Interreg
CENTRAL EUROPE
European Union
European Regional Development Fund
DEEPWATER-CE

DEEPWATER-CE
WORKPACKAGE T1, ACTIVITY T1.1

D.T1.2.1 COLLECTION OF GOOD PRACTICES AND BENCHMARK ANALYSIS ON MAR SOLUTIONS IN THE EU

TRANSNATIONAL REPORT

February 2020

Lead Institution	PP8, Croatian Geological Survey
Lead Author/s	Matko Patekar, Marina Filipović
Date last release	

Contributors, name and surname	Institution
Arnaud Sterckx	IGRAC
Staša Borović	Croatian Geological Survey, Department of Hydrogeology and Engineering Geology
Josip Terzić	Croatian Geological Survey, Department of Hydrogeology and Engineering Geology
Boris Bulović	ViK Split
Božidar Čapalija	ViK Split
Vedran Spain	ViK Split
Arno Rein	Technical University Munich, Chair of Hydrogeology
Anne Imig	Technical University Munich, Chair of Hydrogeology
Teodóra Szőcs	MBFSZ
Ágnes Rotárné Szalkai	MBFSZ
Péter Nagy	MBFSZ
Nóra Gál	MBFSZ
Elisabeth Magyar	MBFSZ
Anikó Horváth	MBFSZ
Ferenc Skobrák	MBFSZ
Pál Selmeczi	MBFSZ
Tamás Czira	MBFSZ
Lilian Fejes	MBFSZ
Magdolna Ambrus	Geogold Kárpátia Ltd.
István Striczki	Geogold Kárpátia Ltd.
Antal Serfőző	Geogold Kárpátia Ltd.
Tibor Mátrahalmi	Geogold Kárpátia Ltd.
Sławomir Sitek	University of Silesia in Katowice
Hanna Rubin	University of Silesia in Katowice
Sabina Jakóbczyk-Karpierz	University of Silesia in Katowice
Ewa Łupikasza	University of Silesia in Katowice
Jacek Różkowski	University of Silesia in Katowice
Marek Sołtysiak	University of Silesia in Katowice
Norbert Jaźwiński	State Water Holding “Polish Waters”
Joanna Troińska	State Water Holding “Polish Waters”
Piotr Zimmermann	State Water Holding “Polish Waters”
Roksana Kruć	CSSG, Adam Mickiewicz University in Poznań
Krzysztof Dragon	CSSG, Adam Mickiewicz University in Poznań

Józef Górski	CSSG, Adam Mickiewicz University in Poznań
Štefan Rehák	Water Research Institute, Department of of Water Management Concepts, Programmes and Planning
Dana Vrabliková	Water Research Institute, Department of of Water Management Concepts, Programmes and Planning
Andrea Vranovská	Water Research Institute, Department of of Water Management Concepts, Programmes and Planning
Alena Kurecová	Water Research Institute, Department of of Water Management Concepts, Programmes and Planning
Viliam Novák	Water Research Institute, Department of of Water Management Concepts, Programmes and Planning - external

Table of content

1. INTRODUCTION

D.T.1.2.1 “Collection of good practices and benchmark analysis on MAR solutions in the EU” is a thematic report within DEEPWATER-CE WP T1 – Development of transnational knowledge base on the applicability of managed aquifer recharge (MAR) in CE. The report is based on existing research papers from the domain of MAR. Furthermore, this report contains national inputs from five DEEPWATER-CE participating countries – Croatia, Germany, Hungary, Poland and Slovakia regarding water management, priority issues and experiences in managed aquifer recharge. It aims to provide a knowledge base for practical and theoretical aspects of MAR operation. However, to cover all existing MAR types, technologies, applied areas and other particularities would be practically impossible and therefore, this report will focus on the most important topics in order to provide a broader understanding of the MAR concept.

The first part of this report presents a compilation of existing knowledge regarding the concept of MAR. While compiling this chapter, essential literature sources used were:

- Dillon (2005): Future management of aquifer recharge
- Casanova et al. (2016): Managed Aquifer Recharge: An Overview of Issues and Options
- Sprenger et al. (2017): Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives
- Dillon et al. (2019): Sixty years of global progress in managed aquifer recharge

Second part of this report focuses on experiences from existing or ongoing MAR projects from DEEPWATER-CE participating countries. A questionnaire was designed and sent to the participating project partners to provide an overview of national water management and differences between the particular EU countries. The purpose was to pinpoint underlying issues which require a MAR operation as a solution. In order to add value to the knowledge base, national case studies are presented within this report.

This report will also provide a basis for activity A.T1.3 "Capacity building to stakeholders in order to ensure integrated environmental approach on MAR", in particular D.T1.3.2 "National training sessions on MAR topics and collection of good practices and benchmark analysis".

2. MANAGED AQUIFER RECHARGE

2.1. DEFINITION

Managed aquifer recharge (MAR), is a term conceived by the British hydrogeologist Ian Gale, who was the founding co-chair of the International Association of Hydrogeologists (IAH) Commission on Managing Aquifer Recharge from 2002 to 2011 (IAH-MAR 2018a). Managed aquifer recharge refers to a suite of methods which are increasingly used to maintain, enhance and secure groundwater systems under stress. Simplified, MAR is an intentional process by which excess surface water is directed into the ground — either by spreading on the surface, by using recharge wells, or by altering natural conditions to increase infiltration in order to replenish an aquifer. Whereas formerly, the term “artificial recharge”, has been used when focussing on augmenting the quantity of recharge, but with much less attention given to managing water quality. The MAR term nowadays describes that both quantity and quality are managed effectively. In spite of a sound knowledge base, implementation of MAR schemes has tended to be localised and geographic expansion has been limited by lack of understanding of hydrogeology and knowledge of MAR.

2.2. BRIEF HISTORY

The modern history of methods covered by the term MAR begins with two techniques which are prominently represented up to present day: induced bank filtration and surface-spreading methods. The first reported MAR site in Europe was in Glasgow (UK). In the Glasgow Waterworks Company constructed a perforated collector pipe parallel to the Clyde River (Ray et al., 2003) and abstracted bank filtrated water in the year 1810. The idea of naturally filtered groundwater was born and spread to continental Europe. This method was successful at the beginning and many other cities in the UK (e.g., Nottingham, Perth, Derby, Newark; Ray et al., 2002) adopted the idea; thus, the 1860s became the first heyday of naturally filtered water in the UK (BMI 1985). However, many of these early sites experienced problems with decreasing well performance and had to be abandoned in later years (BMI 1985); nevertheless, the idea of naturally filtered underground water^ was born and spread to continental Europe, and it was soon adopted by cities in the Netherlands, Belgium, Sweden, France, Austria and Germany. The historical development of MAR in Europe is shown in Fig. 1. Maintenance strategies and clogging aspects are known to be important to consider for MAR practices, but were only rarely reported in the available literature for the European historical sites. Presumably, main issues included turbidity, costly pre-treatments, lack of end use water monitoring and uncertainty in aquifer hydraulics. The progressing industrialization in the 19th century and growing population in European cities presented the water suppliers with new challenges. The traditional water supply based on surface water was impaired by increasing contamination from the new industries and improper sanitation. At that time, based on the experiences in the UK, Adolph Thiem proposed the application of riverbank filtration to cope with degrading hygienic surface-water quality and increasing water demand (Sprenger et al., 2017). Research and development of well injection methods began in the 1960s.

The last 60 years has seen unprecedented groundwater extraction, and overexploitation as well as development of new technologies for water treatment that together drive the advance in MAR (Dillon et al., 2019). The combined availability of deep wells, electric power and electric submersible pumps radically escalated water withdrawal from aquifers and quickly reduced groundwater in storage. Between 1900 and 2008, 4.500 km^3 of depletion had occurred globally. Alarmingly, the depletion rate is still accelerating, reaching 145 km^3/y between 2001 and 2008 (Konikow, 2011). Although there is considerable uncertainty in estimates of annual groundwater exploitation and recharge, Margat and van der Gun (2013) report annual exploitation of groundwater of ~980 km^3/y in 2010, which is less than 8% of estimated global mean natural recharge (which exceeds 12,000 km^3/y; Margat 2008), but nonetheless causes substantial depletion in some areas. It is clear that for sustainable-water-resource utilization, stabilization of storage decline is important and there are only two means of accomplishing this for groundwater: reducing demand (through increased water use efficiency or conjunctive use with other water sources) or increasing replenishment (Dillon et al. 2012).

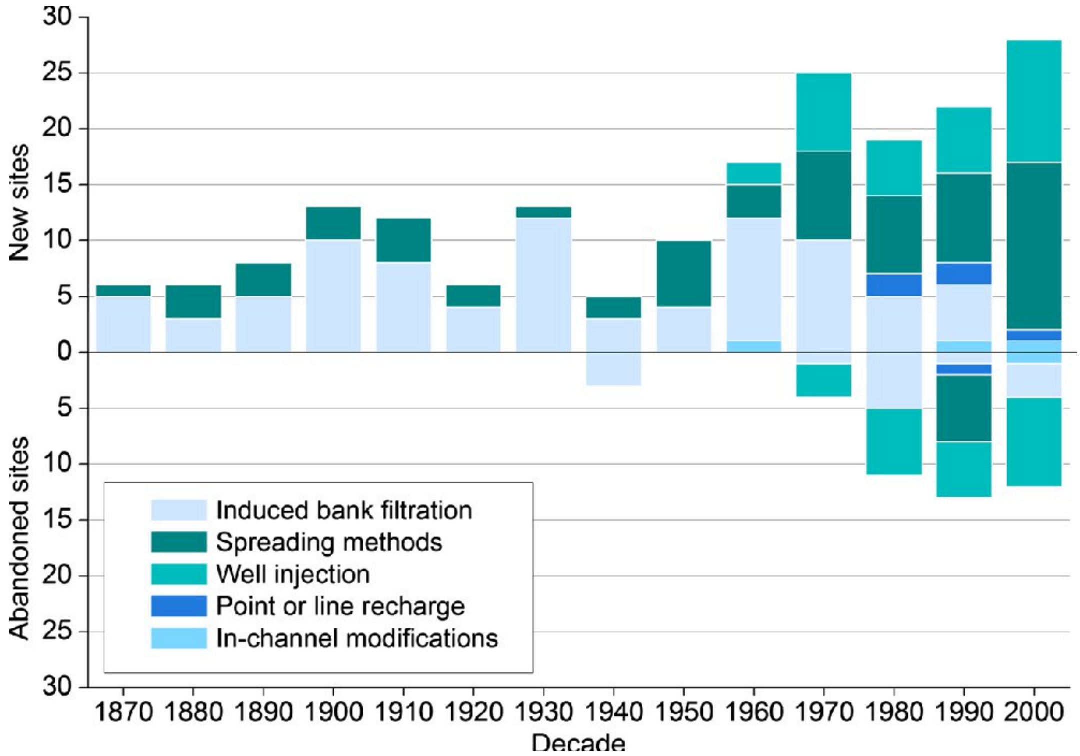


Figure 1. Outline of the historical development of MAR in Europe showing the number of MAR sites opened or closed per decade between the 1870s and 2000s (Sprenger et al., 2017)

2.3. OBJECTIVES AND CRITERIA

MAR has application in sustaining and augmenting groundwater quality, quantity and also in environmental management (Grutzmacher and Kumar, 2012). More detailed objectives are:

Water quality:

- to improve water quality in degraded aquifers (e.g. nutrient reduction from agricultural pollution, prevention of seawater intrusions), reducing the concentration of geogenic pollutants like fluoride or arsenic
- to reduce effort for water treatment (e.g. making use of natural purification processes, such as riverbank filtration).

Water quantity:

- to store water in aquifers for future use (e.g. water supply);
- to increase groundwater levels in over-exploited aquifers.

Environmental management:

- to prevent storm runoff and soil erosion;
- to preserve environmental flows in rivers and streams;
- to mitigate floods and flood damage;
- to control seawater intrusions;
- to reduce land subsidence;
- to provide hydraulic control of contaminant plumes.
- to increase groundwater levels to maintain or improve the status of groundwater dependent terrestrial ecosystems

Although the criteria for initiating MAR projects differ from location to location, certain similarities can be singled out. Central Groundwater Board of India (Grutzmacher and Kumar, 2012), summarizes the following potential areas for MAR implementation:

- groundwater levels are declining;
- groundwater availability is inadequate, especially in dry months;
- a substantial amount of aquifer has already been desaturated;
- the site is adjacent to a leaky fault or semi-confining layer containing contaminated water or water of poor quality;
- the aquifer contains water of poor quality and is highly heterogeneous or has a high lateral flow rate;
- aquifers show signs of seawater/saline intrusions.

2.4. TYPES OF MANAGED AQUIFER RECHARGE

MAR encompasses a large variety of applications that can serve many purposes, in different environments, and settings, and at different scales. These applications can be grouped into five types describing several similar engineering techniques (Table 1).

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

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

Several classifications of MAR types can be found, with minor differences in nomenclature and categorisation, e.g. Sprenger et al. (2017) distinguish four main MAR types: surface-spreading methods, induced bank filtration, well injection and enhanced storage. Dillon (2019) classifies types into streambed channel modification, bank filtration, water spreading and recharge wells. Selection of appropriate MAR type is adapted to the local hydrology, hydrogeology, type of aquifer, topography, land use, ambient groundwater quality and intended use of recovered water. An understanding of the local hydrogeology is fundamental for determining viable options and the technical feasibility of MAR projects. Details on specific requirements for application, advantages and limitations of each technique are briefly described and presented in the following section (based on IGRAC (2007) and Dillon et al. (2009):

- Spreading methods

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

- Induced bank filtration

Induced bank filtration is benefitial both for water quantity and water quality aspects. In cases of low (poor) surface water quality (river or lake), a series of wells can be installed parallel to a water body to enhance the infiltration of water through the ground induced by pumping. The water recovered at the wells will be of better quality as it benefited from the filtration process taking place when travelling through the river or lake bed, removing dissolved and suspended pollutants.

- Well, shaft and borehole recharge

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

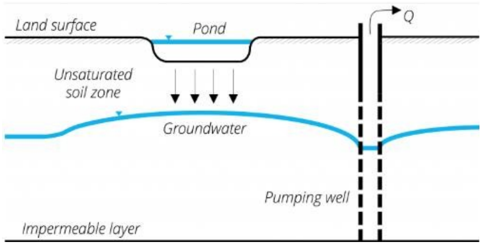
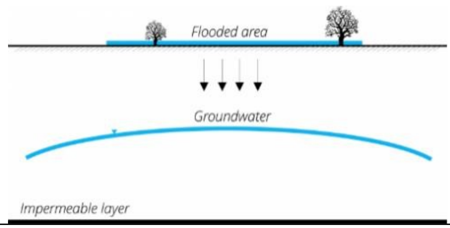
- In-channel modification

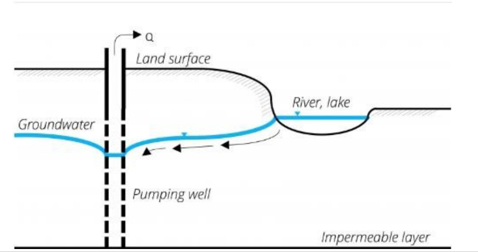
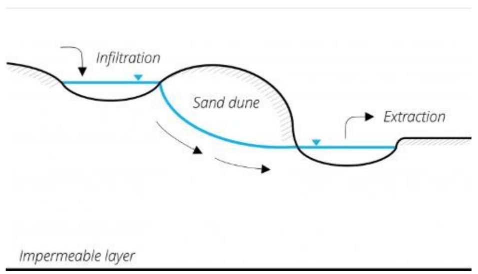
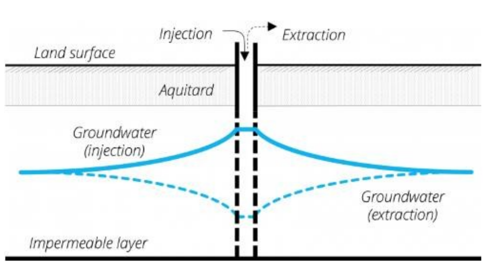
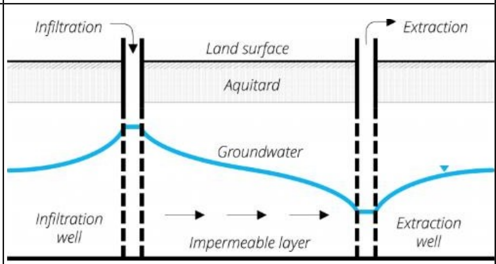
Several MAR techniques consist in modifying the stream flow to enhance infiltration of water. Some of them aim at intercepting the flow in intermittent streams with dams built across the streambed. These structures can be used to control the release of water downstream to match the capacity of infiltration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

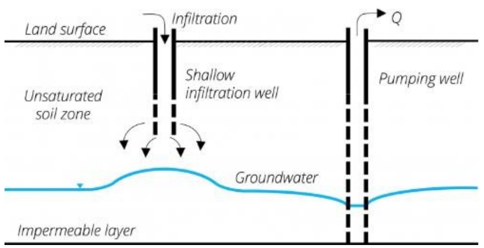
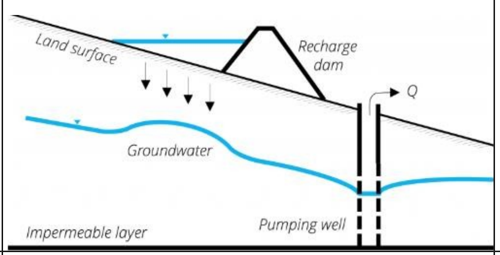
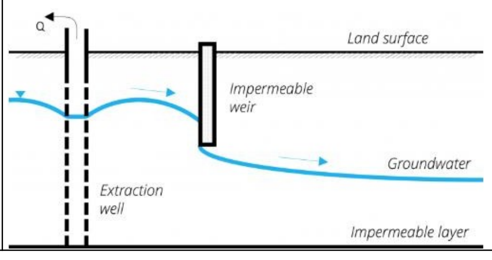
- Runoff harvesting

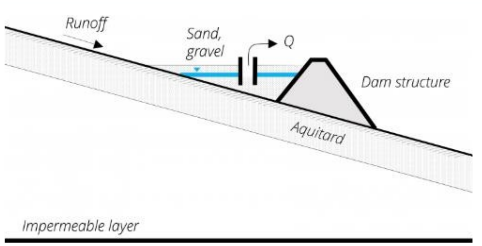
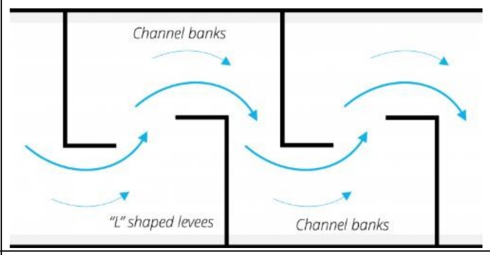
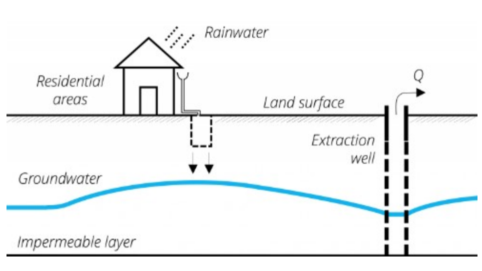
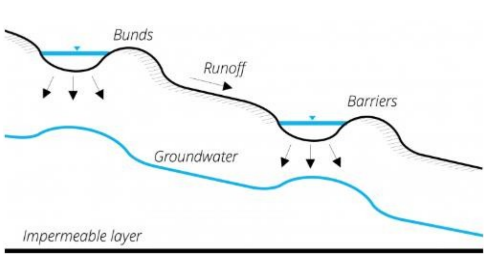
Rainwater can be harvested at the scale of a household to a village and directed to storage tanks that can contribute to groundwater recharge. Several structures allow collecting rainwater such as trenches or reverse drainage. Rooftop rainwater harvesting is being increasingly used in urban areas, helping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

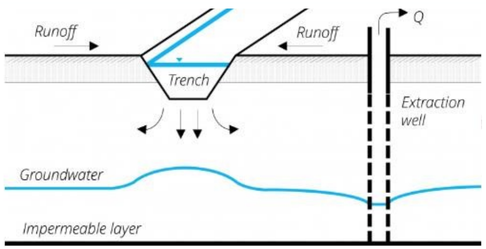
Table 2. Overview of existing MAR techniques based on IGRAC (2007) and Dillon et al. (2009)

	Main MAR methods	Specific MAR methods	Scheme	Advantages	Constraints	Suitable environment
Techniques referring primarily to infiltrate water	Spreading methods	Infiltration ponds		Infiltration of large quantities of water at relatively low cost, maintenance and anti-clogging procedures relatively simple, organic contaminants in source water filtered out in soil	Requires large flat permeable surface area, potential for surface water related breeding of disease vectors, potential for water pollution, potential for high evaporation	Flat of gently sloped terrains underlined by an unconfined aquifer composed of permeable sedimentary rocks and fractured crystalline rocks with permeable soils
		Flooding		Infiltration of large quantities of water at relatively low cost		Flat of gently sloped terrains close to rivers, underlined by an unconfined aquifer composed of permeable sedimentary rocks and soils
		Ditches and furrows	Linear structures that allow for the recharge water to infiltrate to the aquifer underneath. They are usually shallow, flat-bottomed and closely spaced structures that are excavated	In case of reversed drainage, structures can be installed underground, and therefore do not interfere with land use	Requires large permeable surface area, potential for surface water related breeding of disease vectors	Flat or gently sloped terrains close to rivers, underlined by an unconfined aquifer composed of permeable sedimentary rocks and soils
		Excess irrigation	Excess water is spread over the area during dormant or non-irrigated seasons to allow for aquifer recharge	limited costs due to use existing facilities		

Techniques referring primarily to infiltrating water	Induced bank filtration	River/lake bank infiltration		Large quantities of good quality water can be withdrawn, organic contaminants in source water filtered out in soil	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging	Floodplains or lake banks underlined by an unconfined aquifer with coarse soils (sand, gravel)
		Dune filtration		Large quantities of water can be withdrawn and pollutants contained in source water may be removed by filtration process	Intensive monitoring of system performance is required with high potential of clogging	Dunes underlined by an unconfined aquifer with coarse soils (sand, gravel)
	Well, shaft and borehole recharge	Aquifer storage and recovery (ASR)		Clogging partially removed during recovery cycle, infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high quality requirements of source water	Confined or unconfined aquifers composed of unconsolidated rocks
		Aquifer storage, transfer and recovery (ASTR)		Infiltration of large quantities of water at relatively low cost	Complex design, complex construction, complex operation and maintenance, intensive monitoring required, high potential for well clogging, high quality requirements of source	

					water	
		Shallow well/shaft/pit infiltration		Use of existing facilities reduces costs, recovery from same structure reduces clogging	High quality requirements of source water	Unconfined aquifers composed of unconsolidated sediments with a low permeability surface layer
Techniques referring primarily to intercepting water	**In-channel modifications**	**Recharge dams**		Structures are installed in streambeds, and therefore do not interfere with land use	Breached structures may result in significant damage downstream	Intermittent or ephemeral streams underlined by an unconfined aquifer and a permeable river bed
		Subsurface dams		Low cost structures, community based, low maintenance, structures are installed in streambeds, and therefore do not interfere with land use	Potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water, quality control of the structure difficult	Intermittent or ephemeral streams underlined by an unconfined aquifer with an impermeable layer located a few meters below the surface

		Sand dams			Potential ownership issues, potential for water pollution, infiltration of relatively small quantities of water	Intermittent or ephemeral streams with sandy river beds
		Channel spreading		Low cost technique, structures are installed in streambeds, and therefore do not interfere with land use	Structures are easily breached during high runoff; sediment deposition due to artificially forced changes in river course and dynamics	Natural drainage channels underlined by an unconfined aquifer with a permeable river bed
	Runoff harvesting	**Rooftop rainwater harvesting**		Use of already existing structures; storage of rain events mitigating floods	Water quality might be problematic; potential soil stability issues - high recharge may cause damage in foundations of the buildings	Urban areas underlined by an unconfined aquifer with sandy soils
		Barriers and bounds		Low cost technique, simple design, simple construction, simple operation and maintenance, prevents soil erosion as well as recharging the groundwater	Infiltration of relatively small quantities of water	Gently sloping rural areas underlined by an unconfined aquifer with sandy soils

		Trenches	Runoff Runoff Q Trench Extraction well Groundwater Impermeable layer			

2.5. SOURCE WATER FOR MANAGED AQUIFER RECHARGE

A prerequisite of MAR is to have a sufficient source of water for recharge, which includes various types such as surface water, rain water, storm water, reclaimed water or groundwater (Gale, 2005; Dillon et al., 2009). Depending on the initial quality of the source water and the desired final use, a phase of pre-treatment before recharge and eventually post-treatment after recovery might be necessary to bring the water to a requested quality standard (by legislation) that ensures the protection of public health and environment (Dillon et al., 2010; DWA, 2010). The selection of specific sources primarily depends upon the availability, as well as the quality that could be achieved with least pre-treatment effort.

2.6. FACTORS INFLUENCING FEASIBILITY AND PERFORMANCE OF MANAGED AQUIFER RECHARGE

Extensive research described numerous approaches on determination of factors and criteria for selecting the suitable MAR site. Although they differ in methodology, level of detail and ranking system, common factors for most approaches include:

- Hydrogeological settings

The feasibility of a MAR system depends largely on local hydrogeological conditions (Dillon et al., 2005). Understanding natural recharge, its evolution, and therefore the storage capacity of the subsurface will be a fundamental criterion for decision support in the choice of an artificial recharge site. This step of feasibility needs a detailed hydrogeological analysis with the help of hydrogeology experts who can advise about the drawbacks or benefits of the considered MAR site. The aim of hydrogeological analysis is to identify aquifers that store large quantities of water and do not release them too quickly. Scientifically, the vertical hydraulic conductivity should be high, while the horizontal hydraulic conductivity should be moderate. However, coexistence of these two conditions is rare in natural geologic settings (Grutzmacher and Kumar, 2012). Furthermore, essential data includes knowledge of geological and hydraulic boundaries, inflow and outflow of waters, aquifer parameters (lithology, depth of the aquifer, tectonic boundaries, storage capacity, porosity, hydraulic conductivity, and transmissivity) obtained through pumping tests and various hydraulic flow models, natural discharge and recharge, water availability and water balance. MAR operations are observed in different hydrogeological settings (Grutzmacher and Kumar, 2012), such as:

- Alluvium, which usually consists of highly permeable, unconsolidated sediments ranging from coarse gravel to impermeable silt and mud. Alluvial aquifers are often found in lower reaches of river basins. In most regions with alluvial aquifers, the water table is observed at shallow depths, except in arid regions.
- Fractured hard rocks, which act as potential zones for groundwater in many parts of the world. In these rocks the upper weathered zone is responsible for absorbing and storing intermittent rainfall. In the case of hard rock terrains the success of MAR operation is mainly dependent on the location of the saturated weathered zone. However, the fractures and lineaments also may be targeted. However, recharging the deep aquifer can only be done with injection wells.
- Consolidated sandstones, as one of the favorite geological formations for groundwater storage because of their good storage capacity and transmissive properties. However, if

the aquifer permeability is too high, the recharged water may dissipate quickly and is thus be lost to the base flow in rivers. A thorough knowledge in aquifer hydraulics is necessary for the successful implementation of MAR in this kind of aquifers.

- Carbonate rocks, such as karst, are highly dynamic formations in terms of hydrogeochemistry. Due to their high reactivity, groundwaters in these formations often exhibit high hardness. Carbonate aquifers can show high dissipation of recharged water and fast pathways for pollutants. Despite of this behaviour, carbonate aquifers are considered as good water bearing formations all over the world. A considerable modification in the flow patterns can be expected in carbonate aquifers within a short period. MAR in these formations demands a good understanding of aquifer hydrogeology.

- Climate and hydrology

Climatic conditions determine the need, dimensions and type of structure required for MAR operation. Most important data include mean annual rainfall, number of rainy days, water table fluctuations, alternations of dry and wet season, frequency of high intensity rainfall and variability in temperature.

