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.
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 re-evaluation. 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.

Table 1: Classification of MAR types.

<table>
<thead>
<tr>
<th>Recharge technique</th>
<th>Main MAR type</th>
<th>Specific MAR type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Enhanced infiltration</td>
<td>Surface spreading methods (Areal recharge)</td>
<td>Infiltration ponds</td>
</tr>
<tr>
<td>(2) Induced bank filtration</td>
<td>Point or line recharge</td>
<td>Soil-aquifer treatment</td>
</tr>
<tr>
<td>(3) Well injection</td>
<td>In-channel modifications</td>
<td>Excess irrigation, ditches, trenches</td>
</tr>
<tr>
<td>(4) Enhanced storage</td>
<td>Reverse drainage, shaft recharge</td>
<td>Well-borehole infiltration</td>
</tr>
</tbody>
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MAR AND ENVIRONMENTAL CONSIDERATIONS
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.

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, the design of the MAR field site. Impact zones of MAR structures can be divided into a hydraulic impact and attenuation zone.

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) (Springer et al. 2015).
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 small local aquifers which are not visible in the scale of the aquifer type map (scale 1:1,500,000).

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

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).
**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 Mm³/a.

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**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 Mm³/a of drinking water.

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**SANT VICENÇ DELS HORTS – BARCELONA (SPAIN)**

The Sant Vicenç d’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 m²) and an infiltration pond (4000 m²). The purpose of this aquifer recharge system is to increase groundwater resources at the local scale. 4 Mm³ 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.

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**VALL D’UXÓ – CASTELLÓN (SPAIN)**

The recently constructed reservoir in the Vall d’Uixó allows the storage of 2 Mm³ 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 m³ 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.

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**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.

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Cover design and layout: broondesign · www.broon.de

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