districts, in which consultation with civil society and professional organisations would play an important role. The resulting management plans are valid for six years after their adoption and their revision is required after this period.

The WFD allows Member States to deviate periodically from their water quality improvement objectives under exceptional circumstances (e.g., floods or droughts). At the same time, Member States must take all necessary steps to restore the former state of their surface waters within the shortest possible time frame. The WFD, on the other hand, requires a higher level of protection for waters of protected areas (recreational waters, nutrient-sensitive waters) and for critical aquatic species. An important duty of Member States is the compliance with these requirements during the planning and monitoring.

In addition to ecological aspects, economic aspects are also important elements of the Directive. Article 9 of the WFD requires Member States to take account of the principle of recovery of the costs of water services and ensure the most cost-effective combination of water use and treatment measures. The Directive also contains new provisions to regulate pollution from dangerous substances. These provisions include the development of a combined approach that allows for the application of both environmental quality standards and fixed emission limit values (as set out in the River Basin Management Plans).

In summary, the WFD assesses the ecological and chemical status of surface waters based on the following criteria:

- biological quality (freshwater ecosystem status);
- hydromorphological quality (e.g., riverbank structure, river continuity, or riverbed composition and morphology);
- physicochemical quality (e.g., temperature, oxygen supply, and nutrient conditions); and
- chemical quality, which refers to the environmental quality standards of river basin-specific pollutants (e.g., EU directives for mercury, nitrate, cadmium, hexachlorocyclohexane, and other hazardous substances).

The WFD does not cover specifically the various applications of the MAR, but it phrases several relevant statements and obligations regarding its significance. According to this, the WFD considers artificial recharge of groundwater both as a water management measure and a complementary tool that EU member states can effectively use to improve groundwater status (Murray et al., 2007). Article 11 of the Directive requires the artificial water recharge to be listed by member states in their River Basin Management Plans, as a basic measure. Also, the provisions of control and the prior authorization are requested, as well. As a result, Article 11 of the Directive provides the necessary regulatory controls, which ensure that such practices are carried out carefully and do not jeopardise the achievement of environmental objectives for groundwater resources. The relevant provisions of the WFD are therefore intended to ensure that the necessary controls are carried out to avoid the inappropriate utilisation of the applied MAR technology, thus avoiding the deterioration of groundwater.

The WFD does not set quality limits for groundwater discharges but prescribes that the adaptation of the MAR must not jeopardise the achievement of the objectives set out in the River Basin Management Plans. Accordingly, Member States have a high degree of flexibility in applying the MAR.

3.2. Directive on the protection of groundwater against pollution and deterioration (2006/118/EC)

The purpose of the Groundwater Directive (GWD) is to protect groundwater against pollution and deterioration caused by external influences, in accordance with the criteria set out by the WFD, and to set up the necessary control mechanisms. By its nature, the GWD can be interpreted as a more concrete, operational further development of the WFD. Accordingly:

- the GWD sets concentration limits for nitrates and pesticides; and
- require member states to set thresholds for such as, As, Cd, Pb, Hg, NH_4, Cl, SO_4, PCE, TCE, and specific electrical conductivity.

The justification for groundwater protection demanded by the European Union is vital, given that subsurface water resources provide more than 97% of the world's freshwater reserves (excluding glaciers and ice caps) (Žurman et al., 2019). The remaining 3 percent consists mainly of surface waters (lakes, rivers, wetlands) and soil moisture. It should also be emphasised that until recently, the protection of underground water was primarily limited to the use of water resources as drinking water (approximately 75% of the population of the European Union has a water supply based on underground water resources). Recognising that groundwater is also a crucial resource for industry and agriculture (e.g., irrigation), it became obvious that groundwater reservoirs and aquifers should not be only protected for water resource abilities but their environmental values as well. This is because groundwater reservoirs play a crucial role in maintaining the hydrological cycle and can be considered critical for maintaining the flow between wetlands and rivers and can be used as a buffer during drought seasons. It is known that groundwater resources provide the continuous supply of surface water resources, in many rivers in Europe more than 50 percent of the annual flow, but in drought seasons up to 90 percent, comes from groundwater resources. Therefore, deterioration of groundwater quality may directly affect associated surface waters and terrestrial ecosystems. In addition, the impact of anthropogenic activities may persist for a long time due to groundwater flow and transport processes. This means that pollution from a few decades ago –whether it is originated from agricultural, industrial, or other communal activities – can still threaten groundwater quality today. That is why the protection of groundwater reservoirs is critical in environmental protection.

Upon considering MAR, it is important to note that the Directive lists several exceptions for which it is not technically feasible to eliminate fully the infiltrations of all hazardous components. Especially, for the environmentally insignificant amount of hazardous components, which do not endanger groundwater quality. In such cases, under Article 6 of the Groundwater Directive the application of MAR falls within the scope of those exceptions. However, it is important to emphasise that the managed recharge of water must not jeopardise the quality of groundwater resources to result in a significant deviation from the threshold- and target values outlined in the Directive and specified individually by the Member States, so all reasonable measures must be taken to avoid the infiltration of hazardous substances from entering groundwater. However, the Directive does not set any additional requirements for the application of MAR systems, so the Member States – similarly to the provisions of the WFD – have considerable flexibility in their implementation.

3.3. Urban wastewater treatment Directive (91/271/EEC)

The aim of the EU Urban Waste-Water Treatment Directive (UWTD) is to protect surface water resources from pollution potentially caused by domestic and industrial wastewater or rainwater (collectively municipal wastewater). The UWTD is crucial from the perspective of MAR, as some of its technological forms are specifically designed to facilitate the underground storage of rainwater or treated wastewater. Therefore, the regulations for municipal wastewater treatment also significantly affect the application conditions of MAR.