Hydrology is a key factor in locating the appropriate areas for MAR and also in determining the amount of water available for recharge. Availability of naturally suitable sites is always helpful in bringing down the implementation and operational cost. Factors to consider for available water determination are: terrain characteristics (topography, elevation, slope), land use, vegetation cover, flow availability and conveyance system for bringing the water (gravity flow, energized pumping, suitability for canals, pipe networks etc.)

- Biogeochemical processes

In the case of artificial recharge systems that involve infiltration techniques, geochemical and microbiological processes might occur in the unsaturated zone that enable the purification of the recharged water. Furthermore, the unsaturated zone must allow the water to infiltrate to the aquifer, the aquifer must be able to store the infiltrated water, and then release it without excessive “dissipation”, which would cancel out the storage effect (Casanova et al., 2016). It is, however, possible to identify the main criteria that can affect the geochemical and microbiological processes that enhance the purification of the recharge water as it moves through the unsaturated zone: (i) pH, (ii) redox potential, (iii) organic matter content, and (iv) mineralogy. Regarding water quality consideration, following parameters must be taken into consideration: salinity and sodicity, turbidity and particulates, nutrients, organic chemicals, pathogens and inorganic chemicals. Complex interactions between MAR activities and induced changes in microbial community is provided by Barba et al. (2019).

- Monitoring

Essential part of an efficient MAR operation is monitoring. Monitoring is required so that changes in water quality and quantity can be detected. MAR operations entail the installation of localized systems that transfer a portion of surface water flow towards the subsoil. This operation usually increases the vulnerability of the aquifer, as it is connected to preferential flow routes that could potentially contain pollutants (e.g. intentional releases, diffuse pollution, occasional accidents, etc.). Therefore, the recharge infrastructure must be equipped with systems for detecting the presence of undesirable substances in the water allocated for infiltration. An example of efficient way of monitoring is the usage of multi-parameter probe systems, that can continually measure several important chemical-physical variables (turbidity, electrical conductivity, temperature, dissolved oxygen, redox potential and pH). By measuring same parameters in end-use water, a better understanding of aquifer properties and changes induced by MAR operation can be achieved. However, in practice, limited information on subsurface properties and processes that control groundwater flow may lead to low levels of recapture of infiltrated water, reducing the efficacy of MAR operations. A common clogging problem for many MAR operations, in spite of huge progress in understanding driving mechanisms, lack of standardized predictive instruments and often – the lack of adequate water quality monitoring and geochemical, mineralogical and biological evaluations at operational sites has inhibited the creation of better predictive tools and more efficient management (Dillon et al., 2018). A Working Group of the IAH Commission on MAR has produced one monograph on clogging (Martin, 2013), and a subsequent monograph on management of clogging is in preparation to help address this. Common practices use isotopes to study origin and age of ambient groundwater, mixing processes and travel times of recharged water and biogeochemical processes such as denitrification, sulphate reduction, fate of organic carbon and dissolution of minerals due to disequilibrium. The IAEA (2013) provides an anthology of methods and their numerous applications to MAR investigations. Furthermore, modelling of flow and water quality changes in MAR operations has also been extensive and a review of the range of models (unsaturated/ saturated flow, solute transport and reactions, geochemistry and clogging) and their uses in planning, design, and improving operations at MAR sites for all types of MAR are summarized by Ringleb et al. (2016). A recent example by Rodríguez-Escales et al. (2017) simulates improved degradation of organics by varying the flow fields beneath infiltration basins to vary redox conditions.

- Costs and risks

The financial and economic performance of MAR is a key determinant of its global uptake. Few studies are available and this report focuses on following:

- Dillon et al. (2018): Advances in multi-stage planning and implementing managed aquifer recharge for integrated water management
- Rodriguez-Escales et al. (2018): A risk assessment methodology to evaluate the risk of failure of managed aquifer recharge in the Mediterranean Basin
- Ross and Hasnain (2018): Factors affecting the cost of managed aquifer recharge (MAR) schemes

MAR schemes show a great diversity of type and scale. This diversity is reflected in the wide range of costs of MAR schemes. The costs are mainly influenced by a wide variety of hydrogeological, socio-economic, legal and institutional factors. Ross and Hasnain (2018) concluded from their study that the main factors that determine the relative cost of MAR scheme are the type of aquifer recharge and recovery technology used in the scheme, source of water which is linked to the end use of water and the consequent amount and degree of water treatment period. Other significant factors that affect costs of operation include the range of objectives that the operations have to meet, scale of the operation, frequency of utilization and operating period, life expectancy of operation and hydrogeological setting including soil and aquifer characteristics. In their study, Ross and Hasnain (2018) contains analyse financial data from 21 MAR schemes in five countries from the global MAR inventory (IGRAC, 2018; MAR portal: https://www.un-igrac.org/ggis/mar-portal). In their research, they described and considered four metrics for comparing the costs of MAR scheme: levelised cost of water supply, water supply security insurance cost, water recharge cost and recovery cost. They concluded that the costs of MAR vary substantially between different types (Table 3).

Table 3. Average MAR scheme costs, by MAR type (Ross and Hasnain, 2018)

MAR operation Type/ Water Source	Capital cost / m^3 recharged	O&M* cost / m^3 recharged	Levelised cost (US$ / m^3 recharged)
Recharge wells / recycled water (4 schemes)	$ 8,07	$ 0,53	$ 1,16
Infiltration basins / recycled water (3 Schemes)	$11,41	$ 0,84	$ 1,89
Recharge wells/ natural water (5 schemes)	$ 3,29	$ 0,19	$ 0,45
Infiltration basins / natural water (8 Schemes)	$ 0,77	$ 0,13	$ 0,19

*operation and management cost

Levelised cost is a widely accepted method of costing infrastructure projects. Levelised cost of a water supply project is defined as the constant level of revenue necessary each year to recover all the capital, operating and maintenance expenses over the life of the project divided by the annual volume of water supply. Levelised costs provide an effective means to compare the costs of water from alternative projects (Dillon et al., 2009).

Data presented in Table 3. indicates that operations using natural water have much lower costs that operations using recycled water. Infiltration/spreading basins using natural water have the lowest recharge cost.

Schemes recharging unconfined aquifers using infiltration basins with untreated water are relatively cheap, while schemes using wells or advanced water treatment are expensive. Regarding source water, especially urban storm water and recycled water treatment before recharge and recovery is expensive. Despite the expenses, storm and wastewater recycling offers lowest cost opportunities for improving water security when natural surface water and groundwater is scarce.

Another major factor to consider while planning and implementing a MAR scheme is failure risk. Rodriguez-Escales et al. (2018) define MAR failure as the need to stop the operation of the facility. Failure can be either complete or partial. Basic events that can lead to MAR failure were compiled based on literature review of the problems encountered by different facilities around the world, and data is provided for 51 MAR facilities located around the world. Problems were classified in technical and non-technical. They concluded that the most frequent technical problems were clogging and presence of nutrients, in 40-50% of reviewed facilities. Three types of clogging were reported: biological, physical and chemical. Nutrient issues were mainly related to presence of nitrogen and phosphorus in the recharge water. Other technical problems include metals, droughts, low infiltration rate and salinity-sodicity. Regarding the non-technical aspects, they were classified into four groups: legal constraints, economic constraints, social unacceptance (e.g. ecosystem changes) and governance-related problems (e.g. downstream changes in hydromorphological regime, cooperation between communities and regions). Most common actual issues in this category were related to costs (maintenance and installation), sanitary issues, land permissions and urban planning issues. Sorted list in terms of frequency of appearance of the main problems observed in reviewed facilities of deep well injections and infiltration basins is presented in Figure 2.

There are still several operational issues that must be addressed on a site-specific basis. These concerns are related to project sustainability, treatment needs, public health impacts, and economic and institutional constraints. In the short-term, project sustainability is controlled by operating and managing the system so as to prevent or control clogging. Long-term sustainability is dependent on finding the best combination of pre-treatment, soil-aquifer treatment, and post-treatment for determining whether the source waters will exceed the treatment and removal capacity of the soil-aquifer treatment system.

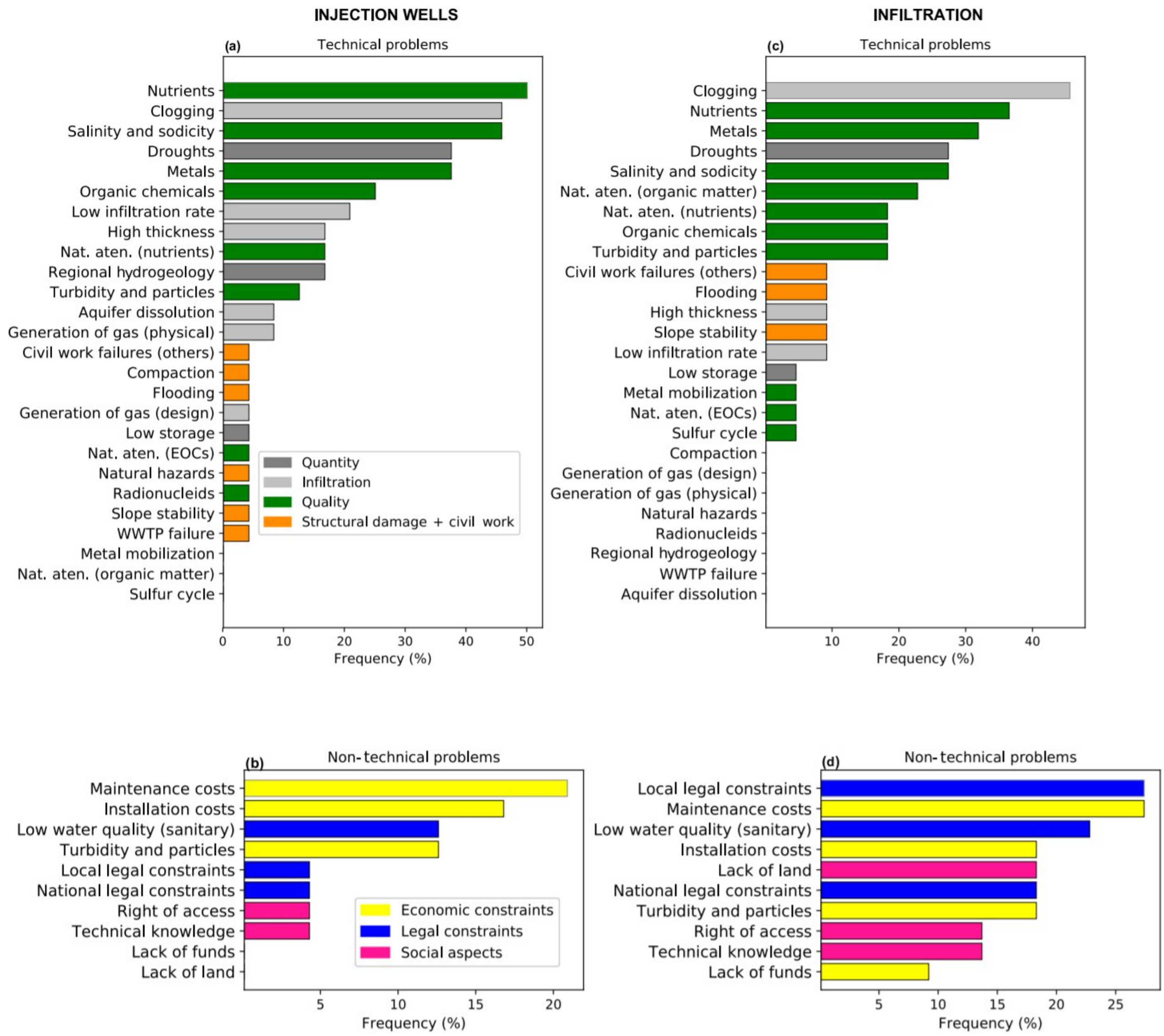


Figure 2. Main technical and non-technical problems in injection wells (a, b) and infiltration schemes (c, d) (Rodriguez-Escales et al., 2018)

Once the MAR site has been identified, taking into account constraints such as the availability of water, hydrogeological characteristics and regulations, five steps are usually necessary:

- a preliminary evaluation of the feasibility of a recharge system at the chosen site based on existing data or modelling;
- designing the recharge system;
- carrying out a detailed study of the site in order to validate or supplement the results obtained in the first step;
- building a pilot or experimental system at a scale that makes it possible to carry out preliminary tests;
- extrapolation to an operational scale.

2.7. MANAGED AQUIFER RECHARGE IN EUROPE

The catalogue presented in Sprenger et al. (2017) includes 224 MAR sites active in year 2013, across 23 European countries. Number of sites and MAR type distribution by country can be seen in Figure 3.

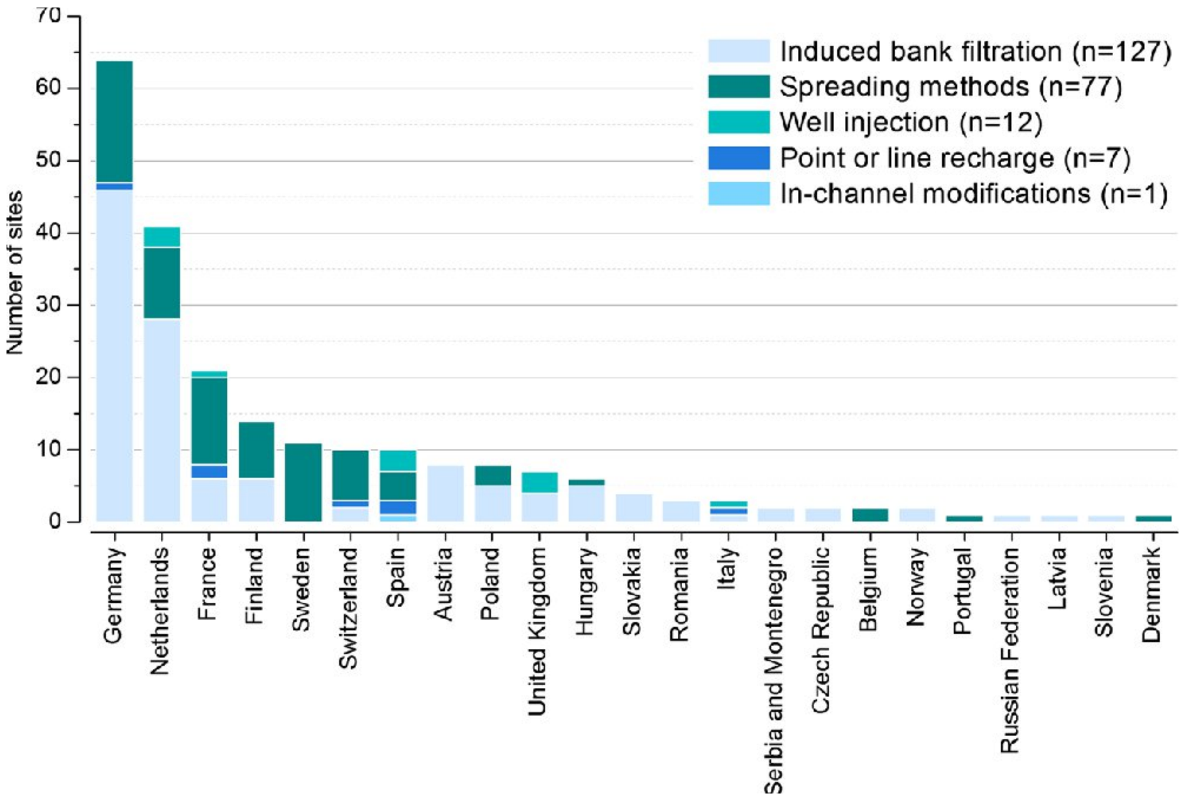


Figure 3. Number of MAR sites and types in Europe active in 2013 (Sprenger et al., 2017)

The most widespread MAR type is induced bank filtration (IBF) with 127 sites (57% of total active sites); surface-spreading methods rank second among all MAR types with 77 sites (34% of total active sites). Well injection schemes form the third largest group of MAR types with 11 active sites (5% of total active sites) and 23 abandoned sites. Active-point or line-recharge and in-channel modification sites have been found seven and one time(s), respectively. Enhanced storage MAR types, e.g. sub-surface dams, were not found in the literature for Europe.

The spatial occurrences of MAR sites and aquifer properties are shown in Figure 4.; these were derived from the International Hydrogeological Map of Europe ('IHME 1500') as reported in BGR & UNESCO (2014). IHME 1500 is a generalized hydrogeological map series covering the European continent. Aquifer properties are displayed by their hydraulic productivity and dominant rock type.

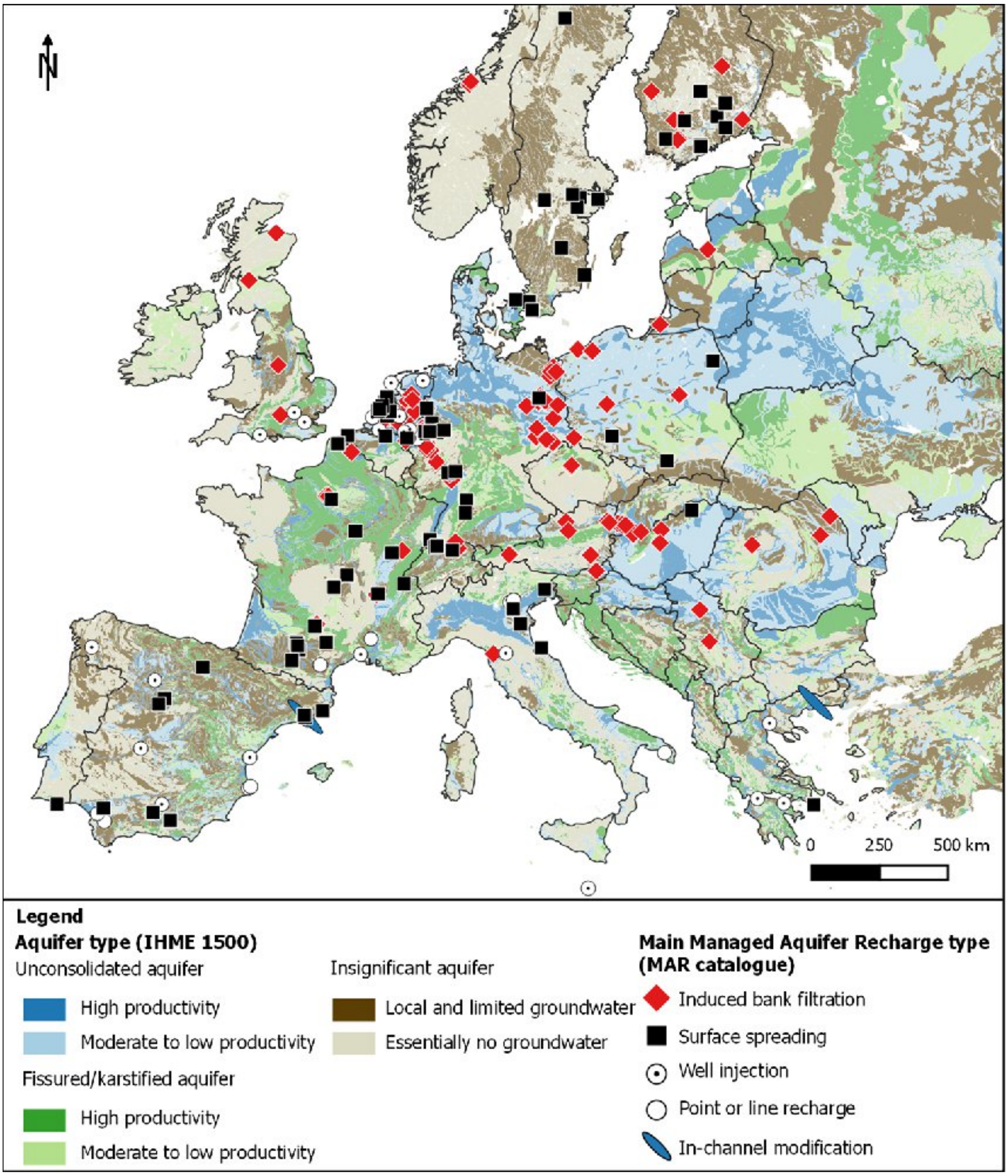


Figure 4. Overview of MAR sites in Europe and simplified hydrogeological formations (Aquifer types reported in the International Hydrogeological Map of Europe, 'IHME 1500', BGR & UNESCO 2014)

The volumetric contribution of MAR-derived water to drinking water supply of European countries according to the operational scale of MAR sites is shown in Figure 5. The operational scale gives insight into the total water quantity produced by MAR schemes. Currently about 190 MAR sites in Europe produce drinking water and are operated by water utilities (mostly public bodies). The percentage contribution of MAR-derived drinking water to the total drinking water supply is calculated with data from the European Environmental Agency for the year 2007 (EEA 2010).

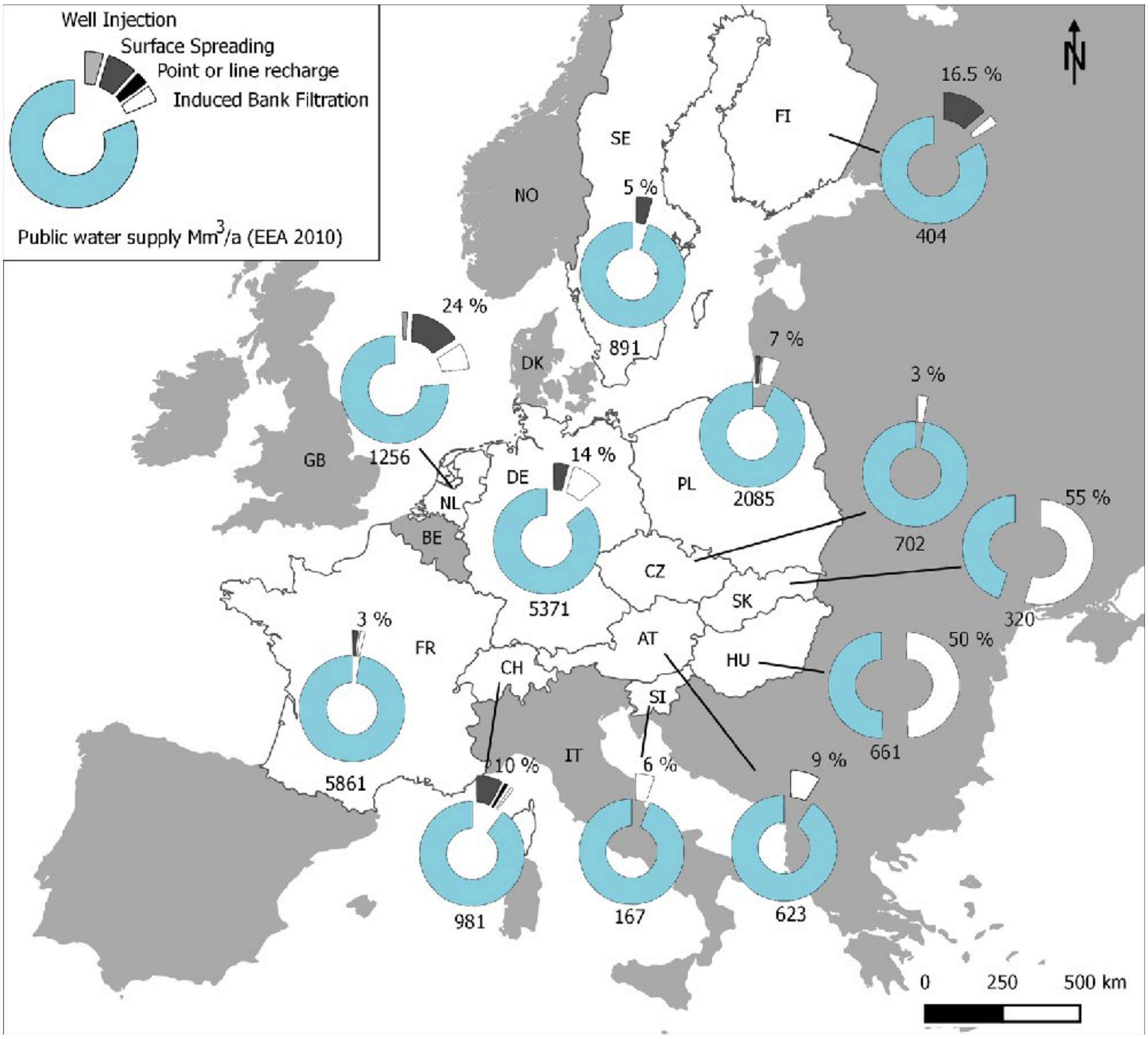


Figure 5. Percentage contribution of MAR-derived drinking water (calculated from the MAR catalogue) to public water supply (taken from EEA 2010) for European countries. Countries with a MAR contribution <1% are not shown.

The contribution of MAR-derived water to drinking water production varies greatly from country to country. In some countries, e.g. Hungary or Slovakia, MAR water may contribute ≥ 50% to the drinking water supply. Some of the largest MAR sites exist on islands in the Danube River, upstream and downstream from Budapest in Hungary (IBF sites in Csepel and Szentendre). The installed well capacities (indicating the operational scale) of these sites are reported to be 146×10^6 m^3/y and 219×10^6 m^3/y, respectively (Grischek et al. 2002). Along with all other MAR sites in Hungary included in the catalogue, the total drinking water volume derived from MAR is about 327×10^6 m^3/y, making up ~50% of the public water supply (total public water supply 661×10^6 m^3/y, EEA 2010). Laszlo and Literathy (2002) estimated the share of riverbank filtrated water in drinking water supply of Hungary to be around 40% (in total ~470×10^6 m^3/y), but the source of these figures remains unclear. Also the Slovakian public water supply relies on MAR to a large extent. The sum of operational scale for all Slovakian MAR sites (entirely IBF) makes up approx. 55% of total public water supply (175×10^6 m^3/y from total 319×10^6 m^3/y). According to authors, MAR sites in Germany produce around 14% water of the total public water supply (mostly induced bank filtration and surface-spreading sites). Interestingly, by looking on the city scale, e.g., in Berlin, the MAR catalogue includes eight active MAR sites producing about 135×10^6 m^3/y of water, contributing 67% to the total water supply which was 202×10^6 m^3/y in Berlin in 2006, taken from Möller and Burgschweiger (2008).

Dillon et al. (2019) provided international evolution of MAR capacity by decade from 1960s to 2000s and 2011–2015.

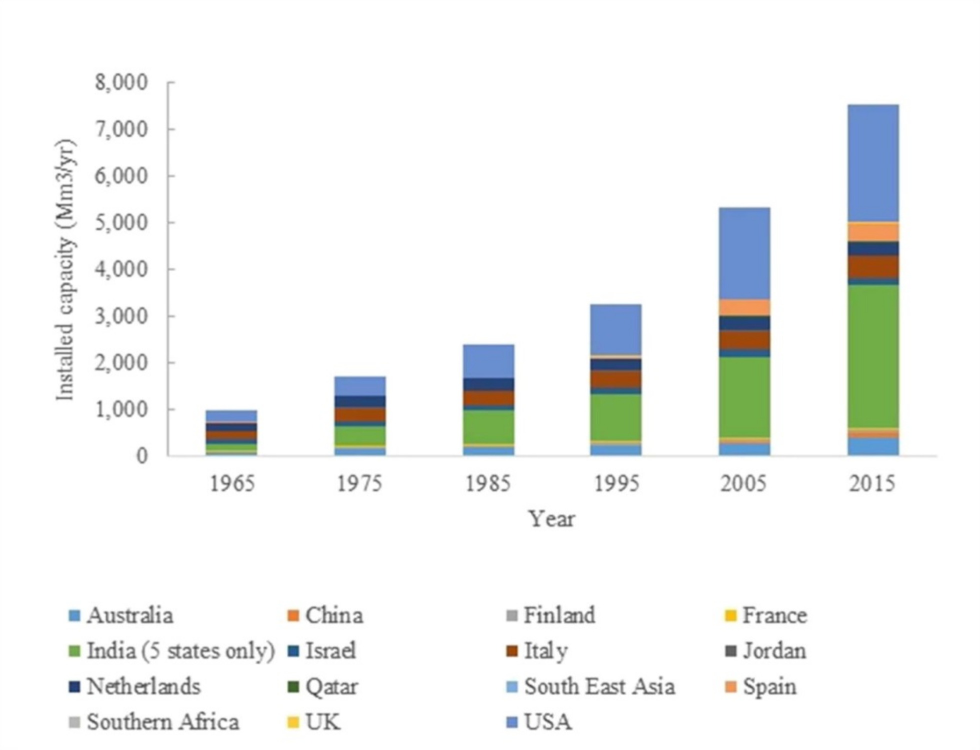


Figure 6. International evolution of MAR capacity by decade from 1960s to 2000s and 2011–2015 (Dillon et al., 2019)

Figure 6. includes only the countries or regions where historical estimates from 1965 were available. These 15 countries/areas account for 76% of reported installed MAR capacity in 2015 and for 34% of global groundwater use in 2010. Bar stacks from bottom up and follow the alphabetical order of countries as per the legend.

