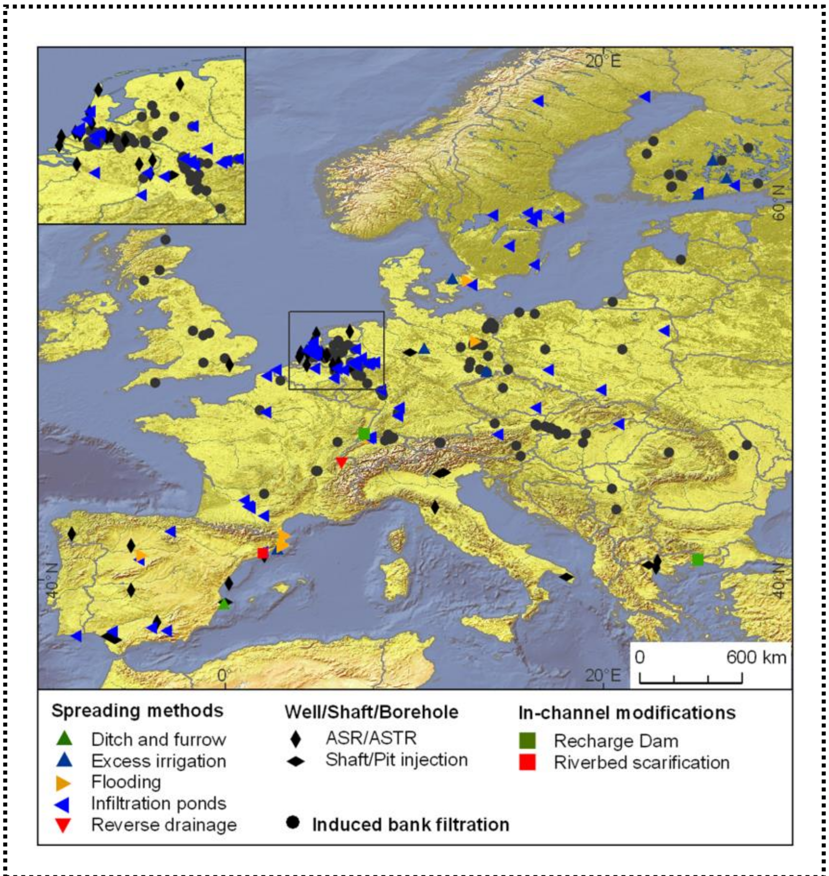
RECOMMENDATIONS FOR FURTHER DATA GENERATION



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Title: Recommendations for further data generation

Abstract: Different types of managed aquifer recharge (MAR) schemes are widely distributed and applied on various scales in the European countries, but no systematic categorization and compilation existed up to now. The European MAR catalogue presented herein includes a wide range of parameters, e.g. operational information, hydrogeological properties and water quality monitoring for different types of MAR. The database includes currently 270 MAR sites, but is neither a representative nor an exhaustive data compilation. Nevertheless, based on the available data it is shown that MAR plays an important role in the European water supply producing large water quantities for the domestic water supply.

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available information for each site in the MAR catalogue

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1 Introduction

DEMEAU is a three-year, EU-funded demonstration project on promising technologies that tackle emerging pollutants in water and waste water. Within the DEMEAU project one of the water treatment technology focused on is Managed Aquifer Recharge (MAR). Different types of MAR are widely distributed and applied on various scales in the European countries, but no systematic categorization and compilation existed up to now. To enable insight in the wide range in applications and operations for European MAR sites, a catalogue in the form of a relational database was developed.

The European MAR catalogue presented herein includes a wide range of parameters, e.g. operational scale, various aquifer properties and water quality. Analysis of the data is presented in this report. For the sake of convenient data entry, modification and display of data is enabled through various graphical user interfaces (Figure 1). Specific knowledge of relational database is not required to take advantage of the European MAR catalogue. It is intended as an evolving database that allows continuous improvement and expansion of the data in the catalogue. Therefore, this report provides a snapshot of the current content.

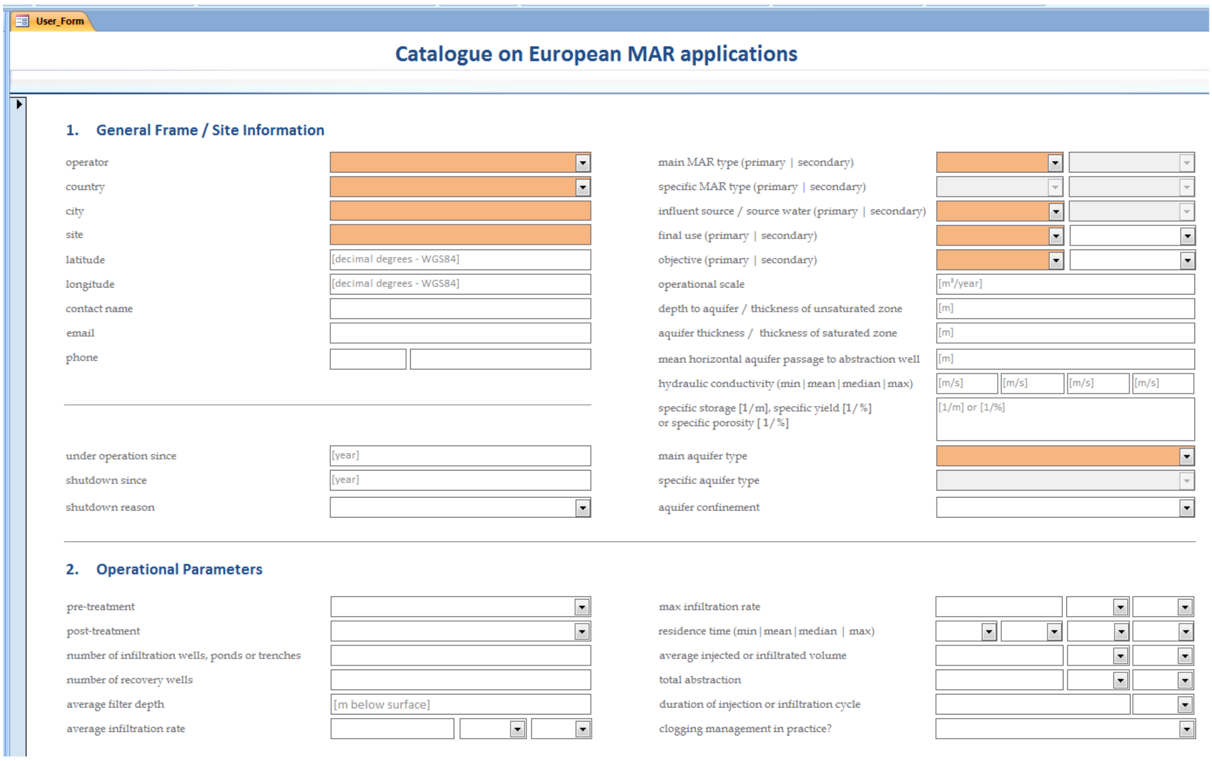

Figure 1: **Example of the graphical user interface displaying the site specific user form of the MAR catalogue**

1.1 Motivation and objectives

The European MAR catalogue aims at providing an information platform of European MAR sites for technical experts, authorities and scientists. With the help of the catalogue it is also possible to identify the current state of knowledge for the respective site or MAR type. Therefore, this unique catalogue provides a valuable information source of MAR in Europe.

1.2 MAR definition

Managed aquifer recharge (MAR) can be defined as the intentional recharge, storage and treatment of water in aquifers. Depending on the type and purpose of the MAR intervention one or more of the three main objectives are dominant. There are a number of different techniques available using boreholes, dug wells, infiltration ponds, furrows/trenches, ditches/barriers and/or wells to infiltrate, induce infiltration or inject water into the aquifer (Figure 2).

MAR types can be divided into five main groups (IGRAC, 2013):

i) Bank filtration is a category by its own and describes the induced infiltration of surface water from a river or a lake by well pumping. Water quality improvement, which is commonly observed during the subsurface passage, is often the main objective of this MAR type.

ii) Rainwater harvesting includes MAR types which collect rain and surface run-off. Barriers and trenches are made e.g. to reduce the surface run-off and erosion and to enable agriculture in hilly terrain. This MAR type increases the water contact area and provides additional recharge potential. Rooftop harvesting collects rain and stores the water in settling tanks before it is recharged through defunct dug wells or boreholes to the aquifer.

iii) In-channel modifications are structures built in streams to intercept or detain the stream flow and enhance groundwater recharge. This type of MAR is common in arid and semi-arid areas where intermittent or ephemeral stream conditions prevail. Sand dams e.g. are usually small structures built in ephemeral/intermittent streams to store water during rainy season to overcome periods of drought. Check dams are used to stop part of the seasonally (monsoon, storm events) occurring stream flow to enhance infiltration through the stream bed. The controlled discharge of the stored water through recharge releases provides additional options at times of limited infiltration upstream of check dam.

iv) Well, shaft, dam and borehole recharge comprise a wide range of types of recharge by gravitation in dug wells, shafts, pits or injection of water by wells (e.g. aquifer storage and recovery, ASR). Please note that in contrast to the classification by IGRAC (2013) the underground dams is not classified here as in-channel modification. MAR structures of this type are mostly below ground level and are also constructed to prevent or counteract seawater intrusion.

v) Spreading methods are used when the geology and hydrology allows the aquifer to be recharged from ground level directly. MAR structures of this type are mostly above or at ground level. Infiltration ponds are often operated until fully saturated conditions below the pond are developed, while soil aquifer treatment (SAT) always requires unsaturated conditions below the infiltration basin. During SAT treated effluent is recharged through a biological active zone (soil), a vadose zone and finally to the saturated zone where the recharged water is recovered and reused.

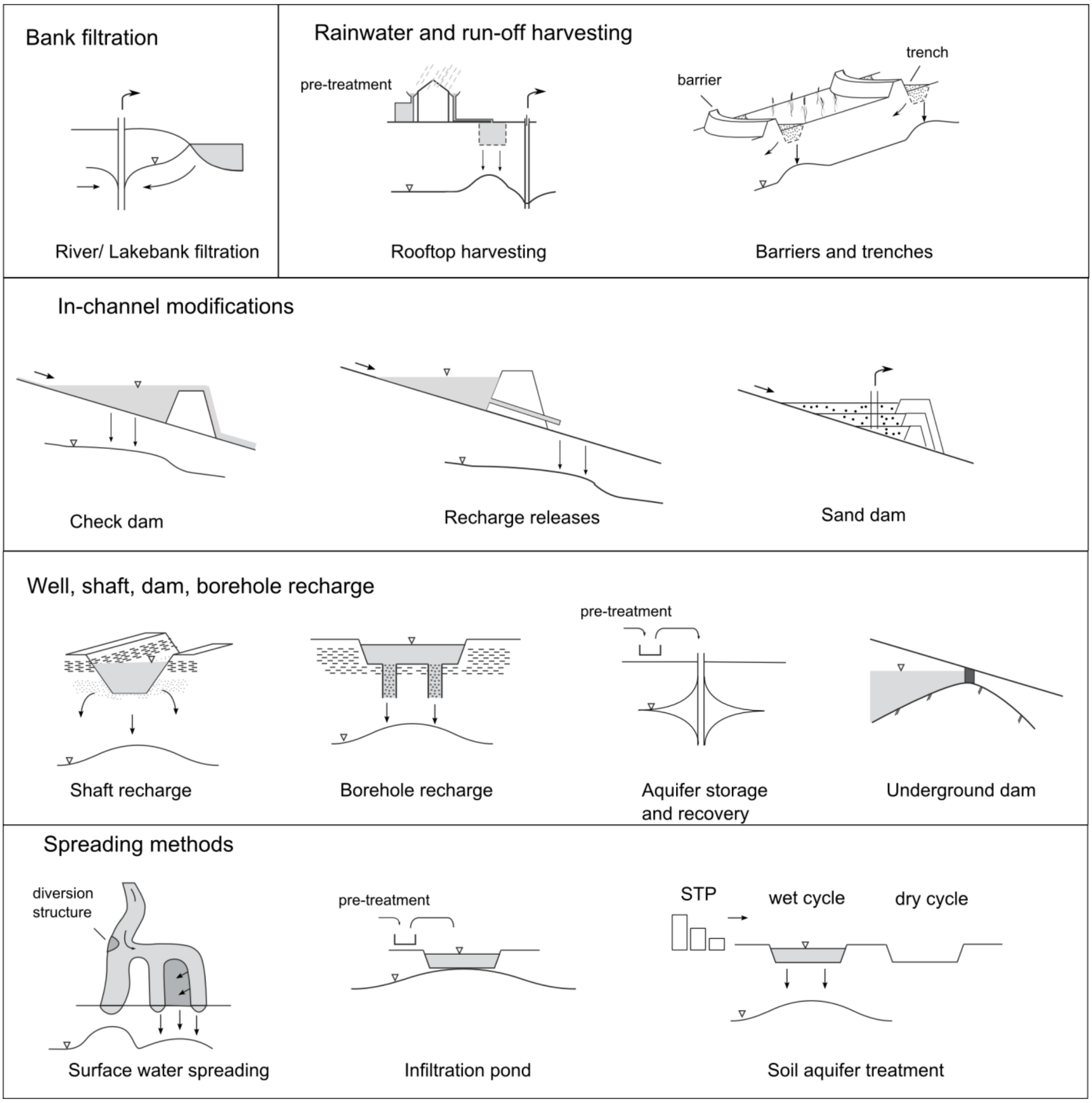

Figure 2: **Sketches of MAR types (modified and extended from Dillon (2005)). STP = sewage treatment plant**