Consequently, the Directive lays down minimum requirements for the collection, treatment, and discharge quality standards of wastewater and sets schedules for achieving the requirements (e.g., for the treatment of sewage sludge). An important requirement of the UWTD is that all settlements in the European Union with a population more than 2,000 must have a sewage collection (sewerage) system. Municipal wastewater entering these collection systems must be subject to treatment requirements that set ever stricter requirements parallel to the growing size of the municipal agglomeration. According to the provisions, the generated wastewater also needs secondary treatment, which usually includes biological treatment with secondary sedimentation. The installation and technologies required for this task vary depending on the size of the served population. Depending on population size or economic activities tertiary wastewater treatment is needed be applied to avoid water pollution. Areas where tertiary wastewater treatment is required are defined by the EU member states themselves, following the criteria set in the UWTD. Such areas include:

- wetlands exposed to eutrophication (in which case significant reduction of nitrates and / or phosphates is required);
- surface water bodies intended for drinking water abstraction with high nitrate content;
- other water bodies where higher management standards are necessary to meet the requirements of other community directives.

Similarly, the UWTD requires EU member states, in certain cases, to identify less sensitive coastal and estuarine areas where conditions on waste-water treatment can be less stringent. In such areas, the UWTD only requires primary waste-water treatment (a physical and / or chemical process involving the sedimentation of suspended organic matter). However non-endangered areas or settlements under 2,000 inhabitants are obliged to create "adequate" waste-water treatment conditions to ensure the minimum requirements of the Directive, which also means meeting the quality standards for treated wastewater for MAR.

3.4. Directive on the quality of water intended for human consumption (98/83/EC)

The EU Drinking Water Directive (DWD) includes standards regarding the quality of water intended for human consumption. It aims to protect human health from the harmful effects of drinking water pollution by ensuring its healthy and clean state. The DWD can be considered particularly important regarding the application of MAR, because MAR technologies can even be used for storing groundwater that is intended for drinking water use. Therefore, it is important to review the relevant community legislations to facilitate the adaption of MAR.

The DWD extents to these categories:

- every distribution system that provides water for more than 50 people, or supply more than $10m^3$ of drinking water daily, or every supply system with smaller capacity if the water is used as a part of economic activity
- drinking water from bottles or tankers (the Directive does not refer to natural mineral waters certified by national authorities)
- water used in the food and processing industry, except if the competent national authorities can certify that the quality of the used water does not affect the quality of the food prepared.

The main criterion of the DWD is that it defines a total 48 microbiological and chemical indicators at EU level, which must be complied with by all the EU member states. Most of these parameters are based on the World Health Organization (WHO) guidelines for drinking water and the resolutions of the European Commission. So, the application of law by the EU member states also means the adoption of WHO standards, although Member States have the freedom to define stricter limits in national competence. At the same time the EU member states may also grant derogations if the quality of the surface water or the method of water treatment does not mean potential harm for human health, if there is no other rational option in the area to maintain drinking water supply for human consumption.

Other important requirement of the Directive is that EU member states must review the quality of drinking water in every 3 years and report the results to the European Commission. The measurement data provided this way is evaluated by the European Commission in accordance with the DWD and after each reporting period a summary report is prepared summarizing the quality of drinking water and its development at European level.

Regarding the fact that there are still 2 million European citizens still living without adequate drinking water today, the European Parliament and the council of the European Union adopted a new drinking water directive on 16th December 2020 (based on the Righ2Water citizens' initiative) with actualised regulations (updated quality standards), so the legislation came into force in 21st January 2021. Following this the EU member states have two years to apply the provisions of the legislation into their national law. The new directive provides safer access to drinking water for all European citizens than before, parallel to the zero pollution targets announced in the Green Deal, and the aim to guarantee the right to water for all EU citizens.

The provisions of this new DWD oblige the Member States to improve and maintain access to safe drinking water for all citizens, especially for the vulnerable and marginalised social groups. The directive sets further obligations providing citizens with better access to information on water providers, which primarily manifests through the publication of information regarding the water quality and distribution system in their residential areas. As a result, the new DWD directive can improve the trust of the consumers in the drinking water available in their households and the supply system that provide it.

3.5. Directive on the assessment and management of flood risks (2007/60/EC)

Europe was affected by more than 213 severe floods in the past decades, including for instance, the catastrophic summer floods in the summer of 2002 and 2005 along the Danube and the Elbe. These devastating floods reinforced the need for coordinated action at European Union level. In addition to economic and social damage, floods also cause severe environmental damage, such as flooding facilities containing large amounts of toxic chemicals or by the destruction of wetlands. Floods are natural phenomena, but with appropriate preventive measures - such as, adapting MARs for flood protection purposes - we can reduce their likelihood and limit their adverse effects.

Regarding the above, European Union legislation adopted the Floods Directive in November 2007, which aims to prevent and minimise the adverse effects of floods on human health, the environment, cultural heritage, and the economy. To achieve this aim the Floods Directive required the Member States to carry out a preliminary evaluation, by 2011, identifying river basins at risk of flooding and their coastal areas. After that, for such areas, EU member states had to produce flood risk maps by 2013 and flood risk management plans by 2015 focusing on prevention, protection, and preparedness.

Following the legal requirements, the Floods Directive needs to be implemented in line with the Water Framework Directive, notably through the coordination of flood risk management plans and river basin management plans with the involvement of the public and professional organizations. In addition, Member States must harmonise their flood risk management practices for transboundary river basins, including third countries, and in a spirit of solidarity will not take any actions to increase flood risk in neighbouring countries. In addition, Member States should consider the potential long-term risks, including climate change, and the risks associated with sustainable land use in the flood risk management cycle, as detailed in the Floods Directive.