Based on current application of MAR it is likely that the demand for MAR where groundwater systems are under stress would be 10% of the water demand; hence the current status of MAR development (~10 km^3/y) is likely to expand to the order of 100 km^3/y. The rate of expansion will depend on having a sound understanding of the capabilities and constraints of the suite of techniques, effective risk management and knowledge of the economics of MAR in comparison with alternatives (Ross and Hasnain, 2018).

2.8. GOOD PRACTICES

Due to a wide variety of MAR types, underlying needs and conditions, socio-economical aspects and all other factors, the concept of sustainability of MAR operation is not easy to define. There are no clear definitions, indicators or good practices. Several efforts have been made to unite definitions, indicators and good practices, but no conclusive document has been produced so far. Instead, efforts should be focused on individual case studies, specific guidelines and capitalization of existing knowledge (past projects, MAR groupations) from various countries and regions. An example of such guidelines is provided by the National water quality management strategy of Australia (Natural Resource Management Ministerial Council, 2009), which addresses various sustainability factors such as:

- selection of recharge methods and areas;
- definitions of non-viable situations or areas;
- legal and institutional framework with proper assessment;
- risk characterization and preventive measures;
- monitoring and verification of water quality and environmental performance;
- operational issues and their management (e.g. clogging).

Access to full document: http://www.nepc.gov.au/system/files/resources/5fe5174a-bdec-a194-79ad-86586fd19601/files/wq-agwr-gl-managed-aquifer-recharge-final-200907_1.pdf

Another set of good examples is provided in the IAH and UNESCO document - Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas (Gale, 2005). Besides water quality issues, hydrogeological settings and control of recharge, methodologies and institutional issues, the Strategy contains examples of various schemes implemented throughout all continents.

Further efforts are provided by the IAH Commission on Managed Aquifer Recharge (IAH-MAR). Besides organising symposia and workshops, the Commission also sets up working groups regarding various topics, such as clogging, global MAR portal (in association with IGRAC), MAR for sustainable development, economics and so on. IAH MAR also participates in collaborative research and projects, namely:

- IGRAC MAR Portal - https://www.un-igrac.org/ggis/mar-portal
- MARSOL - Demonstrating Managed Aquifer Recharge as a Solution to Water Scarcity and Drought, http://www.marsol.eu/
- DEMOWARE - Innovation Demonstration for a Competitive and Innovative European Water Reuse Sector, http://demoware.eu/en
- DESSIN - Demonstrate Ecosystem Services Enabling Innovation in the Water Sector, https://dessin-project.eu/
- MARVI - Managing Aquifer Recharge and Groundwater Use through Village-level Intervention (India), https://recharge.iah.org/marvi
- GRIPP - Groundwater Solutions Initiative for Policy & Practice, http://gripp.iwmi.org/

The DEEPWATER-CE project partnership aims to capitalize upon existing knowledge from these projects and to actively participate in collaboration with various researchers and working groups. The project also aims to produce an added value to global knowledge and understanding of MAR by providing first hand experiences from operational MAR sites located in participating countries (Croatia, Germany, Hungary, Poland and Slovakia), which can be seen in the continuation of this report. The project will also develop useful tools throughout work packages T2, T3 and T4, such as (i) Transnational decision support toolbox for designating potential MAR location in Central Europe, (ii) Pilot feasibility studies of MAR schemes with integrated environmental approach in porous and karstic aquifers and lastly, (iii) Development of policy recommendations and national action plans.

3. National case studies on MAR

To begin with, this chapter provides an overview of essential issues in water management on country level. Project partners were asked a series of questions regarding various topics. Besides water management questionnaire, this chapter also includes national MAR case studies.

National inputs were collected through step-by-step questionnaires where each PP country provided necessary information regarding different topics. Additionally, the preparation of this report was based on the knowledge and findings of earlier EU-funded projects (e.g. CC WARE, DRINKADRIA, PROLINE-CE and CAMARO-D).

3.1. Water management

3.1.1. Organisation of water management

Water is essential for life, it is an indispensable resource for the economy, and also plays a fundamental role in the climate regulation cycle. The management and protection of water resources, of fresh and salt water ecosystems, and of the water we drink and bathe in is therefore one of the cornerstones of environmental protection. This is why the EU's water policy over the past 30 years focuses on the protection of water resources. The last complete policy overview is provided in a document titled the 'Blueprint to safeguard Europe's water resources' (2012) which aims at ensuring the good quality, sufficient quantity, and availability for all legitimate uses of water. Some more recent insight is offered by the fifth implementation report (2019) of the Water Framework Directive (2000), the central piece of environmental legislation concerning European waters. A summarized view of the Project Partner government bodies and other organizations in charge of water policy control, management and implementation is given in the table below.

Table 4. Condensed data depicting the organizations in charge of water policy control, management and implementation according to Project Partner countries

Country	Water policy control & management	Drinking water policy control & management	Legal & administrative organization of water policy	Legal & administrative organization of drinking water policy	Management & coordination of implementation of state water policy
Croatia	Croatian Waters	Croatian Waters	Ministry of Agriculture (Water Management Administration), Croatian Waters, National Water Council, Water Service Council and the National meteorological and hydrological service	Ministry of Agriculture (Water Management Administration), Croatian Waters	Croatian Waters
Germany	Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety	Federal Ministry for the Environment, Nature Conservation, and Nu- clear Safety (Bundesministerium	Federal Ministry of Economics and Technology	Federal Ministry for Health	County offices and governments in cooperation with the Federal Environemntal Agency and the State Offices for Water Management
Hungary	Ministry of Interior, General Directorate of Water Management	Ministry of Interior, General Directorate of Water Management	Ministry of Interior, National Directorate General for Disaster Management, Ministry of Human Capacities	Ministry of Interior, National Directorate General for Disaster Management	Ministry of Interior, Ministry for Innovation and Technology, General Directorate of Water Management
Slovakia	Ministry of the Environment of the Slovak Republic	Ministry of the Environment of the Slovak Republic	Ministry of the Environment of the Slovak Republic	Ministry of the Environment of the Slovak Republic	Ministry of the Environment of the Slovak Republic
Poland	Water management ministry, National Water Management Authority, Regional Water Management Board, Voivodeship Governor, local government authorities	Water management ministry, National Water Management Authority, Regional Water Management Board, Voivodeship Governor, local government authorities	Regional Water Management Boards	Regional Water Management Boards	National Water Management Authority

Water in **Croatia** is the responsibility of the Ministry of Environment and Energy – Administration of water management and sea protection. The Ministry proposes laws and regulation, and adopts by-laws in the field of water management, performs administration and inspection, establishes international cooperation. Ministry of Environment and Energy proposes the River Basin Management Plan for adoption to the Croatian Government after the completion of the strategic assessment has been done. River Basin Management Plan has to be harmonized with other relevant bodies and with neighbouring countries.

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: preparing documents, analysis of the situation and problems, defining a program of measures, the implementation of the planned measures (independently or in collaboration with other stakeholders), monitoring and the assessment of effects of implemented measures, public information and consultation and reporting to the European Commission.

Germany has a federal structure: administrative and legal areas are separate by Federation followed by 16 Länder (federal states) and subdivided into municipalities. Legislation rests within the Federation. The duties in water resource management are subdivided between several federal ministries. Federal ministries have at their disposal advisory authorities, e.g. Federal Environmental Agency or Federal Institute of Hydrology. Länder can adopt the provisions for water policy topics made by the Federation or change it if the Federation has not exhausted its legal competence or has left room for decisions on Länder level within the Federal Water Act. Municipalities should accept legislatives made by the Länder, although they have their own scope (right to self-administration) which is protected in constitutional law (e.g. several municipalities in GER have voluntarily decided to install high-performance water treatment plants). A scheme of the administrative structure in water resource management is shown in Figure 7.

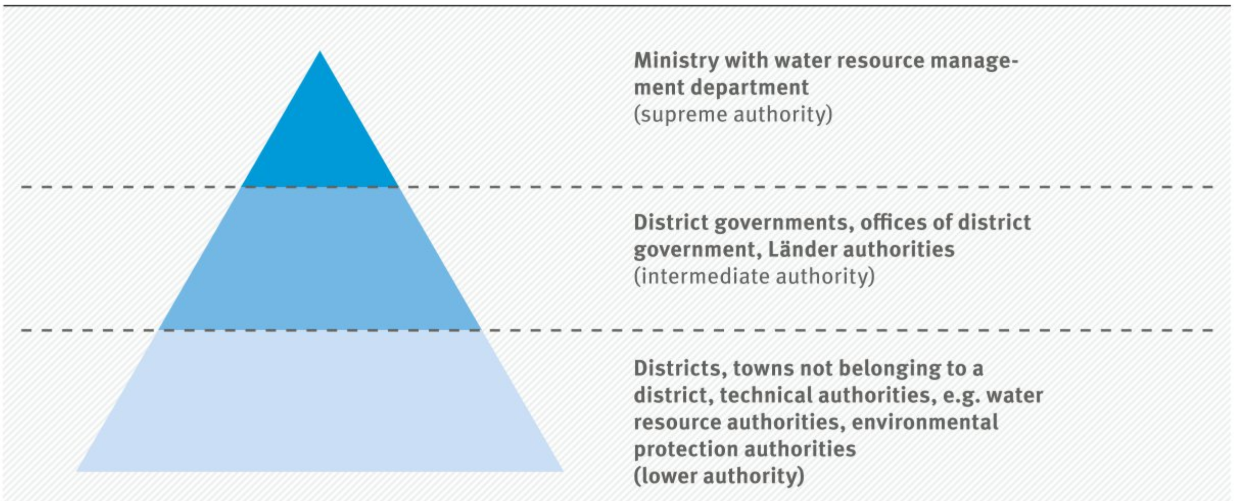


Figure 7. Administrative structure in water resource management from (German Environment Agency, 2017a) adopted from (German Federal Environment Agency, 2014a)

The governments of the 16 federal states/Länder are responsible for the regulation of water supply and wastewater disposal in their territories, within the framework of the federal laws. The organization and implementation of the water supply and wastewater disposal belong to the traditional duties of the municipalities, in accordance with state water laws. In order to cover incurred expenses, the municipalities charge consumers with tariffs and fees (Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2001). Whoever wishes to utilize natural water resources or water bodies must apply for a permit. Lower water authorities grant permits for smaller projects and intermediate authorities grant permits for bigger projects. The overlying framework for granting these permits are anchored in the

European Union legislative (Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2001).

As it is seen in Table 4, in **Hungary** the Minister of Interior is responsible for legal and administrative organisation of water policy and water governance including the implementation of Water Framework Directive (WFD). The 12 Regional Water Directorates implement the water policy which is coordinated, supervised and controlled by the General Directorate of Water Management, as a central governing body operating under the direction and supervision of the Ministry of Interior.

In **Slovakia** the Ministry of the Environment of the Slovak Republic is responsible for legal and administrative organisation of water policy. Directorate for water protection managed by the Ministry is responsible for implementation of water policy. There are organizations instituted by the Ministry, who participate in water policy implementation, namely: Water Research Institute (WRI), Slovak Hydrometeorological Institute (SHMI), Slovak Water Management Enterprise, Water Management Construction Bratislava, State Geological Institute of Dionýz Štúr, Slovak Environmental Inspection, Slovak Environmental Agency, as well as State Nature Conservation Agency. All the institutions together with regional and local environmental offices and municipalities share duties and responsibilities in various areas of water resources administration, monitoring, assessment, research and protection.

In **Poland**, according to the Water Law Act (Journal of Laws of 2017, item 1566), the state legal entity for inland flowing waters and groundwater is the State Water Holding - Polish Waters, which consists of organizational units: the National Water Management Authority (based in Warsaw), 11 regional water management boards, 50 catchment management boards and 330 water supervisions. The Minister of Maritime Economy and Inland Navigation sets the directions of water management, supervises Polish Waters and state services in the field of waters: hydrological and meteorological service (The Institute of Meteorology and Water Management – National Research Institute), hydrogeological service (The Polish Hydrogeological Survey) and the service for the security of damming buildings (the National Security Service of Dam Structures). The minister's advisory body is the State Council for Water Management.

3.1.2. Overview of groundwater abstraction

Water management is an individual country responsibility and should serve its best interest. It implies control and motion of water resources in order to maximize their efficient utilization and to minimize the negative aspects such as pollution, flood and drought, just to name a few. In Figure 8. the analyses of some water utilization categories are presented for Croatia, Germany, Hungary, Slovakia and Poland. From this data it can be concluded that Croatia, Germany and Slovakia are the largest consumers of water per inhabitant. On the other side, Germany has the largest consumption of groundwater per area unit.

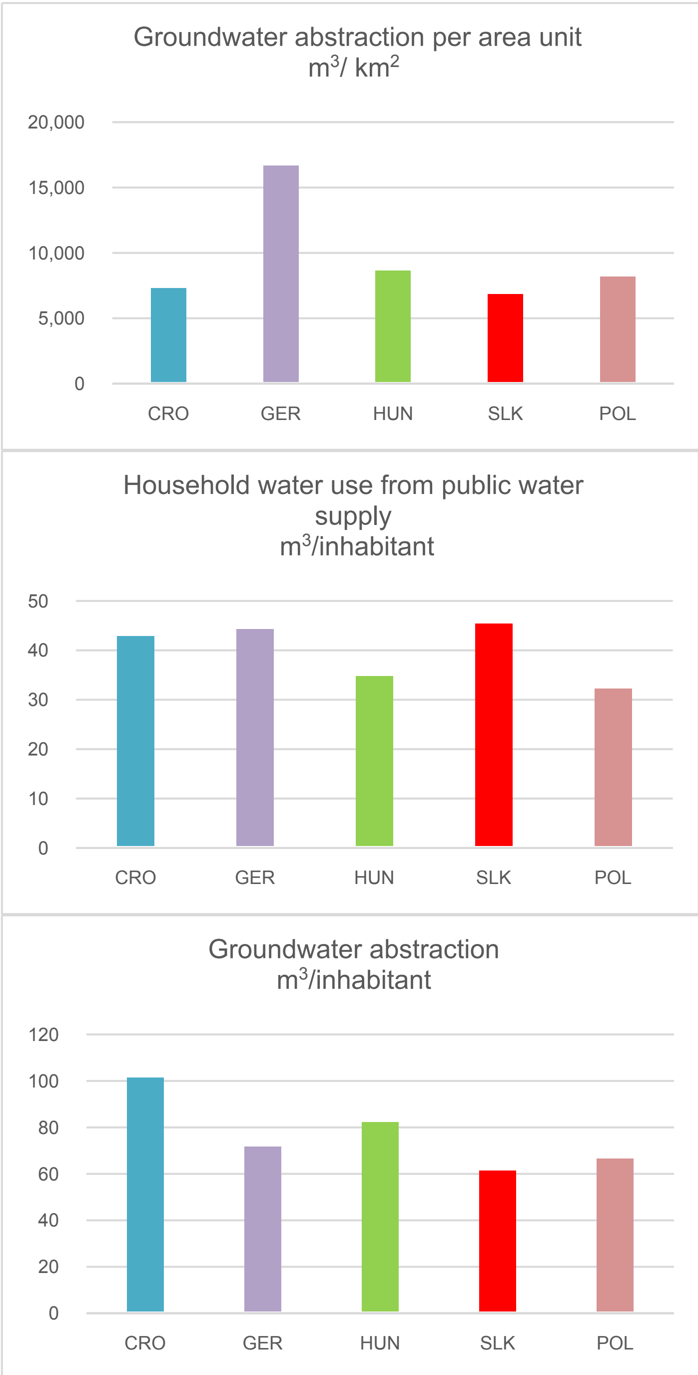


Figure 8. Water utilization in Croatia, Germany, Hungary, Slovakia and Poland in 2017 (Eurostat, 2017)

In 2012 in **Croatia** about 0.95 km^3 of water for different purposes (without hydropower) was extracted. Water resources used for the extraction are groundwater, springs, accumulations, lakes and rivers. Groundwater makes about 41%, springs 17% and the remaining 42% are abstraction of surface water. Almost half of the extracted water (0.46 km^3/year) is used for public water supply, from which groundwater makes about 49% and springs an additional 35% (total 84%) of the water volumes. The remaining 0.49 km^3/y of abstracted water is for technological and similar purposes.

In **Germany** besides the 3.60 km^3 groundwater used for public water supply in 2016, further 1.14 km^3 were extracted for mining, 0.73 km^3 for manufacturing, 0.23 km^3 for agriculture, forestry and fishing, 0.08 km^3 for electricity production and 0.17 km^3 for the remaining industrial sectors. The total groundwater volume extracted of 5.96 km^3 in 2016 represents approximately 12 % of the annual groundwater recharge in Germany, which has been estimated at 48.2 km^3 (Federal Institute for Geosciences and Natural Resources, 2019).

In **Hungary** the principle aim of groundwater abstraction is to provide drinking water supply. In addition, groundwater is abstracted for industrial, agricultural (irrigation and animal-husbandry), spa, balneology, energy and other purposes. Around 0.80 km^3/y of groundwater is abstracted, while total protected resources within drinking water protection zones is around 0.003 km^3/day.

In **Slovakia** the assessment of relationship between potentially available groundwater resources and groundwater used for human purposes is carried out by the Slovak Hydro-meteorological Institute (SHMI) through the annual water balance. The groundwater zone is a basic unit for the assessment of groundwater balance. Slovakia is divided into 141 hydrogeological regions, where evaluation of exploitable groundwater amount is assessed every year. Quality of the evaluation depends on accessible information (hydrogeological survey, monitoring of quality and quantity) in these regions. A part of exploitable groundwater amounts in Slovakia are approved by the Commission for Approving the groundwater amounts instituted by the Ministry of Environment of the Slovak Republic, and the rest amounts are estimated by SHMI. In Slovakia, according to the information from report of State Water Management Balance for year 2017, there is 76.53 m^3/s of exploitable groundwater (including geothermal and mineral water). This amount represents 52.2 % of natural groundwater resources in Slovakia. Declared amount of groundwater abstraction is 10.60 m^3/s, which represent less than 14 % of exploitable groundwater amounts, but reality is probably higher. Main purpose for groundwater abstraction in Slovakia is drinking water supply (7.85 m^3/s), next are food industry (0.23 m^3/s), other industry (0.80 m^3/s), agriculture: livestock (0.22 m^3/s) and crop (0.18 m^3/s) production, social purposes (0.23 m^3/s) and other usage (1.06 m^3/s).

In **Poland**, groundwater was abstracted for the needs of the national economy and population in the amount of about 1.7 km^3 in 2017, according to the latest data published by CSO (Statistical Office of Poland, 2018). For production purposes, 0.21 km^3 of groundwater and 0.05 km^3 of water from mine and building constructions drainage were exploited. Also, 0.002 km^3 was abstracted for irrigation in agriculture and forestry.

3.1.3. Percentage of groundwater in overall water supply

Most of the drinking water supply for Croatia, Germany, Hungary and Slovakia comes from groundwater.

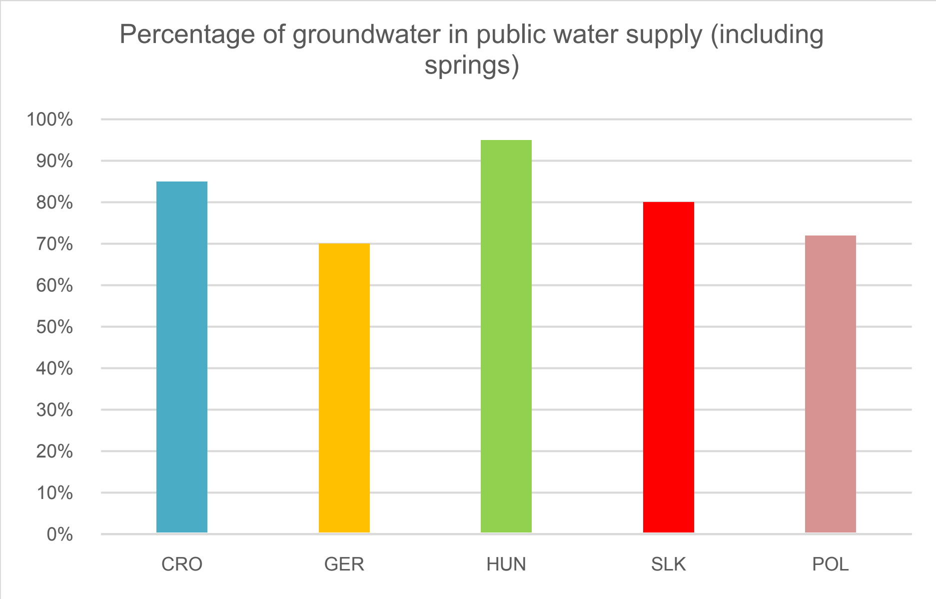


Figure 9. Percentage of groundwater in public water supply for Croatia, Germany, Hungary, Slovakia and Poland

According to the data from Croatian Bureau of Statistics, public water supply in **Croatia** is obtained mostly from groundwater – around 85 %. Groundwater category also includes springs.

In **Germany**, 74 % of groundwater is used in public water supply in average (Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2008) and 69 % was used in 2016 (Federal Institute for Geosciences and Natural Resources, 2019)

In **Hungary**, the total annual surface water abstraction is 5066 million m^3/y. Two-third of this amount is abstracted for energy purpose; the rest is mainly used for irrigation. Minor part of the surface water is used for drinking water, industrial utilization, and fishery or recreation purpose. Aim of groundwater abstractions and their rough distribution between the different sectors (based on the yearly average values for the 2008-2013 time interval in million m^3/y) are the following: drinking water: 0.63 million m^3/y, industrial water: 0.048 km^3/y, irrigation: 0.01 km^3/y, spa, balneology: 0.047 km^3/y and other (around 0.07 km^3/y). Total groundwater abstraction is 0.805 km^3/y. Omitting surface water utilization for energy purposes (which will return to the watercourse directly after utilization), groundwater abstraction is 35 % of the total water abstractions (surface and subsurface together). It is important to mention, that 95 % of drinking water is derived from groundwater in Hungary.

In **Slovakia**, almost 89 % of Slovak population is connected to drinking water supply. Almost 80 % of drinking water comes from groundwater that is 7.85 m^3/s. Surface water as source of drinking water in Slovakia represented less than 20 %, i.e. 1.5 m^3/s in 2017.

In **Poland**, groundwater accounts for around 17 % in total water supply (industry, agriculture, and water supply network). For the needs of public water supply network groundwater constitutes 72 %.

3.1.4. Dominant types of aquifers

Intergranular and karstic aquifers are present in all PP's countries (see Figure 10). In comparison with other PP countries, karstic aquifers are more dominant in Croatia and cover roughly half of the national territory. Intergranular aquifers are dominant in Hungary, Poland and Slovakia.

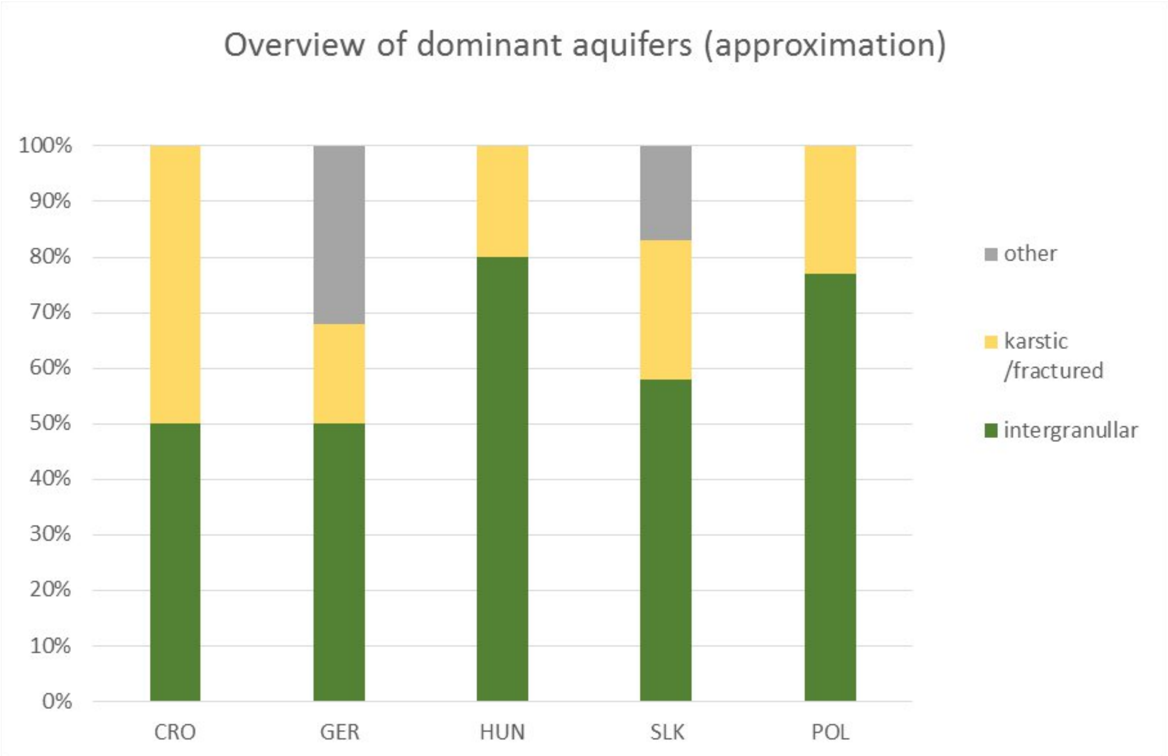


Figure 10. The ratios of dominant aquifer types in Croatia, Germany, Hungary, Slovakia and Poland

Two types of aquifers dominate in **Croatia** – alluvial aquifers of intergranular porosity (Pannonian basin and northern region) and karstic aquifers (Dinaric karst area). Quaternary alluvial aquifers of intergranular porosity in the valleys of the Drava and Sava Rivers with favourable hydraulic properties ensure the majority of developed and planned public water supply in northern Croatia. Karst aquifers are distinctive for their fracture-cavernous porosity, high velocities of groundwater flows, karstification rate, rapid transfer of pollution from the surface to the aquifer, deep groundwater flows and abundant spring discharge.

In **Germany**, some 49 % of the country has intergranular (porous) aquifers, partly with high yields. About 12 % is made of fractured aquifers and some 6 % karst aquifers. Approximately one-third of the country has only local aquifers with low potential (Federal Institute for Geosciences and Natural Resources, 2019)

In **Hungary,** drinking water sources are mainly supplied from groundwater stored either in the porous Pleistocene-Holocene or Upper Pannonian formations, however older carbonate formations have a key role as well. These confined porous aquifers are the most widespread for groundwater supply and the largest hydraulically interrelated body groups of groundwater in Hungary. The maximum depth suitable for groundwater (especially drinking water) extraction is typically 400 m in the Great Hungarian Plain, because, due to the high geothermal gradient, under this depth water temperature exceeds 30 °C which is less suitable for drinking water supply (or even for industrial and agricultural usage).