2 Development of the European MAR catalogue

2.1 Structure of the database and classification of fields

The underlying set-up of the MS ACCESS database and relational structure is presented in detail in the report "Development of a catalogue on European MAR sites: Documentation" available under http://demeau-fp7.eu/results. . In total 38 parameters (plus references) were categorized in general site information (e.g. name of operator, location, MAR type), hydrogeological properties (e.g. aquifer type, hydraulic conductivity), operational information (e.g. operational scale, number of abstraction wells) and water quality monitoring (e.g. bulk chemistry monitoring schedule). Table 1 documents the number and percentage of entries in the catalogue. The fields "site name", "country", "city", “geographic location” and “main MAR type” are mandatory fields, while all other fields are optional. The documented information of sites in annex a contains in addition to

Table 1:Overview of field parameter and entries included in the MAR catalogue (* Fields are mandatory)

No.	Field parameter	Entry count (%)	Category	No.	Field parameter	Entry count (%)	Category	No.	Field parameter	Entry count (%)	Category
1	Name of operator	270 (100)	General site information	14	Aquifer confinement	155 (57)	Hydrogeological properties	27	Recovered infiltrate	39 (14)	Operational parameter
2	Email of operator	270 (100)		15	Aquifer thickness	123 (46)		28	Infiltration rate	22 (8)	
3	Country*	270 (100)		16	Horizontal aquifer passage	108 (40)		29	Final use	245 (91)	
4	City*	270 (100)		17	Specific aquifer type	220 (81)		30	Objective	231 (86)	
5	Site name*	270 (100)		18	Hydraulic conductivity	108 (40)		31	Monitoring regularity bulk chemistry	57 (21)	Water quality
6	Latitude*	270 (100)		19	Main aquifer type	221 (82)		32	Monitoring micro biological parameters	57 (21)	
7	Longitude*	270 (100)		20	Average injected or infiltrated volume	95 (35)	Operational parameter	33	Monitoring emerging pollutants	30 (11)	
8	Main MAR type*	270 (100)		21	Operational scale	189 (70)		34	Monitoring in situ	52 (19)	
9	Specific MAR type*	270 (100)		22	Number of infiltration wells	81 (30)		35	Monitoring heavy metals	47 (17)	
10	Influent source	266 (99)		23	Number of recovery wells	75 (28)		36	Monitoring organic compounds	30 (11)	
11	Under operation since	185 (69)		24	Residence time	87 (32)		37	List of emerging pollutants	25 (9)	
12	Shut down since	56 (21)		25	Pre-treatment	97 (36)		38	References	270 (100)	
13	Filter screen depth	95 (35)		26	Post-treatment	63 (23)					

the 270 sites in table 1 ten more sites, which are already added to the database, but not finally proved at the time this analysis was written.

To characterize the content of the catalogue, a selection of fields are classified according to their importance or significance for later interpretation. The selected fields are important hydrogeological and operational parameters shown in Table 2.

Only records which contain all important hydrogeological parameters are class 1 sites. Class 2 sites are characterized by the hydraulic conductivity and at least one additional field information. Class 3 sites do not contain the information about the hydraulic conductivity but at least one of the other fields. Class4 sites do not contain any of the information.

Table 2: Classification of records based on the availability of important hydrogeological and operational information

	Hydraulic conductivity	Aquifer thickness	Horizontal aquifer passage	Number of recovery wells	Operational scale
Class 1	Contains all field information of the five parameters				
Class 2	Must be available	At least one field of the four parameters			
Class 3	Does not contain	At least one field of the four parameters			
Class 4	Residual				

Nineteen MAR sites in the catalogue, corresponding to 7 % were classified as class 1 sites. Class 2 contains 103 sites, corresponding to 38% of all MAR sites. Class 3 sites make up approx. 45 % (124 sites) and class 4 contains the residual 24 sites (approx. 9 %) of all MAR sites (Figure 3).

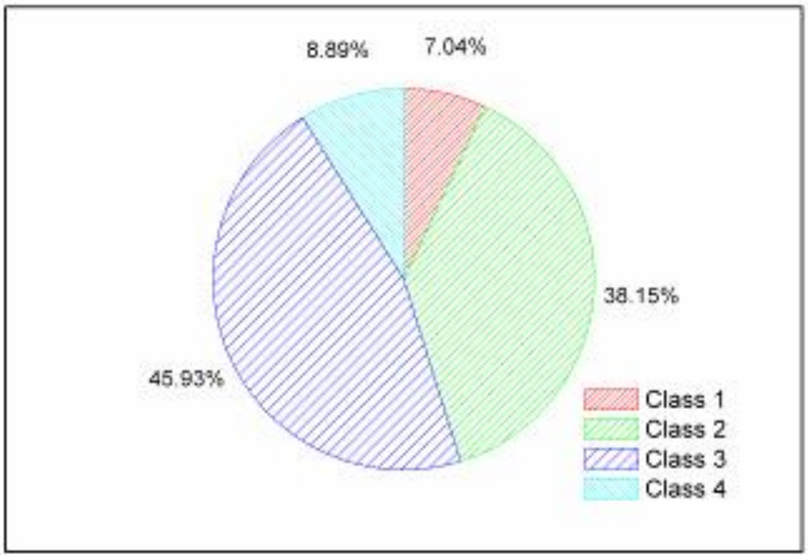

Figure 3: Classification of sites based on record completeness of essential hydrogeological and operational information

MAR sites with relatively complete data entries (class 1 and class 2) make up approx. 45 % of all sites included in the MAR catalogue. Class 3 sites are considered to be moderately characterized. Sites with very poor availability of hydrogeological and operational information (class 4) are only 9 %. It must be noted that many of the European MAR sites considered are likely better characterized, but the information was not available from the considered literature.

Information of European MAR systems was compiled from 264 different information sources which were cited 564 times in total (Table 3). The largest share of information sources consists of scientific publications (i.e. research papers, books, PhD, Diploma and Master's theses), followed by information from community and operator websites (24%) and technical documents (12%). The remaining source types, i.e. presentations (both talks and posters), reports from previous governmental and non-governmental research projects, personal communication with specialists and operators, as well as newspaper articles (10%).

Table 3: **Type and number of information sources, citations per category and ratio**

Category	Sources per category	Citations per category	Ratio citation/source
Newspaper articles	3	3	1.0
Personal information	5	5	1.0
Presentations	8	8	1.0
Research projects	10	16	1.6
Scientific publications (peer reviewed paper, Master thesis …)	140	321	2.3
Technical documents	31	109	3.5
Websites	67	102	1.5
Total	**264**	**564**	**2.2**

By looking at the numbers of citations obtained per category large differences can be observed. On average each reference was cited 2.2 times (Table 3) but scientific publications and technical documents were cited more frequently and offer a higher degree of information. In contrast, newspaper articles, presentations, research projects and websites usually address only a few aspects and contain less information.

Some of the parameters are displayed as box and whisker plots. Box and whisker plots are standardized ways of displaying the distribution of data based on: minimum, first quartile, median, third quartile, and maximum. The central rectangle spans the first quartile to the third quartile (the interquartile range or IQR). The red line inside the rectangle shows the median and "whiskers" above and below the box show the minimum and maximum, as long as they do not lie 1.5 × IQR or more above the third quartile or 1.5 × IQR or more below the first quartile. Outliers, plotted as small circles, lie either 1.5×IQR or more above the third quartile or 1.5×IQR or more below the first quartile. Extreme values, plotted as small stars, are either 3×*IQR* or more above the third quartile or 3×*IQR* or more below the first quartile.

2.2 Quality assurance and plausibility control

During data acquisition and entry, several persons from various institutions contributed. Besides the risk of human error during data entry, other factors, e. g. outdated sources will challenge the quality of the collected data. Thus, following the data acquisition period, various quality control measures were carried out to ensure a high level of data integrity.

Identified outliers and conspicuous extreme values of the database's numerical fields were double checked using the respective references. Besides these relatively simple statistical tests on individual fields, logical checks were performed between related parameters in order to identify data gaps. For example, it can be assumed that information on the year of closure and the reason for closure are usually jointly available. Therefore, for record sets where only one of these parameters was filled, the literature was consulted once more to make sure no available information was omitted. Implausible or unlikely combinations of parameter values were also checked and corrected if necessary. An example would be the combinations of the parameters "specific MAR type" and "number of infiltration wells". Sites that have a specific number of infiltration wells should also either have ASR, ASTR or dug well / shaft / pit injection as the "specific MAR type". Where that was not the case site information was double checked. Subsequently, a selection of datasets was cross checked by different personnel and specialists of partner institutions and affiliated operators (BWB, Dunea and Eskap).

The MAR catalogue does not claim to be a representative and certainly not an exhaustive database. The lack of data for specific countries does not necessarily mean the lack of MAR sites. It can rather be attributed to the fact, that language barriers restricted the literature research to languages spoken by members of the research team (i.e. English, Spanish, German, Polish, Dutch and French). Moreover, many sources of information i.e. technical reports are simply not available in the public or scientific domain.

3 Results and discussion

3.1 General overview and historical development of MAR sites in Europe

The database contains 270 MAR sites of which 53 sites were closed due to various reasons. A spatial overview of all currently operating and shut-down European MAR sites included in the catalogue is given in Figure 4.The spatial distribution of currently active MAR sites covers most of the European countries with distinct differences in occurrence frequency from region to region. MAR hot spot regions can be identified in The Netherlands, Belgium and West Germany where induced bank filtration is the dominant MAR type. Also in the region around Berlin and Dresden in East Germany as well as along the Danube River in Austria and Hungary many bank filtration sites can be found. In contrast to these hot spots other regions in Europe are not or sparsely represented, namely the Balkans region, Norway, Ireland, Denmark, the Baltic states and other eastern European countries.

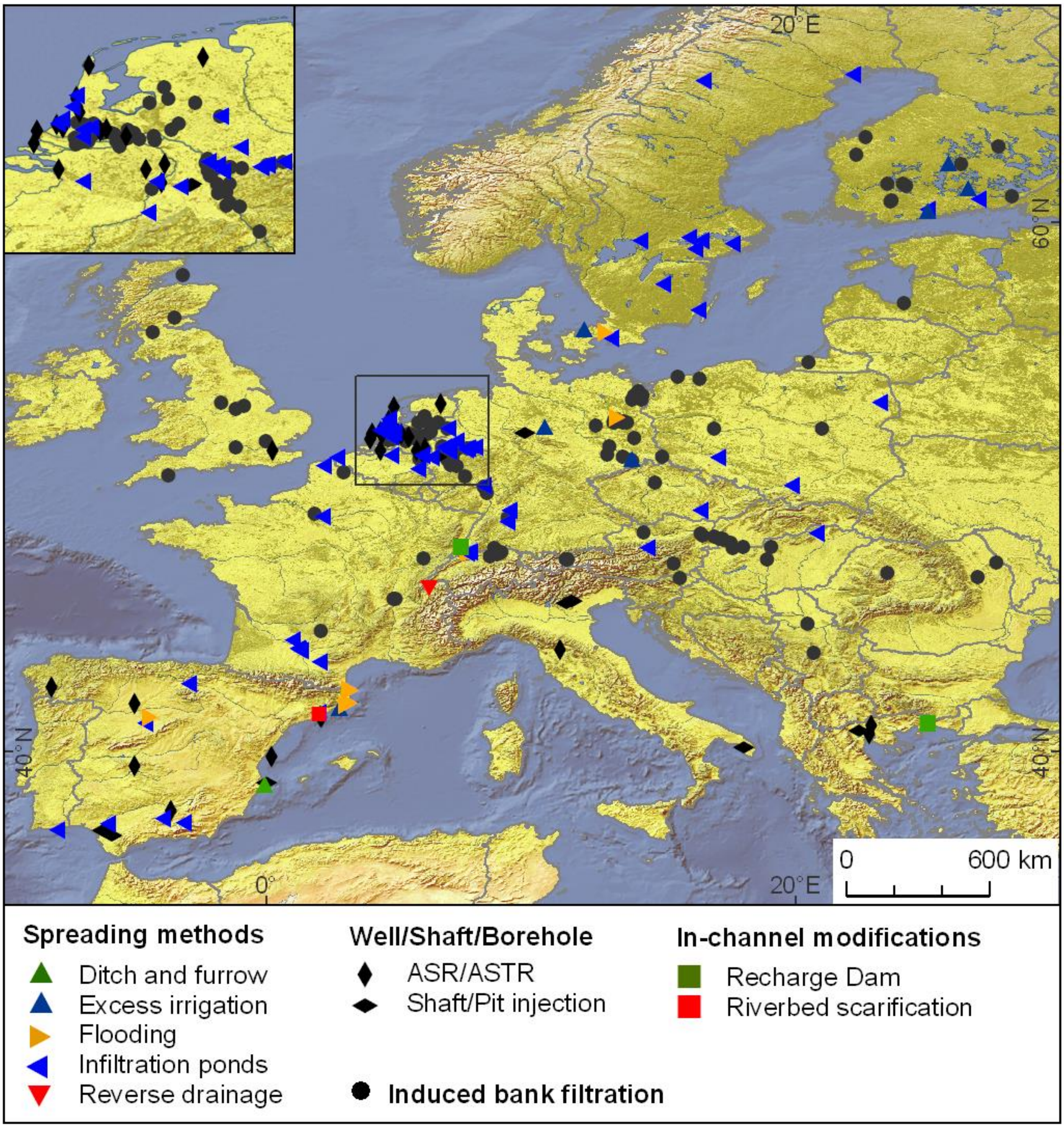

Figure 4: **Spatial occurrence of MAR sites in Europe**

The distribution of main and specific MAR types in the database is presented in Figure 5. With 145 out of the 270 systems (54 %) induced bank filtration is the most dominant MAR type. Surface spreading methods rank second among all main MAR types with 79 systems (29%). Well, shaft and borehole recharge systems form the third largest group of main MAR types with 44 sites in Europe (16%) and in-channel modifications are applied at 2 sites only (0.7%). Rainwater harvesting was not an applied MAR technology at any of the analyzed sites in Europe.