3.6. Relevant national regulatory framework

It is clear from the case-law of the European Union that, in the field of the environment – mainly due to its shared policy competences with the Member States – the Union is pursuing coordination legislation, which aims to harmonise water protection provisions between EU member states, in a way to provide high degree of legislative flexibility for the Member States to meet the specific regulatory needs arising from their specific geographical location. Therefore – next to the main directives of the EU and due to the high degree of legislative flexibility of the Member States – it is worth looking at the practices in the national levels that were the first ones in Europe to initiate more specific regulatory processes for the consistent adaptation of MAR. Regarding all this gained experiences, we can have a more specific regulatory picture, and we can formulate conclusions and proposals for those EU Member States who has limited or no regulations relevant to MAR yet.

3.6.1. The Netherlands

Among the member states of the European Union, we can identify the most comprehensive regulatory environment relevant to MAR in the case of the Netherlands. Thus, the Dutch legislation can be considered a pioneer in implementing EU legislation and promoting managed groundwater recharge through national legislation. In the case of the Netherlands, the following legislation can be considered relevant to MAR:

- **Groundwater Act (1981):** The Act lays down rules for groundwater abstraction and the artificial groundwater recharge. The legislation aims to balance the interests in the development of groundwater resources while stating that the provinces are primarily responsible for groundwater management. Consequently, legal supervision (permitting, rulemaking) falls within the provincial competence in the field of groundwater abstraction and artificial recharge of aquifers. Thus, the provinces can claim fee for groundwater abstraction, as well as for the payment of groundwater treatment examinations, and demand financial compensation for revocation of permissions and for unreported damages. In addition, the law lays down quality requirements for the supply of rainwater to groundwater, compliance with which must be reported to the provinces by the water management authorities on a monthly basis.
- **Soil Protection Act (1987)**: The Act defines groundwater as a liquid component of soil. It aims to prevent soil and groundwater pollution and to set standards for groundwater

treatment. The Soil Protection Act states that the managed recharge of water to the soil must not damage the groundwater reservoirs and sets threshold limits for the concentration of chemical compounds. As a result, the Dutch Soil Protection Act lays down specific groundwater protection requirements for application of the MAR.

- **Environmental Management Act (1993)**: The Environmental Management Act makes no specific reference to the artificial recharge of groundwater reservoirs, that is the use of MAR technologies, but at the same time lays down rules for the protection of groundwater quality. Accordingly – like the Groundwater Act – the legislation obliges provincial authorities to develop and operate provincial legislation and monitoring mechanisms to conduct regular environmental assessments in order to ensure groundwater protection.
- **Water Act (2010):** determines which authorities are responsible for water management and groundwater recharge permits, records, and taxes. The law itself can be considered a national implementation of the Groundwater Directive and the Water Framework Directive adopted by the EU.

3.6.2. Switzerland

In case of Switzerland, due to the high independence of the cantons, the federation can only give coordinated frames for surface and groundwater protection. At the same time, Switzerland is an exemplary European country in terms of its advanced legislation regarding the adaptation of MAR. Based on the current legal environment of confederation, the framework conditions of water treatment are regulated by two legislations. These are the (1) **Federal Act on the Protection of Water (1991)**, and the (2) **Water Protection Ordinance (1998) which is** a supplementary legislation.

Both legislations refer to MAR as a possible technology for 'managed groundwater supply', for which mainly river basin regulations apply. It should be emphasized that any of the legislations mention the regulation of the impact of MAR on water quality. However, the Federal Act on the Protection of Waters explicitly states that the injection of pollutants into the groundwater is prohibited and sets obligations for potential pollutants and limit values of treated wastewater. Similarly, to the Netherlands, each canton has a high degree of autonomy in terms of authorisation and control. Therefore, each canton has significantly different regulations regarding the MAR. The two federal legislations, however, seek to provide a common legislative foundation for the cantons by setting minimum requirements. The following water protection regulations are regarded mandatory at the federal level:

- concentrations of pollutants must not exceed the threshold values suggested by legislations;
- groundwater quality must not jeopardise the surface water during its exploitation;
- the water temperature fluctuations, as the consequence of surface and groundwater flow, must not exceed the 3°C threshold;
- the surface water infiltration must not cause either any unpleasant smell or colour changes, or anoxia or changes in pH values compared to the natural state of the groundwater;
- the infiltration facilities or any other construction activities must not damage the top layers or the hydrodynamics to such an extent as to negatively affect the quality of the water resources.

The Swiss Federal Act on the Protection of Water sets out obligations for the natural or artificial recharge of groundwater resources. For groundwater resources to be considered usable or suitable for drinking water supply, the following criteria have to be fulfilled:

- Damage and pollution of the environment must be prevented in the catchment area, thus also the prevention of pathogenic and bacterial contamination.
- The flow time from the outer boundary of the catchment area to the artificial water supply facilities must not exceed 10 days.
- The management of the cantons must ensure that the groundwater is in good condition. The negative effects of over-exploitation or the depletion of water reserves must be balanced by the reduction in water recovery, the recharge of aquifers, or the safe storage of drinking water.

3.6.3. France

The drinking water supply is highly dependent on the successful application of MAR, in France. The predictable water supply of France is increasingly threatened by climatic conditions that are gradually becoming more hectic. Therefore, the application of the MAR systems and the regulation of their operation is a strategic national interest in France.

The relevant French law deals with water policy at three levels of jurisdiction in accordance with European Union directives: the national level, the levels of river basins and the levels of local water commissions. The regulatory basis of this is laid down in the **French Water Act** (1992), which contains the legal framework for the management of surface water bodies and groundwater.

French water law can be divided into two distinct parts, concerning the adaptation and operation of MAR, which lay down the details of notification and licensing. If the area used by the MAR system is less than 20 hectares, only the notification is required. Accordingly, a licensing procedure is only required for MAR systems with an area of more than 20 hectares. The issuance of the permit (licence) depends on the results of a preliminary environmental assessment which must be in accordance with the mandatory water quality standards.

3.6.4. Germany

The MAR technological implementation is regulated by the **Groundwater Legislation** in Germany. The followings have to be fulfilled in accordance with European Union Groundwater Directive with regard to the utilisation of MAR technology and groundwater protection:

- the groundwater systems have to be revised every 6 years, during which the impact of recharge processes on groundwater need to be assessed according to the standardized system of criteria;
- groundwater systems that fall into the vulnerable category need to be monitored more carefully, moreover the water and land use of the recharge areas also have to be specified.

