DEMEAU

DEMONSTRATION OF PROMISING TECHNOLOGIES TO ADDRESS EMERGING POLLUTANTS IN WATER AND WASTE WATER

MANAGING AQUIFER RECHARGE

SUBSURFACE TREATMENT, STORAGE AND RECOVERY

Managed Aquifer Recharge (MAR) is a cross-cutting technology applicable to both drinking water and wastewater treatment, and is often used in combination with additional engineered treatment systems. The term MAR describes the intentional recharge (and storage) of water into an aquifer for subsequent recovery and/or for environmental benefits.

MAR can be used as a source for drinking water supply, process water for industry, for irrigation and for sustaining groundwater dependent ecosystems when appropriate pre-treatment (if necessary) prior to recharge and post-treatment (if necessary) after recovery is applied. MAR relies on naturally occurring processes in the subsurface, such as mechanical filtering, sorption and biodegradation. These natural treatment processes do not require additional chemicals and were observed to be sustainable over several decades.

DEMEAU, a project funded under the 7th Framework Programme for Research and Technological Development of the EU, aims to demonstrate the importance of MAR, focusing on water quality impact and safety assurance. At present, the European legislation does not specify requirements for MAR and defines only a broad legal framework. To facilitate the uptake of MAR, the concept of an attenuation zone in the subsurface is highlighted as an integral part of MAR. Additionally, possible points of compliance with European water directives are shown. As part of DEMEAU, a Life Cycle Approach (LCA) was also applied to MAR sites in order to assess their economic and environmental impacts.

An inventory of European MAR sites, compiling information from more than 270 sites, showcases a wide range of different MAR types that are already being applied at various operational scales and for various purposes across the European countries. It was found that some countries in Central and Northern Europe have a substantial share of MAR derived water for their water supply, while MAR is still underutilised in countries in the Mediterranean region.

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INTRODUCTION

BACKGROUND

Various MAR types have already been in use for decades. However, in the light of the increasing number of new chemicals entering the water bodies, these natural treatment systems similarly require a reevaluation. MAR has the potential to effectively attenuate a number of undesired substances, including pathogens, thus improving source water quality. However, the complex dynamics of subsurface conditions, such as flow regime and redox conditions make interpretation of contaminant attenuation a daunting task. Ongoing and renewed research of MAR is working to better understand such complexity.

UNDERSTANDING MAR

MAR is used to store and treat water from a variety of sources, including river water, reclaimed water, desalinated seawater, rainwater or even groundwater from other aquifers. As elaborated in *Figure 1*, water from MAR systems can be used as a drinking water, as process water for industry, for irrigation and for sustaining ground-water dependent ecosystems when appropriate pre-treatment (if necessary) prior to recharge and post-treatment (if necessary) after recovery is applied. In addition, the MAR system must be adapted to local hydrogeological conditions, to the water source type and to the required end-use. MAR must also be implemented within the existing legal and water management framework.

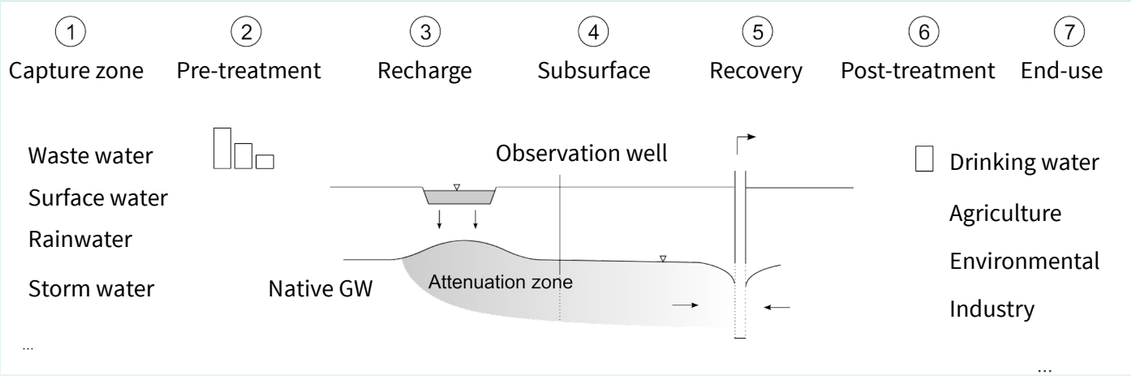

Figure 1: *An overview of the seven main components of a MAR system from source to end-use for an infiltration pond in an unconfined aquifer (modified from Dillon et al. 2010).*

MAR IN PRACTICE

CLASSIFYING MAR

MAR can be classified into four major groups based on recharge and storage technique applied *(Table 1)*.