Together with induced bank filtration, ponds & basins with 61 sites (23%) are the most important specific MAR types. For the latter, none of the considered MAR sites in Europe belonged to either of its two sub-types (i.e. sub surface dams and sand dams).

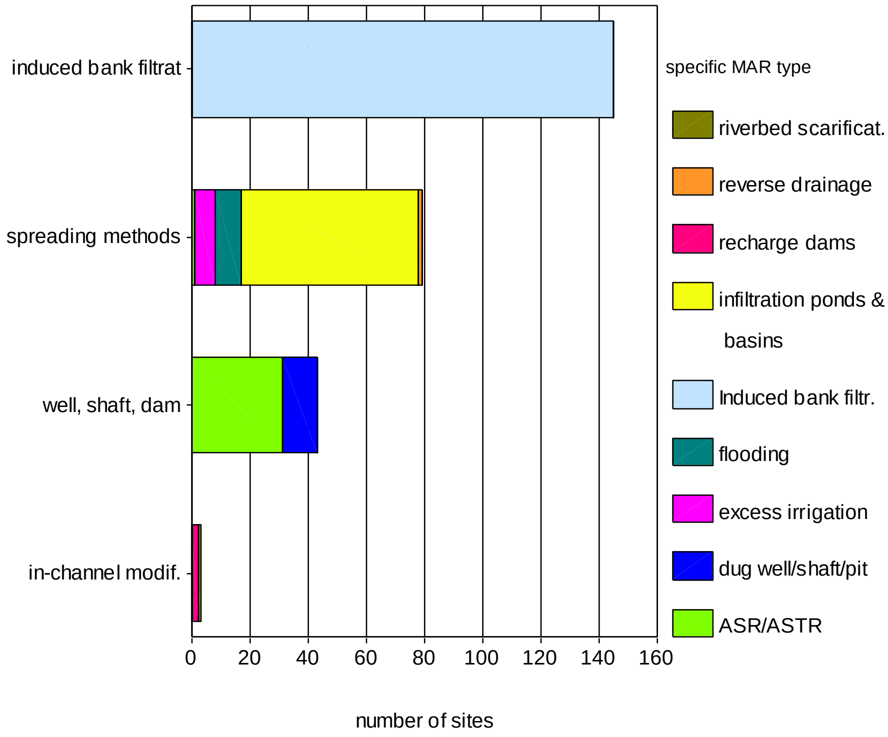

Figure 5: **Distribution of main (labels) and specific (colours) MAR types**

The distribution of MAR types per country is shown in Figure 6. In terms of total numbers, Germany and The Netherlands together have 136 out of the 270 known MAR sites (50 %), followed by 25 Spanish and 13 French sites (9% and 5%, respectively). For Finland, Sweden, Switzerland and the UK have between 10 and 18 sites (17 % in total) could be identified, while the remaining 19 % of the sites are distributed amongst 15 other countries.

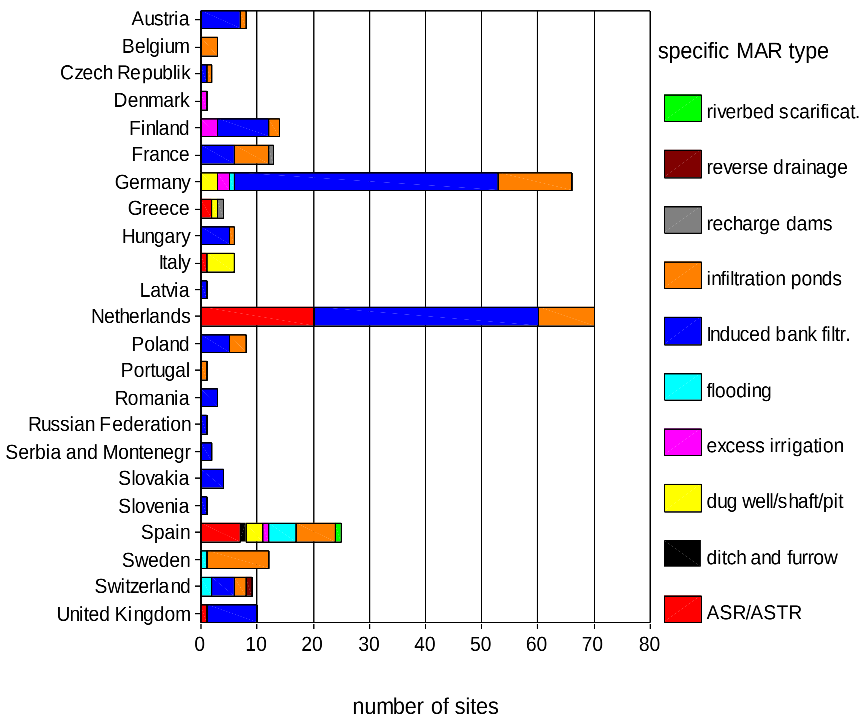

Figure 6:MAR type distribution per country

Information on the year of first operation and the year of shut down allows drafting the historical development of MAR in Europe. In Figure 7, the number of MAR sites opened between 1870 and 2012 classified in a 10 year interval are shown. The modern history of what is called MAR today begins with two techniques which are most prominently represented in the MAR catalogue: i) bank filtration and ii) groundwater replenishment by infiltration ponds. The first reported MAR site in Europe was in Glasgow (UK) where in 1810 the Glasgow Waterworks Company constructed a perforated collector pipe parallel to the Clyde River (Ray et al., 2002) and abstracted bank filtrated water (BMI, 1985). 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 and in the 1860´s it came to a 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 been abandoned in later years (BMI, 1985). For many of these early sites the exact starting and ending year of operation was not found in the literature and are not included in Figure 7. Nevertheless, the idea of "naturally filtered water" induced by pumping was born and spreaded to continental Europe, where it was soon adapted by cities in The Netherlands, Belgium, Sweden, France, Austria and Germany.

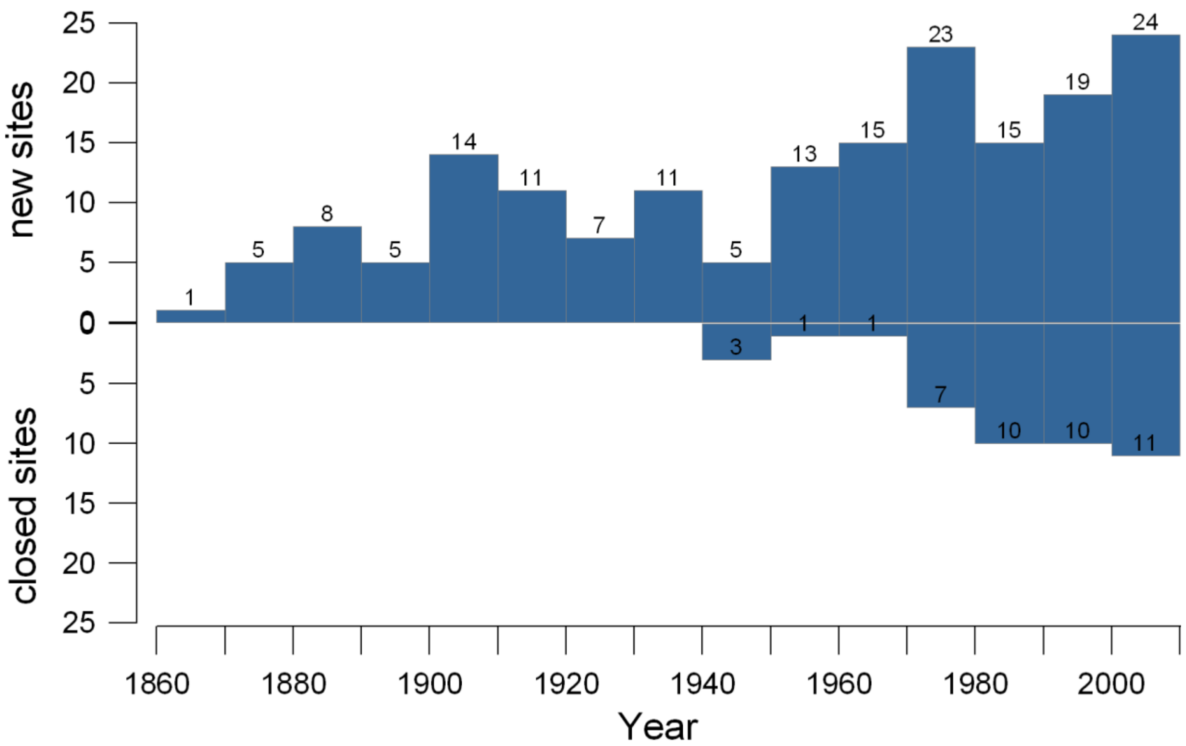

Figure 7: **Historical development of MAR sites in Europe showing the number of new MAR sites opened between 1860 and 2010**

The increasing industrialization and growing population in European cities confronted the municipal water supply with new challenges. The traditional water supply with surface water was impaired by increasing contamination of the new industries and improper sanitation. The pioneers of MAR in Germany were at the Rhine River (e.g. WW Düsseldorf 1870) and at the Ruhr River (e.g. WW Essen 1875), at the Elbe River (e.g. WW Saloppe 1875, WW Hosterwitz 1908) around Dresden and in the Berlin area (e.g. WW Müggelsee, switched to groundwater in 1904-1909, WW Tegel 1901-1903). Similar to the development in Germany and Sweden, river bank filtration (RBF) and infiltration ponds found application in The Netherlands and Switzerland. In The Netherlands e.g., the first known RBF based water supply was reported to have started its operation in 1890 (Stuyfzand, 1989). The first MAR site in Switzerland started its operation in Basel "Langen Erlen" in 1912. Eastern European cities then followed and in Hungary the first RBF site was installed north of Budapest on a Danube island (Szentendre) in the 1920´s (Homonnay, 2002). To date, this MAR system is the main drinking water source for Budapest (Homonnay, 2002). Additional RBF sites have been developed on other Danube islands (e.g. Csepel) and nowadays several RBF sites exist along the rivers of Raba, Drava, Ipoly, Sajo and Hernad (Homonnay, 2002). In Romania the MAR history starts with the operation of the Iasi water supply system at the Moldova River in 1911 and the cities of Cluj Napoca followed in 1935 with conjunctive use of RBF and infiltration ponds and Bacau in 1961 (Rojanschi et al., 2002). In Finland the first plant using groundwater replenishment by infiltration ponds started its operation in 1929 in Vaasa (Tapio et al., 2006). A few other plants were developed before and after world war II, but the systematic development of MAR in Finland only started in the 1960´s (Tapio et al., 2006). It is reported that in the year 1992 about 20 water suppliers relied on different MAR types mainly constructed in 1970´s. In 2002 already 25 operating water works utilized MAR in Finland (Tapio et al., 2006). Finally, Tapio et al. (2006) report that after several decades of experience with MAR, this technique is continuously favored by water suppliers.

Based on the analysis of the MAR database it is observed that the amount of new sites is increasing with time. This finding is a clear indication of the growing appreciation within the water sector of this long-known technique for the modern challenges in water management and production.

Finally, it must also be noted that due to different reasons 56 (21%) of the sites listed in the database were shut down. While for more than half of them the reason for closure is unknown, many of the remaining sites where only used as pilot studies for a limited period of time. At other sites, operation has been suspended temporarily or was shut down entirely due to economic or political reasons.