The legislation defines threshold limits above which authorities need to take actions to maintain the desired surface water and groundwater quality.

The German **Federal Water Act** is the other legislation which is relevant to MAR. Although the adaptation of MAR is not explicitly mentioned in the Federal Water Act and its interpretation is quite broad, the Act indirectly contains two important findings that primarily affect the utilisation of MAR:

- the law states that no official permit or agreement is required for the injection of rainwater into the aquifers.
- legislation also emphasises that groundwater management options must guarantee that the quality of water does not deteriorate during the activities carried out.

In the **German Ordinance on soil protection and contaminated sites** (BBodSchV), it has to be checked if recharging water exceeding certain threshold values. Meaning that recharging water is not allowed to decrease the groundwater quality. Measurements shall be taken in the transition between unsaturated to saturated zone. Hence the accepted value from contaminated sites reaching groundwater is defined by this regulation.

3.6.5. Italy

In Italy the “Decreto Legislativo del 2006, n. 152” is the Italian reference legislation which transposes the European Waters Frame Directive (WFD) into the national legislation (DEEPWATER-CE, 2021). Groundwater controlled recharge on aquifers represents an additional measure to contribute to the achievement of the environmental quality aims of groundwater bodies, in line with the measures aimed at preventing or limiting the inputs of pollutants into the groundwater referred to the article 7 of “Decreto Legislativo 2009, n. 30”.

The groundwater artificial recharge is also controlled by the regulation on Environmental Impact Assessment (Decreto legislativo 152/06 and subsequent amendments) which is also implemented at regional level (Regione del Veneto, Aquor Life project, 2015)). Among other Italian laws, following the above mentioned Dl.vo 152/2006, the “Decreto ministeriale 2 maggio 2016, n. 100 (Ministero dell’Ambiente e della Tutela del Territorio e del Mare, 2016) regulates the "criteria for granting the authorization to recharge or raise the groundwater bodies artificially in order to achieve the quality aims".

4. Technical, environmental, regulatory possibilities and challenges for implementation of MAR

The DEEPWATER-CE report (2020a) developed in the framework of the WPT1 (Development of a transnational knowledge base on the applicability of MAR in CE) work package of the DEEPWATER-CE project provides a detailed description of managed aquifer recharge systems through the presentation of case studies. The experience of existing systems shows that the biggest challenges in their design are the significant differences between the natural characteristics of the involved areas, which are crucial for all aspects of MAR systems.

Even though MAR systems have been successfully used for decades to overcome local water shortages, it is not possible to develop generally applicable technical solutions due to the variability of hydro(geo)logical settings, rechargeable water quantity, quality and availability, topographic and land use conditions, utilisation of the recharged water and the system operation. The implementation of managed aquifer recharge therefore requires different solutions from site to site. Sometimes, a combination of several techniques is required to be used to achieve the desired goal within the same area.

As a result, the biggest challenge to the feasibility of MAR systems is that the design of the system must be preceded by a detailed examination of the area involved. Planning can only be started, and suitable technological solutions can only be chosen after the interpretation of the detailed studyof the selected site. These also help to outline the cost of the investment, the operating conditions, and the expected revenue generation of the installed facilities.

The DEEPWATER-CE project aims to reduce the predicted negative effects of the climate change by examining the MAR techniques in CE countries. To achieve this, the possibilities of the underground injection of irregular and large amounts of precipitation is investigated as well as its retention and storage. Excess water stored in this way can be exploited during increasingly frequent and prolonged periods of water scarcity to supply various uses, such as, drinking water, irrigation, industrial water supply, etc. (e. g. Ebeling et al. (2019) use the term “water banking”). The use of excess water from heavy rainfall to recharge water sources creates more difficult planning and implementation conditions in many aspects which are further detailed below.

4.1. Technical challenges

4.1.1. Recharge methods

There are two main groups of MAR systems based on the applied technology (IGRAC, 2007). One group uses the method of natural infiltration and direct injection, whereas the other one involves the capture, storage, and managed infiltration of excess water.

Bank filtration method is an infiltration method according to the IGRAC classification and it is not defined as MAR technology in some publications. Other studies (De Filippis et al., 2017) however, identify this as a filtration process that facilitates the improvement of water quality and consider it as the third group of MAR technologies. The method is suitable for the natural treatment of potentially contaminated surface waters, by which it can be used to recharge aquifers with good quality water or to improve the condition of deteriorating, poor quality surface water bodies.

Six MAR technologies have been selected during the DEEPWATER-CE project that are suitable for the recharge of aquifers. These are the followings:

- ditches
- infiltration pond
- induced river and lake bank filtration
- aquifer storage and recovery
- underground dam
- recharge dam

4.1.2. The process of designing MAR systems

The following questions should be asked prior to the implementation of a MAR System (Dillon et al. 2009b):

- Is there a need to extract and use additional water in the area?
- Is there a suitable source of water used for the recharge?
- Is there a suitable aquifer in which water can be stored and from which it can be extracted?
- Is there a suitable area for the facilities?
- Is there suitable knowledge for the implementation and sustainable operation?

This set of criteria does not yet consider the climatic effects of global warming nor their expected further intensification in the future. The installation a MAR system is no longer determined by whether there is a need to increase water production in an area. It has become more important to consider whether future climatic changes which will limit the water production are expected in the area. The primary goal is therefore the sustainable supply of water demand and MAR system can help us shift the water balance (which is impacted by climate change) to our benefit.

The protection of the aquifers used for drinking water supply, therefore of high importance, because some aquifers may reach a critical, poor condition before the forecasted climate change occurs. It is therefore advisable to apply the MAR approach for water bodies in poor or deteriorating conditions even if no increase in consumption is expected in the near future.