(1) Enhanced infiltration relies on gravitational infiltration and percolation, and includes surface spreading, point or line recharge and in-channel modifications. Surface spreading methods are among the simplest and most widely applied MAR techniques. In such methods, source water is spread over a land surface and allowed to percolate to the target aquifer. Most of the existing large scale recharge schemes in European countries make use of this technique, and typically utilise infiltration ponds to enhance the natural percolation of water into the subsurface. During point or line recharge, source water is infiltrated either in elongated (e.g. shafts, drains) or punctual (e.g. abandoned dug wells, bore holes) structures. In-channel modifications are structures found in stream or channel beds (e.g. check dams).

(2) Induced bank filtration, another MAR technique, describes the infiltration of surface water induced by pumping from a nearby well. During bank filtration water quality improvement (treatment) of induced surface water is commonly the main objective. Bank infiltration schemes commonly consist of a well gallery or a line of abstraction wells parallel to the bank of a surface water body. Induced bank infiltration systems are typically installed near perennial streams and lakes that are in hydraulic contact to the adjacent aquifer.

A third MAR technique, **(3) well injection** techniques are used where thick, low permeability strata overlie the target aquifers. Aquifer storage and recovery (ASR) is the direct injection of water by a well for subsurface storage and recovery from the same well. Water storage to bridge seasonal gaps in water supply is often the primary goal when applying this technique.

Sub-surface dams, which are rarely used, do not lead to additional recharge but **(4) enhanced groundwater storage** where required. Other techniques include rooftop water harvesting (also called rainwater harvesting), a method for collecting source water in the capture zone. Rooftop water harvesting can be combined with injection or infiltration techniques as per local conditions and requirements, and therefore, is not considered a MAR technique.

Table 1: Classification of MAR types.

Recharge technique	Main MAR type	Specific MAR type
(1) Enhanced infiltration	Surface spreading methods (Areal recharge)	Infiltration ponds
		Soil-Aquifer treatment
		Excess irrigation, ditches, trenches
	Point or line recharge	Well/borehole infiltration
		Reverse drainage, shaft recharge
	In-channel modifications	Check dams
		Riverbed scarification
		Sand dams
(2) Induced bank filtration (IBF)		Riverbank filtration
		Lakebank filtration
(3) Well injection		Aquifer storage and recovery
		Aquifer storage, transfer and recovery
		Aquifer storage (hydraulic barriers)
(4) Enhanced storage		Sub-surface dams

HYDRAULIC IMPACT AND ATTENUATION ZONE

The purification capacity depends on several factors that include: the water quality of the source water, travel time of infiltrated or injected water to the abstraction well, and the design of the MAR field site. Impact zones of MAR structures can be divided into a hydraulic impact and attenuation zone (*Figure 2*).

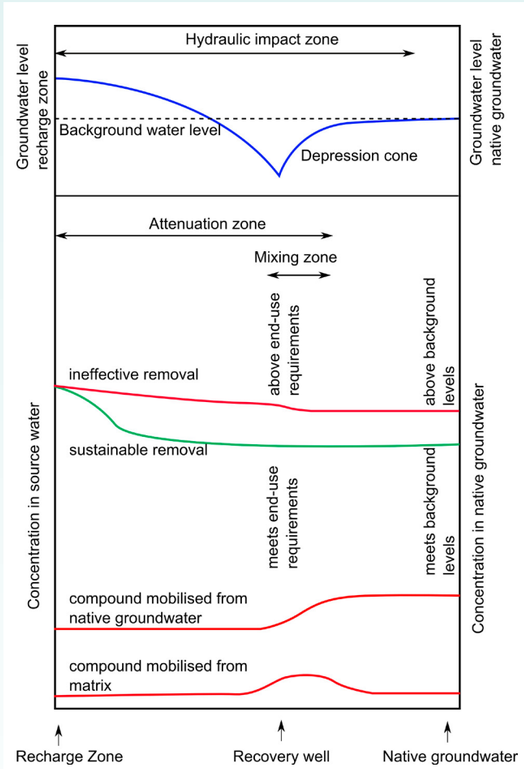

Figure 2: *Concept of hydraulic and attenuation zonation during MAR (Red lines indicate ineffective removal or mobilisation of undesired compounds, green line indicates sustainable removal) (Sprenger et al. 2015).*