Fractured and karstified limestone and dolomite aquifers are regional drinking water aquifers as well. These form major karst aquifers in the Transdanubian Range, where the thick Mesozoic sequence consists of mainly Triassic limestone and dolomite rocks. They are in close hydraulic relationship with the overlying younger, mostly Eocene or Cretaceous limestones. Karst drinking water aquifers can also be found in the Mecsek and Villány Mts., Aggtelek Karst as well as in the Bükk Mts. In other mountainous areas the aquifers are dominantly formed by fractured or regionally fractured porous rocks. These aquifers are generally poor, considering their water supply potential. In the margins of mountains, in alluvial sediments or in the upper zones of the thick porous basin fill sediment series, shallow porous layers act as good aquifers. They are exploited mainly for agricultural purposes, but at some special places they supply drinking water. These aquifers are vulnerable to the impact of the climate change and pollution.

Bank-filtered drinking water supplies, where more than 50% of the produced water originates from the connected surface water body while the rest from the background groundwater, are quite important in drinking water supplies in Hungary. All the future perspective drinking water reserves are delineated in aquifers with potential bank-filtration possibility.

Hydrogeological regions in **Slovakia** are represented by Mesozoic (18.4 %), Quaternary (26.3 %), Neogene sedimentary (15.9 %), Neogene volcanic (11.5 %), Paleogene (19.9 %) and Crystalline complex (pre-Mesozoic) (8 %). The biggest part of exploitable groundwater amounts comes from Quaternary intergranular aquifers (58.3 %) and the Mesozoic karstic aquifers are the second biggest suppliers (25 %).

The major groundwater resources in **Poland** come from Quaternary aquifers. Rich in groundwater are structures of contemporary river valleys and of buried valleys, that comprise sands and gravels of glaciofluvial origin. According to data for 2017, groundwater exploitable resources amounted to 18.0 km^3, of which about 77 % (~13.8 km^3) came from Quaternary and Tertiary porous aquifers (Statistical Office of Poland, 2018). Other groundwater exploitable resources originated from fissure and karst aquifers of the Cretaceous age and older.

3.1.5. Quantitative and chemical status of groundwater bodies (according to River Basin Management Plans and Water Framework Directive classification)

The chemical status of all GW bodies in **Croatia** is good except for Varaždin (due to high concentration of nitrates), South Istria (due to high concentration of nitrates) and Bokanjac-Poličnik (seawater intrusions into karstic aquifer). The quantitative status is good for all GW bodies except for Bokanjac-Poličnik (due to overabstraction during summer months).

According to the Water Framework Directive, in Germany, 64 % of groundwater bodies are of good chemical status (main issue nitrate contamination 27% and 4 % due to contamination of pesticides), 96 % are in quantitative good status (German Environment Agency, 2017b)(German Federal Environment Agency, 2014b).

The status of groundwater bodies in **Hungary** is characterized according to the 2nd National River Basin Management Plan (2015) adopted by the Hungarian Government on 9. March 2016. According to this document one third of groundwater bodies are in poor condition. Most of these are partially the shallow cold groundwater bodies, which have weaker status both from qualitative and quantitative point of view. 37 of the 185 groundwater bodies are in poor quantitative status and other 20 are in good status but have a risk for poor status. The chemical status of groundwater bodies (GWB) is poor in 38 cases, and they have a risk for poor condition in 17 cases.

Hydrogeological regions (141) in **Slovakia** were regrouped to 75 groundwater bodies (16 Quaternary groundwater bodies, and 59 Pre-Quaternary groundwater bodies). The evaluation of the condition of groundwater bodies is performed by evaluating their chemical and quantitative status. Out of the total number of 75 groundwater bodies, the following bodies have been evaluated:

11 groundwater bodies in the poor chemical status – 7 Quaternary and 4 Pre-Quaternary

64 groundwater bodies in the good chemical status

The evaluation of the quantitative condition of groundwater bodies consists of assessment of the influence of documented impacts on the groundwater bodies as a whole. The basic indicator of the quantitative condition of groundwater bodies was the stabile regime of the groundwater level (or abundance of springs); the others included the balance evaluation of groundwater quantities and changes in the groundwater regime based on the monitoring programme results. In the Slovak Republic, three groundwater bodies were included in the poor quantitative condition.

In **Poland**, quantitative status (according to River Basin Management Plan) 299,736 km^2 or 165 groundwater bodies are in good status; 12,242 km^2 or 13 groundwater bodies are in poor status (EEA, 2018). As for year 2017 – the results of monitoring of groundwater quality in domestic network in % of total measurement points specify that for unconfined aquifers 63.82 % had good quality and 36.18 % had poor quality; for confined aquifers – 67.06 % had good quality and 32.94 % had a poor quality.

3.1.6. Significant pressures on groundwater

Most significant pressure on groundwater in **Croatia** is agriculture, namely the improper use and/or overuse of plant protection products, including pesticides and manure, resulting in high concentration of nitrates and phosphates in some GW bodies. Discharge of waste waters without previous treatment is a problem since around 54 % of Croatian population is not connected to public sewage systems and only around 35 % of total waste water amount enters purification and treatment systems before discharge. Many households are connected to cesspits which are often improvised and are prone to leakage. This problem is emphasized in drinking water protection zones in karst part of Croatia (Adriatic region). The number of unsanitary and illegal waste disposal sites is unknown due to poor inspection and lack of data in registers. Furthermore, hydromorphological stress (anthropogenic) causes changes in groundwater / surface water regime due to construction of flood protection infrastructure, energy production (hydro powerplants), melioration infrastructure and inland waterways (for cargo transport).

Agriculture causes pressure on groundwater in **Germany** due to use of nitrate, pesticide input, organic fertilizers (biogas, livestock), leaching of organic contaminants and heavy metals. Further pressures come from construction industry (building products, accidents, mismanagement), contaminated sites, landfills, pharmaceutical products, leaking sewer system, mining, surface sealing, rainwater infiltration; climate change (Wojtalla, 2007; Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2008).

A few pollutants, like nitrate, ammonia, sulphate and atrazine were identified in **Hungary**, which caused GWBs to fail for good chemical status, while significant increase in electrical conductivity can poze a risk in some cases. Nitrates turned out to be the dominant pollutant, but other pollutants derived either from agriculture or industry also endanger groundwater bodies. In cases of organic material or nutrient pressures, communal or industrial point sources were considered as significant. In cases of diffuse sources from agriculture, nutrients and pesticides were also considered as significant pressures. Overabstraction also endangers groundwater bodies both on local and regional scales. Abstractions without permission pose a specific pressure type mainly on shallow, but also on deeper porous groundwater bodies.

In **Slovakia**, the main human activities influencing groundwater quality are agriculture, industry, mininig, hydropower, households – settlements with no wastewater treatment, tourism and transport. Major sources of contamination of water bodies include residential agglomerations, industry and agriculture. The main point sources of surface water pollution comprise industrial plants and wastewater treatment plant outlets. Applications of fertilisers in agriculture represent a diffuse source of pollution. Point sources of groundwater bodies' pollution are stored in 3 types of registers (Water plan of the Slovak Republic, 2010):

- KV-ENVIRO containing 13,004 potential sources of pollution;
- Register of environmental loads containing 1,814 localities;
- Database of Integrated monitoring of pollution sources (IMZZ) containing 310 sources of pollution, mostly landfills.

From the 178 groundwater bodies in **Poland**, 154 have no significant anthropogenic pressure. The pressures causing failure to achieve the good quantitative status of groundwater bodies are mainly associated with diffuse sources of mining or agriculture origin (22), over-abstraction (13), point sources: waste disposal site and mine waters (6).

3.1.7. Status of groundwater monitoring

In **Croatia**, surveillance monitoring is performed on piezometers and wells at sites where water for public water supply system is abstracted or at most significant karst springs. Surveillance monitoring covers chemical status and other parameters specified in EU Groundwater Directive for all groundwater bodies in Croatia, although the number of stations varies significantly. Frequency of monitoring is four times a year in karst aquifers and in unconfined aquifers with intergranular porosity, while only once a year in confined aquifers with intergranular porosity. Operational monitoring is performed on groundwater bodies which have deteriorated chemical status or are at risk. Monitoring sites are located at piezometers, wells and springs which are under direct influence of pollution source. Six groundwater bodies are currently under operational monitoring. Minimum frequency of operational monitoring for groundwater bodies which are at risk is four times a year.

Based on EC Water Framework Directive, monitoring networks for the assessment of quantitative and chemical statues are established in **Germany**. The monitoring networks are maintained by the Länder. In total, the Länder have 5,682 surveillance measuring points, 3,979 operational measuring points, and 8,960 points for monitoring quantitative status (German Federal Environment Agency, 2014b). At the surveillance measuring points oxygen, pH, electrical conductivity, nitrate and ammonium are measured. The surveillance and operational measuring points aim to determine the anthropogenic impacts (German Federal Gouvernment, 2010). The Länder operate their own specific measurement network as well as two cross Länder networks for reporting to the European Environmental Agency (EEA). One is for the nitrate measurements and the other one is for documenting the groundwater status in Germany. The two networks together comprise 1,200 measuring points (Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2008) (German Environment Agency, 2017b). Data on nitrate, pesticides and relevant metabolites, arsenic, cadmium, lead, quicksilver, ammonium, chloride, sulphate, sum of tri- and tetachlorethen are necessary for determination of chemical status for the water framework directive (German Federal Government, 2010). At least once per year, the following values are measured: water temperature (°C), pH, electrical conductivity (mS/m), dissolved oxygen (mg/l), base capacity until pH 8.2 (KB 8.2) (mmol/l), acid capacity until pH 4.3 (KS 4.3) (mmol/l), calcium (mg/l), magnesium (mg/l), sodium (mg/l), potassium (mg/l), iron (µg/l), manganese (µg/l), boron (mg/l), aluminium (mg/l), ammonium (mg/l), nitrate (mg/l), nitrite (mg/l), orthophosphate (mg/l), chloride (mg/l), sulphate (mg/l), dissolved organic carbon (mg/l) (information provided by Federal Environmental Agency). The frequency of sampling is decided by the Länder themselves. The collected data must be sufficient to describe long and short term trends of groundwater recharge and managed groundwater extraction or recharge (German Federal Gouvernment, 2010). Groundwater levels at the different measuring points are taken at least twice per year. Measurements to educate farmers on application of pesticides and fertilizers are taken in order to decrease contamination by those (Bund/Länder Arbeitsgemeinschaft Wasser, 2018). Regulations for manure application are applied as well as educative programms for the public to raise awareness (Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2008). For some water suppliers the health authority demands safety ozonation or chlorination availability at the water works.

Groundwater monitoring has a long tradition in **Hungary** due to the dominance of drinking water supply from groundwaters. Today groundwater monitoring is operated based on the requirements of the Water Framework Directive, so Hungary has put surveillance and operational monitoring programmes in place. In monitoring programmes for vulnerable groundwater bodies, besides the basic chemical parameters, measurements are carried out for special pollutants, like industrially used organic compounds (solvents, carcinogenic substances, heavy metals, pesticides, etc.). Trend assessment was carried out for the design of monitoring programmes and for the selection of parameters. The Hungarian RBMP reports 2014 surveillance and 427 operational groundwater quality monitoring sites, while at 1,802 sites groundwater quantity parameters are measured. Quantitative monitoring of all the 185 groundwater bodies is carried on continuously. There are more than 5,000 monitoring points where groundwater level is registered and yield of 70 springs are measured. Hungary is also participating in the basin wide transboundary groundwater monitoring programme coordinated by ICPDR.

In **Slovakia**, the monitoring of groundwater quality and chemical status was divided in accordance with the Water Framework Directive 2000/60/EC (WFD) into basic monitoring (175 sites) and operational monitoring (415 sites). The sampling frequency is from one to four times per year depending on the type of rock environment. The samples are taken in spring and autumn when the extreme condition of groundwater could be monitored. In 2017 in Slovakia, 220 sites were monitored within the operational monitoring programme (except the Žitný ostrov region) where the potential input of pollution to the groundwater from potential pollution source/sources was expected. The region of Žitný ostrov represents a separate part of the SHMI monitoring network since this region is the most significant drinking water resource. The monitoring network of Žitný ostrov comprises 34 piezometric multilayerwells (84 layers) that are monitored from two to four times per year. For fulfilling requirements of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources, within the operational monitoring there were 110 sites monitored in nitrate vulnerable zones. In 2017, totally 183 indicators (field indicators, basic physico-chemical indicators, trace elements, relevant substances, pesticides and other specific organic substances) were monitored. The selection of parameters for the evaluation of the groundwater quality have been adapted to the requirements of the WFD. The Slovak Republic adopted Government Regulation no.354/2006 Coll. laying down requirements on water intended for human consumption and quality control of water intended for human consumption, in which the Directive 98/83/ EC is transposed. The groundwater quantity monitoring network in Slovakia consists of springs monitoring and wells monitoring (piezometers). Springs are monitored within the primary network. Monitoring consists of free-flowing as well as captured springs for drinking water use in all main hydrogeological regions (mostly Mesozoic formations). In total, 353 springs were monitored in 2017. Observations at 179 springs are taken weekly. Furthermore 174 springs were outfitted with automatic and limnigraphic recorders with hourly or continuous recording. Water temperature is measured in addition to spring yield. The primary and secondary network of groundwater monitoring wells (piezometers) operated by SHMI consists of 1,133 sites (in 2017). Water level and groundwater temperature are in general recorded weekly by voluntary observers (on Wednesdays) in 273 wells. Automatic recorders with hourly intervals and limnigraphic recorders with continuous recording were installed at 860 sites. In all 860 site the water temperature was measured daily and at 26 sites weekly. Most of the monitoring wells are situated in Quaternary sediments, only few (80 wells) are situated in pre-Quaternary formations - from Neogene to Crystalline complex.

The monitoring network in **Poland** comprises of 1,250 points (as of March 2019). Measurements (water level), depending on the function of each type of monitoring, are carried out over various timescales. Groundwater level measuring is conducted daily in first-tier hydrogeological stations or weekly in second-tier hydrogeological stations. Within the framework of chemical state monitoring, two types of monitoring are conducted – surveillance monitoring and operational monitoring. Surveillance monitoring is carried out on a national level every three years. In the years between surveillance monitoring, operational monitoring is carried out, which involves sampling, once or twice a year, of groundwater bodies that are at risk of failing to achieve good status until 2021. In 2018 groundwater level was measured in 1,234 monitoring points, chemical analysis was conducted in 384 monitoring points (operational monitoring). The monitored parameters are major ions (HCO_3^-, SO_4^{2-} Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+) minor ions (Fe, Mn, Al, NO_3^-, NO_2^-, NH_4^+ and organic matter) microconstituents (As, Ba, B, Cr, Zn, F, Al, Cd, Cu, Ni, Pb) and selected water physicochemical properties (PEW, pH, temp., dissolved oxygen, phenols).The waters of good quality were the most frequent (42 %) while acceptable quality occurred in 31 % of cases, poor in 7 % cases. Only in 5 % of cases water quality was very good. In remaining cases Fe and Mn compounds were most frequent above the standards (50 %) as well as N compounds (18 %).

3.1.8. Status of drinking water protection

Directive 2006/118/EC on the protection of groundwater against pollution and deterioration, point 15:

”Measures to prevent or limit inputs of pollutants into bodies of groundwater used for or intended for future use for the abstraction of water intended for human consumption, as referred to in Article 7 of Directive 2000/60/EC, should, in accordance with Article 7(2) of that Directive, include such measures as are necessary to ensure that under the water treatment regime applied, and in accordance with Community legislation, the resulting water will meet the requirements of Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. Those measures may also include, in accordance with Article 7 of Directive 2000/60/EC, the establishment by Member States of safeguard zones of such size as the competent national body deems necessary to protect drinking water supplies. Such safeguard zones may cover the whole territory of a Member State.”

Drinking water protection zones (DWPZs) take up around 19.08% of **Croatia's** territory. Authorities responsible for water management are Ministry of Agriculture (Water Management Administration) and Croatian Waters who cooperate with regional and local government units. Criteria for delineation of DWPZ in intergranular aquifers are groundwater travel time and discharge rate, while in aquifers with fracture and fracture-cavernous porosity criteria additionally take into account groundwater flow velocity. In Croatia there are three defined water protection zones in intergranular aquifers and four in aquifers with fracture and fracture-cavernous porosity. Legislation in Croatia also allows establishing special protected areas in the sense of water protection reserves in the remote and mountainous regions where several DWPZ can be joined together. DWPZ are implemented within “Terms of use, development and protection of space” of physical planning documents on national, regional and local level. In these documents for each established zone interdictions and protection measures are given, while the borders of zones are implemented in cartographic representation of plans. According to the Croatian regulations for DWPZ, there are a number of limitations and restrictions in the particular sanitary protection zones. In aquifers with fracture and fracture-cavernous porosity, restrictions are more rigorous then in intergranular aquifers. According to the level of limitations and restrictions DWPZ are divided into IV zones of limitations which include following activities:

IV. zone

- wastewater discharge without previous treatment,
- construction of production facilities for hazardous substances,
- construction of facilities for recovery, treatment and disposal of hazardous waste,
- construction of facilities for storage of radioactive, hazardous or oil-based fuels and materials,
- removal of topsoil,
- use of powder explosives,
- exploration and exploitation wells, except for water research,

III. zone

> all prohibitions from zone IV and additionally,
> temporary or permanent waste disposal,
> pipeline construction (hazardous fluids),
> construction of gas stations without proper technical precautions,
> surface of underground mining excluding geothermal and mineral waters,

II. zone

> all prohibitions from zone IV. and III. zone and additionally,
> agricultural production, except ecological (organic),
> cattle production (maximum 20 livestock units),
> the formation of new cemeteries and expansion of existing ones,
> construction of all industrial facilities that pose threat to water environment,
> forest clear cuts except sanitary cuts,

I. zone

> The first zone is intended to protect all the intake facilities (e.g. springs, wells, drainages, etc.) and the area which directly drains toward these facilities. First zone must be fenced. In the I. zone, all activities except those related to abstraction, conditioning, and transfer of water in the supply system are prohibited.

The relevant water inspection defines penalties that are laid down in accordance with the applicable laws. Drinking water protection zones in Croatia are shown in Figure 11.

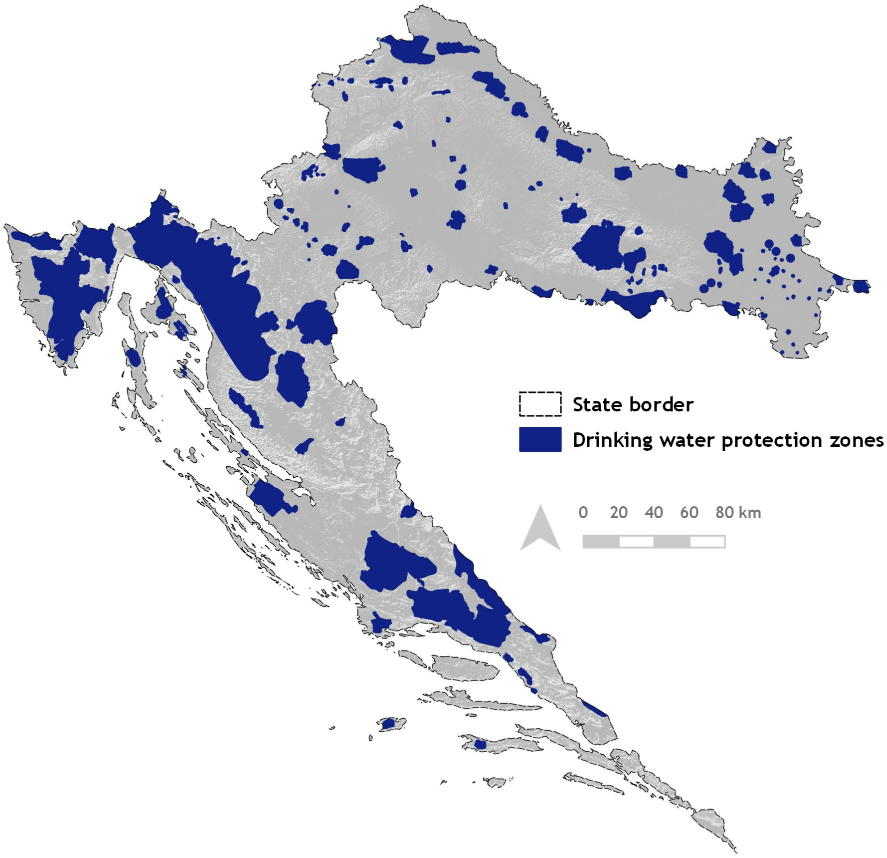


Figure 11. Drinking water protection zones in the Republic of Croatia (taken from PROLINE-CE)

In **Germany**, according to §51 in The German Federal Water Act (Wasserhaushaltsgesetz - WHG), water protection zones (**Fig. 12**) are determined as far as it is required for the general well-being. The principles and aims during the determination of DWPZ are:

- the protection of water bodies which are assumed to be of particular interest for currently existing or prospective public water supply;
- to quantitatively enrich the groundwater aquifer;
- to protect the water bodies from harmful rainfall runoff and discharges from agricultural land carrying soil particles, fertilizers or pesticides.

Basically, limitations and restrictions are mostly adapted to site-specific characteristics and thus may differ between water protection zones. However, general valid requirements are given by a model ordinance of the Bavarian Environmental Ageny (LfU) (LfU, 2010). Within the model ordinance, general limitations and restrictions are made for:

- activities intruding into the subsurface (e.g. limitations for activities intruding into aquifer protective layers),
- handling of substances hazardous to water (e.g. restrictions for the construction and use of installations for the treatment or distribution of substances hazardous to water),
- wastewater treatment and disposal (e.g. interdiction to implement overflow tanks for the discharge of rain or mixed waters),

- traffic routes, spaces for specific purposes and house gardens (e.g. interdiction to implement storage facilities for construction materials),
- structural installations (e.g. interdiction to designate new building areas) and agricultural, silvicultural and horticultural land uses (e.g. interdiction to spread sewage sludge).

Data within the .shp provided by Project Partner include only DWPZ within Bavaria, and they take up around 1.01 % of the total German territory. DWPZ borders are in line with the relevant spatial planning documentation and should be drawn so that they are following land plot borders (LfU, 2010a). The responsibility to control the implementations of measures as well as their success (in terms of enhanced water quality and/or quantity) is legally transferred to the water supplier. The water supplier thus performs a self-monitoring. Furthermore, penalties may be imposed in case of negligent or intentional non-compliance with the limitations and restrictions defined for each DWPZ.

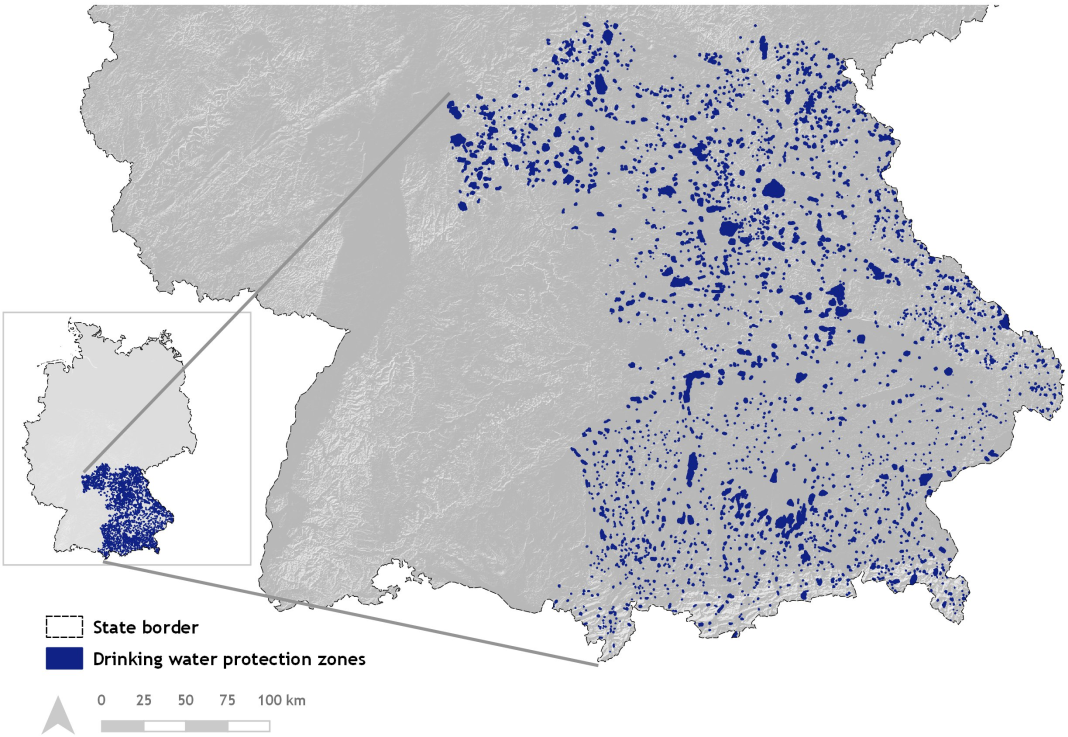


Figure 12. Drinking water protection zones in Germany (Project Partner provided data only for the Bavaria area, taken from PROLINE-CE)

In **Hungary**, the legal and administrative organization of water policy is the responsibility of the Ministry of Interior in Hungary. General Directorate of Water Management and 12 water management directorates are responsible for water management. Government Regulation 123/1997 (VII.18.) on the protection of the actual and potential sources and the engineering structures of drinking water supply defines the criteria of water protection zones. The scope of this regulation extends to the sources of water serving the supply of drinking water, mineral and medicinal water development, regardless whether actually exploited, committed or designated for future use, further to the facilities which serve the treatment, storage and distribution of water for such uses, and which supply water to at least 50 persons on a daily average.

Protection includes determination, designation, establishment and maintenance of a protective block or area or zone (**Fig. 13**). Protection is realised by the implementation of part, or all of the safety measures. The boundaries of the protection zones shall be determined by assessing the particular hydrological and hydrogeological conditions considering the permitted rate of abstraction or in the case of future sources of supply the full capacity of the aquifer(s). The protective measures set forth in the regulation to serve the following purposes:

- The inner protective block, zone: protection of the abstraction works and the water supplies from direct pollution and damage,
- The outer protective block, zone: protection against refractory, further bacterial and other decomposable pollutants,
- The hydrological or hydrogeological block, zone: Protection against refractory pollutants by measures prescribed for the entire, or part of the catchment (recharge) area of the abstraction. The hydrogeological protective block or area is subdivided to “A”, “B” and “C” protective zones, the delineation all of the protective zones is based on the estimation of the travel time, assuming steady groundwater seepage flow.

The most stringent restrictions are in the inner zone, for example: The inner zone shall be fenced or guarded in another effective manner. The owner of the inner zone shall be the same as that of the water facilities. Depending on the type of protection zone several activities are prohibited, or prohibited for new facilities and activities, or may be allowed depending on the outcome of an environmental audit or environmental impact assessment (EIA). Other activities are allowed if they operate without any pollution, new facilities and activities can be established/ started depending on the outcome of an EIA, or environmental audit, or an equivalent investigation. Some activities are not restricted at all in the hydrological or hydrogeological zones.

Spatial planning documents take into consideration all the vulnerable DWPAs and DWPZs (including those areas which are determined or estimated, but not yet designated by the authority). DWPZs are part of the national water quality protection zone on the National Spatial Management Plan.

DWPZ take up around 7.96 % of the Hungarian territory (according to the data provided by the Project Partner).