3.2 Operational parameter

3.2.1 Primary influent source water

The primary influent source water is the main water type which is used as input water for a particular MAR type. In the database it was possible to choose between wide ranges of different water types (i.e. river water, lake water, storm water, reclaimed domestic wastewater etc.).

Figure 8 illustrates the distribution of influent source water per specific MAR type. In some cases distinct correlations between specific MAR types and influent sources can be observed. As induced bank filtration only occurs along the banks of rivers and lakes this MAR type has two primary influent sources: river and lake water. Groundwater which is in virtually all cases of bank filtration also an influent source water is not shown here, despite of the fact that groundwater may contribute significant to the abstracted water. However, it is not intended to be the primary influent water.

In the case of recharge dams, which are built within riverbeds, river water is the influent source. Since only two records with information on the influent source exist for the MAR type “ditch and furrow”, characteristic influent sources cannot be determined.

The remaining MAR types are not restricted to a location near river or lake banks and thus show a larger variety of influent sources.

With a total of 44 available data sets, the main MAR type of well, shaft and borehole recharge (i.e. ASR/ASTR and dug well / shaft / pit injection) shows a large variety of primary influent water sources. ASR/ASTR systems are often used for pilot studies and scientific research purposes and they also use the rather exceptional influent sources of storm water and groundwater.

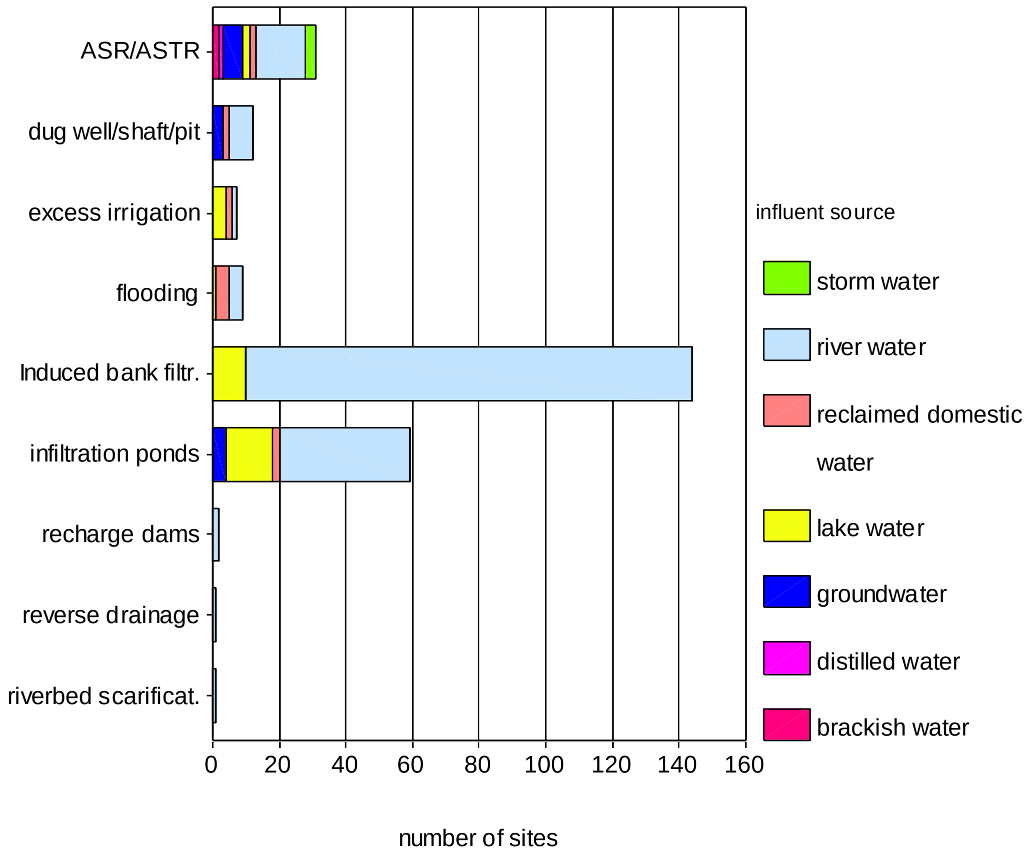

Figure 8: **Distribution influent source water per specific MAR type**

Alternative influent sources such as reclaimed or storm water can be found in areas which are prone to water stress (e.g. Spain), but also in moderate regions (e.g. north Germany) (Figure 9).

Distilled water was used as input water at an ASR site in The Netherlands (Den Burg) between 1977 and 1990. Surplus water from a seawater desalination plant in the winter time was injected and abstracted in the summer period when water demand was increased (Stuyfzand et al., 2012).

Reclaimed domestic water is used as an influent source at 12 sites in Europe. In most cases it is used for agricultural purposes. In Braunschweig (Germany) the sewage works Steinhof is infiltrating about 12 Mio. m^3/a of treated sewage by flooding and sprinkler irrigation. This high operational scale makes this system the largest MAR system utilizing reclaimed water in Europe. At the Llobregat aquifer in Barcelona (Spain) reclaimed water is injected via injection wells or infiltrated through infiltration ponds to act as a hydraulic barrier against seawater intrusion (Ortuno et al., 2012).

Only a few sites in Europe produce domestic water with reclaimed water. In Torreele/St-Andre (Belgium) tertiary treated wastewater is infiltrated in a dune area. The MAR system, in combination with advanced technical treatment, produces potable water in the range of 2.5 Mio. m^3/a (van Houtte and Verbauwhede, 2008). Another example is found at a small scale pilot site in Giannitsa (Greece) (Ferreira et al., 2007).

Apart from the direct usage of reclaimed water via various MAR types several other sites exist which use treated wastewater or a blend of fresh and treated effluent water as source water. E.g. bank filtration sites situated downstream of a sewage treatment plant (i.e. Berlin Tegel (Germany)).

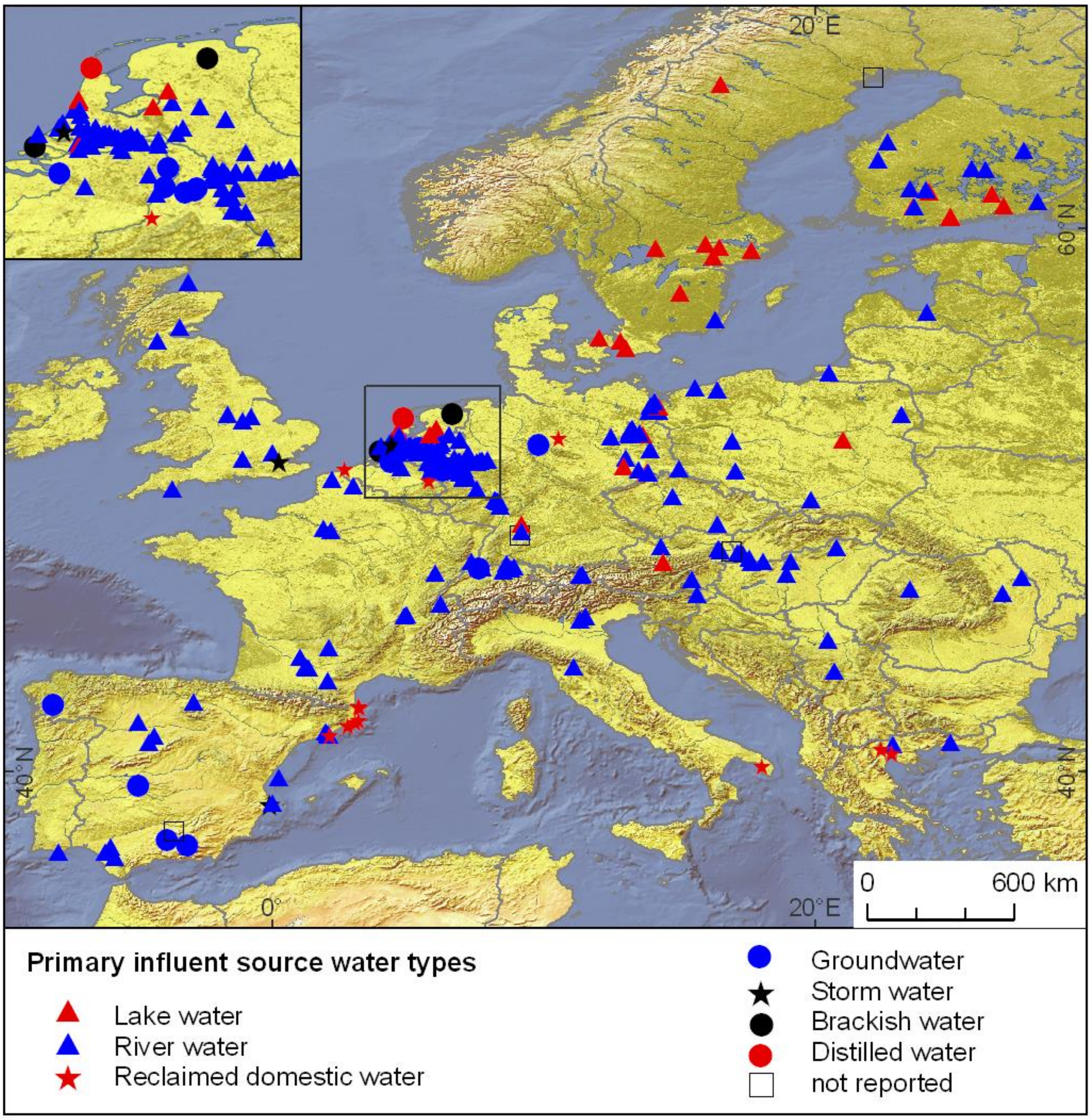

Figure 9: Primary influent source water types of MAR sites in Europe

3.2.2 Final use and main objectives of MAR sites in Europe

The final use describes the intended usage of the output water of the respective MAR system. The catalogue allows distinguishing between agricultural, domestic, ecological and industrial usages. The main objective describes the purpose of the MAR system which can be differentiated between water quality management, physical aquifer management, maximizing storage, management of the water distribution system, ecological benefits and other benefits. Final use and objective are closely related as e.g. an ecological usage is often connected to e.g. the conservation of groundwater dependent ecosystem which is summarized under the objective ecological benefits. However, an ecological or agricultural usage may also contribute to water quality management in which the MAR system is operated to improve or restore groundwater quality.

Figure 10 shows the percentage share of objectives related to the final use of MAR systems. MAR water used for agriculture purposes shows various objectives. At a site in Portugal (Campina de Faro aquifer system) river water was recharged through infiltration ponds in order to improve groundwater quality (Ferreira et al., 2007) . The objective “physical aquifer management” is realized when the MAR system is mainly for stabilizing or restoring groundwater heads. In Marbella (Spain) e.g. injection wells are designed to restore hydraulic gradient to counteract seawater intrusion (Bueso et al., 2006). Maximizing natural storage of the aquifer is intended to be realized by MAR at a site in Greece (close to the city of Kilkis), where river water is injected to bridge seasonally occurring water shortages (Panagopoulos et al., 2004).

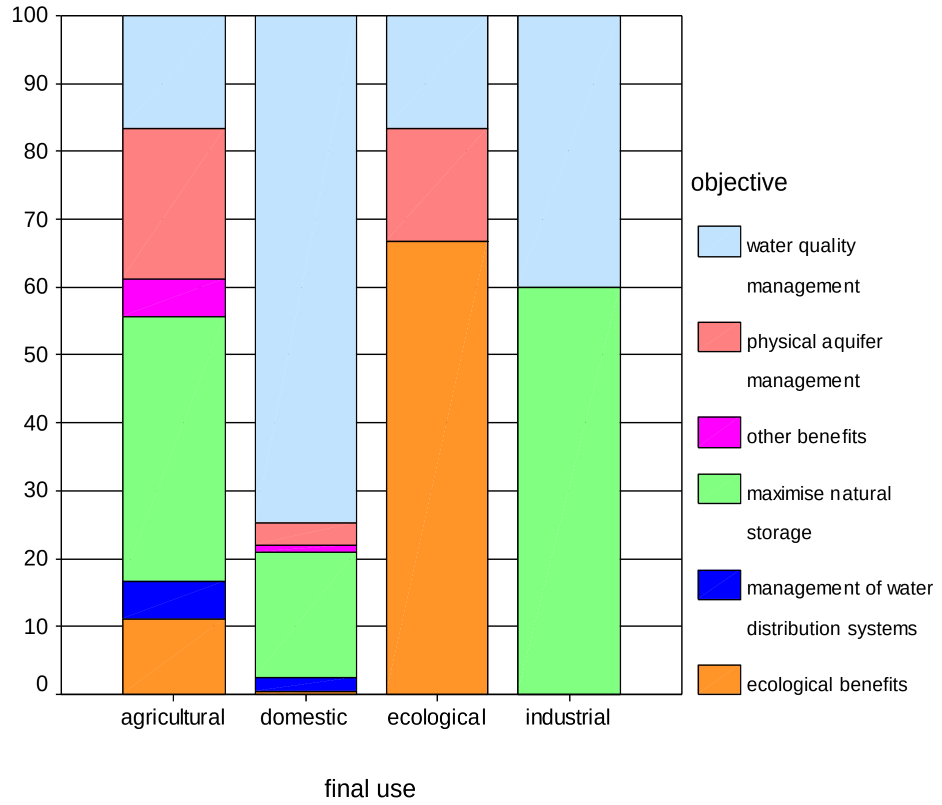

Figure 10: **Percentage share of main objective per final use of European MAR systems**

Using MAR water for agricultural purposes appears to be much more common in Spain than anywhere else in Europe (Figure 11). Ecological uses are common in Germany, Spain and in The Netherlands, while most industrial uses can be found in Germany.