The infiltration of water into an aquifer results in increased hydraulic pressure at the recharge zone. The **hydraulic impact zone** is characterised by measurable hydraulic changes derived from the MAR system. The hydraulic impact zone is usually many times larger than attenuation zone, especially for confined aquifers.

The **attenuation zone** is the area surrounding the recharge zone where changes of the infiltrated water quality take place due to natural processes in the aquifer. These natural attenuation processes may vary in time and space within the aquifer, particularly along the flow path from the area of recharge to the recovery well. Most attenuation processes in the subsurface occur at or close to the recharge zone. Part of the attenuation zone is the mixing, where native groundwater and the recharged source water mix.

MAR AND EMERGING POLLUTANTS

During subsurface passage of source water, several attenuation processes occur. These processes can be broadly divided in biotic and abiotic processes. Abiotic processes that occur in MAR include: sorption, dilution and photolysis (only occurring in surface spreading methods). Biodegradation also contributes significantly to the elimination of undesirable substances in groundwater. Temperature and redox conditions along the groundwater passage produce different degradation rates of undesirable compounds and also affect the chemical structure of the substances. Removal of emerging pollutants during MAR results primarily from sorption and biotransformation processes. Based on a literature study the percentage of removal of selected emerging compounds is classified in relation to the predominant redox condition and the residence time in the subsurface (*Figure 3*).

Due to the redox dependant degradation of some contaminants, only MAR systems comprised of an oxic to anoxic redox sequence ensure maximum attenuation efficiency. Long soil-aquifer passage and high residence time favours interaction with sediments and the communities of microorganisms in the porous media, allowing for removal of pollutants through natural processes.

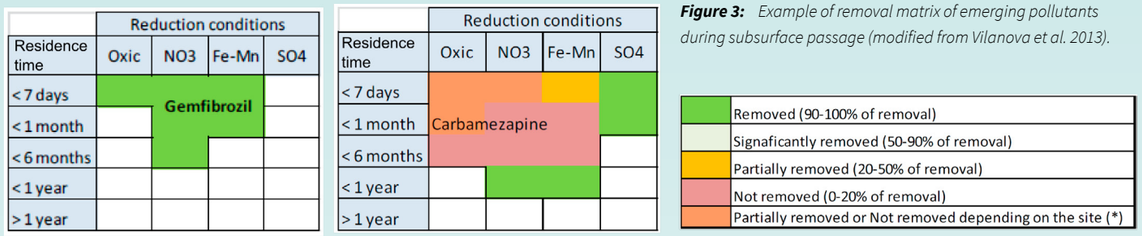

Figure 3: *Example of removal matrix of emerging pollutants during subsurface passage (modified from Vilanova et al. 2013).*

IMPACT

MAR IN EUROPE

The European MAR catalogue, developed within DEMEAU, is the first systematic categorisation and compilation of information for all MAR types. This catalogue includes current information from more than 270 active MAR sites in more than 20 European countries (*Figure 4*).

Figure 4 shows that the most common types of MAR are induced bank filtration and surface spreading. Clusters of MAR sites can be seen in the Netherlands, in Germany along the rivers Rhine and Elbe, as well as in Berlin and along the Danube River in Austria, Slovakia and Hungary.

In Central European countries (but also in the northern countries) MAR plays an important role in the water supply, and is mostly used for drinking water purposes. In Mediterranean countries, mostly surface spreading sites are found, but in-channel modifications and point or line recharge facilities are also used to a lesser degree. Compared to Central and Northern Europe, MAR in the Mediterranean region is underutilized, as the map shows. Consequently, there is a large potential for MAR in this region (*Figure 4*). MAR has also a large potential in areas with dominant hardrock aquifers, such as the Iberian Peninsula or parts of Scandinavia. In these areas, MAR utilizes utilises small local aquifers which are not visible in the scale of the aquifer type map (scale 1:1,500,000).