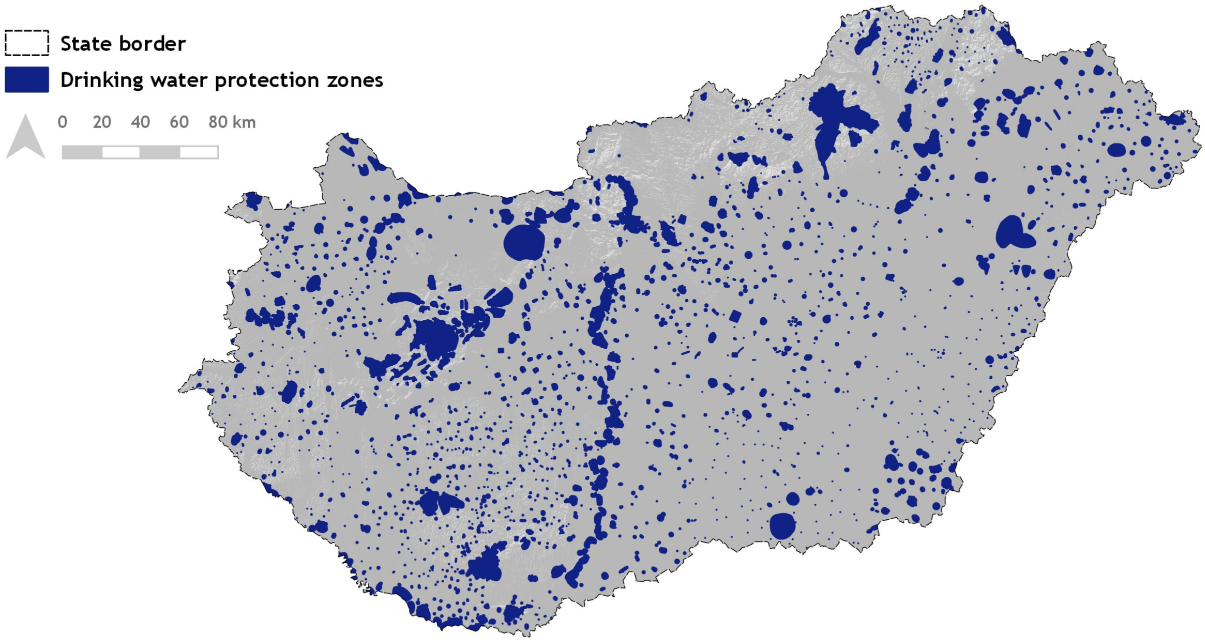


Figure 13. Drinking water protection zones in Hungary (taken from PROLINE-CE)

Regional offices of the Directorate General for Disaster Management control the compliance with the provisions, obligations and restrictions on designated and established protective blocks, protective areas and zones. Authorities also define fines and suspensions in case of non-compliance with the DWPZ requirements.

All surface and groundwater supply sources in **Slovakia** are protected by law (Act No. 364/2004 Coll., Resolution No. 29/2005 Coll.) by delineation of the protection zones. Protection zones are proposed, delineated and approved to protect the capacity, quality and health faultlessness of the water supply source. Each water supply source is protected by the protection zone of the 1st degree. The 1stdegree protection zone is estimated to protect the area in the proximate surroundings of the source against negative affecting or endangering the water source, or against damaging of its intake structure. The protection zone of the 2nd and 3rd zone can be delineated when there is no other special protection of water in the area of its formation and circulation, or the protection of the water source in the 1st protection zone is inefficient. Other special protective measures are resolution of (1) protected water supply areas, (2) sensitive areas, or (3) vulnerable areas. Protected water supply areas, or protected areas of natural accumulation of water, are declared by the Act No. 305/2018 Coll., there are ten protected water supply areas declared in Slovakia. Sensitive areas (Act No. 364/2004 Coll.) are surface water bodies where the quality of water can be endangered by increase of nutrients, or areas used as water supply sources or areas where is an increased demand for waste water treatment to ensure the increased water quality protection. The vulnerable areas (Act No. 364/2004 Coll.) are all agriculturally used areas where the surface runoff formed by rain water flows into the streams or infiltrates into soil recharging groundwater, and the concentration of nitrates is higher than 50 mg/l or such concentration might be reached in the near future.

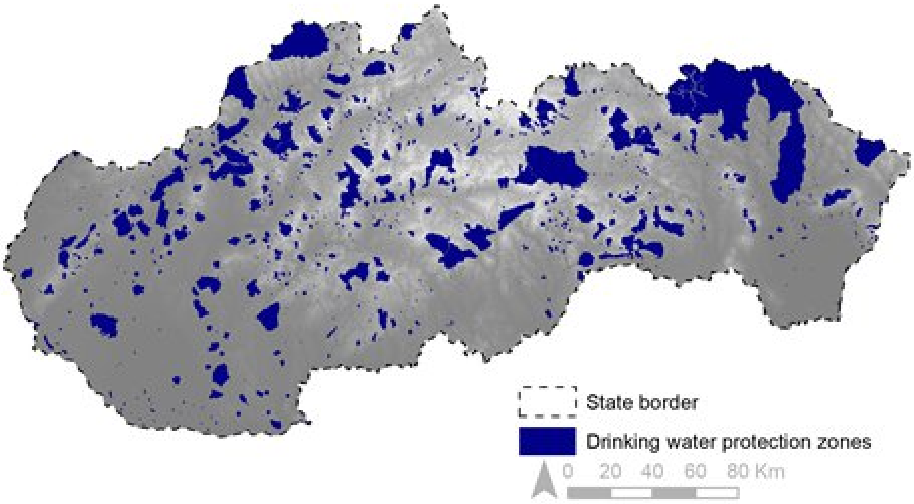


Figure 14. Drinking water protection zones in Slovakia (taken from WRI database)

According to the Water Law (Journal of Laws of 2017, item 1566), the drinking water protection zone in **Poland** consists of a direct protection zone, established arbitrarily for each well field, and an outer protection area. The establishment of the outer protection zone depends on the results of a risk analysis (Art. 133.3). This analysis is performed for well fields supplying more than 10 m^3/d or for water supply for more than 50 people. The risk analysis must be updated at least every 10 years, and in the case of well fields supplying less than 1.000 m^3 - at least every 20 years. The owners of well fields for which no outer protection zone has been established are to conduct a risk analysis within 3 years from the date of entry into force of the Water Law Act and submit applications for the establishment of inner and outer protection zones if justified based on results of risk analysis. A direct drinking water protection zone is established by the competent authority of Polish Waters by way of a decision. The drinking water protection zone consisting of inner and outer zones is established by the voivode through an act of local law. In the area of the established protection zone, it is possible to prohibit or limit works or other activities that may affect the water quality or well field efficiency. 26 proposals for these prohibitions are provided in the Water Law Act. Information on protection zones and protection areas is collected in the Water Management Information System (SIGW).

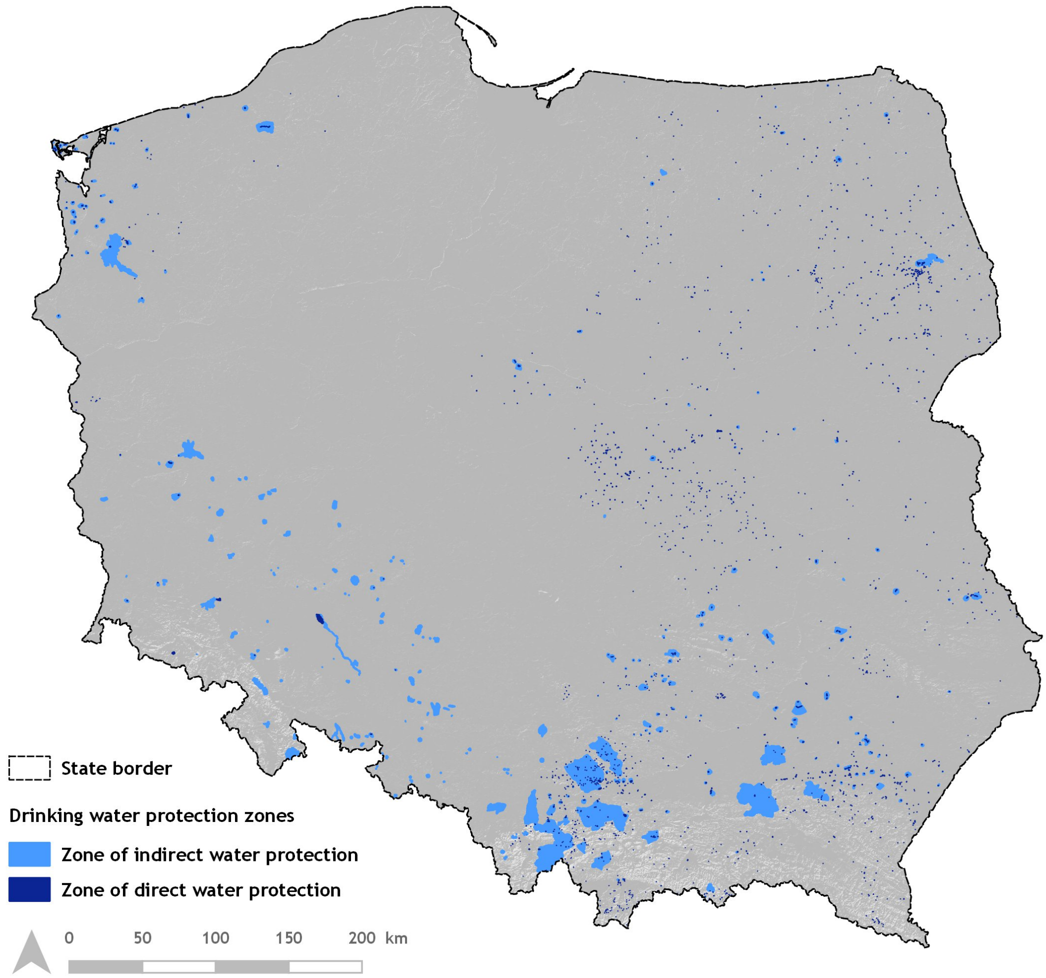


Figure 15. Drinking water protection zones in Poland (taken from PROLINE-CE)

3.2. MAR case study in Germany

Legal framework regarding MAR in Germany

MAR is regionally a fundamental part of sustainable water management and water supply. On federal level 17.4 % of overall water supply is obtained from MAR schemes (8.8 % from riverbanks infiltration and 8.6 % from groundwater recharge through wells or infiltration basins). MAR is incorporated into Federal Water Act (Wasserhaushaltsgesetz) and Federal Waste Water Regulation (Abwasserverordnung). Implementation is done by water suppliers. Water supply is a public sector. Implementation is done by water suppliers. In Germany, MAR schemes are established in areas with limited drinking water supply (Kuehn and Mueller, 2000) and for irrigation purposes.

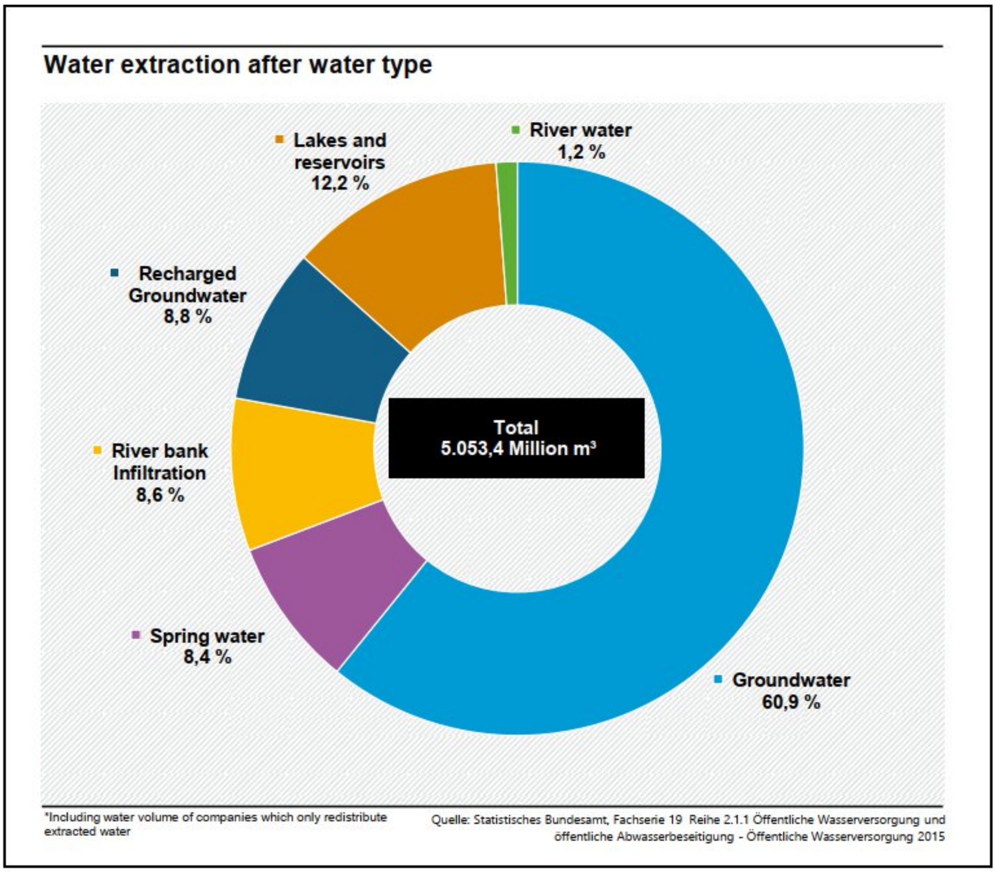


Figure 16. Water extraction by water sources (Statistisches Bundesamt DSTATIS, 2018)

Site Hessian Ried

In the Hessian Ried area, in Germany, since 1989, surface water from the river Rhine is treated and then infiltrated into the aquifer. The MAR scheme is required to stabilize the groundwater recharge to support the supply of groundwater for drinking water purposes and maintaining the groundwater ecosystem in seasonal fluctuations.

In the area the yearly precipitation is 653 mm, it is divided in 56 % during the hydrological winter and 44 % in the hydrological summer. Elevation is around 100 m a.s.l. and the annual average temperature is 9.5 °C. The hydrological situation results for long time average in a negative water balance because of high potential evaporation losses during the summer months. During dry years, groundwater recharge is only several mm/y, in wet years it can be up to 100 mm/y.

The Hessian Ried is located in the northern part of the Upper Rhine Rift with Quaternary and Tertiary depositions. In the north it is restricted by the river Main, in the west by the river Rhine, in the east by the Odenwald forest and the Spendlinger Horst forest and in the south the restriction is the border to the Land/Federal State Baden-Württemberg. It has a diameter of 60 km, a width of 15 to 20 km and an area of 1,100 km². Of hydrogeological importance are sandy and gravely-sandy sediments above Pliocene formations. For the groundwater recharge, tributaries from the Odenwald forest, precipitation and intergranular aquifers are of significant importance. The wet origin of the reed area of the Hessian Ried results from good subsurface water retention potential and the slight gradient. Forest and agriculture as well as residential and industrial areas are the main land use types in the Hessian Ried (Hessisches Ministerium für Umwelt ländlichen Raum und Verbraucherschutz, 2005).

Several methods for well injection and enhanced infiltration trenches are chosen in the Hessian Ried. The MAR type is aquifer storage, transfer and recovery (ASTR) according to the definition by Gale, 2005; Dillon *et al.*, 2008; Sprenger *et al.*, 2017. In Figures 17 and 18 schematics of the infiltration wells and trenches used are displayed. Furthermore, adsorption wells and infiltration trenches are used.

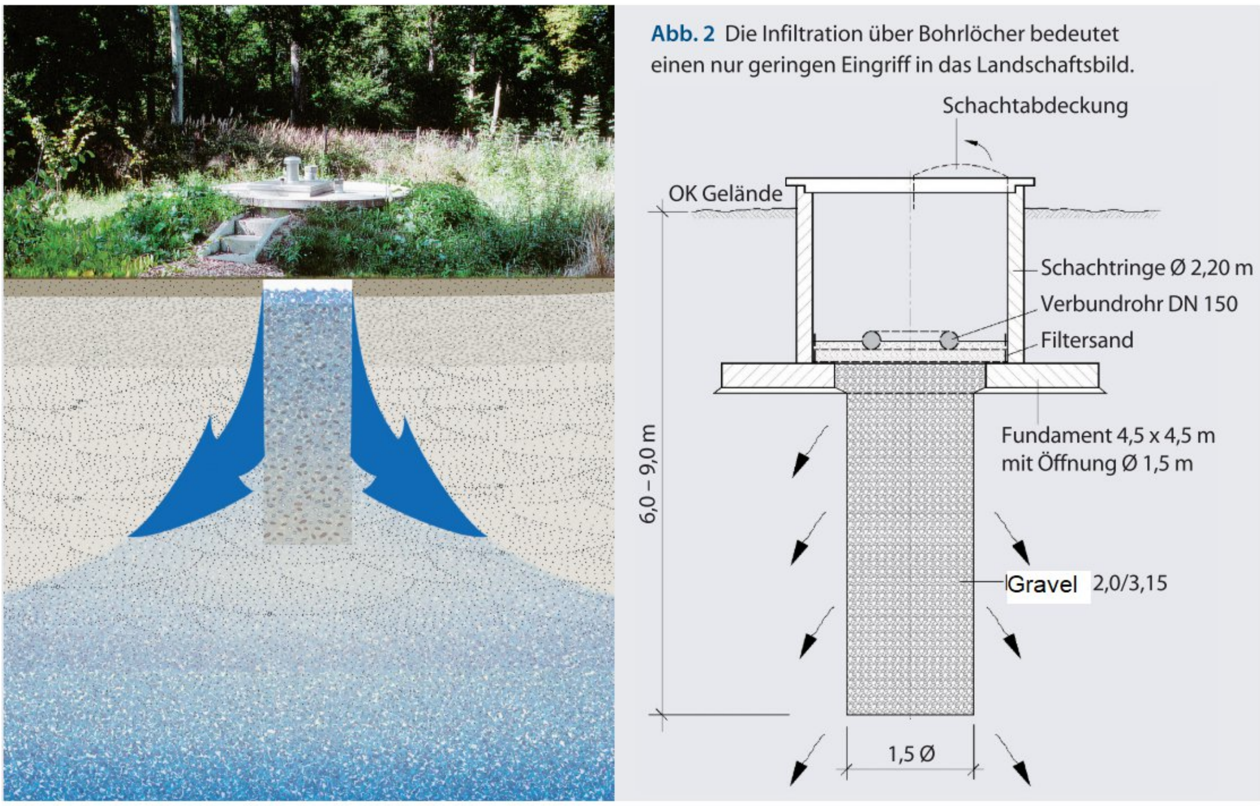


Figure 17. Infiltration Well at Hessian Ried (Weber and Dr. Mikat, 2011)

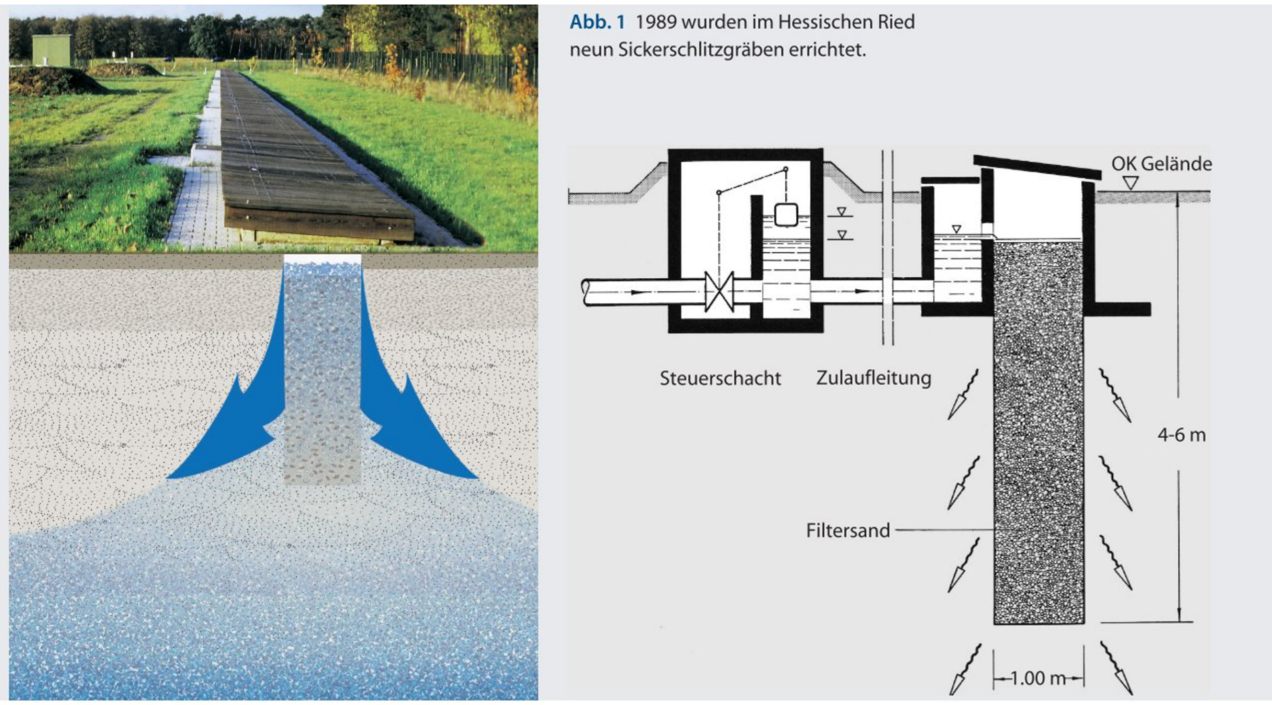


Figure 18. Split Pit infiltration at Hessian Ried (Weber and Dr. Mikat, 2011)

The water from the river Rhine is intensively pre-treated in several steps: mechanical filtration, preozonation, primary flocculation, sedimentation, main ozonation, secondary flocculation, several layer filtration and activated carbon filtration.

The system is operated seasonally, in times of high demand for agriculture (March-September) when the infiltration amounts are decreased and agriculture is supplied. Outside of cultivation periods all treated water is being infiltrated into the aquifer and in wet periods, no infiltration is done.

The MAR site is requiring high maintenance due to the regulatory requirements. Every second m^3 is treated twice.

Lessons learned from Hessian Ried

In one article it was described, that infiltration wells were chosen/preferred over trenches or split pits because of the lower space requirement. Furthermore, at new drilling sites, site specific filling medium was chosen after evaluation of drilling profiles and hydrogeological modelling. By these measures, suffusion and colmatation was also reduced. Well regeneration must be done frequently to maintain productivity (Hessisches Ministerium für Umwelt ländlichen Raum und Verbraucherschutz, 2005; Weber and Dr. Mikat, 2011).

The MAR sites at Hessian Ried are parts of an integrated groundwater management plan. 800 groundwater monitoring wells are evaluated monthly and the MAR sites are managed within the regulatory requirements. Chemical and quantitave groundwater quality is supervised, in accordance with the Federal Water Act (Bundesministerium der Justiz, 2014; Manger, 2018).

Lake Tegel - Berlin

The city of Berlin, capital of Germany, relies to 56 % on riverbank Infiltration and to 14 % on artificial recharge for their drinking water supply which is practiced since 1850 (Statistisches Bundesamt DSTATIS, 2018). At the Tegel lake (Fig. 19) more than 40 production wells for lakebed infiltration were installed in 1901 and 1903 (BWB, 2019). In 1960, three infiltration ponds (8,700 m^2 with 3 m depth) commenced operation to enhance groundwater recharge for drinking water supply as well. The Tegel lake is recharged to 14-28 % by water treatment plant effluents (Greskowiak *et al.*, 2005).

The MAR type according to is enhanced infiltration though surface spreading methods with infiltration ponds and induced bank infiltration at the lakebeds.

The aquifer is composed by Quaternary sediments of fluvial and glacio-fluvial, medium-sized sand deposits with 50 m thickness; average range of hydraulic conductivities: 10 to 100 m/d. Lake Tegel is underlain by silts and clays that are rich in organic material and form a relatively impermeable layer. Hence, the most important flow path is through the thin layer of till at the bank of Lake Tegel. The recharge of groundwater through the silt and clay layer and groundwater flow beneath Lake Tegel is of minor importance (Ray, Melin and Linksy, 2003).

Annual precipitation is 645 mm/y. Lake Tegel is located in the north west of Berlin. It has a surface area of 4 km^2. The northern part of the lake has a depth of 16 m, the rest of the lake has an average depth of 6 m (Ziegler, 2001). Main land use is forest and agriculture.

Clogging is encountered in the system due to physical processes and microbial activities. A microstainer is used as pre-treatment. At the beginning of the operational cycle, an infiltration rate of 3 m/d and after clogging 0.3 m/d were documented. In case of clogging, around every 3-4 months, remediation measures are taken. About 10 cm of the sedimentation layer is abraded (Greskowiak *et al.*, 2005).

13 groundwater monitoring wells are installed, four of them are located in the saturated zone at 19-25 m depth and 9 of them in the unsaturated zone at 2-9 m depth (Ziegler, 2001). The infiltration wells/ponds are monitored once per year. The water taken from more than 40 production wells are post-treated and monitored daily according to the Federal Water Act (Bundesministerium der Justiz, 2014; Gruetzmacher and Kumar, 2016).

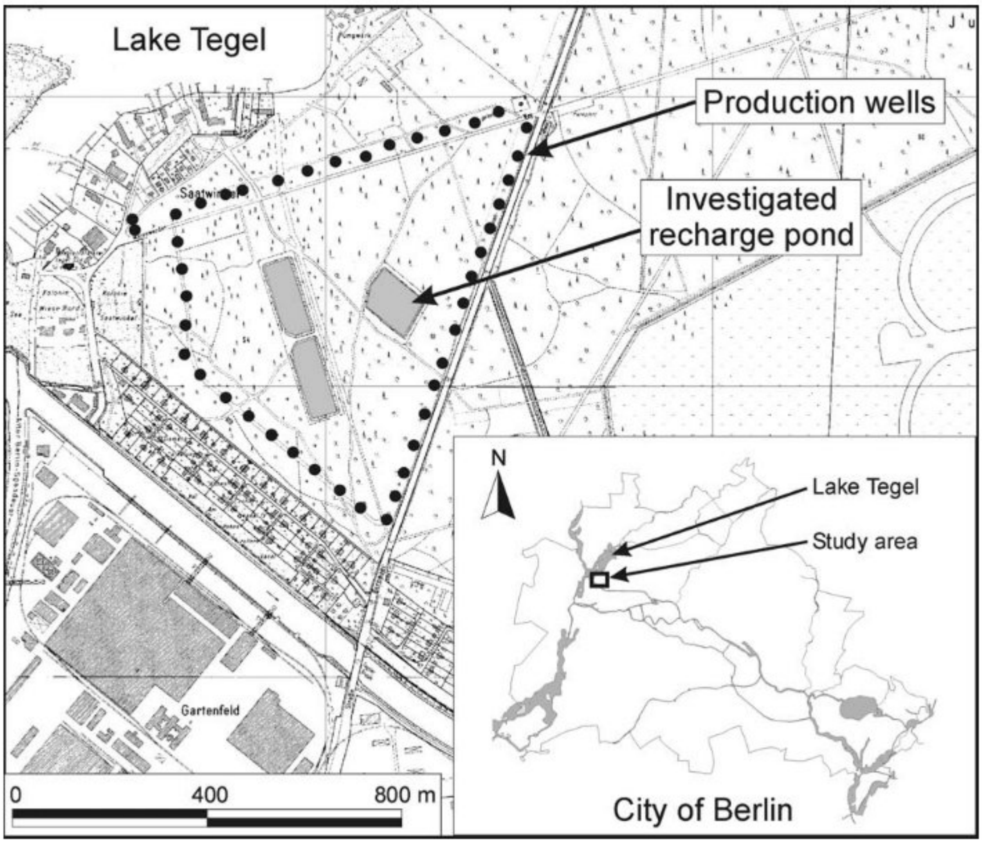


Figure 19. MAR site Tegel Lakes in Berlin (Greskowiak et al., 2005)

The tributaries Tegeler Fließ and Nordgraben of the Tegel lake are pre-treated with phosphate elimination by Fe(III)-Sulphate in order to avoid eutrophication. Further the water conveyed to the infiltration ponds is passed through micro sieves. With the phosphate elimination pre-treatment, 25-30 % of phosphate is eliminated. The phosphate originates also from the effluent of the upstream water treatment plant (Ziegler, 2001). Post treatment is aeration for iron/manganese removal (Grünheid, Amy and Jekel, 2005).