It is obvious that the main objective for MAR systems producing water for domestic use is in most cases water quality management, but also other objectives such as maximizing natural storage are realized. In Italy e.g. at the Bisenzio River the local aquifer was overexploited over decades and the declining water table threatened the water supply wells. A pilot MAR site explored the potential of MAR in this context (Landini and Pranzini, 2002). At surface water spreading sites in Sweden (Luleå and Landskrona) physical aquifer management appears to be the primary objective but water quality management was also reported to be an important objective. At an ASR site close to London (Horton Kirby) water is stored to bridge seasonal, peak and drought domestic water demand (Riches et al., 2007).

MAR sites with reported ecological use are rare with an amount of 2% for all records of final use data. At an open-pit lignite mining area in West Germany injection wells are operated to stabilize the groundwater table for ecological benefits. The injected source water is groundwater which is pumped from the active mining area to the surrounding area.

Industrial use of MAR water (2% as well) was identified in Germany where process water is produced by bank infiltration for the steel industry and another site in Cologne where bank filtration produces process water for the chemical industry.

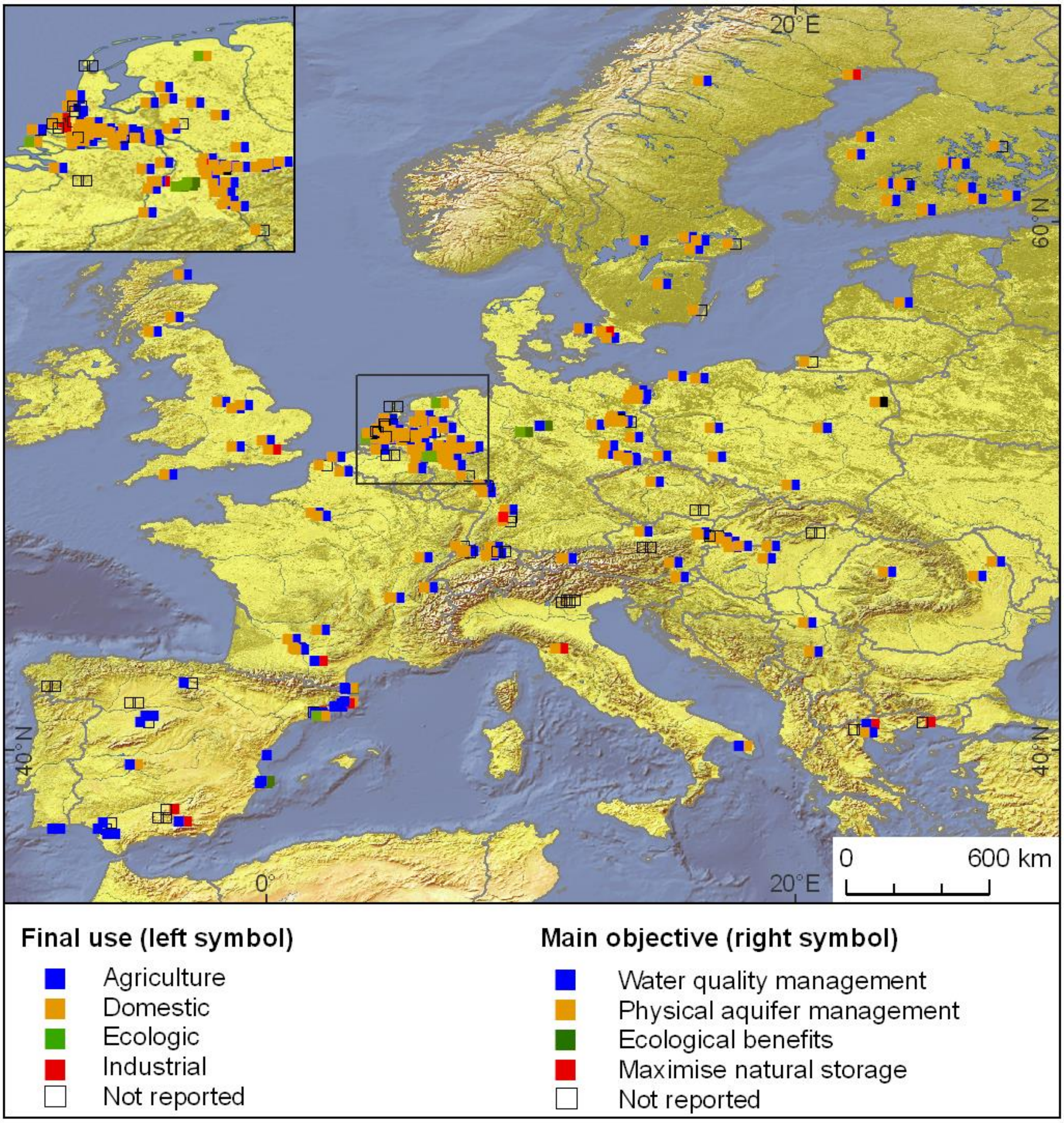

Figure 11: Final use and main objective of MAR sites in Europe

3.2.3 Operational scale

The operational scale gives insight in the total water quantity produced by the MAR system. The operational scale of a water plant which utilizes MAR but also other water sources such as direct groundwater abstraction, is often not differentiated in MAR and other sources. Therefore, the operational scale is often a rough estimation. Anyhow, information on the operational scale allows a (semi-) quantification of water which is produced by MAR.

There is no doubt that MAR plays an important role in the European water supply and induced bank filtration often combined with infiltration ponds produces large water quantities. Large quantities (>

36.5 × 10^6 m^3/a) of MAR water are produced by sites in Hungary, Slovakia, The Netherlands, Germany, Poland and France.

Some of the largest MAR sites exist on islands (Csepel and Szentendre) in the Danube River in Budapest (Hungary), where the operational scale of the river bank filtration sites are reported to be 146 and 219 × 10^6 m^3/a, respectively. Along with all other MAR sites in Hungary included in the catalogue, the total water volume is contributing approx. 59 % to the public water (total public water supply 661 × 10^6 m^3/a in 2006 based on EEA (2010)). Laszlo and Literathy (2002) estimated the share of river bank filtrated water alone to the drinking water supply be about 40 %. This high share of MAR derived water makes Hungary one of the top MAR countries in Europe in terms of share of MAR water to the total public water supply.

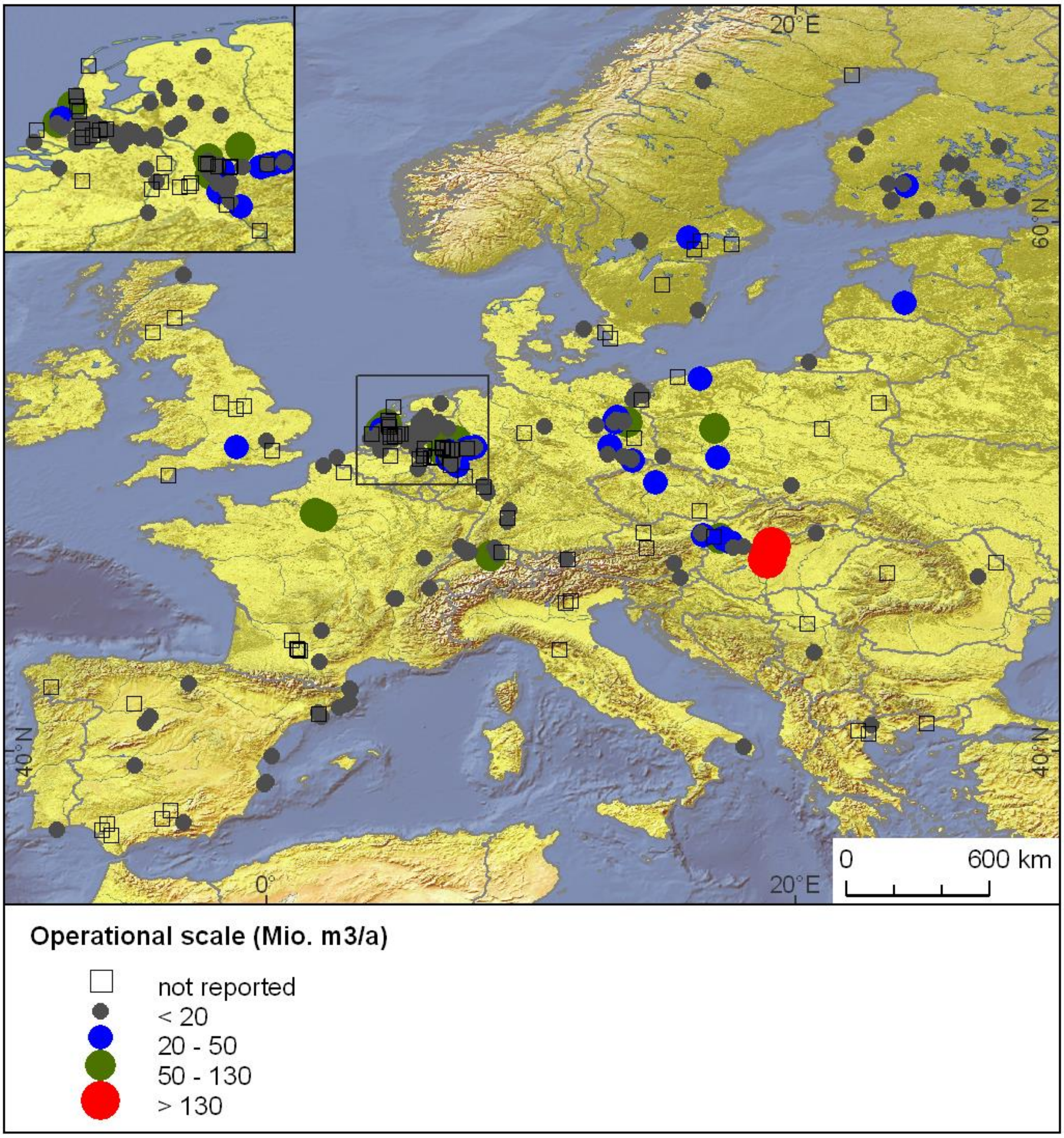

Figure 12: Spatial distribution of operational scale of sites utilizing MAR in Europe

Also the Slovakian public water supply relies on MAR to a large extend. The sum of operational scale for all Slovakian MAR sites (entirely Riverbank Filtration) makes up approx. 55 % of total public water supply (total public water supply 320 × 10^6 m^3/a in 2007 based on EEA (2010)).

The MAR database includes 48 sites in Germany producing domestic water that were in operation until the year 2007. The sum of operational scales from these sites yield 868 × 10^6 m^3/a, which is about 16 % of the total public water supply (total public water supply 5371 × 10^6 m^3/a in 2007 based on EEA (2010)) This finding is identical to the value Schmidt et al. (2003) calculated.

The sum of operational scale for all MAR sites in The Netherlands producing domestic water and were in operation until 2007 is about 373 × 10^6 m^3/a. The share of MAR water to the public water supply is therefore 30 % (total public water supply 1256 × 10^6 m^3/a in 2007 based on EEA (2010)). This finding is in contrast to estimations from Stuyfzand (1989) given with approx. 7 % for Bank Filtration systems for the year 1981, but may can be explained by an disproportionally increase of operational scale of MAR sites and the inclusion of other MAR techniques.

Other figures, such as the 50% of bank filtered water in France as given in Doussan et al. (1997) based on a study by Castany (1985) appears to exaggerate the share of MAR water for public water supply. The MAR catalogue includes 8 sites producing domestic water until 2007. The sum of operational scale from these sites make up approx. 3 % of the public water supply in France (total public water supply 5861 × 10^6 m^3/a in 2007 based on EEA (2010)). This large contrast may be explained different definitions of bank filtration among the countries. In France wells which are situated in alluvial strata were considered as surface water influenced and therefore categorized as river bank filtration wells. This rough simplification may have led to the high share of RBF water, but the actual figures are likely lower.

Estimations for the importance of MAR in Finland are in the range of 13-15% of RBF and infiltration pond water contribution to the total municipal water supply in 2003 given in Tapio et al. (2006) based on personal communication with Kivimäki. The catalogue lists 16 MAR sites from Finland with a total operational scale of 82 Mio.m^3/a. Total annual public water supply in 2007 was 404 Mio. m^3 (EEA, 2010), which results in a contribution of 20 % MAR water to the total water supply.