MAR technology shall involve additional water sources therefore, has low impact on other utilizations. MAR can also play an important role in balancing such disproportions. Sustainability of drinking water supply is of course a priority for such systems, but MAR has importance in irrigation water supplying too.

It is recommended to implement a MAR system – without claiming completeness and exclusivity – according to the sections and work phases outlined below. The list below seeks to cover all possible activities related to MAR schemes based on the available literature, but of course it cannot be comprehensive and mandatory.

A. Preparation, assessment
    1. determination of the purpose and necessity of the implementation of MAR;
    2. a detailed assessment of the condition of the aquifer and water body involved in managed aquifer recharge; assessment of the effects of previous remedial measures;
    3. assessing the availability of water resources suitable/available for recharge;
    4. examination of the conditions ensuring implementation, operation, and efficiency.
B. Pre-feasibility state
    1. selection of MAR systems that can be implemented based on the identified conditions and features, risk analysis of the potential systems, reasoning in favour of the chosen system; local regulation must be considered;
    2. elaboration of proposals for measurements, exploration, studies, pilot site inspections necessary for the implementation of the chosen system;
    3. elaboration of a preliminary environmental impact assessment;
    4. elaboration of a pre-feasibility plan.
C. Preliminary/theoretical licensing
D. Conducting the authorised examinations
    1. measurements, explorations and if necessary, setting up a test operation/experimental system, long-term test operation on a pilot-scale system.
E. Evaluation of test operation and results
    1. data analysis, determination of the details of the suitable system.
F. Elaboration of the feasibility plan
    1. Risk analysis and elaboration of the feasibility of a suitable system chosen based on the conducted examinations, measurements, and the results of the test operation.
G. Implementation and construction plan
    1. designing the managed aquifer recharge facilities;
    2. designing the water supply facilities;
    3. designing the system responsible for the quantitative and qualitative monitoring of the entire recharge process;
    4. designing the operation of MAR;
    5. elaboration of a detailed environmental impact assessment.
H. License of implementation
    1. licensing and design documentation;
    2. licensing procedure.
I. Implementation of the system

Based on the experience of existing facilities, 1–2 years test run is necessary to assess efficiency and identify possible failures after the implementation. After that, the documentation required for the license to operate can be prepared followed by the actual operation of the system.

Based on the experience of actively operating MAR systems, the implementation of the final system is facilitated and optimised by the installation and at least 1–2 years test run operation of a small size pilot facility during the first stage of the implementation process (points D and E) that is characterised by the same operating principles as the actual system. From a construction, financial and licensing point of view, it is also favourable to build the actual MAR facility by the expansion and development of the experimental site.

The preparation and assessment phases are crucial for the implementation of sustainably operated water supply systems. A significant part of the parameters, processes, and conditions important for feasibility are examined during these phases. A detailed description of this is included in the document prepared in the framework of the Work Package 3 of the DEEPWATER-CE project (DEEPWATER-CE, 2020c).

In the following sections, the details of the preparation and assessment phases are presented, which are important for the implementation and feasibility.

4.1.3. Site selection

MAR system can be an efficient tool of water management in water-scarce areas to ensure water supply for its various consumptions. The DEEPWATER-CE project would like to promote the application of MAR systems to capture and store surplus water for later use. The potential locations of the installation and the need for the facilities can be determined based on the condition of the surface water bodies and groundwater bodies of a given area, region, country. The artificial recharge of water bodies in good or excellent condition that are able to meet the increased water demands of future climate conditions is not recommended because as the intervention may result in unexpected negative effects in the groundwater system, which may even lead to the degradation of the aquifer. MAR facilities therefore should be considered for installation primarily in the case of water bodies that are already in a poor quantity status or that are expected to deteriorate due to the increasing consumptions and the effects of climate change.

The River Basin Management Plans, which are revised every five years, play a key role in the selection of MAR sites. One of their tasks is to regularly revise and, if necessary, modify the quantitative and qualitative conditions of water bodies. River Basin Management Planning in the EU provides a common set of criteria for revising the quantitative and qualitative conditions, thus decisions with similar reliability can be made regardless of the countries. The identification of water bodies with a poor status or deteriorating tendency is possible by using these Plans, which can be targeted by the MAR approach.

Sorting based on the quantitative and qualitative conditions defined in the River Basin Management Plans should be followed by more detailed, targeted studies. During these it is necessary to identify the factors which are responsible for the poor quantitative and qualitative conditions of the aquifer. If the overabstraction, which exceeds the natural water recharge, is the cause then water production licenses, their observance, water management, illegal water exploitation must be revised additional to the implementation of managed aquifer recharge.

An important step in the preparation of a MAR facility is the most accurate assessment of the water recharge conditions of the given water body/water bodies at the local level. The River Basin Management Plans do not specify the hydrogeological features of the water bodies and the sources, pathways, velocity, etc. of the recharge. Clarification of these is essential, as is assessing the extent to which the expected climate change and the associated socio-economic factors will affect this natural supply. In case of unfavourable prospects, it is justified to plan artificial supply. The importance of the assessment of the hydrogeological conditions is supported by the document "Transnational Decision Support Toolbox for Designating Potential MAR Locations in Central Europe" prepared in the framework of the WP2 work package of the DEEPWATER-CE project (DEEPWATER-CE, 2020c).

4.1.4. Study of the Potential Aquifer

The efficiency and operability of a MAR system can be determined based on geological and hydrogeological investigations, hydraulic measurements and aquifer characterization. The aim of these measurements is to answer two questions:

- is the storage capacity and hydraulic conductivity of the aquifer suitable to accommodate the projected recharge of water?
- Is the aquifer suitable to yield the expected amount of water?