The management scheme of the MAR site is implemented by the operator, the Berlin Water Works. In general, more water is abstracted in the summer months (Grünheid, Amy and Jekel, 2005).

After (Ziegler, 2001) a reduction of 2550 % of dissolved organic matter due to river bank filtration is documented at the Tegler Lakes.

Böckinger Wiesen

- 2 km long, 1.2 km² area in the floodplains of river Neckar
- Agricultural land use
- Drinking water supply for the city of Heilbronn
- River Neckar water, retained at a weir 1.5 km downstream is creating a reservoir
- Geology: Quartary deposition with Holocene loam, silt depositions originating from river meandering

- Hydrogeology: first groundwater storey: intergranular aquifer (10 m depth 4 m thick), second: Lower Keuper (Karst aquifer), third: Upper Muschelkalk lime stone and upper dolomite of the upper Muschelkalk limestone
- 8 production wells in integranular aquifer river bank infiltration
- 60 groundwater monitoring sites

(Heinz Hötzel and Reichert, 1996).

3.3. MAR case studies in Hungary

Legal framework regarding MAR in Hungary

Bank-filtered water supplies have a key role in Hungary in drinking water abstraction. The artificially recharged groundwater supplies are only sporadic in the country. As artificially recharged groundwater supply systems have no great tradition in Hungary, therefore the legal and regulatory background is incomplete. The following legislations only indirectly affect this type of groundwater recharge.

As both types of MAR type water supplies (i.e. bank-filtered and artificially recharged supplies) are vulnerable, therefore they are subject to Government Regulation 123/1997. (VII.18.) on the protection of the actual and potential sources, and the engineering structures of drinking water supply. 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 the 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.

Bank-filtered aquifers play a key role in drinking water supply in Hungary. 35-40 % of the population of Hungary (almost 4 million people) is provided from bank-filtered aquifers. 75 % of the future water supplies are to be bank-filters making it a key player in the future water management. 52 % of current and future water supplies are bank-filtered aquifers.

Two waterworks (Borsodszirák and Bátonyterenye) have already artificial recharge systems for drinking water supply. Responsibility for the implementations of MAR systems is subject to the owners of water supplies (local administrations) and operating companies of the waterworks.

Waterworks of Borsodszirák

The groundwater is highly contaminated near the water supply of Borsodszirák in many components: (ammonium, nitrate, chloride, sulfate, iron, manganese, all water hardness, spec. electrical conductivity, 1,1,2- trichloroethane). Contamination is caused by industrial and communal sources.

The aims of artificial recharge are screening, protection from background-sourced pollutants and increasing the capacity of the waterworks.

The final use of water is drinking water for the residents of Borsodszirák.

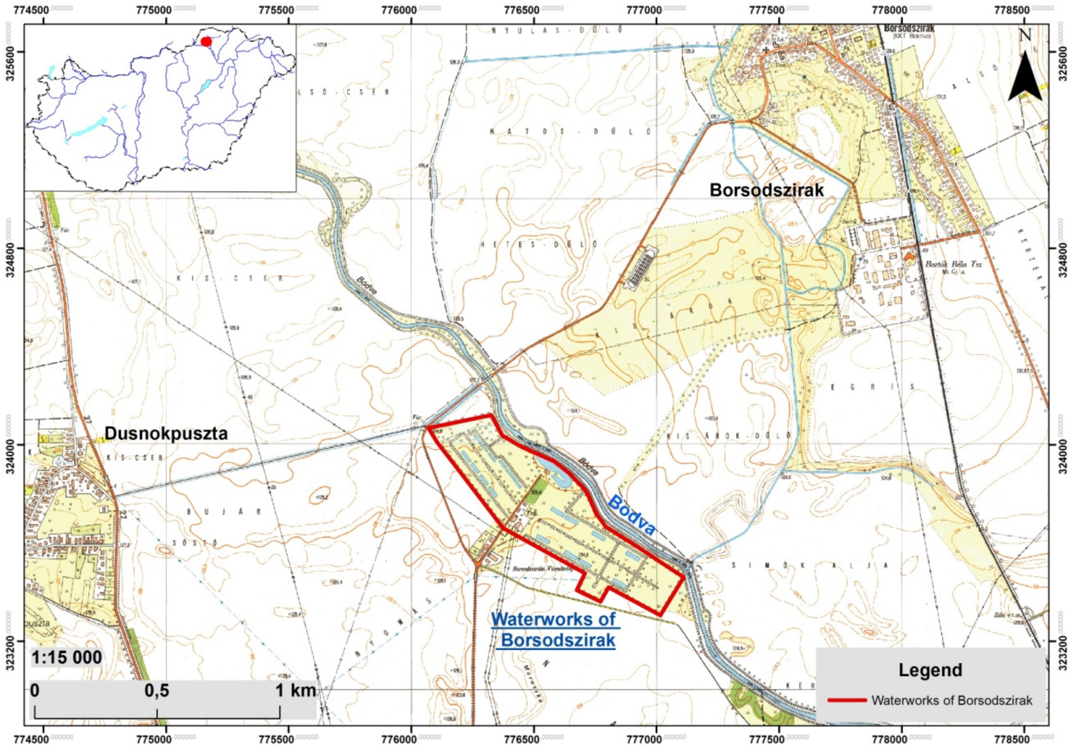


Figure 20. Location of Borsodszirák water supply

Geography

The water supply is located in the north-eastern part of the country, in Borsod-Abaúj-Zemplén county, surrounded by the Sajó and Bódva River (Fig. 20). The area is a low-lying hillslope that gradually decreases in the south-east, then passes into the plains. The average elevation is 150-170 m BSL (meter above Baltic Sea Level) at N, and 120-125 m BSL lower at NW. Precipitation from the area is collected by the Sajó and Bódva River through tributaries and intermittent streams.

Geology

The area belongs to the Eastern-Borsod brown coal basin with structural geological borders of Bükk Mts on the south (mainly east-west orientated arched range) and the Darnó Tectonic Zone on the west (with NNE-SSW orientation). On the east the Pannonian Basin is the border which is parallel with the Bódva River (North-West orientation).

The Darnó Tectonic Line intersects the region in the middle and this is reflected in the deep geological structure: to the north of the tectonic line, Devon-Carboniferous metamorphic formations are present, and to the west, Triassic carbonate rocks form the bedrock. Later, mainly Oligocene marl, sand, Miocene sediments with brown coal deposits, sand and sandstone are settled here. About 60 % of the surface is covered by loess and loess derivatives and 15 % by glacial loam (adobe).

The region is one of the focal areas of the Borsod brown coal deposits. The Paleozoic-Mesozoic rocks and partly the Tertiary sediments host coal deposits formed in the Lower Miocene.

Hydrology

River Sajó - The area of interest wholly belongs to the Sajó catchment area. The River Sajó has a total length of 229.4 km, a catchment area of 12,708.3 km^2, and the length of the Hungarian section is 131 km. The Sajó valley is 173.6 km long, its cross section gradually expanding in Hungary, 2 to 4 to 7 km. The relief of the river decreases from 50-70 cm/km in the upper part of Hungary to the Hernád estuary, and gradually to 20 cm/km below it. The most significant tributaries of the Sajó are the Bódva and the Hernád.

The upper section of the River Sajó is characterized by a narrow valley and a well-embedded bed. The area used to be the floodplain of the Sajó, with some abandoned riverbeds and an old riverbed of the Stream Szuha.

Precipitation in the Slovakian catchment area of River Sajó could quickly lead to flood waves. Due to the heavy rainfall and the narrow valley, the flood waves reach the border in about 12 to 24 hours from its formation. The flood waves from the Slovak part of Sajó and the Rima (the tributary of the Sajó) flood waves regularly meet at the country border. Due to the floods of the two branches and due to the decrease of the flooding, very high floods can develop in the Hungarian section of the Sajó. In the Hungarian section, the decline of flood waves is slower. The frequency of floods occurring in the Sajó is moderate and tertiary floods are rare. Sediment transport of Sajó is very significant, with an average sediment amount in water is 1.060 g/m^3 at Kazincbarcika.

River Bódva - River Bódva is about 900 m above sea level. The total length of the riverbed is 110.7 km, of which the Hungarian section is 64.7 km. The difference between the highest and lowest points of the domestic river bed is 55.0 m, which means an average relief decrease of 0.9 m / km. In the border section, the average annual discharge is 5.8 m^3/s, the maximum monthly discharge (April) is 9.44 m^3/s and the minimum (September) is 2.62 m^3/s.

Stream Szuha - The catchment area of Szuha Stream is 212 km^2. The section between 0 and 5 river km are the northwest boundary of the study area.

Hydrogeology

The area's groundwater reservoir is a Pleistocene-Holocene coarse-grained river sediment, settled on the denuded surface of the mainly aquitard Miocene strata. No other significant aquifer is known in the area. The grain composition of the groundwater reservoir is extremely diverse, according to the nature of river sedimentation and redeposition. Due to this, the hydraulic conductivity and the porosity show a changing trend at the site. The average hydraulic conductivity for sandy gravel aquifers is $5x10^{-4}$ m/s, i.e. 43 m/d. The drilling data did not show stratification in the aquifer gravel, and since no other anisotropy has been reported, the aquifer is considered to be isotropic.

The groundwater level in the area is situated between 2.0 and 4.5 m below the surface. The piezometric pressure in the northwest corner of the study area, below Múcsony, is 127 m BSL, which is the highest value, while the lowest in the southeast corner of the area at 120 m BSL.

In the Sajó and Bódva valleys the direction of the groundwater flow is the same as the surface run-off. According to the data of the waterworks, the rivers drain the groundwater for most of the year, and rivers can only be used as water supplies during floods.

Supply conditions of the groundwater aquifer

The average groundwater discharge above the waterworks is 12,500 m^3/d. On the cross-section affecting the area of the waterworks, it is 7,250 m^3/d.

Climate and precipitation trends

In the area the coldest month is January (-3.4 °C) and the warmest month is July (20 °C), which makes it one of the coldest areas in the country. Average annual temperature is 8.5 °C while average annual temperature fluctuation is relatively high, around 23.5 °C. A characteristic feature of the Sajó Valley's climate is the extreme frequency of low winter temperatures. The number of frosty days ranges from 166 to 179 days/year and the number of these days in the valley increases rapidly from E to W.

Among the climatic elements, precipitation is best known in the region (1952-1998). The period at the end of winter and early spring is very dry (the driest area of the country), while early summer continental precipitation maximum can be observed well. In addition, the area is characterized by a late autumn (November) secondary rainfall maximum. The average annual precipitation is 573.1 mm, which is below the national average. Generally, there is no excess water for one month. Dominant wind directions are N and NW. Evaporation equals 500-500 mm/y from free water surface and 500-520 mm/y from soil surface (Golder Associate (Hungary) Ltd., 2000).

Dominant land use type

Land use in the studied area shows a rather mixed picture (settlements, arable lands, industrial areas, other agricultural areas, complex agricultural areas, non-cultivated areas (meadow, pasture, lawn, scrub, etc.), cemeteries, waste dumps and raw material excavation areas).

Most of the areas under investigation are privately owned, including undivided cooperative lands. The proportion of municipally owned areas is also significant.

Aquifers

In the flatland area of the Sajó valley, the groundwater reservoir is the younger Pleistocene and partly Holocene Sajó-Bódva gravel terrace, which is at 115-125 m BSL.

It lies on the north-western edge of the area directly on the lignite deposit, and then towards the south-east, the gradually thickening Sarmatian formations, which are practically impermeable to water. The floodplain forming the roof of the terrace is a product of clayey, sandy surface Holocene formations, that are usually the products of recent floods. Their thickness is between 0.5 and 5.0 m, 3 m on average. Various rock composition (sand, loamy-silty-sometimes pebble sand, silt, loamy and sandy silts, clay) characteristic of the cover formations.

The coarse detrital terrace formations are mostly more than 3 m thick in the area of interest. The groundwater level is 2.0-4.5 m below surface. The average groundwater level is at 121.5-125 m BSL, inclined towards SE. Temporary upwellings are characteristic to the groundwater flow. Groundwater level is influenced by Sajó and Bódva, which usually cause draining.

Source water for MAR

The water supply for the artificial recharge system is the River Bódva. The water of Bódva is channelled to a horseshoe-shaped storage (made from an oxbow lake) through a series of sluices and gates (Fig. 21). The storage functions as a silt basin, storage for the river water and ensuring continuous water supply.

Required engineering processes

Pre-treatment is needed seasonally to reduce the quantity of suspended soil and algae in the withdrawn Bódva water. As post-treatment, chloride gas is added to the production wells' manifold.

Type of MAR operation

Enhanced infiltration: Surface-spreading method (areal recharge)

Specific MAR type: Infiltration ponds

Monitoring status of recharged and reclaimed water

Ensuring the continuous monitoring of water quality, a monitoring system has been installed. The monitoring stations are automatically sampling and measuring water quality parameters. The sampling takes place at the Bódva (from the river), at the storage and the pre-treated water.

18 monitoring wells are present across the water supply area with continuous monitoring.

Risks and sustainability issues associated with MAR operation

In order to maintain active protection of the water aquifer, the waterwork shall always operate at 120 % recharge (regarding the produced water quantity). This is because the groundwater is highly polluted in the vicinity of the Borsodszirák waterworks, resulting from industrial and communal pollution. Enhanced infiltration technique creates a hydraulic potential dome in water table (about 5 cm high), and changes the water flow direction, which prevents the entering of any contamination to the area of the water base. At the same time, production capacity can be increased.

In case of heavy rainfall, when the groundwater level rises by 5 cm, the system does not work properly. Therefore it is necessary to wait until the flood wave passes. In summer, the reproduction of algae in the infiltration ponds can inhibit the infiltration. Due to the colmation of the infiltration ponds the gravel beds needs to be replaced every 2 years.

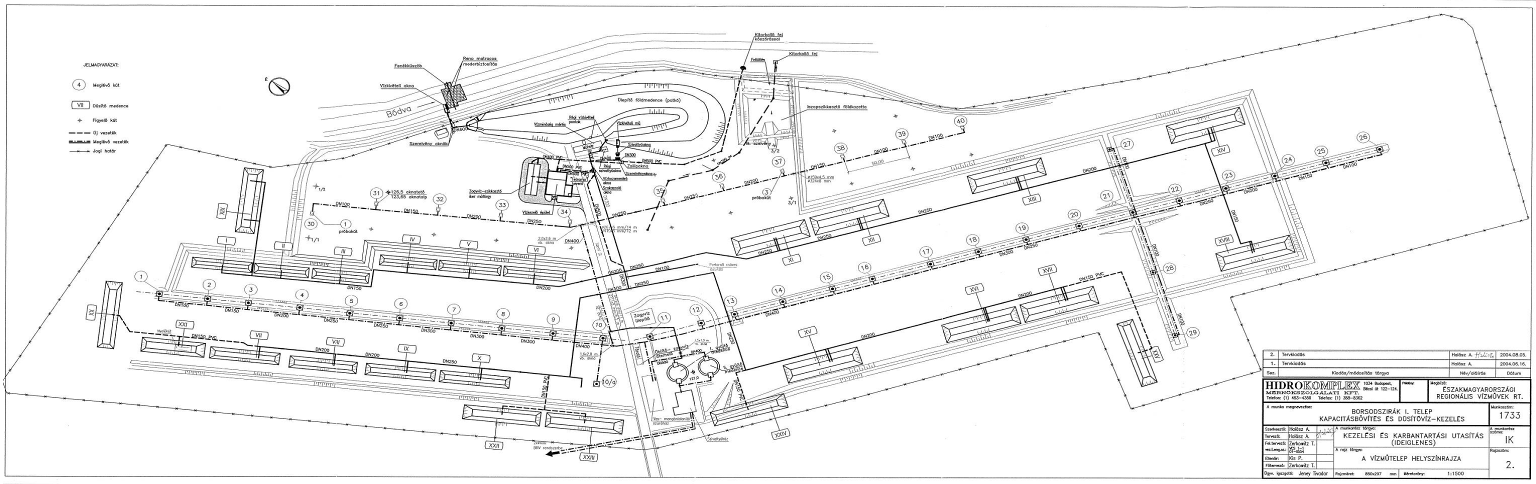
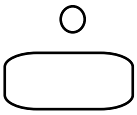


Figure 21. Borsodszirák waterworks (Source: North Hungarian Waterworks Co.)

Legend



existing abstraction well

infiltration pond

\+ monitoring well

Bank-filtered water recources on the Szentendre and Csepel Islands

Bank filtration systems have important role in drinking water supply in Hungary. These systems are situated along the main rivers (Duna, Dráva, Rába) and represent the future potential drinking water reserves of Hungary. The most important bank filtered water supply area is located in the country along the Danube at the region of Szentendre and Csepel Islands. These bank-filtered water resources supply mainly Budapest and about 150 settlements in its agglomeration with drinking water, in total about 2.5 million inhabitants.

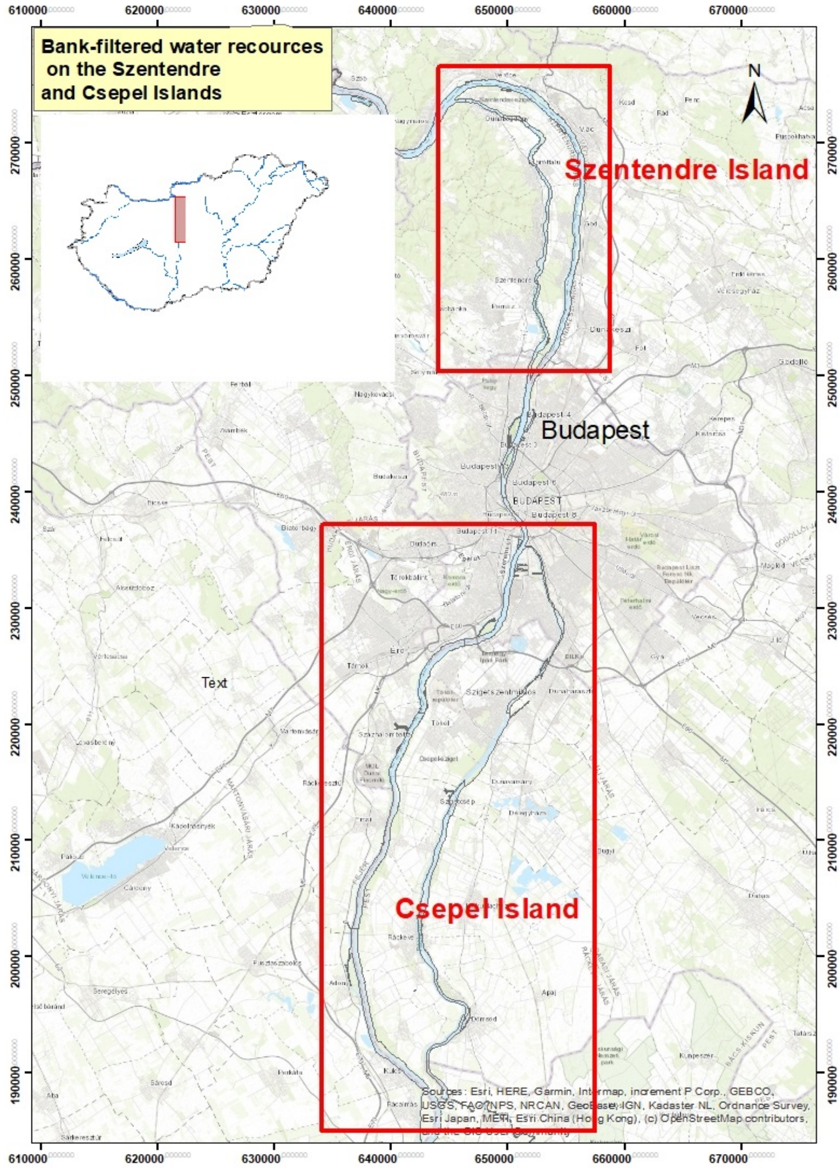


Figure 22. Location of bank-filtered water recources on the Szentendre and Csepel Islands

Descriptions below capitalize on the following deliverable of the PROLINE-CE Interreg Central Europe project: D.T2.1.4 Descriptive documentation of pilot actions and related issues - Along Danube bend (2017).

Geography

The Szentendre and Csepel Islands are located in the northern part of Central Hungary, in the section of Danube between Nagymaros and Tass.

The geographic structure of the area is much diversified: on the left bank, it includes the southern part of the Börzsöny Mountains, the western edge of the Gödöllő Hills and the Pesti Plain with alluvial cone-terraces. The right bank belongs to parts of the Transdanubian Range: the Visegrád Mountains, the Pilis, the Buda Hills as well as the northern part of the Mezőföld Plain, emerging from the southern.

Geology

In the centre of the pilot area, there is situated the Danubian Plain, where the basement is predominantly formed from the Triassic carbonate formations. On the top of the Oligocene-Miocene formations, the formation of the large alluvial cone of the Danube started at the beginning of the Pleistocene, or at the end of Pliocene. At present the surface is covered with several meters of alluvial mud, but the river gravel succession situated under these was accumulated during the quaternary dislocation of the river bed. At the end of the Pleistocene, there was a formation of blown sand on the high floodplain on the Szentendre Island.

On the Csepel Plain (southern part of the pilot area) the basement is comprised of different formations, being fragmented along Paleozoic-Mesozoic structural lines. On top of the Pannonian sediments there are coarse-grained fluvial deposits. The generally 10-20 m thick gravel layer is close to the surface, with good water retention capacity and it contains significant exploitable gravel reserves. Most of the surface is covered by thin Holocene formations. In the eastern parts and on Csepel Island, there are also smaller Pleistocene highland terrains covered by blown sand (MTA Geography Science Research Institute, 2010: Microregions in Hungary).

Hydrology

The main channel of the Danube and the Szentendre- and Soroksár (Ráckeve-) Danube branches dominate the pilot area. The Danube slows down after breaking through the Visegrád-mountain, the Szentendre and Csepel Island was formed from its alluvium, along with several smaller islands. A lot of streams flow into the Danube from the surrounding highlands. Floods in early summer, low water in autumn and winter are characteristic for the Danube. At the gauge of Nagymaros (minimum water level: -53 cm, maximum flood water level: 751 cm), located in north of the Szentendre Island, the average water level was 91 cm in year 2015. At the gauge of Budapest, the minimum water level was 51 cm, whilst the maximum flood water level 891 cm. The average water level was 204 cm in year 2015. The Danube River significantly influences the surrounding groundwater level. The hydromorfological characteristic of the Danube at Budapest significantly differs from the upper sections. The Capital city has influenced the extension of the flood control structures, as well as has a great impact on the physical-chemical and ecological state of the river.

The hydrological cycle of the Ráckeve (Soroksár) Danube (RSD) is artificially controlled. The RSD ensures the drainage and the water supplementation of the channels on lower plains by Danube.

On the Csepel Island, there are some artificial mining lakes.

Hydrogeology

In the area of Danubian Plain, there are 5-25 meters thick highly productive aquifers deposited by the Danube at the end of Pleistocene.These are characterized by gravel and sandy gravel strata and lenses with medium thick coarse-grained sand and thin floodplain clay interbeddings. The abstracted yield of the wells from these gravel and sand layers exceeds 800 l/min.

On the Szentendre Island, the groundwater table is determined by the alterations of the water level of the Danube. Therefore, on the higher points of the island, the water table can reach 8-10 meters depth under the surface. Farther from the river the correlation decreases.

Direction of groundwater flow is parallel with the river flow in natural state, but near the banks it can be perpendicular or two-way. The water regime of the island is based on the river Danube. Above 2 meters Danube water level at Budapest gauge station, groundwater recharges from the river, under this level groundwater flows in the opposite direction.

On the Csepel Plain, groundwater is significantly abstracted from the Pannonian and Quarter layers. The tens of meters of thick highly productive later Pannonian aquifers consist of the alternation of medium-sized sand, aleurite and clay. These are situated on the north and south border of the area, and on the west they can go down until 100-300 meters depth.

The upper aquifer is articulated to stripes which consist of sand-gravel layers containing unconfined groundwater, which mainly get the recharge from precipitation. The water table is lowering from north and east.

To the north from Ráckeve the water table is in the depth of 3-4 meters, whilst it can be found deeper only in the region of Tököl-Szigetcsép and Szigetújfalu. This is caused by the bank-filtered drinking water abstractions (along the Danube) which create smaller depression. The groundwater table is situated mainly in the gravel (National Water Resources Protection Program, Diagnostic studies of drinking water resources with vulnerable geological environment 1997-2017).

Climate and precipitation trends

Due to the proximity of mountainous region, Szentendre Island has mild cool and mild humid climate. Warm and dry climate is characteristic in Budapest and surroundings. The southern part in Csepel Island region has continental climate, mild warm and dry.

The annual average temperature in the highlands is 8-10 °C, in Budapest 10-11.2 °C, in southern areas of the pilot area 11 °C. The annual precipitation is 580-750 mm in the northern area. Towards the southern areas (Budapest surroundings) precipitation is 550-600 mm, while in the southern part of the Csepel Island is only 510-560 mm. The annual average potential evaporation is about 700 mm. Over the last two decades evaporation values have increased. The annual average evapotranspiration is 480-540 mm. The general direction of the wind is northwest, but because of the diverse relief it can be westward (MTA Geography Science Research Institute, 2010: Microregions in Hungary).

Dominant land use type

On the Szentendre Island the highest land use rate is represented by non-irrigated areas (43%), broad-leaved forests (18%), pastures (11%), and complex cultivation (7%).

On the Csepel Island the highest land use rate is represented by non-irrigated areas (49%), discontinuous urban fabrics (17%), and the broad-leaved forests (11%).

Aquifers

The aquifer on the Szentendre Island is formed from Pleistocene Danube' beds sediment (gravelly, sometimes scrolling coarse sand, with sand on the top).The depth of the aquifer is 2-4 m from the surface, its thickness varies between 7-9 m. The Oligocene-Miocene fine grained bedrock is situated in 9-15 m depth.

The most important aquifer in terms of drinking water supply on the Csepel Island is a mixture of Pleistocene gravel and sand. It has a minimum thickness of 1.5 m in the northern part of the island and 15 m in the southern end of the island. The gravel thickness of the intermediate areas of the island is 5-10 m. The whole aquifer is heterogeneous multi-accumulated sediment. The aquifers porosity is 15–45% and the hydraulic conductivity ranges from 15 to 150 m/day.

Source water for MAR

The source water for the bank-filtration is the river Danube.

Required engineering processes

The water abstracted on Szentendre Island is of drinking water quality, and after disinfection it can be discharged directly into the water network, so no further treatment is required.

The Fe and NH_4 (+) concentration of the extracted water on the Csepel Island is high (200 µg/l Fe, 0.50 mg/l NH_4), which originates from strata; to this is added the impact of significant sewage load on the Danube section below the capital city. To decrease this impact, two water treatment plants were built on the island. The water treatment (extraction of iron and manganese) is done by oxidation with ozone. The precipitated pollution is filtered through a sand filter and an activated carbon filter. The small quantity of dry sludge residue is treated as waste.

Monitoring status of recharged and reclaimed water

The waterworks operate monitoring network on the two islands, which regularly registers the level and quality of the groundwater. The frequency of the observation is different; it can be weekly, monthly, seasonal, annual, and also continuous water level registration is carried out. The waterworks also regularly analyse the water quality of the Danube.

Risks and sustainability issues associated with MAR operation

One of the most serious operation problems is the high water level of Danube and floods. In such cases the river's water can directly flow into the wells, or can form stagnant water around the wells. Both cases can result deterioration of the water quality. To prevent this, the structure of the wells in the flood plain is raised above the surface and is designed in a way to prevent direct water flow into the well. The well environment is designed to facilitate fast drainage from the surface after flood events.

Low water level of the Danube can result water quality problems too.

Lessons learnt

In case of bank-filtration the particular challenge is the necessity of protection from both the river side and the background, so the system is exceptional vulnerable. In the frame of Drinking water Protection Program detailed hydrogeological studies (field measurements and hydraulic models were included) were done to save the bank filtered drinkingwater reserves and supply as the basis of outlining protection zones.