In Switzerland it is estimated that about one third (25-30 %) of groundwater originates from induced bank filtration (EAWAG, 2013). The catalogue lists 8 MAR sites in Switzerland producing domestic water with a total operational scale of approx. 127 Mio. m^3/a. Public water supply in 2007 was 981 Mio. m^3/a (EEA, 2010) yielding 13 % contribution of MAR water.

In countries without a strong MAR tradition, or weak representation much lower shares (<1 %) of MAR water contribution to public water supply are calculated, but not shown here.

Operational scale against the specific MAR type is illustrated as box plots in Figure 12. Induced bank filtration, closely followed by infiltration ponds & basins, are the MAR types with the highest maximum operational scale. In addition, these two types also stand for 83 % of all available data on operational scales which closely reflects the general distribution of MAR types in Europe.

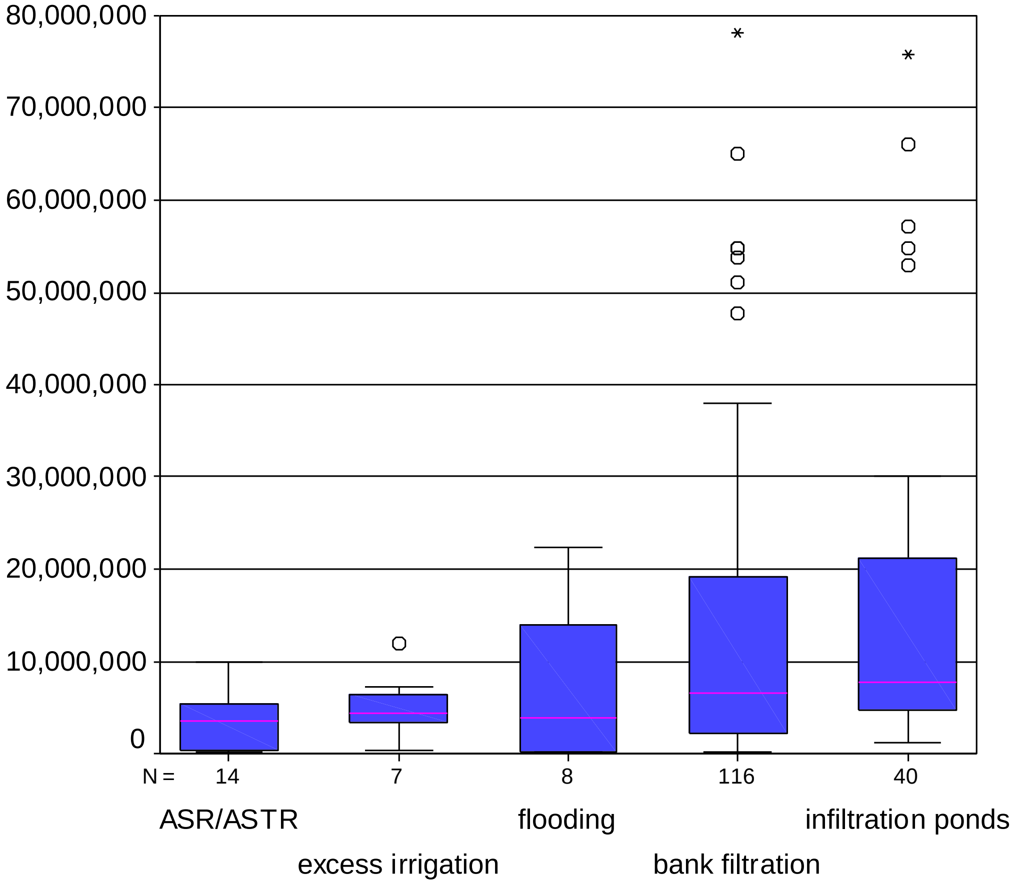

Figure 13: Box and whisker plots showing the distributions of operational scales per specific MAR type (only n>2 shown, for box and whisker explanation see section 2.1, last paragraph)

3.3 Hydrogeological properties

3.3.1 Aquifer type, thickness and confinement

The main aquifer types distinguished are consolidated and unconsolidated lithological formations. Both types can be further differentiated by specific aquifer properties describing the geological genesis of the aquifer. The aquifer confinement describes if the aquifer is under confined/semi-confined or unconfined hydraulic conditions.

Information on aquifer confinement and aquifer types is available for 155 and 220 cases respectively, which is equivalent to 57% and 82% of all currently operational MAR sites. About 79% of the 155 sites are located at unconfined aquifers, 16% at semi-confined ones and 5% of them inject water into confined aquifers.

Spatial occurrence of European MAR sites according to the specific aquifer type is shown in Figure 14. 97 % of all MAR sites included in the catalogue are situated in unconsolidated sediments, only 3 % in consolidated aquifers such as sandstones or carbonate terrains. MAR systems in karstic aquifers were not found in the literature.

MAR sites realized in consolidated geological media are rare. Close to London (UK) at the Thames River the fissured chalk aquifer (limestone) is hydraulically connected to the overlying riverbed deposits and used for Riverbank Filtration. Other examples of MAR in consolidated media can be found in the Salento region in Nardò (Italy), where treated municipal wastewater is injected into a fractured limestone and dolomite aquifer. Recharge capacity of infiltration ponds were investigated during a pilot study in the Alcala La Real (Spain) calcarenites aquifer. This pilot study showed promising results but the site was abandoned due to limited underground storage capacities. Based on the data included in the catalogue it can be observed that MAR in consolidated aquifers is the exception in Europe. The complex hydraulic conditions (e.g. flow conduits, secondary porosity) and often decreased sorption capacity in consolidated aquifers (e. g. sandstones) compared to porous aquifers complicate the realization of MAR systems.

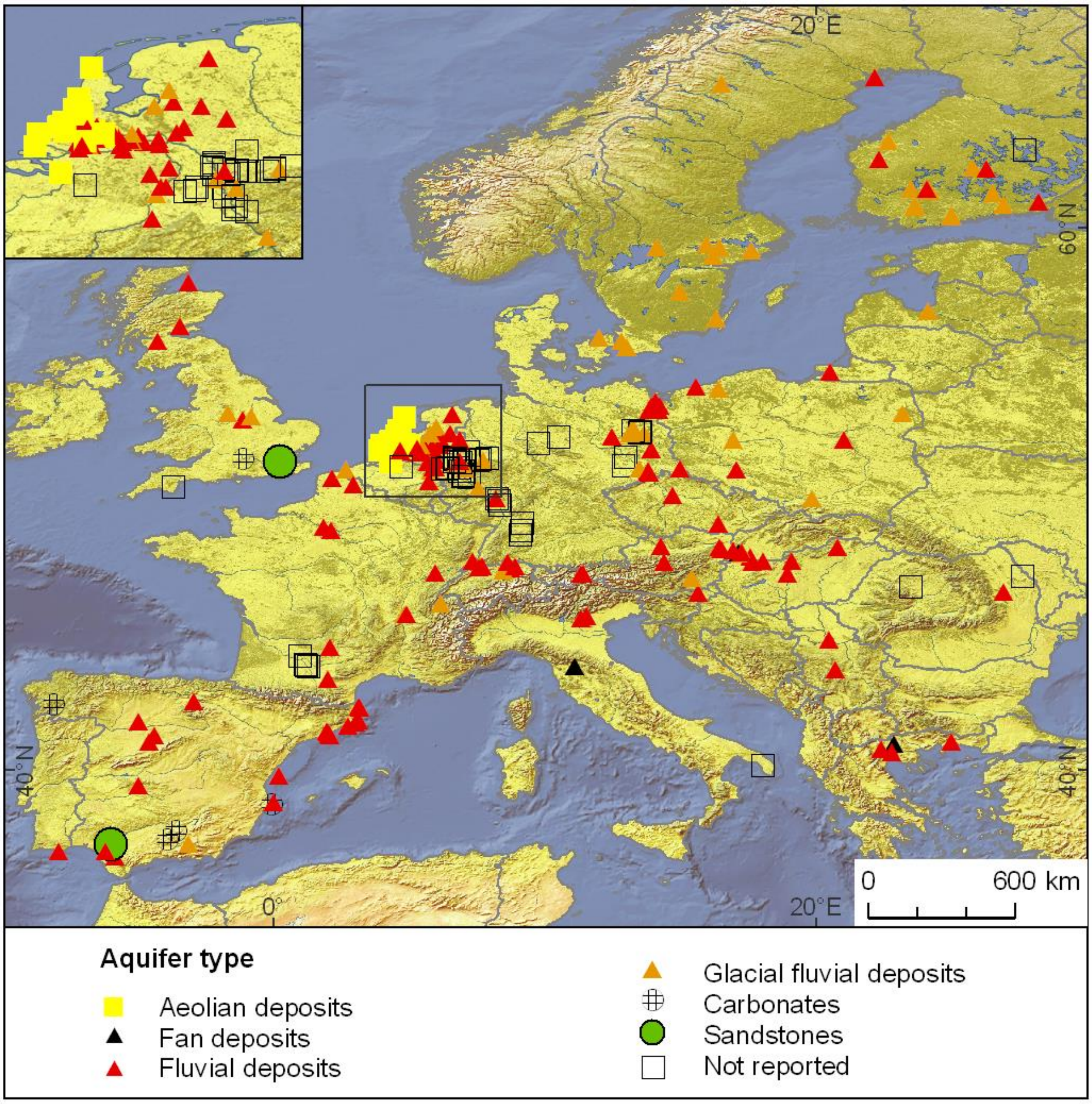

Figure 14: **Main aquifer types for MAR sites in Europe**

Fluvio-glacial detrital and fluvial sediments constitute the two largest aquifer types (57 and 131 cases respectively). While these two types are most common in northern and mountainous regions, aeolian sediments can mostly be found in flat coastal areas, such as The Netherlands.

Figure 15 presents relative shares of specific MAR types per specific aquifer confinement, while Figure 15 shows the number of sites per specific aquifer type and specific mar type. Considering aquifer types with more than five record sets of MAR types only, induced bank filtration shows highest relative shares for the specific aquifer types “fluvial deposits” and “fluvio-glacial detrital sediments”. In addition, “recharge dams”, “excess irrigation” and “reverse drainage methods” are also only found in combination with these two aquifer types.

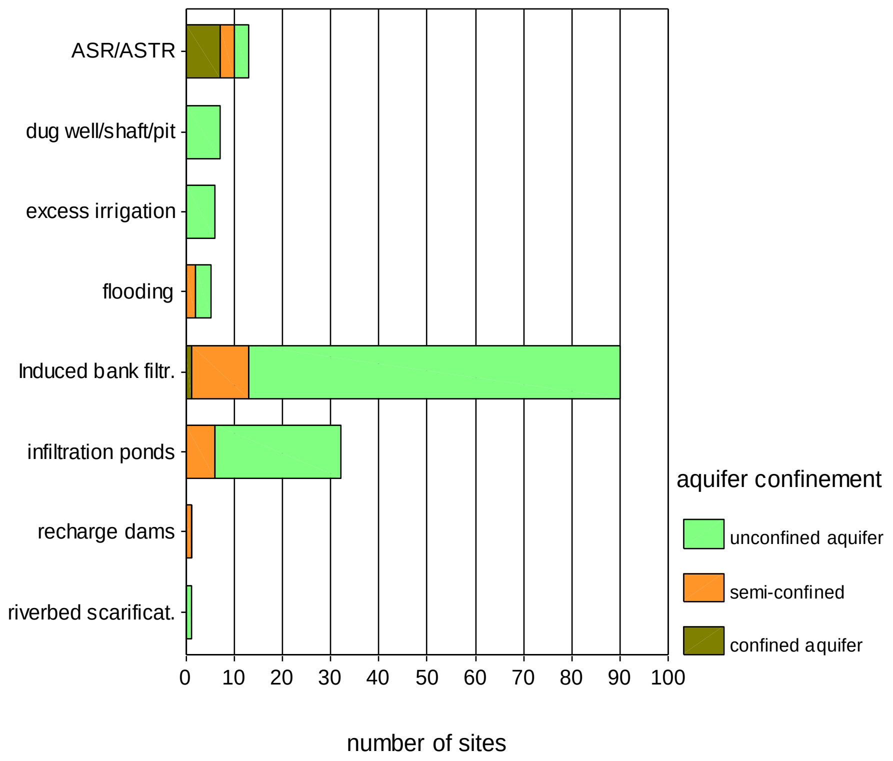

Figure 15: Relative shares of different types of aquifer confinement vs. specific MAR type