Figure 4: *Overview of MAR sites in Europe active during 2013.*

source: Hannappel et al. 2014

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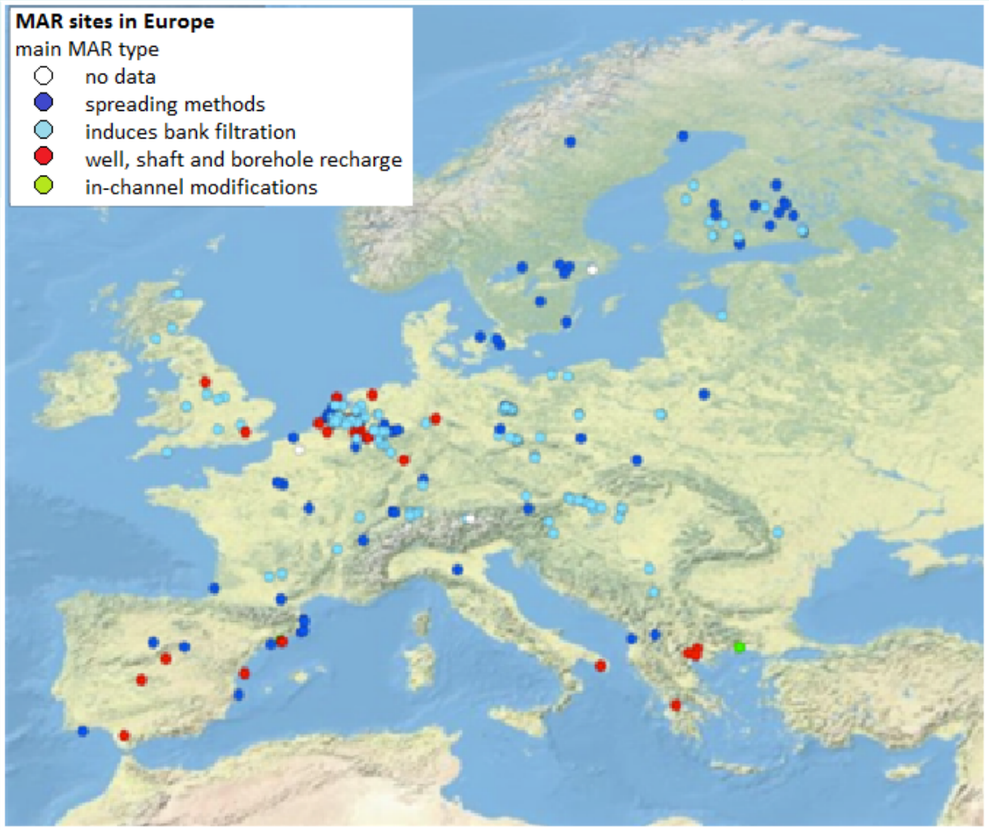

Several years of research and experience have shown that MAR is a competitive technique for water quality improvement as well as for attenuation of certain emerging pollutants. The major advantages and challenges of MAR are summarized in *Table 2.*

Table 2: Summary of advantages and challenges of MAR.

Advantages	Challenges
► Ability to store water in aquifers for later use, which allows balancing out supply and demand gaps (except for Induced Bank Filtration (IBF)).	► Requires suitable water source and appropriate hydrogeological conditions.
► Replenishment of groundwater levels where currently over exploited and counteracting salinity ingress (except for IBF and enhanced storage techniques).	► 'Clogging' (physical, chemical and/or biological) of infiltration/percolation surfaces, can reduce recharge rates drastically and is often the major limiting factor to infiltration.
► Improving water quality by natural attenuation processes in the subsurface and balancing out seasonal fluctuations in water quality.	► Site specific hydrogeological exploration, wide range of information is required (monitoring, hydrogeological investigation etc.) and feasibility/pilot projects are often necessary.
► Applicable to drinking water and wastewater treatment and can be combined with engineered treatment systems.	