3.4. MAR case study in Poland

Legal framework regarding MAR in Poland

According to the Water Law Act, any intentional artificial groundwater recharge is understood as a special use of water. The owner of the site where MAR is incorporated has to operate in accordance with the following legal acts: 1) Water Law Act (Journal of Laws 2017, item 1566); 2) Geological and Mining Law Act (Journal of Laws 2011 No. 163, item 981); 3) Ordinance of the Minister of the Environment on hydrogeological documentation and geological and engineering documentation (Journal of Laws 2016, item 2033); 4) 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); 5) Announcement of the Prime Minister on the publication of a uniform text of the Regulation of the Council of Ministers on projects that may have a significant impact on the environment (Journal of Laws 2016, item 71).

Any type of managed aquifer recharge has to be in accordance with the legal regulations described above. It is required to obtain a water law permit for special use of water which must be preceded by the preparation of an aquatic legal survey, which is made on the basis of the hydrogeological documentation. The scope of an aquatic legal survey is defined by the Water Law Act, and the scope of hydrogeological documentation is defined by Regulation of the Minister of the Environment. Hydrogeological documentation is approved by the Starosta (head of the county) if the water abstraction is less than 50 m^3/h, or by the voivodship marshal if it exceeds 50 m^3/h. Permission for water abstraction is issued by the State Water Holding Polish Waters. The decision on environmental conditions is issued by the head of the commune/mayor or president of the city.

In the case of planning of devices enabling groundwater abstraction or artificial groundwater recharge systems with a water capacity of no less than 1,100 m^3/h, it is necessary to conduct an environmental impact assessment and obtain a decision on environmental conditions. The planning of devices enabling groundwater exploitation or artificial groundwater supply systems, with a water withdrawal no less than 10 m^3/h, is one of the projects that can potentially have a significant impact on the environment. In this case, an environmental impact assessment may be required by the authority administration.

From among 12,958 of groundwater abstraction (for the needs of public water supply) sites in Poland, less than 50 applied MAR techniques. However, it is applied locally for some cities in Poland (Warszawa, Poznań, Bydgoszcz, Tarnów etc.) MAR can play an important role in water supply. The most widespread MAR type is riverbank filtration (21 sites) or combined riverbank filtration with other MAR types such as infiltration ponds or ditches (10 sites).

This MAR example from Poland shows a riverbank filtration site in Krajkowo. The area of operation was a subject of an investigation under AquaNES project (received funding from the European Union's Horizon 2020 Research and Innovation Program under grant agreement no. 689450) The research on site was conducted by Krzysztof Dragon, Józef Górski and Roksana Kruć from Adam Mickiewicz University in Poznan, Institute of Geology, Department of Hydrogeology and Water Protection.

River bank filtration site in Krajkowo

The Krajkowo well field is an example of river bank filtration site (RBF) supplying potable water for Poznan agglomeration (Wielkopolska region, Poland). The Krajkowo site is located 30 km south of Poznan city on Krajkowo Island (52°12'47"N 16°56'49"E) in the Warta River valley (Fig. 22). The source water for RBF system is the Warta River.

The Krajkowo well field comprises 29 vertical wells (RBF-c) located on the left bank of Warta River at the distance between 60 and 80 m from the river (Fig. 23). The second well field component is the horizontal collector well (HW). This well receives water from 8 radial drains located 5 m below the river bottom. There are two more well-field components: 56 vertical wells located on a higher plane between 400 and 1,000 m from the river (RBF-f) and 11 vertical wells recharged from artificial ponds

As part of the AquaNES project on the Krajkowo well field, two years long monitoring was performed which included the investigation of organic micropollutants investigation. To investigate water quality samples were taken every month from sampling points located on two transects along flow paths from the river to the wells (Fig. 23).

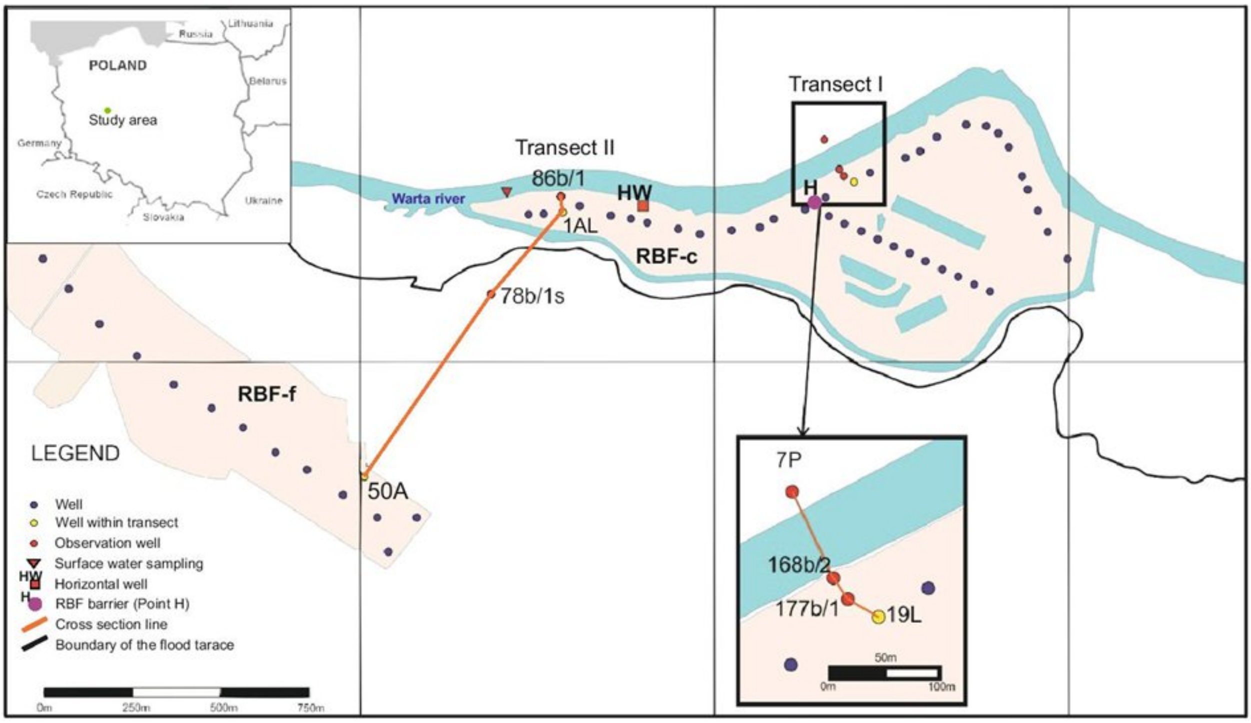


Figure 23. Map of the study area (after Dragon et al., 2018)

The Warta River catchment and Krajkowo site characterization

The topographic conditions of this river system are characterized by two main factors: postglacial relief and the general northward slope of the land surface. In the southern part of the catchment, the Warta River flows to the north. Then, the river turns west in the lowland area of the Warsaw-Berlin ice-marginal valley in the middle section of the catchment (Górski et al., 2019).

The average annual precipitation from the period of 1985 to 2017 in the area is 554 mm. Three long dry periods were documented. The first dry period spanned from 1989 to the end of 1992 (until the end of the summer). The second dry period occurred between 2003 and 2006. The other long hydrological drought occurred between 2013 and 2016, and a very wet year occurred in 2017. The latter is reflected by a notable increase in the water level of the Warta River.

The Krajkowo site is located on an artificial island area (Fig. 23). This is a strictly protected area, where human activity is restricted according to law regulations. The wells located on higher terrace also belong to protection zone of the well field.

The wells are located in the region where two main groundwater bodies overlap: The Wielkopolska Burried Valley (WBV) and the Warszawa-Berlin Ice Marginal Valley (WBIMV) which form ~40 m thick porous aquifer. The lithology of the upper aquifer (WBIMV) is dominated by fluvial fine and medium sands (to a depth of 10 m) and by fluvio-glacial origin coarse sands and gravels in the deeper portions (to a depth of 20 m) (Fig. 24). The deeper aquifer (WBV) is also composed of fine and medium fluvial sands in the upper part (to a depth of 25–30 m) and by coarse fluvio-glacial sands and gravels in the deepest part of the aquifer. Unconfined aquifer conditions dominate in the study area and the static water level is approximately 3–5 m below the ground surface.

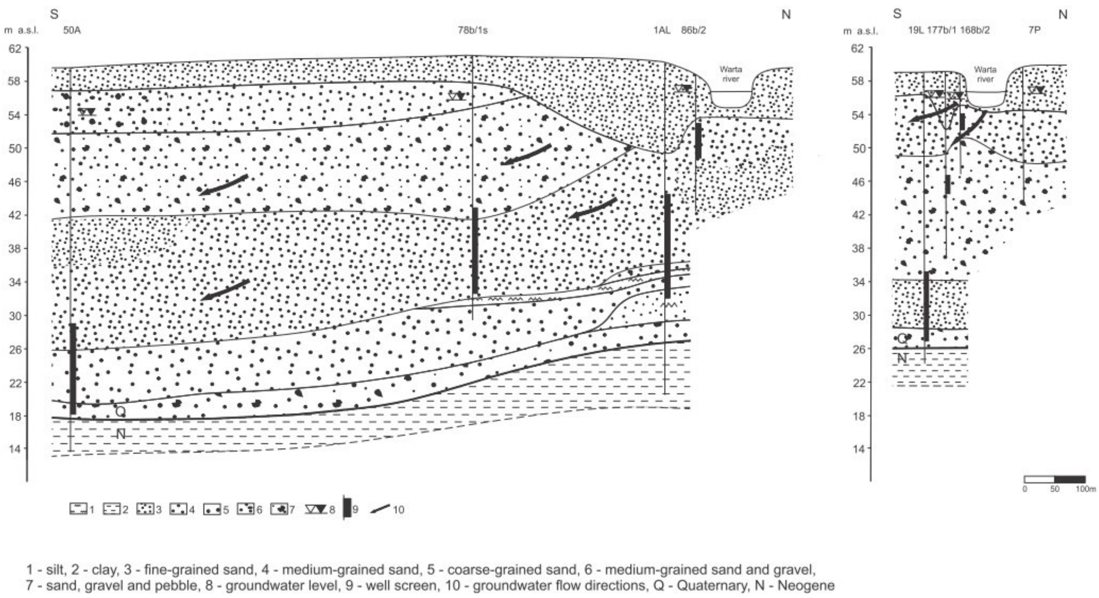


Figure 24. Hydrogeological cross-sections from Fig. 22 (after Dragon et al., 2018).

The main RBF system benefits

Figure 25 presents fluctuations in some parameter concentrations of RBF water relative to the source water in the Warta River. The most apparent difference is observed in the case of coliform bacteria. Despite the high concentration of bacteria in river water, almost no bacteria were found in bank filtrate. This is a common effect observed at RBF sites as a result of filtration due to the processes of adsorption and inactivation or die-off with time. A high removal efficiency is also observed for parameters reflecting the occurrence of natural organic matter (NOM) in water. The chemical oxygen demand (COD) reflected good removal of NOM from source water. In the Warta River, the maximum concentration occasionally reached levels higher than 50 mg O_2/l (median 24.5 mg O_2/L) whereas in the bank filtrate the level of COD was much lower (maximum 27.0 mg O_2/L, median 13.0 mg O_2/L). The dissolved organic carbon (DOC) concentrations showed large fluctuation in source water from 5.0 to 10 mg/l, while the concentration of DOC in bank filtrate was relatively stable and much lower (maximum concentration of 6.0 mg/l, median 5.0 mg/l). The relatively stable level of DOC achieved by RBF is important for post-treatment. In contrast to COD, the DOC concentration did not follow seasonal fluctuations in source water. The reduction of NOM caused a significant decrease in water colour. A 30–40 mg Pt/l decrease in colour to less than 15 mg Pt/l was observed in RBF wells.

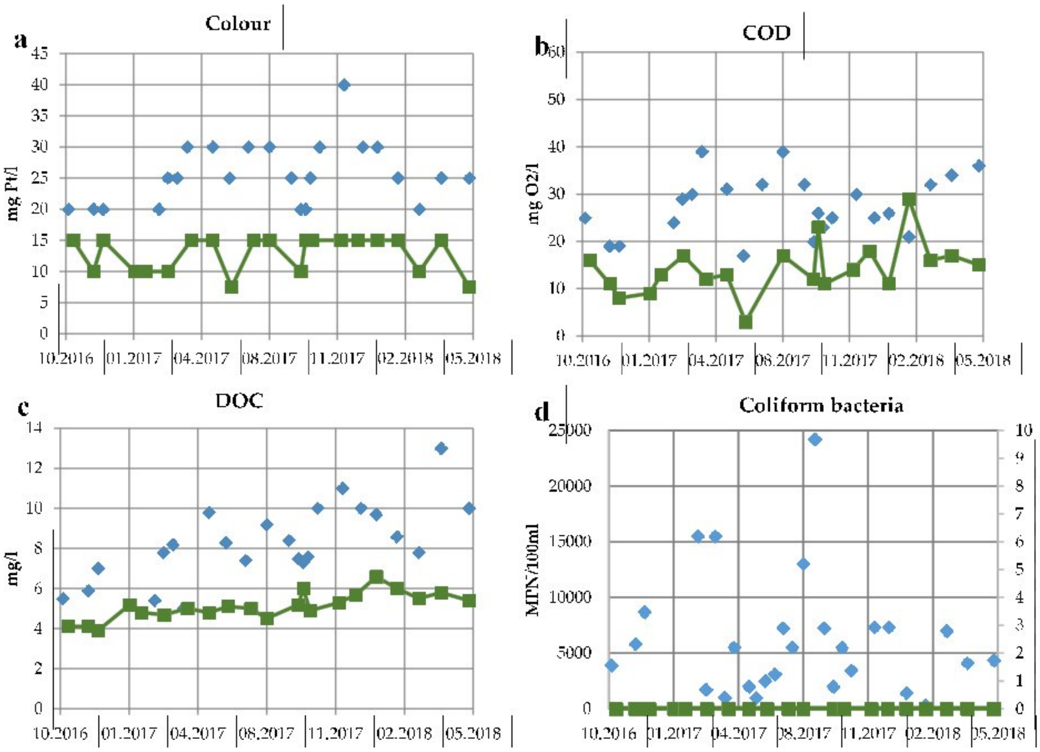


Figure 25. Temporal changes in selected parameters in bank filtrate (green dots and lines) and Warta River source water (blue dots) (a) Colour, (b) COD, (c) DOC, (d) Coliform bacteria, (modified after Dragon et al., 2018)

Among the multiple benefits of RBF systems, the removal of natural organic matter (NOM), which is usually present in surface waters at relatively high concentrations, is significant. During RBF, an effective removal of dissolved organic carbon (DOC) of more than 50% can be achieved. The significant reduction in chemical oxygen demand (COD) is also important. It has been documented that the effective reduction of high molecular weight organic fractions is achieved during RBF, but with a lower removal of low molecular weight fractions. This finding is important for further water treatment due to the formation of by-products during water chlorination. Due to these benefits the RBF system is used as natural pre-treatment system which enables the further steps of engendering post-treatment to be more effective (Gorski et al., 2018).

The significantly reduced but still relative high concentrations of parameters reflecting NOM occurrence in raw water the engineering post-treatment is applied on Krajkowo site. After high-rate anthracite sand filters ozonation is applied and then activated carbon filtering is used. As the end treatment step, the disinfection with use of both ClO_2 and NaOCl is applied.

The nature of RBF system induces strong dependence of the quality of bank filtrate on surface water quality. Currently, it is extremely important due to emerging contaminants (e.g., pharmaceuticals and pesticides) detection in river (source) water.

On Krajkowo site in total 30 pharmaceuticals were analysed. A removal rate of these organic micropollutants was investigated. Concentrations of pharmaceuticals in Warta River water were found similar to levels detected in other European rivers. Among the 30 analysed micropollutants, 14 were detected in the Warta River. Out of these 14 substances 5 were detected in the bank filtrate. The high attenuation potential is visible during water passage through the aquifer and depending on flow path length (Fig. 26). The pharmaceutical concentrations in the HW and piezometers located close to the river are at levels observed in the source water, while after further flow, the concentrations decrease considerably. In wells located 60-80 m from the river (travel time 40-50 days), the concentrations are significantly lower, while at the distance of 250 m from the river (point 78b/1s), only 3 substances were detected at relatively small concentrations (Fig. 26). Further away from the river, no pharmaceuticals were detected.

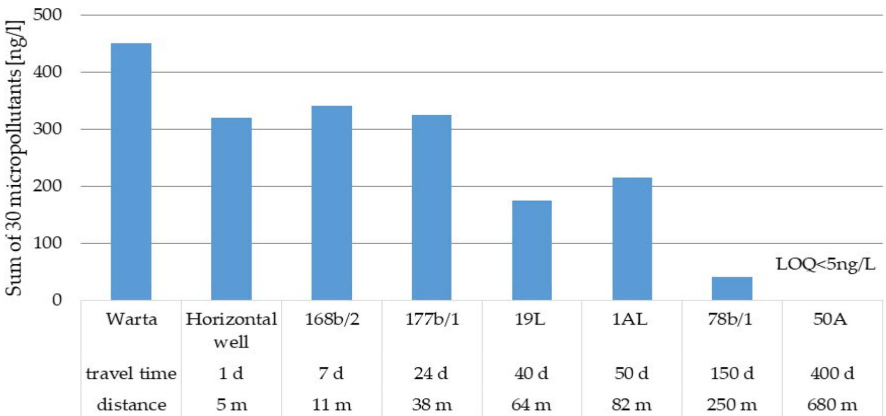


Figure 26. Changes in total pharmaceutical concentrations along the flow path

Pesticides, similarly to pharmaceuticals, were also reduced significantly during RBF (Fig. 25). The similar constituents and concentrations detected in the Warta River and the HW indicate that this well is vulnerable to pollution from the river. Water passage through 5 m thick sediments is not sufficient to remove micro-pollutants from the drained water. In vertical wells located 60-80 from the river (RBF-c wells) pesticide concentrations in the wells were much lower than those in the river and HW, but some pesticides are still present. The smallest pesticide concentrations (close to detection limits) were found in wells located farther from the river (Fig. 27).

The well field monitoring system conducted by waterworks operator

The well field monitoring system covers source water (Warta River), HW and sampling point representing RBF-c vertical wells (H point – Fig. 23). The mixed water from all well field components is monitored as well. The water analyses are performed every month and include macro and micro components, parameters reflecting NOM occurrence in water (DOC, COD, colour) and heavy metals. Selecting micro-pollutants (required by Polish legal regulations) are monitored as well.

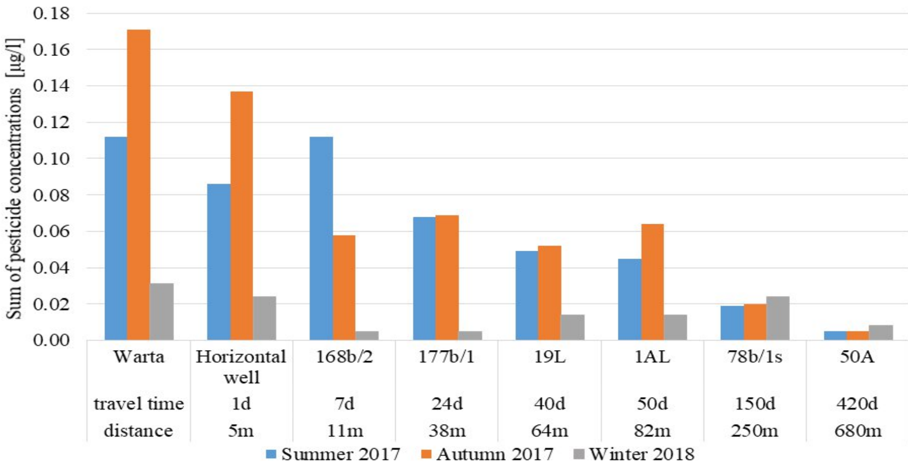


Figure 27. The sum of pesticide concentrations along the flow path

Risk for RBF system exploitation associated with climatic factors

The RBF systems are vulnerable to extreme weather conditions, especially floods (when the quality of source water is usually deteriorated) and long term hydrological droughts. The water quality changes after the summer flood in 1997 are visible on COD behaviour, reflecting organic matter occurrence in water. The contamination of HW water after flood is clearly visible as a sharp positive peak is following the peak observed in river water (Fig. 28). In the vertical wells (RBF-c), the influence of the flood is also visible, but these wells are less sensitive to changes in surface water quality (temporal changes of COD are smaller than in the HW). Moreover, in these wells after flood, periodical occurrence of bacteriological contamination and plankton was detected (Górski et al., 2018).

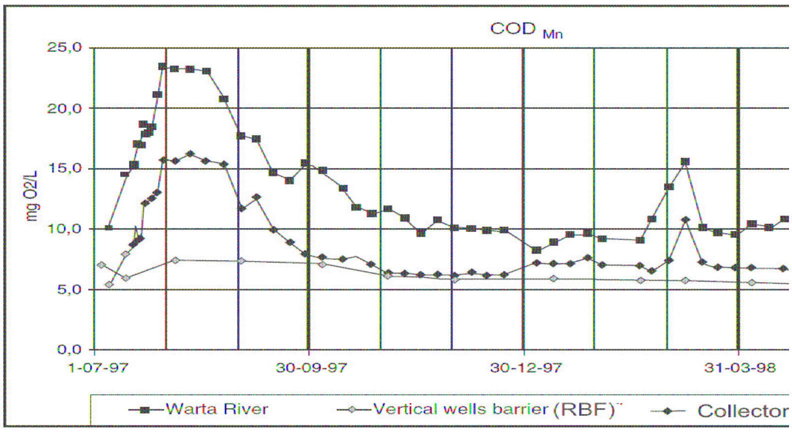


Figure 28. Temporal changes in COD during and after flood (afte Górski et al., 2018).

The main risk assiociated with long-term hydrologic drought is clogging of the river bed. At the investigated site during a hydrological drought between 1989 and 1992, the high rate of water exploitation performed in dry periods caused development of a regional cone of depression. These conditions favour developing of clogging of the river bottom which causes a decrease of effective infiltration of river water into the aquifer and then during countinious exploitation, expansion of the cone of depression to the opposite site of the river. These conditions cause development of the unsaturated zone under the river bottom. After this event the unclogging activities was performed by artificial hydraulic dredging, which causes rinsing and loosening of the river bottom sediments. Natural unclogging occurs also during floods and causes deep river bottom erosion (Przybyłek et al., 2017).

Lessons learnt

The RBF system enables good quality of raw water and it is a good method to replace direct use of surface water as drinking water.

The RBF systems are natural pre-treatment processes which allow reducing organic matter occurrence in raw water that can prevent or limit the creation of by-products during engineering treatment of water and it is important for further post-treatment processes to be more effective. At the investigated site, the reduction of organic matter reflected by DOC, COD, and colour was found in the ranges of 40–42 %, 51–70 %, and 42–50 %, respectively. A much lower reduction of DOC (26 %), COD (42 %), and colour (33 %) in the horizontal well was observed, confirming that this well is more vulnerable to contamination from surface water than the vertical wells.

The RBF operation enables to reduce concentrations of organic micro-pollutants considerably. The research performed at the investigated site demonstrates a gradual lowering of concentrations along the flow path. In the RBF wells the reduction rate of the sum of pharmaceutical concentrations is greater than 50 %. Lower reduction rates (approximately 30 %) were found for the HW. Results of pesticides investigation show also gradual decrease of concentrations along the flow path. High reduction rates are visible in RBF wells (about 80 % for the sum of pesticide concentrations).

The RBF systems are sensitive to extreme climatic conditions (floods and droughts). The main risk during and after floods is the influence of poor water on river water quality with respect to organic matter occurrence on RBF systems. During long-term hydrologic droughts the main risk is clogging the river bed which limits the infiltration rate. The clogging processes are enhanced by the creation of a cone of depression caused by intensive water exploitation during drought periods.

The presented results prove a high efficacy of contaminants removal by the riverbank filtration system. Significantly lower contaminant removal was documented in the horizontal well, which received river water after a very short travel time. For RBF sites with similar conditions, the suggested distance from the river should be at least 60 m. However, higher removal rates can be achieved for wells located at a distance of 250 m from the river.

3.5. MAR case study in Slovakia

In Slovakia there is no legal framework for MAR. The conditions for water abstraction are specified under the Water Act (364/2004 Coll.), but not specifically on MAR.

In Slovakia there are just riverbank filtration types of MAR sites. These are used as one of the most common methods to abstract water in the Danube lowland, but also near other big Slovak rivers (Hron, Váh, Hornád). None of institutions is responsible for implementation of these types of MAR as it is considered as a common technical solution to abstract water from river fluvial sediments.

The reason why “MAR schemes” i.e. bank filtration are used in Slovakia is to abstract high quality groundwater for drinking water supply.

Žitný Ostrov

Geology

The Žitný Ostrov (Fig. 29) (Žitný island) area is located in the southwestern part of Slovakia, on the border with Hungary. Its boundaries are formed in the south by the banks of the Danube, in the north by the branches of the Malý Dunaj (Little Danube) river, and on a short stretch in the east, it is bounded by the river Váh. The territory belongs geographically to the Low Danube Plain. The island has an elliptical shape, its length is 84 km, its width ranges between 15 and 30 km, and its total area is 1,885 km^2. With these dimensions, this island is the largest river island in Europe.

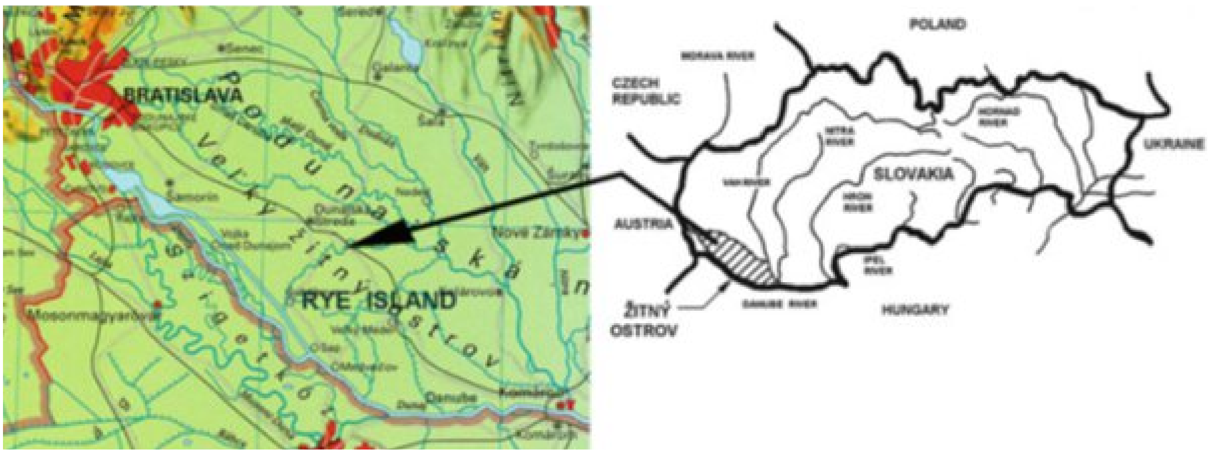


Figure 29. Map of Žitný ostrov (Dušek & Velísková, 2019)

The territory of the island is of a flat character. The longitudinal slope of the area reaches only 0.25 %, with a decreasing tendency in the south-east direction. This small slope was created by the gradual deposition of gravel, sand, and flood sludge. The highest point on the Žitný Ostrov area is located near Šamorín (134 m above sea level), and the lowest is the area at Komárno (105 m above sea level). The altitude of the terrain in the locality is 108.4 m a.s.l. up to 121.5 m a.s.l. The terrain is lowering from the Danube watercourse to the Little Danube and at the same time from the west or northwest boundary of the territory to the east or south-eastern boundary. The area of interest is geologically included in the area of the Holocene floodplain of the Žitný Ostrov. The geological structure is characterized by the emergence of fluvial sediments. In their overburden, there are strata of fluvial sediments of the Quaternary, with a thickness up to 200–500 m. The poorly permeable Danube floodplains are filled with water and form a massive phreatic horizon. The groundwater level is affected by the changes of the water level in River Danube, which cause a fluctuation in the groundwater levels in the range of 250 to 600 cm. Another groundwater level influencing factor is the water level fluctuation in nearby channels; groundwater level varies according to the overall water level in the drainage system linked to the Little Danube. In the core of the island, there are sandy sediments reaching a thickness of up to about 300 m in the central, subsiding part of the island. Gravel sediments range from 50 or 70 cm below the surface in the central and upper parts of the island up to 6 or 8 m in the lower part. Due to its predominantly gravel foundation, Žitný Ostrov is an important groundwater aquifer which is extensively used as drinking water supply resource (Dušek & Velísková, 2019).