As the goal is to recharge water bodies (without deteriorating their quality) that are affected by water production and are in poor quantitative condition due to overproduction, in theory a positive answer to both questions is expected. However, it should be noted that due to the characteristics of the aquifers, negative changes in the hydraulic properties of the layer(s) may occur during the recharge, therefore their specific examination is necessary. For example, there might be problems recovering the water from aquifers having high hydraulic conductivity and storage capacity. In the case of ASR, especially if the aquifer is fractured, rapid leakage of the recharged water may occur. These leaking waters can be extracted by wells installed parallel to in their flow direction, or by using ASTR technology, but these also require a detailed hydrologic-hydraulic examination. The water level of large and porous aquifers with very good hydraulic properties can be increased significantly during long-term and in response to a large amount of recharge, which would improve production parameters (Murray et al., 2007). Consequently, in the case of limited water recharge, the artificial replenishment of these aquifers is not expected to be effective.

In addition to the detailed field measurements of aquifers/water bodies of poor status or at risk, geological and hydrogeological conceptual models have to be developed to identify the flowpaths and model to the expected effects of the proposed MAR facility.

4.1.5. Water demand and supply

The third important part of the assessment is the availability, and quality evaluation of the water used for recharge. In the case of facilities that operate based on the use of excess precipitation, the annual amount and distribution of precipitation makes the availability of usable water resources uncertain and variable. The latter can be refined by meteorological studies, statistical evaluation of meteorological and hydrological data sets, and climate modelling. The D.T2.4.3 report of the WP2 work package presents the exposure of the areas of interest to climate change in the period up to 2100, based on which the areas requiring managed recharge can be identified (DEEPWATER-CE, 2020c). The results of the Manual provide a basis for forecasting changes in annual or seasonal precipitation surplus, temperature, and evapotranspiration, which determine how the excess water is captured, the extent of the reservoir and the potential recharge systems. The extent of the water surfaces (in case of temporary storage) providing the minimum loss of water become important based on the temperature time series, the expected maximum temperatures, and the associated evaporation-evaporation values.

Even though we have long term climate models, the expected annual precipitation changes and the extreme meteorological scenarios and their unpredictability require the development of storage solutions that can capture excess water in larger areas. The watercourses with a larger catchment area will therefore be suitable for the construction of MAR facilities. Examination and sorting these watercourses should precede the planning phase. During this, the opportunities offered by floods on large rivers should also be considered, as their excess water can be retained. This is also important from a flood protection point of view and has already been implemented in many places.

Another major challenge is to identify sites suitable for catching excess precipitation, as surface waters carrying the excess precipitation can be at a considerable distance from the aquifer considered suitable for the MAR system.

4.1.6. Water quality and human health risks

The quality of the recharging and stored waters is of particular importance during the hydrogeological examination of the managed aquifer recharge. In addition to improving the quantitative conditions, managed recharge techniques also facilitate the protection or improvement of water quality and in accordance with the water protection directives those must not cause deterioration or significant change in natural water quality

The hydrochemical interactions between the artificially recharged source water and the groundwater should be investigated to avoid negative changes and, to identify the required water treatment methodology if necessary.

If the composition of precipitation collected from a large area shows great variability, it can cause difficulties. Pollutant and their concentrations can change frequently and significantly due to activities in the involved catchment area, and the “first flush” of urban runoff can contain large concentrations of hydrocarbons, chlorinated solvets and heavy metals. This requires the adequate buffering capacity of water retention system. A good example of this is the variety of chemicals used in agriculture and their seasonal application. Appropriate water quality monitoring is of high importance in this regard. During the assessment, the need to use procedures to optimise the quality of the rechargeable water (water treatment, water purification, etc.) should also be examined. To avoid energy- and cost-intensive cleaning technologies, the range of procedures known as the SAT (Soil and Aquifer Treatment) has gradually developed. A detailed review of its literature and results is presented in the document “Guideline for Water Quality Requirements at MAR sites” published in 2015 within the framework of the EU project “MARSOL - Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought” (MARSOL, 2015). Most of these systems benefit from the purification and filtration processes during the infiltration through the soil and into the aquifer

It should be noted that although water natural purification processes generally take place during infiltration (for example, this is one of the advantages of the bank filtration technique), application of some water treatment technologies can be required. Preliminary and detailed examination of this is necessary during the assessment. The need and method of the recharging water treatment is determined by the properties of the involved aquifer: mineralogical composition, particle size, hydraulic conductivity, porosity, and quality of stored water (Dillon et al., 2008). In addition, the water protection directives and their recommended concentration values have to be considered.

The importance of the chemical reactions between the recharged water and the aquifer materials cannot be neglected. The chemistry of the porous or fractured aquifer also undergoes changes similarly to the stored groundwater mainly due to the differences in redox potential. As neither the chemical characteristics of groundwater nor aquifer can be changed, the only option is to change the composition of the recharging water in a way that does not cause negative changes in the composition of either the extracted water or the aquifer. Hydrochemical studies for this are a major challenge of the designing phase and require reaction modelling by using hydrochemical data.

4.1.7. Infiltration

A fundamental challenge and a significant risk to the operation of managed supply systems is the existence of appropriate infiltration and its long-term availability. Therefore, it is important to examine the initial, natural infiltration properties of the involved areas, which is recommended to be done with specific field measurements. The so-called infiltrometer measurements are recommended to be done for the entire area, together with infiltration tests conducted on smaller parcels. Both vertical and lateral hydraulic conductivity must be considered (Bouwer, 2002). In case of well recharge - if there are not enough former wells in the area, the results of which are suitable for determining the parameters - it is necessary to build and test a well network to determine the expected extent of infiltration.

The values obtained during the determination of the infiltration make it possible to predict any blockage that may occur during the operation of the system, which is primarily indicated by a decrease in the infiltration values or an increase of pressure during the recharge.

The decrease of the hydraulic conductivity value due to changes in the physical properties of the water cannot be ignored in the designing process of the systems. Changes in the viscosity of the recharging water because of the temperature conditions play an important role in this. As a result, infiltration during winter can be as much as half of summer values. However, summer infiltration may be reduced by clogging due to increased biological activity. As it is difficult to predict these conditions, the long-term test operation of mostly small systems and pilot plants can provide answers to these challenges. The experience and results of the test operation contribute to the optimisation of the system operation plan.