BARRIERS AND SOLUTIONS

To foster the implementation of MAR, it is important to ensure that it does not compromise the protective goals or threshold values given in European and national legislations. The present European water directives (e.g. the Water Framework Directive, the Groundwater Directive, etc.) do not specify requirements for MAR schemes and only define a broad framework in which MAR may be developed.

A principal requirement of the Groundwater Directive (GWD) is to assess the actual or potential impact of MAR on groundwater in the vicinity of the site. An important element of the risk screening process is the choice of the points at which compliance with the GWD will be evaluated. Points of compliance (POC) can be applied to MAR facilities, as shown in *Figure 5*.

In the case of MAR schemes, the receptor at risk can be defined by the groundwater beyond the attenuation zone at POC 3. The attenuation zone is the area surrounding the recharge area where groundwater quality changes takes place due to natural processes in the aquifer (e.g. straining, degradation, sorption, dissolution/precipitation, inactivation (die-off), decay or mixing).

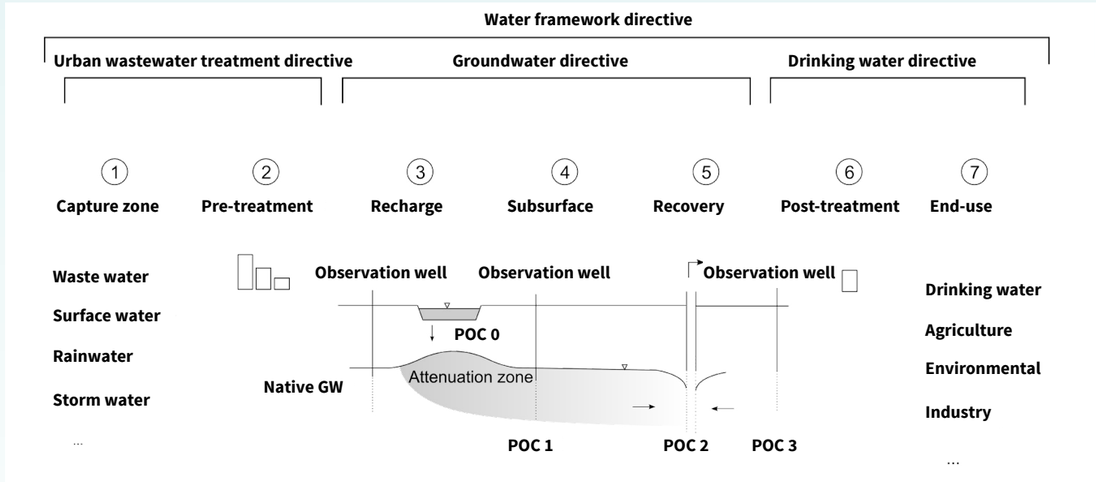

Figure 5: *Components of MAR and possible points of compliance (POC) with most relevant European legislation (Vilanova et al. 2015).*

LIFE CYCLE ANALYSIS AND ENVIRONMENTAL IMPACTS

MAR can provide a variety of benefits, such as increasing the volume of stored water and improving water quality through natural aquifer treatment processes. However, the implementation of MAR is often hampered by uncertainty relating to economic and environmental profiles.

Within the DEMEAU project, several MAR sites have been evaluated in their economic and environmental impacts, following the methodology of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

These tools are based on a set of indicators selected for environmental impacts (e.g. carbon footprint, primary energy demand, ecotoxicity) and costs (e.g. annual operational costs per m^3) that show how the respective MAR site performs in comparison with other technologies for water treatment.

Life Cycle Assessment	Life Cycle Costing
► direct impacts on water quality (e.g. removal of nutrients and emerging micropollutants)	► operational costs for MAR feasibility, construction and maintenance
► indirect impacts from efforts for construction and operation (e.g. fuel consumption for machinery, excavation of ponds, and maintenance)	► investment costs for MAR feasibility, construction and maintenance

MAR LCC AND LCA IN THE LLOBREGAT AREA (SPAIN)

LCA analysis was conducted for different MAR scenarios with similar operational goals which are already in use or could be implemented in one of the case study sites in the Llobregat area close to Barcelona. The LCA case study of Llobregat consists of a variety of different MAR techniques (*Figure 6*) which have been analysed for their carbon footprint and annual costs.