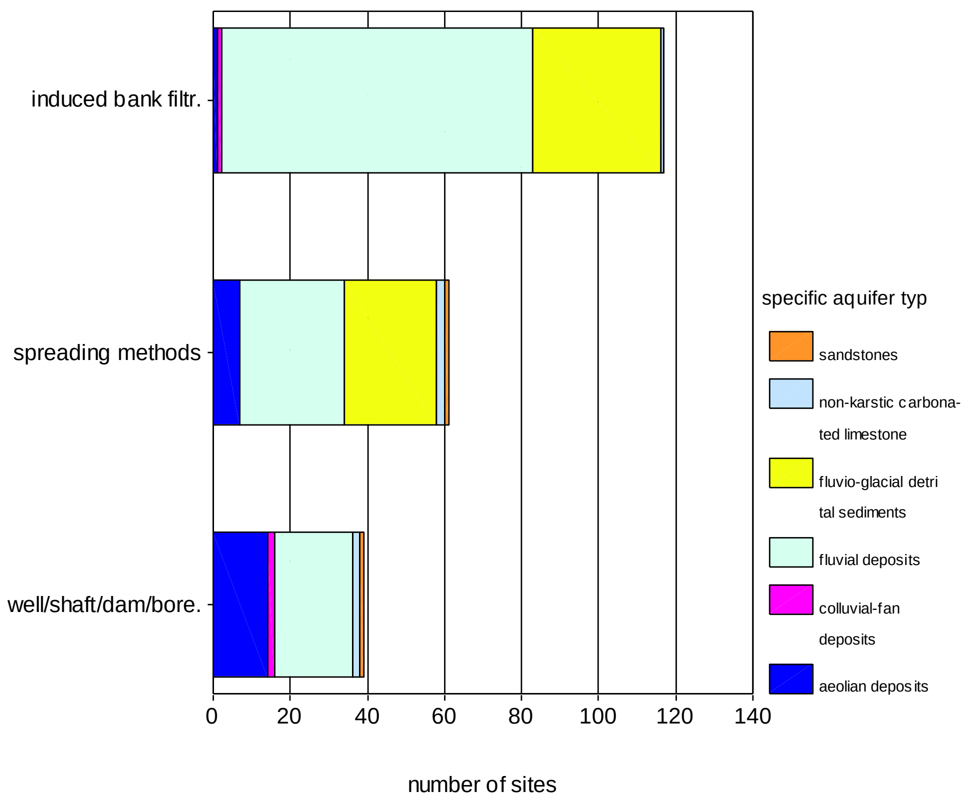

Figure 16: Relative shares of different types of aquifer confinement vs. specific MAR type

This may not be of surprise because these MAR types are usually located near rivers or lakes that are naturally more abundant under geological conditions which were formed by the water and ice instead of wind. In contrast to that, aeolian deposits contain the lowest relative share of induced bank filtration since this aquifer type is often found in dune areas located along the coastline and not alongside rivers or lakes. For this aquifer type, well, shaft, dam and borehole methods show much higher relative shares.

With 231 out of 270 cases, the overwhelming majority of MAR types utilizing some form of spreading technique and induced bank filtration. They are almost always located in areas with unconfined or semi-confined aquifers (Figure 14).

The application of spreading techniques intrinsically depends on the availability of a hydraulic connection from ground surface to the aquifer, meaning unconfined conditions. Under these conditions the effectiveness of groundwater recharge is primarily dependent on the permeability and thickness of the unsaturated zone when applying spreading techniques (e.g. infiltration ponds & trenches and flooding). For induced bank filtration, unconfined aquifer conditions are common since the technique depends on the hydraulic connection with a surface water source. However, semi-or unconfined conditions can result when rivers or lakes have incise (shallow) confining layers, such as Holocene peat and clay deposits. Overall, spreading techniques, induced bank filtration and in-channel modifications are usually applied in cases where the aquifer to be recharged is at or near to the ground surface. In contrast, MAR sites using some sort of well, shaft and borehole recharge technique contain much higher shares of confined aquifers as these systems are designed to inject or infiltrate water directly into the aquifer, thus making them less dependent of the permeability and thickness of the unsaturated zone or the possible existence of aquitards.

Comparing the aquifer thickness with the specific MAR type (see Figure 16) we see, those sites with induced bank filtration and infiltration ponds – the two classes with the most entries in the catalogue – aquifer thickness varies over a large range of meters. Sites with ASR and ASTR methods however are using aquifers with larger thicknesses. Since these techniques commonly depend on injection and extraction from wells, available aquifer thickness controls the maximum well screen length which is linearly related to well production capacity for a given aquifer.

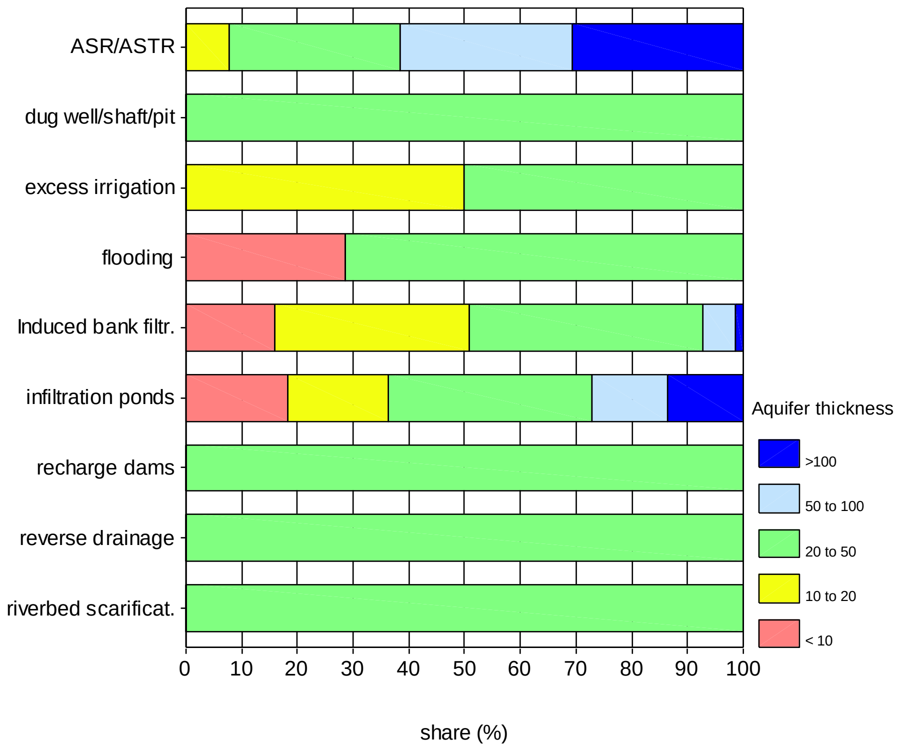

Figure 17: Relative shares of aquifer thickness (Meters) vs. specific MAR type

3.3.2 Horizontal aquifer passage, recovery rate

The horizontal aquifer passage is the distance between the point/area of recharge (e.g. river banks during induced bank filtration or the injection well during ASTR) and the point of recovery (e.g. the production well). Horizontal aquifer passage roughly relates to the residence time of the infiltrated source water during aquifer passage, but is not equal to the flow path.

For 108 cases information is available on the average horizontal aquifer passage at the MAR site. Figure 17 shows the ranges except of one site with the dug-well-shaft-pit-injection type.

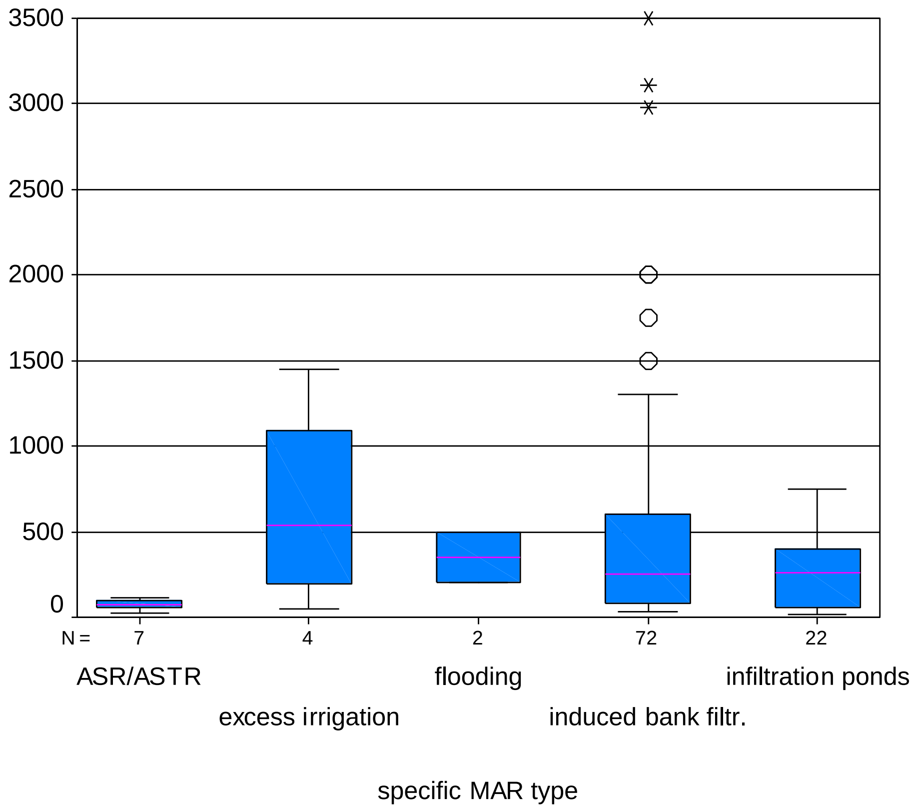

Figure 18: Box plots showing the distribution of horizontal aquifer passages

Induced bank filtration sites show a wide range of horizontal aquifer passages from a few tens of meter (e.g. 30 m at Remmerden in The Netherlands) to few kilometers (e.g. 3.5 km at Aalst in The Netherlands). For short distances, bank filtration mainly acts to strain physical and biological particles, whereas chemical transformations commonly require longer travel and/or residence times.

Shares of bank filtrate in the production well (recovered infiltrate) cannot be assessed by the horizontal aquifer passage, although shares of source water increase with shorter distance from the surface water source for a particular site. It is however also dependent on the aquifer thickness, the regional hydraulic gradient and other local hydrogeological properties. BF sites with short aquifer passage e.g. Remmerden (NL) are usually characterized by high shares of bank filtrate (82%), but also BF sites with long aquifer passages e.g. Aalst, Kolff and Druten (horizontal aquifer passage ≥3000 m) may abstract high shares of bank filtrate (29 - 68%) in the production well. Overall, typical horizontal aquifer passage for bank filtration systems (10^{th} to 90^{th} percentile) are between 50 – 1250 m (median 250 m).

Horizontal aquifer passage at ASTR sites included in the catalogue were not longer than 113 m. Dug well, shaft and injection do not have sufficient records to be evaluate horizontal aquifer passage. For infiltration ponds and basins the range in the database for the horizontal aquifer passage is between 20 and 746 m.

During surface spreading the horizontal aquifer passage varies between 1450 m at a sprinkler irrigation site in Finland (Hämeenlinna) and 30 m at an infiltration pond site in Krakow (Poland). Recovery rates for surface spreading sites are often not available. At the Solleveld site (infiltration ponds in dune areas in The Netherlands) the average annual abstracted water volume is lower than the average annual infiltrated volume and the recovery rate can be approximated with 90%.

3.3.3 Hydraulic conductivity, infiltration/injection rates and volumes

The hydraulic conductivity describes the ability for water to move through an aquifer. Among other factors, it relates to the permeability geological media and the water saturation.

Hydraulic conductivity is given for 108 sites and is shown in Figure 19 for the different specific MAR types. As expected, river bank filtration shows the highest density of records compared to the other MAR types with an amount of 68 records (62%). 50% of the sites show a hydraulic conductivity between 10^{-3} and 10^{-2} m/s while 40% are in the range of 10^{-4} and 10^{-3} m/s.

Infiltration ponds and basins provide the second highest amount of records with 16 values (15%). The major range of values for this particular specific MAR type is provided within the amount of 10^{-4} and 10^{-3} m/s (44%).