4.1.8. Clogging

In the case of a MAR system based on either infiltration or direct injection, the most significant challenge and risk factor during the operation is clogging (DEEPWATER-CE, 2020b; Jeong et al., 2018). The phenomena can be caused by physical, chemical and biological processes, gas production and soil compaction. Some types can be reversible, but others are not. For example, if the clogging is caused by the mud layering in the bottom of the infiltration pond, colmatation can be effectively removed and prevented by regular bed dredging. In more severe cases, however, the pores and cracks of the aquifers are gradually clogged due to unfavourable composition of the recharging water, its suspended solids content, or the reactions with the host rock. In the case of direct recharge through wells, in addition to the clogging of pores and fractures of the aquifer, clogging due to the deposition of various precipitates on the well structure and perforations can also cause difficulties. Non-repairable blockages make the entire system dysfunctional, so careful operation and continuous monitoring and maintenance of critical parameters is necessary.

Clogging can be prevented primarily by the continuous examination of the recharged water and by appropriate filtration, purification, and treatment. In the case of the capture of large amounts of precipitation, a significant challenge is the efficient filtration that can be applied during the retention of rapid and large-scale excess precipitation (floods). The coarser fractions of these recharging water can be filtered, but the removal of suspensions and suspended solids, which play a significant role in clogging, is a serious challenge.

4.1.9. Major challenges in the application of MAR technologies

The above-listed investigation methods provide a basis for the design of all six MAR technologies selected in the project. Before designing the two methods using managed surface infiltration (infiltration trenches and ditches; infiltration ponds and lakes), it is important to examine in detail the infiltration properties of the involved area. Areas with low or uneven infiltration are not suitable for this type of managed water supply. Geological setting also requires detailed exploration (by geophysical measurements, shallow boreholes, etc.) to avoid impervious layers. It is also important to accurately determine the pressure conditions of the shallow, rechargeable aquifer and the available pore volume for recharge.

The biggest challenge of bank filtration is to determine the quality and dynamics of surface water. A series of injecting wells to be built along larger watercourses are subject to frequently changing water level fluctuations. Furthermore, larger watercourses may contain large amounts of pollutants that science has only recently begun to investigate for adverse health effects (MARSOL, 2015).

Among the methods of excess water catchment, the potential application of the underground dam has been included among the objectives of the project. This technology can be effective in increasing the buffer capacity of available water resources by storing the excess water underground hence avoiding evaporation losses. The possibility of lateral leakage of infiltrated excess water is a challenge for the application of underground dams if the dam was constructed without considering the flowing conditions.

4.2. Environmental challenges

Water extraction and recharge processes have an impact on the environment during the application of MAR systems. Their identification, clarification and detailed exploration have to be done during the impact assessment phase prior to the installation. These should include an assessment of the current condition of the ecosystems concerned to identify potential risks to wildlife.

The environmental risks of the implementation are related to all elements of the potential recharge system. Facilities for the retention and storage of excess water from surface runoff can change the environment depending on their size and the amount of stored water. The water level fluctuations of the surface reservoirs during water extraction and injection affects the surrounding ecosystems. During the application of methods using direct natural infiltration, fluctuations in groundwater levels of shallow aquifers and their surroundings can have a negative impact on the environment, especially on the flora. Special attention should be paid to monitoring water level and water quality during the recharge of shallow aquifers and to providing sufficient water to meet the water needs of the vegetation. Groundwater levels that are too close to the surface can have a detrimental effect on vegetation, infrastructures (e.g., roads), and can be even caused by excess inland wate during wet, rainy periods.

One of the important environmental risks of the recharge through wells is the quality of the recharged water. Special attention needs to be taken to recharge into aquifers that are already in poor condition and used for drinking water supply. This can be done through water treatment, preliminary investigation of water-rock interactions, and the development of prevention methods. Recharge through wells also affects the local lithology. High pressure of confined water can induce fractures in the impervious rocks around the aquifer and cause leakage of the recharge water. This has a potential to cause undesirable mixing and chemical reactions in adjacent aquifers. In addition, changes in hydraulic potentials can modify groundwater flow paths, which can lead to the desiccation of wet habitats and springs and water eruption may occur in places where this was not previously the case.

The establishment and operation of an adequately designed monitoring networks and pilot plant impact assessments have a key role in preventing the above-described processes.

4.2.1. Environmental Impact assessments

Environmental impact assessment is an important tool to explore environmental impacts, and to avoid environmental protection challenges and risks. Based on the experience of the currently operating systems, it is recommended to carry out impact assessments in two stages during the implementation phase. In the framework of a preliminary environmental impact assessment and impact study, the examination of the baseline condition is the most important aspect. Besides this, the environmental impacts of the different recharging methods must be comprehensively examined for each potentially involved area. Based on this, the different recharging methods can be ranked and the most appropriate one can be selected for the implementation.

An environmental impact assessment for the implementation of the final system in the framework of the Feasibility Study would examine the potential environmental risks of the construction and operation phase, thus it also would determine the impact area of the MAR system.

During the identification of environmental impacts, the extent of the direct and indirect impacts, probability of their occurrence, and their treatment and reversibility must be examined. These also include the definition of the limit values that should be followed during the operation (e.g., in the case of shallow aquifers definition of the minimum acceptable water level measured from the surface, in the case of closed aquifers definition of the recharge pressure, etc.).

4.2.2. Monitoring of the environmental impacts

Monitoring of the environmental impacts is required through the development and operation of a carefully designed monitoring network. Depending on the type of the potential system, there may be significant differences in the monitoring systems, but irrespective of this, both the surface water and groundwater have to be monitored. If the quantity and quality of the rechargeable aquifer has been monitored for a longer period, it represents well the condition before the implementation of the MAR and provides an opportunity to follow up subsequent changes.