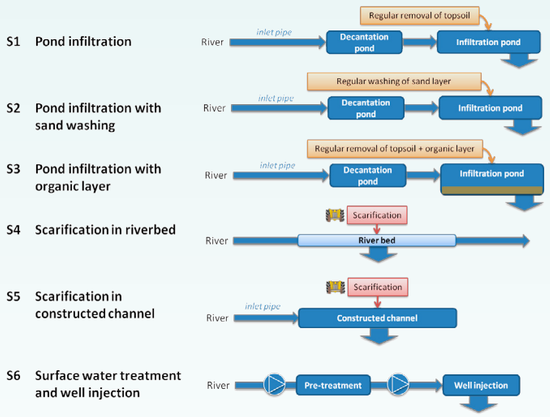

Figure 6: *Different MAR scenarios for the Llobregat area evaluated with LCA and LCC (Deliverable 51.1, unpublished). (S1) base line scenario. (S2) pond layer made of technical sand along with regular washing and refilling of the sand (S3) base line scenario with additional organic layer for improving the removal of organic micropollutants, (S4) traditional riverbed scarification, practiced for several decades in the area (S5) infiltration channels as a new technique for the area, (S6) well injection of pre-treated river water (coagulation/rapid sand filtration/disinfection).*

RESULTS OF LCA AND LCC FOR THE LLOBREGAT AREA (SPAIN)

The assessments shows that groundwater recharge by MAR infiltration ponds in the Llobregat area has low primary energy demand which also makes it a water treatment technique with a relatively low carbon footprint (*Figure 7*). Compared to pond infiltration, traditional riverbed scarification, which has been practiced for decades in the area, causes much higher CO_2 emissions per m^3 infiltrated water and is also associated with the highest annual costs (*Figure 8*).

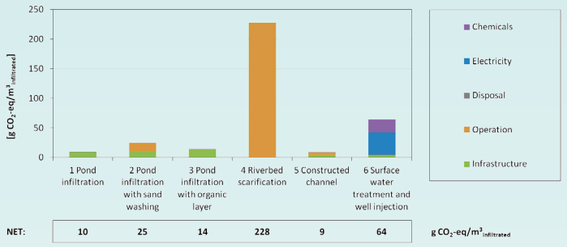

Figure 7: *Carbon footprint in CO_2-equivalents per m^3 infiltrated water for different options of MAR (pond systems at Sant Vicenç dels Horts (SVH) (1–3), traditional riverbed scarification (4), constructed channel for infiltration (5), and surface water treatment + well injection (6)) (Deliverable 51.1, unpublished).*

Adding an organic layer to the infiltration pond enhances the removal capacity for organic micropollutants. With a low additional carbon footprint, this MAR modification is an environmentally friendly option for water treatment. For a long-term sustainable operation and infiltration performance of the MAR ponds, a sand layer with defined quality and regular washing will control the clogging layer in order to maintain a high infiltration rate. Another technical MAR option with low environmental impacts is a simple channel in parallel to a river, where infiltration is maintained by regular scarification.

Assessing the economic profiles of the different technologies gives a similar picture for the different MAR options in the Llobregat area: natural pond systems are associated with costs of 8–19 €-ct/m^3 infiltrated water depending on the long-term infiltration rate that can be realised during operation (Figure 8). In comparison, riverbed scarification is more costly to operate, while surface water treatment and direct well injection is comparable to pond systems in total costs. The constructed channel is the most economical option in this comparison (3 €-ct/m^3), but its long-term, full-scale operability remains to be determined, as it is not yet implemented.