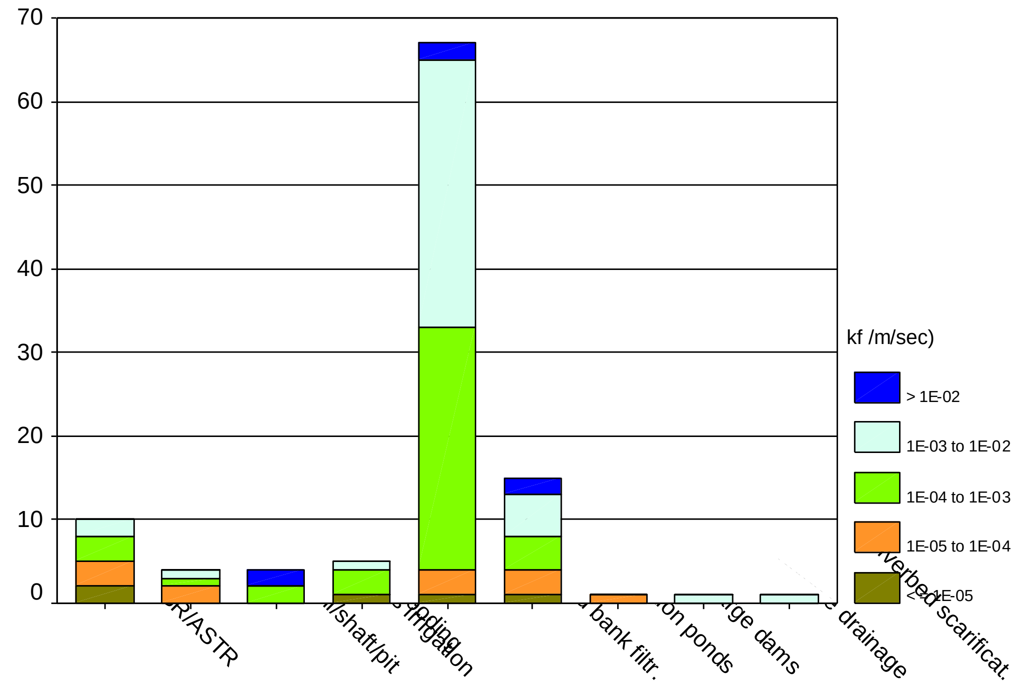

Figure 19: Hydraulic conductivity (k_f values) subdivided into five classes for MAR types

Infiltration rates are obtained from only 22 MAR sites and range from < 1 m/d to maximal 8 m/d. Dune infiltration sites in The Netherlands (e.g. Solleveld) have low infiltration rates < 1 m/d ($k_f = 10^{-4}$ to 10^{-3} m/s). Higher infiltration rates can be found in the Guadix plain (Spain) given with approx. 1-2 m/day and a hydraulic conductivity of 10^{-5} to 10^{-4} m/s. Infiltration rates from some sites decreased during the time of operation. At the Oja River (Spain) e.g. the infiltration rate at infiltration ponds reduced from >10m/d in the beginning to <1m/d after four years of operation. This was explained by clogging effects at the base of the recharge ponds (Diaz Murillo et al., 2002). Highest infiltration rates were found at a sprinkler infiltration site in southern Finland (Hämeenlinna) where between 8 and 10 m/d could be maintained during the snow free period.

3.4 Water quality monitoring

During data acquisition it was tried to obtain information on scheduled frequency of water quality monitoring for the MAR sites. The catalogue allows specifying monitoring frequency for in-situ, bulk chemistry, heavy metals, organic compounds, microbiology and emerging pollutants.

MAR sites which produce water for drinking purposes underlie strict regulations according to EU and national legislations. Most of this sampling and analysis is standard procedure and often not reported in the literature (Figure 19). Therefore, the information included in the MAR catalogue is not representative for monitoring frequency of the European MAR sites.

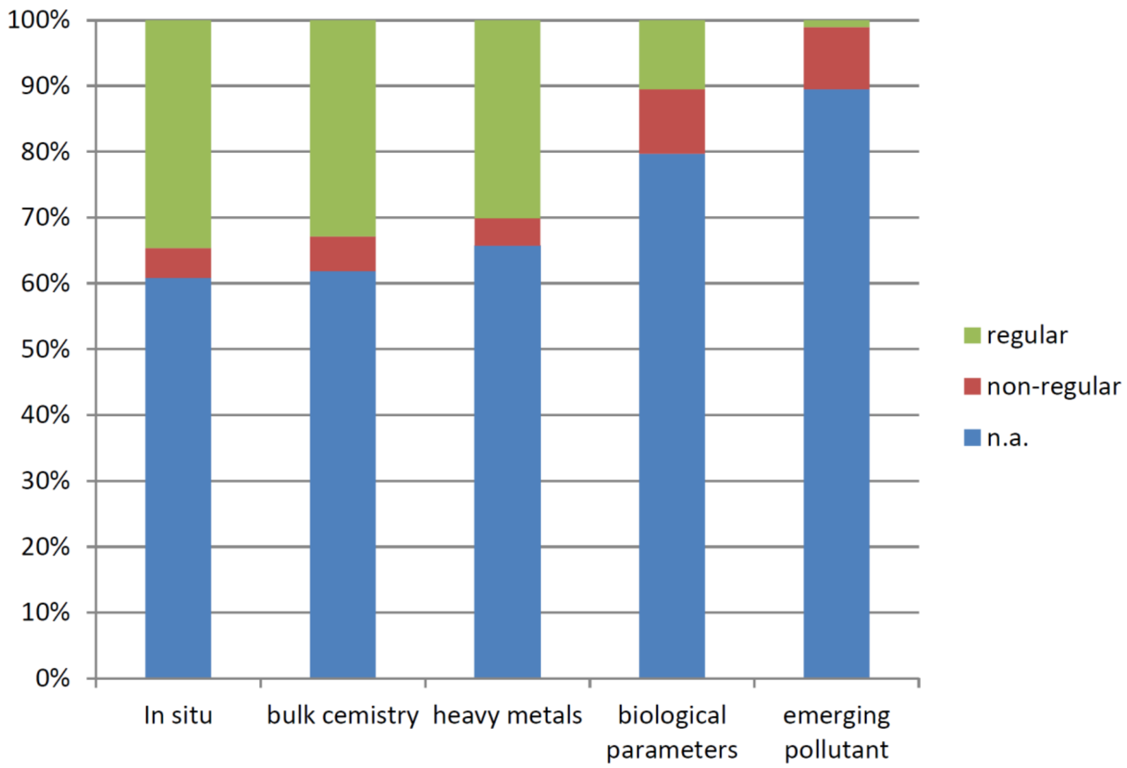

Figure 20: Monitoring frequency for five different water quality parameters ("n.a.": information not available)

3.5 Recommendations for further data generation

For future studies and reports on existing and newly developed MAR sites, it is strongly recommended to explicitly state the main information types of operational aspects types as identified here. To generate a comprehensive and internally robust overview of MAR operations in the EU, site information should at least include values on hydraulic conductivity, the thickness of the aquifer used, the horizontal distance of passage through the aquifer, the number of recovery wells involved and the operational scale at which water is managed within the MAR system.

In addition to these general basic aspects required, a general limited amounts or even a lack of water quality aspects has been documented, particularly for emerging pollutants. Therefore, plans to set up future investigative field tests, should address the issue of emerging pollutants. To set an example within DEMEAU, three sites in France, Poland and The Netherlands are selected for additional sampling within the DEMEAU project (Table 4). These sites allow different approaches for emerging pollutant characterization to be highlighted as they represent a range in operational aspects as well as in their levels of current characterization of emerging pollutants.

Table 4: Selected MAR sites for further investigation

Country	City	Site	Specific MAR type	Source water	Identified knowledge gap
France	Angerville	Beauce area	Infiltration ponds	Reclaimed domestic water	Some data to EP substances available, but no time series
Poland	Krakow	Bielany	Infiltration ponds	River water	no data to EP substances
The Netherlands	The Hague	Dune	Infiltration ponds	River water	Time series, with data on EP substances

4.0 Summary

The present MAR catalogue is a result of DEMEAU´s partner to homogenize and structure existing information of European MAR sites. Information included in the MAR catalogue is used for statistical and geographical analysis and presentation, in order to characterize key parameter of MAR sites. The MAR catalogue is still open for further data entry and is aiming to improve its coverage continually.

The current catalogue contains 214 active and 56 inactive MAR sites and the data indicates an increase of MAR application in Europe over the last decades. For the sites that were shut down reasons were often not reported, but many of those were used as pilot studies for a limited period of time. At other sites, operation has been suspended temporarily or shut down permanently due to economic or political reasons.

More than half of the cataloged MAR sites are induced bank filtration (54%) followed by spreading methods (29%) of which infiltration ponds & basins (23%) make up the largest share. Well, shaft and borehole recharge systems form the third largest group (16%). More than half of all sites are located in Germany and The Netherlands while another 14% can be found in Finland and Spain. However, this ranking is somewhat biased, because it is based on non-representative selection.

River water (78%), lake water (11%) and reclaimed domestic water (4%) are the most common primary influent sources. As induced bank filtration occurs along the banks of rivers and lakes this MAR type has two primary influent sources: river and lake water. Groundwater which is in virtually all cases of bank filtration an influent source water was not evaluated, since it is not intended to be the primary influent water. Reclaimed domestic water is used as an influent source at twelve sites in Europe and in most cases used for agricultural purposes.

The most frequent final use is for domestic purposes (88%) followed by agricultural (8%), industrial and ecological purposes (2% each). Using MAR water for agricultural purposes appears to be very common in Spain than anywhere else in Europe. Ecological uses are common in Germany, Spain and in The Netherlands while most industrial uses can be found in Germany.

During drinking water production, the improvement of water quality is a key target. Water quality management forms therefore, the largest share of all the objective classes (71%) while another 19% of the sites aim at maximizing the natural storage. MAR systems operated to increase the aquifer storage are often concentrated in regions where groundwater extraction rates exceed the natural groundwater recharge while physical aquifer management is mostly used to prevent saltwater intrusion.

Values on operational scale range over four orders of magnitude and are highest for induced bank filtration sites closely followed by infiltration ponds and basins. There is no doubt that MAR plays an important role in the European water supply and induced bank filtration often combined with infiltration ponds produces large water quantities. Large quantities (> 36.5×10^6 m^3/a) of MAR water is produced by individual sites in Hungary, Slovakia, The Netherlands, Germany, Poland and France. The share of the MAR produced domestic water to the total public water supply was calculated for various countries. In Hungary i.e. all MAR sites included in the catalogue contributing approx. 59 % to the public water. In Germany this share is about 16 % of the total public water supply. The sum of operational scale for all Slovakian MAR sites (entirely Riverbank Filtration) makes up approx. 55 % of total public water supply. In Finland the MAR contribution to the total water supply was calculated with about 20%. In Switzerland the MAR contribution was calculated with 13 %. Well/shaft and borehole sites tend to have a lower operational scale between 0.2 – 5.8 Mio m^3/a.

The overwhelming majority of MAR sites are situated in unconsolidated strata. Geological formations such as fluviatile and glacial sediments, but also aeolian deposits (e.g. in The Netherlands) are most commonly utilized. MAR sites realized in consolidated geological media are very rare. Most of the MAR sites are located in unconfined aquifers. Spreading techniques, induced bank filtration and in-channel modifications are obviously applied where the aquifer to be recharged is at or near to the ground surface and the surface consists of permeable material. Well, shaft and borehole recharge schemes are operated more often in confined or semi-confined aquifers. Most of the used aquifers are relatively shallow, 80% of all aquifers have thicknesses between 10 and 50m with only 8% of all entries being larger than 100m. Induced bank filtration and surface spreading methods can be often found at shallow depths, while ASR/ASTR sites also are used at aquifer depths > 100m below ground surface. About 50% of induced bank filtration sites show a hydraulic conductivity between 10^{-3} and 10^{-2} m/s while 40% are in the range of 10^{-4} and 10^{-3} m/s. Common ranges of hydraulic conductivity for spreading methods are between 10^{-5} and 10^{-3} m/s.

Horizontal aquifer passage differs substantially between the various MAR types. Induced bank filtration sites show a wide range of horizontal aquifer passages from a few tens of meters (30 m) to few kilometers (3 km). Typical horizontal aquifer passage for bank filtration systems (10^{th} to 90^{th} percentile) are between 50 – 1250m (median 250 m). During surface spreading the horizontal aquifer passage varies between 1450m at a sprinkler irrigation site and 30m at an infiltration pond site, while the 10^{th} and 90^{th} percentile was calculated with 40 – 690m. Horizontal aquifer passage at well/shaft sites included in the catalogue was not longer than 113m and the 10^{th} and 90^{th} percentile is given with 30 – 110m, but with a low number of cases (n= 7).

Most of the water quality monitoring is standard procedure and often not reported in the literature. Information on water quality monitoring programs applied at the MAR sites was found to be not representative of the European MAR sites.

Characteristic values or ranges of values for the main MAR types induced bank filtration, spreading methods and well/shaft/borehole recharge are summarized in table 5.

Table 5: **Summary of characteristic site parameters for three main MAR types (induced bank filtration, spreading methods and well/shaft/borehole methods); the ranges are calculated by the 10th and 90th percentiles of the distributions for numerical parameters (except for aquifer thickness) and by the most common values for the string parameters**

Site parameter	Unit	Induced bank filtration	Spreading methods	Well/ shaft/ dam/ borehole
Operational scale	Mio. m^3/a	0.7 – 35 (n=116)	1.5 – 27 (n=57)	0.2 – 5.8 (n=15)
Final use	-	domestic	domestic	domestic, agriculture and ecological
Main objective	-	water quality management	water quality management & maximizing natural storage	water quality management and physical aquifer management
Primary influent source water	-	river water	river & lake water	river water & different sources
Horizontal aquifer passage	m	50 - 1295 (n=72)	40 – 690 (n=28)	30 – 110 (n=7)
Aquifer thickness (min-max)	m	<10 – 100 (n=142)	10 – >100 (n=39)	20 – >100 (n=16)
Aquifer confinement	-	unconfined	unconfined	confined to semi-confined
Hydraulic conductivity	m/s	10^{-2} - 10^{-4} (n=142)	10^{-2} - 10^{-5} (n=46)	10^{-3} - 10^{-5} (n=13)

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