Quantitative monitoring can be achieved primarily by measuring water levels frequently, which is recommended to be done with automatic level loggers. Regardless to the recharging technique, observation wells (piezometers) must be set up at adequate depth, both in the storage facility and in its immediate and remote surroundings. The quantitative efficiency of the recharge can be monitored by recording the water level of the involved aquifer. Similarly, to surface infrastructures, the water level beneath the infiltration area, as well as on areas further away have to be monitored in order to determine the extent of the environmental impacts. The continuous evaluation and interpretation of the monitoring network data provides opportunity for the gradual optimisation of the monitoring system and mitigation of unfavourable processes.

In addition to the registration groundwater levels, quality monitoring should also include both the original and post-treatment quality of the rechargeable water and the quality of the water extracted from the aquifer. These studies can confirm the adequacy of the water treatment that was done before the recharge as well as the consistency or improvement of groundwater quality (Murray et al., 2007). Based on the continuous analysis of the data sets, the optimal sampling can be determined and, if necessary, the water quality monitoring system can be modified.

4.3. Regulatory and legal issues

Although all the national regulations of the CE countries are based on the basic European Directives there are some differences in the national adaptions. All these issues are summarized in DEEPWATER-CE DT4.1.2 report (DEEPWATER-CE 2021).

From a technical point of view, the implementation of the MAR system fits into the process and procedure of the traditional water management, which has a developed regulatory framework. Although there are no specific regulations in EU countries for the implementation and operation of an artificial recharge systems, MAR facilities can and should be implemented within the general legal and regulatory framework prescribed by the water management and environmental protection laws and their implementing regulations (EU CIRCAB, 2021). If the legislation does not provide a MAR-specific framework, the above regulations and directives should be applied, and any new regulations should be adapted to them. All the issues in the management of EU waters are regulated by the Water Framework Directive, which mentions only one point about the artificial recharge of water sources as a tool of water quality improvement techniques.

As explained above, the designing process is preceded by extensive research activities during the preparation-assessment phase. A description of the results of these and further studies confirming the possibility of feasibility are included in the Preliminary Feasibility Study, together with the Preliminary Environmental Impact Assessment. Official authorisation of this will allow the process to be continued, and to carry out the proposed further investigations. Due to the differences in water and environmental regulations from country to country, there may be different forms of this authorisation processes.

After the implementation of the planned and approved complex study-research plan – that aims to specify the conditions and details of the feasibility, based on the evaluation of the data and results – the detailed and final planning of the implementation begins. During this, a feasibility plan, a detailed environmental impact assessment, a licencing plan and an implementation plan will be prepared, which together form the documentation required for the granting of the construction licence.

Construction can begin with a licence issued based on approved documentation. Considering the experiences of the already operating systems, a test period of 1 to 2 years after the installation is recommended, which must be included in the licence. The operating licence can only be applied for if the test operation shows favourable results, or the necessary modifications have been made.

There are no special legal risks or challenges in the implementation of the MAR systems, which is due to the lack of the specific regulatory environment for the procedure. This deficiency requires that the activities covered by the licence have to be identified during the pre-implementation stage. There may be unforeseen legal expectations, regulations, and obligations (primarily in connection with the ownership and the use of the concerned real estate) that may be difficult to resolve. Issues to be considered should be for example water rights, effects on groundwater flow direction or hydraulic gradient to the point that some downstream users lose access to water, beneficial use, recharged water migrating off site and to another property owner, or the ownership of the water before recharge and who owns it after.

5. Proposals for MAR adoption in Central Europe

In the European Union, the Water Framework Directive and the implementing River Basin Management Plans consider MAR schemes, as suitable tools for achieving and maintaining good status of surface water and groundwater bodies (Alcade-Sanz and Gawlik, 2017). Based on the findings of this guidance document, the following objectives and regulatory proposals are suggested in order to achieve wider application of MAR:

1. Integrate objectives and measures for the use of MAR systems into each country's strategic planning documents, in particular the documents of water management and climate adaptation.

2. Managed aquifer recharge plays key role in the freshwater management, in the sustainability of water production and in the multi-purpose use of water (drinking water, industrial water, agricultural use, ecosystem services, etc.). It is therefore necessary to include the review of

the applicability of MAR methods in River Basin Management Plan revisions, especially in regions exposed to the effects of climate change and in water bodies with poor conditions or at risk, as an important tool for integrated water resources management.

3. Development of a National Strategic Plan for the application of MAR systems, which covers the entire life cycle of managed water supply activities, sustainability, and risk assessment.

4. The Strategic Plan and the benefits of underground water supply systems must be disseminated in the society, the education, the decision-making organisations, and relevant authorities. Suitable tools for this are the leaflets, educational films, presentations, public, school and university handouts, trainings, and the media. The development of a pilot project for educational and demonstration purposes can play a major role during the promotion.

5. A detailed system of regulation and licencing of MAR methods must be established.

6. Potential areas for the implementation of MAR systems can and should be determined based on the environmental assessments of the River Basin Management Plans.

7. MAR systems can be installed based on extensive, detailed examination and experimental testing of the local conditions.

8. The regulatory and licensing environment and licensing specifications for the implementation of MAR systems differ from country to country, which must be considered during this process.

9. MAR systems can be operated only in parallel with the operation of a monitoring system, which covers all the aspects, including the viability and life cycle of a MAR system. For this, the careful design and operation of the monitoring system is necessary as well as the regular evaluation of the data provided by this system. The artificial recharge of the groundwater should be conducted along with the constant monitoring of the physical and chemical conditions of the rechargeable water and the stored water in the aquifer. If necessary, water treatment technology can be modified during the operation.

10. During the construction of dams and reservoirs for any purpose, the possibility of groundwater recharge in the vicinity of these facilities should be evaluated to minimise evaporation and leakage.

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