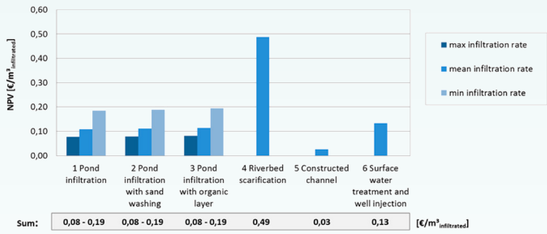

Figure 8: *Total life cycle costs (net present value, NPV) in € per m^3 infiltrated water for different options of MAR (pond systems at SVH (1-3), traditional riverbed scarification (4), constructed channel for infiltration (5), and surface water treatment + well injection (6)) (Deliverable 51.1, unpublished).*

CASE STUDIES

BERLIN - TEGEL (GERMANY)

This site is located in the northwest of Berlin, where three infiltration ponds in the catchment of Tegel Water Works are surrounded by approximately 40 production wells. The site is operated by the local water utility (Berliner Wasserbetriebe) and aquifer recharge started in the late 1950s. Beginning in the 1960s, three infiltration basins have been continuously used for infiltration. Surface water from the nearby Tegel Lake is used as a water source, pre-treated during summer via filtration through a microstrainer to prevent clogging by algae. Total annual abstraction from this site is about 21 Mm^3/a.

Contact information:
Christoph Sprenger (Christoph.Sprenger@kompetenz-wasser.de)

DEN HAAG (THE NETHERLANDS)

The Meuse River is the drinking water source utilised by Dunea. A typical multi-barrier treatment approach ensures that the drinking water meets the high Dutch quality standards. Dunea's multi-barrier consists of three main treatment steps: pre-treatment (coagulation) of surface water, infiltration in and recovery from the dune aquifer system (MAR), and a post-treatment that includes dosing of activated carbon. As a result, the drinking water is distributed chlorine-free to consumers. The MAR systems were implemented around 1950, consisting of 36 infiltration ponds and 22 injection wells that started producing water later on, in 1980, as a response to increased demands. Today, the plant provides approximately 48 Mm^3/a of drinking water.

Contact information: Beatriz de la Loma Gonzalez (Beatriz.Dela.LomaGonzalez@kwrwater.nl)

SANT VICENÇ DELS HORTS – BARCELONA (SPAIN)

The Sant Vicenç dels Horts (SVH) MAR system is one of the most active aquifer recharge systems in the Llobregat area. Recently constructed in 2007, it consists of a decantation pond (5600 m^2) and an infiltration pond (4000 m^2). The purpose of this aquifer recharge system is to increase groundwater resources at the local scale. 4 Mm^3 of raw Llobregat river water have been recharged thus far. In 2011, an organic layer of vegetal compost was installed on the bottom of the infiltration pond to enhance adsorption and degradation processes along the recharge, the first of its kind worldwide at such a large scale.

Contact information: Marta Hernández (mhernandezga@cetaqua.com)

VALL D'UXÓ – CASTELLÓN (SPAIN)

The recently constructed reservoir in la Vall d'Uixó allows the storage of 2 Mm^3 of surplus water of the Belcaire River to be injected into the aquifer during drought periods. Public and private entities joined efforts to carry out the first pilot test by injecting 310,000 m^3 of river water in 2013 and 2014 using two injection wells of 100 m depth. The DEMEAU project collaborated on assessing the use of reclaimed water from the local waste water treatment plant as an alternative source of recharge water to be implemented in a future stage of processing.

Contact information: Marta Hernández (mhernandezga@cetaqua.com)

UNIQUE SELLING POINTS OF MAR

Natural pond systems are a low-cost and low-energy option for groundwater recharge, provided that a suitable long-term strategy for clogging prevention is implemented, backed up by the LCA and LCC assessment. In addition, these ponds can be upgraded or combined with other process steps (e.g. advanced oxidation processes) to enhance their capacity for removal of organic micropollutants. Similar technical processes based on conventional technology (i.e. coagulation, filtration, and injection) are comparable in life cycle costs, but show higher environmental impacts due to electricity and chemicals demand for treatment.

More information on MAR, all deliverables and reports can be found in the DEMEAU tool box: **http://demeau-fp7.eu/toolbox/**

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Authors:
Christoph Sprenger (KWB)
Marta Hernández (Cetaqua)
Ester Vilanova (Amphos21)
Beatriz de la Loma Gonzalez (KWR)
Stephan Hannappel (HYDOR)
Christian Remy (KWB)
Anna Bee Szendrenyi (Ecologic Institute)

Additional Authors:
Kristina Wencki (IWW)
Anna Kounina (Quantis)