The geological structure of the Žitný Ostrov interface is characterized by great heterogeneity. Gravels or sandy gravels are covered by younger alluvial loamy to loamy sand sludge sediments, sandy clay, and clay. There are predominantly clays or sand in the subsoil with a thickness of 8–20 m from the Quaternary period. The hydrogeological conditions here are influenced by the great thickness of the Quaternary sandy gravel. Depending on the grain composition and the sand fraction, the values of saturated hydraulic conductivity range from 10 -2 to 10-6 m/s. The flow rate of the drained aquifers is very high. The River Danube is the source of constantly replenishing groundwater supplies; water infiltrates the to rock environment all year round. The Danube on the territory of Žitný Ostrov creates an extensive branch system. The natural character of the river is altered by embankments and equalizing parts of the watercourse. This also alters the natural hydrological conditions: the Danube's branches and meanders are separated from the main stream by the embankments. The current hydrological conditions are strongly influenced by building of the Gabčíkovo water management project (VD Gabčíkovo). The channel network of Žitný Ostrov consists of six main partially interconnected channels: Gabčíkovo-Topoľníky channel, Chotárny channel, Čalovo-Holiare-Kosihy channel, Aszód-Čergov channel, Čergov-Komárno channel, and Komárňanský channel. The total area covered by the current drainage system is 1,469 km^2. The area of drainage with a built-up channel network is 1,252 km^2. The total length of the channel network is almost 1,000 km. Its density is about 1 km/1.25 km^2 (Dušek & Velisková, 2019).

Climate

The Žitný ostrov area is located predominantly within an area characterized as warm, dry climate, with mild winters and long sunny days. The territory is one of the warmest regions of Slovakia with a lowland climate. Average January temperatures range from -4 to -1 °C, and average July temperatures from 19.5 to 20.5 °C. The territory is characterized by an upper interval of annual precipitation sum is between 530 and 650 mm. The most important climatic factors affecting Žitný Ostrov's water regime are precipitation and evapotranspiration. Groundwater level is primarily affected by the Danube and the Little Danube level fluctuation, precipitation, subsurface geology, slope ratios, and last but not least the channel network of Žitný Ostrov and its manipulation. The direction of groundwater flow is generally eastward, with the groundwater level decreasing with the fall in the terrain (Dušek & Velísková, 2019).

Required engineering processes

One of the significant water sources in Žitný ostrov is the Rusovce-Ostrovné Lúčky–Mokraď (Fig. 30) water source that has been used since 1981. During water extraction, a higher content of Manganese and low Oxygen saturation was observed. In 1988, it was decided to treat groundwater in situ in all twelve pumped wells. The solution was to drill additional 8 wells for injection of Oxygene-rich water and 4 monitoring wells close to 4 pumping wells in 1988-1989. The new system including in situ pre-treatment of the water was completed in 1999 by drilling the new wells. Despite of previous plans, the final system use direct Oxygen injection into the wells instead of injecting Oxygen-rich water.

Post-treatment of the water for drinking purposes is performed in accordance with hygiene requirements of the Government Regulation no.354/2006 Coll.

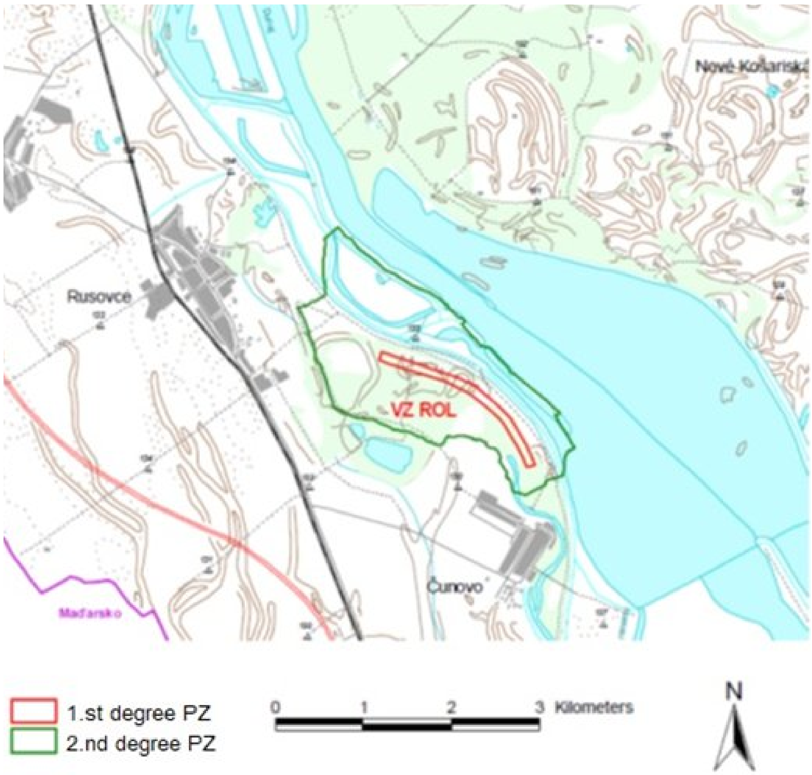


Figure 30. Localization of Rusovce-Ostrovné Lúčky-Mokraď water sources

(Trančíková & Vojtko, 2012)

Monitoring status of recharged and reclaimed water

The monitoring of the recharged water is performed in accordance with the requirements of WFD. The monitoring of groundwater quality and chemical status was divided into basic monitoring and operational monitoring. The sampling frequency is from one to four times per year depending on rock environment. The samples are taken in spring and autumn when the extreme conditions (i.e. snow melting in spring and autumn after the summer dry season) of groundwater could be monitored. The region of Žitný ostrov represents a separate part of the Slovak Hydro Meteorological Institute monitoring network since this region is the most significant drinking water resource. The monitoring network of Žitný ostrov comprises 34 piezometric multilayer wells (84 layers) that are monitored from two to four times per year. Water level and groundwater temperature are in general recorded weekly by voluntary observers (on Wednesdays) in 273 wells. Automatic recorders with hourly intervals and continuous limnigraphic recorders were installed at 860 sites (Dušek & Velísková, 2019).

Risks and sustainability issues associated with MAR operation

The water extraction for drinking water supply brings the risk in water quality and availability in surface water courses. In case of Slovakian rivers the quality problems and insufficient quantity may occur. As the main risks could be considered:

- Legislative aspects
- Water quality in surface water course
- Water quantity in surface water course (conflict of users, climate change impacts)
- Bank clogging blocking proper water infiltration
- Clogging of pumping wells
- Pressures on water demand and related conflict of users

Conclusions and lessons learnt from MAR operation

Although the MAR solutions are not legislatively established in Slovakia, in fact they are widely used for abstraction of water for public water supply, especially in Žitný ostrov from Danube River.

This definitely shows the necessity to include these solutions into the Slovak legislative framework; improve technical solutions of proper MAR schemes and their financial evaluation; and to prepare the conditions to implement them for various purposes, for instance agriculture, during drought periods within the current climate change conditions.

3.6. MAR case study in Croatia

Managed aquifer recharge (MAR) is not often discussed in Croatia since groundwater reserves generally satisfy the water demand. Hence, the need to manage aquifer recharge is not pronounced. Nevertheless, there are some springs used for public water supply which require enhanced recharge during periods of hydrologic drought as well as public wellfields deliberately positioned near rivers in order to either enhance the capacities of pumping wells through river bank filtration, or diminish wellfield protection zones which in many cases occupy urban areas.

Gradole spring

One such exception and the first attempt of managed aquifer recharge in Croatia in karst aquifers is at the Gradole spring located in Istria (Fig. 31). Gradole is the most important spring in Istria used for public water supply. Its catchment area is 170 km^2, with average elevation is 340 m a.s.l. Average precipitation is 1,046-1,120 mm annually and average water abstraction is 0.5 m^3/s. Gradole is a typical karst spring at the contact of highly permeable carbonate rocks and Quaternary clastic deposits of low permeability. Groundwater flow direction is SE – NW and is concordant with the direction of main geological structures and faults.

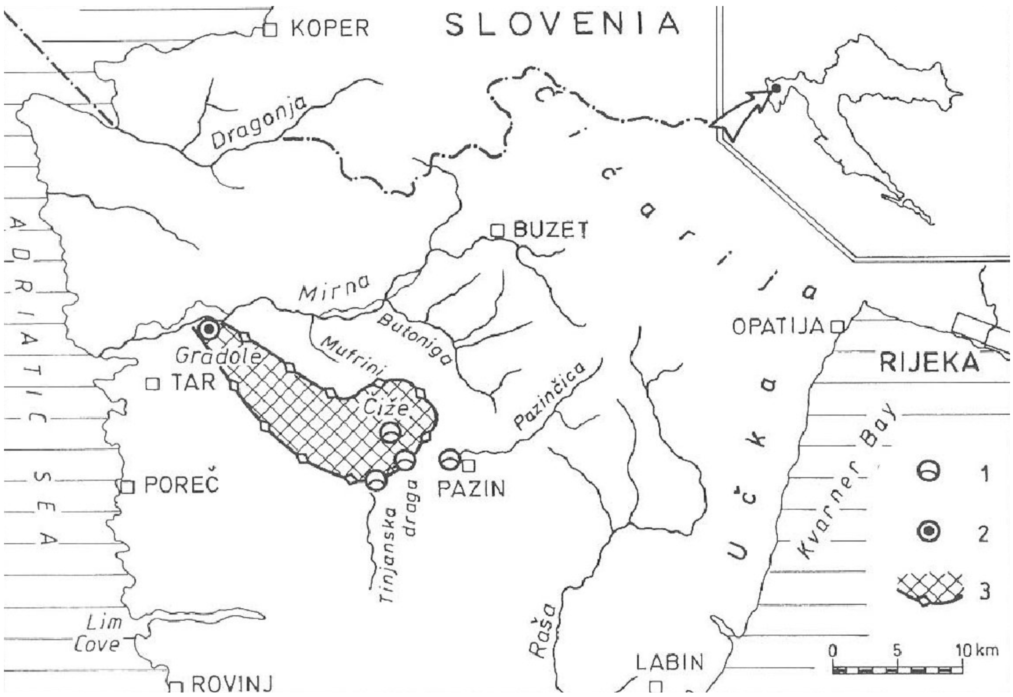


Figure 31. Location of Gradole spring and catchment area (Magdalenić et al. 1995)

Legend: 1) swallow hole, 2) spring, 3) catchment area

The Gradole Spring was artificially recharged from the water accumulated in Lake Butoniga and pumped into the sinkhole Čiže located in Tinjanska Draga. This resulted in a significant increase in spring discharge (Faculty of Geotechnical Engineering, 2009). The type of MAR used in this case was point recharge (direct pumping from the lake into a sinkhole which is hydraulically connected to the spring). The final use of water was public drinking water supply. The Karstic aquifer is considered semi confined, while average depth of the aquifer zone is >100 m. Measurement from 1987 to 2002 show a discharge of 0.264-19 m^3/s, 2.0 m^3/s in average (1987-2002) and the Maillet coefficient (α = 0.007 - 0.008) indicated a slow discharge with long recession periods. Several sinkholes in the vicinity are more than 100 m deep but none reaches the groundwater level, indicating the presence of a deep karst aquifer.

From the late 1980's to early 2000's, an average of 0.873 Mm^3/y water was pumped from Lake Butoniga (Fig. 32) and discharged into the sinkhole Čiže. The maximum volume was pumped in year 1990 (2.8 Mm^3/y) and the minimum was reached in year 1995 (0.1 Mm^3/y). Although this solution was inefficient with respect to the energy consumption required to pump water from Lake Butoniga situated at 40 m a.s.l. up to the sinkhole Čiže situated at some 350 m a.s.l., it helped to increase the discharge of the Gradole Spring during the summer dry seasons.

Figure 32. Lake Butoniga (picture by Istarski vodovod Buzet)

Lessont learnt

This MAR operation was terminated due to construction of water treatment facility directly at Lake Butoniga, as seen in the Fig. 31. This enabled direct distribution of drinking water to consumers and made further MAR actions unnecessary. However, this MAR operation has proven that it is possible to directly increase Gradole spring yield during summer dry season by direct pumping of Butoniga source water into the sinkhole Čiže, a rather simple but expensive procedure.

4. References

Bavarian Ministry for Environment (LfU)(2010): 'Wasserschutzgebiete für die öffentliche Wasserversorgung', retrieved from: https://www.lfu.bayern.de/wir/doc/profil_englisch.pdf pp. 1–25.

BGR & UNESCO (eds.) (2014): International Hydrogeological Map of Europe 1:1,500,000 (IHME1500). Digital map data v1.1. Hannover/Paris.

European Commission, European Environmental Agency (2012): Blueprint to Safeguard Europe's Water Resources (2012). https://www.eea.europa.eu/policy-documents/a-blueprint-to-safeguard-europes#tab-related-indicators

BMI Künstliche Grundwasseranreicherung (1985): Stand der Technik und des Wissens in der Bundesrepublik Deutschland. Bundesministerium des Inneren [Artificial groundwater replenishment: state of the technology and knowledge in the Federal Republic Germany, Ministry of the Interior]. Schmidt, Berlin

Bund/Länder Arbeitsgemeinschaft Wasser (2018): Bericht zu Maßnahmen bei Grundwasserkörpern im chemisch schlechten Zustand aufgrund von Rückständen aus Pflanzenschutzmitteln, retrieved from: https://www.lawa.de/documents/lawa_bericht_pflanzenschutzmittel_2_1552302167.pdf

Bundesministerium der Justiz (2014): Gesetz zur Ordnung des Wasserhaushalts. Available at: www.juris.de.

BWB (2019): Website Berliner Wasser Betriebe. Available at: http://www.bwb.de. (Accessed: 26 August 2019).

Barba, C., Folch, A., Gaju, N., Sanchez-Vila, X., Carrasquilla, M., Grau-Martínez, A., and Martínez-Alonso, M. (2019): Microbial community changes induced by Managed Aquifer Recharge activities: linking hydrogeological and biological processes, Hydrol. Earth Syst. Sci., 23, 139–154, https://doi.org/10.5194/hess-23-139-2019

Casanova J., Devau N., Pettenati M. (2016): Managed Aquifer Recharge: An Overview of Issues and Options. In: Jakeman A. J., Barreteau O., Hunt R. J., Rinaudo J. D., Ross A. (eds) Integrated Groundwater Management. Springer, Cham

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

Dillon P. (2005): Future management of aquifer recharge. Hydrogeol J 13, 313–316. doi:10.1007/s10040-004-0413-6

Dillon, P., Page, D., Vanderzalm, J., Pavelic, P., Toze, S., Bekele, E., Sidhu, J., Prommer, H., Higginson, S., Regel, R., Rinck-Pfeiffer, S., Purdie, M., Pitman, C., Wintgens, T. (2008): 'A critical evaluation of combined engineered and aquifer treatment systems in water recycling', Water Science and Technology, 57(5), pp. 753–762. doi: 10.2166/wst.2008.168.

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

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

Dillon P., Fernandez E. E., Tuinhof A. (2012): Management of aquifer recharge and discharge processes and aquifer storage equilibrium. IAH contribution to GEF-FAO Groundwater Governance thematic paper 4, 49 pp. www.groundwatergovernance.org/resources/thematic-papers/en/.

Dillon, P., Pavelic, P., Palma Nava, A. et al. Sustain. Water Resources Management (2018): 145. https://doi.org/10.1007/s40899-018-0242-8

Dillon, P., Stuyfzand, P., Grischek, T. et al.(2019): Sixty years of global progress in managed aquifer recharge. Hydrogeol J, 27: 1. https://doi.org/10.1007/s10040-018-1841-z

Dragon K., Górski J., Kruć R., Drożdżyński D., Grischek T. (2018): Removal of Natural Organic Matter and Organic Micropollutants during Riverbank Filtration in Krajkowo, Poland. Water 10: 1457.

Dušek P., Velísková Y. (2019): Interaction Between Groundwater and Surface Water of Channel Network at Žitný Ostrov Area. Water Resources in Slovakia: Part I. The Handbook of Environmental Chemistry 69, Springer. https://doi.org/10.1007/978-3-319-92853-1

EEA (2010): European Environmental Agency Core Set Indicator CSI 18, based on data from Eurostat data table: annual water abstraction by source and by sector. European Environmental Agency, Copenhagen. https://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Agri-environmental_indicator_-_water_abstraction

EEA (2018): European waters – assessment of status and pressures 2018 https://www.eea.europa.eu/themes/water/european-waters/water-quality-and-water-assessment. Pg. 67

Wojtalla K (2007) Wasserversorgung in Deutschland - staatlich oder privat ?

Retrieved from https://www.uni-trier.de/fileadmin/fb4/prof/VWL/SUR/Lehre/WS0607/SeminarInfrastruktur/privat/Leistungsnachweise/HA/Wojtalla.pdf

EUROSTAT https://ec.europa.eu/eurostat/statistics-explained/index.php/Water_statistics

Faculty of geotechnical Engineering (2009): Assessment of state and risk of groundwater bodies in karts area of the Republic of Croatia. Archive of Croatian Waters, Zagreb. http://www.ivb.hr/naslovnahidden/30-akumulacija-butoniga

Federal Institute for Geosciences and Natural Resources (2019): Groundwater Resources in Germany. Available at: https://www.bgr.bund.de/DE/Themen/Wasser/Bilder/Was_wasser_startseite_gwleiter_g.html?nn=1542268.

Federal Ministry for the Environment Nature Conservation and Nuclear Safety (2001): 'The German Water Sector Policies and Experiences', retrieved from: https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/2752.pdf

Federal Ministry for the Environment Nature Conservation and Nuclear Safety (2008): Grundwasser in Deutschland, Bundesministerium für Umwelt, Naturschutz und

Reaktorsicherheit (BMU), retrieved from: https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3642.pdf

Gale, I. (2005): Strategies for managed aquifer recharge in semi-arid areas. UNESCO-IHP Publ. https://unesdoc.unesco.org/ark:/48223/pf0000143819. Pg. 3, 5, 10, 15

German Environment Agency (2017a): Water Resource Management in Germany. Available at: www.uba.de/en/water-resource-management.

German Environment Agency (2017b): 'Waters in Germany:- Status and assessment', retrieved from : https://www.umweltbundesamt.de/en/topics/waters-in-germany-status-assessment

German Federal Environment Agency (2014a): Water Resource Management in Germany Part 1: Fundamentals, Federal Ministry for the Environment Nature Conservation and Nuclear Safety, retrieved from: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/waterresourcemanagement_germany_digital_aktualisiert.pdf

German Federal Environment Agency (2014b): 'Water Resource Management in Germany Part 2: Water Quality', Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, p. 150.

German Federal Gouvernment (2010): Verordnung zum Schutz des Grundwassers (Grundwasserverordnung -GrwV). Available at: www.juris.de.

Greskowiak J., Prommer, H., Massmann, G., Johnston, C.D., Nutzmann, G., Pekdeger, A. (2005): 'The impact of variably saturated conditions on hydrogeochemical changes during artificial recharge of groundwater', 20, pp. 1409–1426. doi: 10.1016/j.apgeochem.2005.03.002.

Gruetzmacher G. and Kumar P. J. S. (2016): 'Introduction to Managed Aquifer Recharge (MAR) – Overview of schemes and settings world wide', (April), pp. 1–11.

Grünheid S., Amy G., Jekel M. (2005): 'Removal of bulk dissolved organic carbon (DOC) and trace organic compounds by bank filtration and artificial recharge', Water Research, 39(14), pp. 3219–3228. doi: 10.1016/j.watres.2005.05.030.

Grischek T., Schoenheinz D., Worch E., Hiscock K. (2002): Bank-filtration in Europe: an overview of aquifer conditions and hydraulic controls. In: Dillon P (ed) Management of aquifer recharge for sustainability: proceedings of the 4th International Symposium on Artificial Recharge of Groundwater, Adelaide, September 2002. CRC, Boca Raton, FL, pp 485–488¶

Golder Associates (Hungary) Ltd. (2000): Final Report of the Sajószentpéter I. Water Base Diagnostic Works

Górski J., Dragon K., Kruć R. (2018): – A comparison of the efficiency of riverbank filtration treatments in different types of wells. Geologos 24 (3): 245–251.

Górski J., Dragon K., Kaczmarek P. (2019): Nitrate pollution in the Warta River (Poland) between 1958 and 2016: trends and causes. Environmental Science and Pollution Research 26: 2038-2046.

Grützmacher, G. and Sajil Kumar, P.J. (2012): Introduction to Managed Aquifer Recharge (MAR) – Overview of schemes and settings world wide.

Hessisches Ministerium für Umwelt ländlichen Raum und Verbraucherschutz (2005): Das hessische Ried, retrieved from: https://umwelt.hessen.de/umwelt-natur/naturschutz/arten-biotopschutz/das-hessische-ried

Hötzel H. and Reichert B. (1996): Bd. 4, Schadstfftransport und Schadstoffabbau bei der Uferfiltration am Beispiel des Untersuchungsgebietes 'Böckinger Wiesen' im Neckartal bei Heilbronn. 4th edn, Deutsche Forschungsgemeinschaft. 4th edn.

IAEA (2013): Using isotopes for design and monitoring of artificial recharge systems. International Atomic Energy Agency, TECDOC no. 1723. https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1723_web.pdf. Accessed February 2020

IAH-MAR (2018a): International Association of Hydrogeologists - Commission on Managing Aquifer Recharge. https://recharge.iah.org/. Accessed on December 2019.

IGRAC (2007): Artificial Recharge of Groundwater in the World. Report. Accessed on December 2019.

IGRAC (2018): MAR Portal. International Groundwater Resources Assessment Centre. https://www.un-igrac.org/special-project/mar-portal.

Kazner C., Wintgens T., Dillon P. (2012): Water Reclamation Technologies for Safe Managed Aquifer Recharge, Water Intelligence Online.

Konikow L. F. (2011): Contribution of global groundwater depletion since 1990 to sea-level rise. Geophys Res Lett 38(L17401):1–5

Kuehn W. and Mueller U. (2000): 'Riverbank filtration: An overview', Journal / American Water Works Association, 92(12), pp. 60–69. doi: 10.1002/j.1551-8833.2000.tb09071.x.

Laszlo F., Literathy P. (2002): Laboratory and field studies of pollutant removal. In: Ray C. (ed) Riverbank filtration: understanding contaminant biogeochemistry and pathogen removal. Kluwer, Dordrecht, The Netherlands, pp 229–234.

Magdalenić, A., Vazdar, T., Hlevnjak, B. (1995): Hydrogeology of the Gradole Spring Drainage Area in Central Istria. Geologia Croatica, 48/1, pg. 97-106.

Manger V. (2018): 'Integriertes wasser-ressourcen- management im hessischen ried', Wasser und Abfall, 20(11), pp. 14–18. doi: 10.1007/s35152-018-0128-y.

Margat J. (2008): Les eaux souterraines dans le monde [Groundwater around the world]. BRGM, Orleans, France and UNESCO, Paris. Pg. 180

Margat J. and van der Gun J. (2013): Groundwater around the world. Balkema, Lisse, The Netherlands.
https://www.un-igrac.org/sites/default/files/resources/files/Groundwater_around_world.pdf

Martin R. (2013): Clogging issues associated with managed aquifer recharge methods. IAH Commission on Managing Aquifer Recharge. 1st clogging monograph. https://recharge.iah.org/working-groups/clogging-and-its-management. Accessed Feberuary 2020

Ministry of Environment of the Slovak Republic (2010): Water Plan of the Slovak Republic, retrieved from:
http://www.vuvh.sk/download/rsv/00_vps/water_plan_of_the_slovak_republic.pdf

Möller K. and Burgschweiger J. (2008): Wasserversorgungskonzept für Berlin und für das von den BWB versorgte Umland (Entwicklung bis 2040) [Water supply concept for Berlin and the surrounding area (development until 2040) supplied by BWB]. BWB, Berlin. Pg. 4

2nd National River Basin Management Plan (RBMP) - Hungary (2015), retrieved from: http://vizeink.hu/korabbi-vizgyujto-gazdalkodasi-tervek/vizgyujto-gazdalkodasi-terv-2015/

Natural Resource Management Ministerial Council of Australia (2007): Australian Guidelines for Water Recycling – Managed Aquifer Recharge. National Water Quality Management Strategy Document No 24. http://www.nepc.gov.au/system/files/resources/5fe5174a-bdec-a194-79ad-86586fd19601/files/wq-agwr-gl-managed-aquifer-recharge-final-200907_1.pdf

Przybyłek J., Dragon K., Kaczmarek P. (2017): Hydrogeological investigations of river bed clogging at a river bank filtration site along the River Warta, Poland. Geologos 23, 3: 199-212.

PROLINE-CE (2017-2019): Efficient Practices of Land Use Management Integrating Water Resources Protection and Non-structural Flood Mitigation Experiences. Interreg Central Europe. Output O.T1.2 STRATEGY FOR THE IMPROVEMENT OF POLICY GUIDELINES. https://www.interreg-central.eu/Content.Node/PROLINE-CE/PROLINE-CE-O.T1.2-Strategy-for-the-improvement-of-policy-gui.pdf

Ray, C., Grischek, T., Schubert, J., Wang, J. Z., Speth, T. F. (2002): A perspective of riverbank filtration. J AWWA 94(4):149–160.

Ray, C., Melin, G., Linksy, R. B. (2003): Riverbank Filtration Improving Source-water Quality, Environmental Science and Engineering (Subseries: Environmental Science). doi: 10.1007/0-306-48154-5.

Ringleb J., Sallwey J., Stefan C. (2016): Assessment of managed aquifer recharge through modeling: a review. Water 8:579–609

Ross A. and Hasnain S. (2018): Factors affecting the costs of managed aquifer recharge schemes. Sustain Water Resour Manag 4(2):179–190. https://doi.org/10.1007/s40899-017-0210-8

Rodríguez-Escales P., Fernàndez-Garcia D., Drechsel J., Folch A., Sanchez-Vila X. (2017): Improving degradation of emerging organic compounds by applying chaotic advection in managed aquifer recharge in randomly heterogeneous porous media. Water Resour Res 53:4376–4392

Statistical Office of Poland (2018): Environment 2018. https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/srodowisko/ochrona-srodowiska-2018,1,19.html

Statistisches Bundesamt DSTATIS (2018): Öffentliche Wasserversorgung und öffentliche Abwasserentsorgung., retrieved from: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Wasserwirtschaft/Publikationen/Downloads-Wasserwirtschaft/wasserwirtschaft-2190213169004.pdf?__blob=publicationFile

Sprenger C., Hartog N., Hernández M., et al. (2017): Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives. Hydrogeol J., 25: 1909. https://doi.org/10.1007/s10040-017-1554-8

Trančíková A., Vojtko A. (2012): Pilot territory evaluation from a water management aspect.

Ecotechnology of search and evaluation of substitute drinking underground water, pilot area BSK .(in Slovak)

Water Framework Directive implementation reports (2019). European Commission. https://ec.europa.eu/environment/water/water-framework/impl_reports.htm

Weber L. and Dr. Mikat H. (2011): ‘Grundwasseranreicherungsanlagen im Hessischen Ried’, Fachzeitschrift bbr Brunnenbau.

Ziegler D. (2001): ‘Untersuchungen zur nachhaltigen Wirkung der Uferfiltration im Wasserkreislauf Berlins’ (Dissertation)