Part of D12.2 Pre-requisites and design criteria for new MAR systems in compliance with EU WFD and GWD (including pre-treatment)

Pre-treatment options for Managed Aquifer Recharge

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Title: Pre-requisites and design criteria for new MAR systems in compliance with EU WFD and GWD (including pre-treatment)

Summary: In this report technical pre-treatment methods, which can be combined with MAR treatment to guarantee the requested water quality, are explained and evaluated. A description of existing MAR systems in Europe gives an overview of pre- and post-treatment technologies applied today. Possible pre-treatment steps and their removal efficiencies for contaminants of main concern as well as removal efficiencies in the MAR are listed. This list may be used for the selection of appropriate pre-treatment steps for different MAR types.

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Table of contents

List of Figures

List of Tables

1 Introduction

Successful MAR schemes in Europe have been using stormwater, drinking water, surface water, mains water, rainwater, groundwater from other aquifers, desalinated seawater and treated waste water. Depending on the prevalent conditions, the need and use of pre-treatment may vary considerably. They are mainly determined by the following parameters (Sharma et al., 2015a; Dillon et al., 2009b; Dillon et al., 2008; Asano & Cotruvo, 2004):

- Source water quality used for recharge
- Intended end-use of the extracted water
- Local water quality guidelines
- Local hydrological conditions
- Process conditions in the aquifer (e.g. aquifer mineralogy, grain size, hydraulic conductivity, degree of macro-porosity/fracturing and confinement)
- Ambient groundwater quality
- MAR system (surface infiltration (basins), vadose zone wells or direct injection wells)
- Public acceptance

Pre-treatment is applied in MAR systems primarily for the following reasons (Sharma, 2015b; Dillon et al., 2008; Asano & Cotruvo, 2004):

- Removal of critical contaminants from the source water, which cannot or not fully be removed by the MAR system (e.g. bulk organics, nutrients and organic micropollutants)
- Removal of critical contaminants in order to enhance system performance and removal efficiencies (e.g. total suspended solids (TSS) may cause clogging, nutrients may cause biological change in the redox chemistry)
- Removal of critical contaminants in order to ensure long-term functioning (e.g. clogging)
- Meeting local water quality requirements for artificial recharge and use of reclaimed water (e.g. safe drinking water, no contamination of the aquifer)
- Meeting water quality requirements under future changing conditions and therefore deteriorating source water quality (e.g. climate change, population increase, change in land use, emerging contaminants)
- Ensuring existing beneficial uses of the aquifer beyond the attenuation zone (e.g. the area surrounding the zone of recharge, where natural attenuation of contaminants such as chemicals and microorganisms takes place)

- Ensuring safe future beneficial uses within the attenuation zone on cessation of aquifer use for water treatment

The MAR system components shown in Figure 1 can be combined in various ways depending on source water quality and treatment requirements.

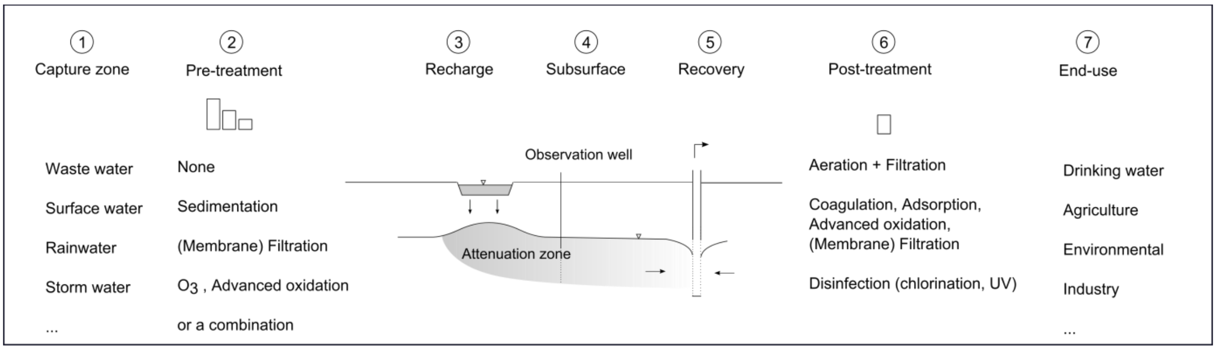

Figure 1: Main components of MAR system with pre- and post-treatment options.

Lower quality source water generally has to be treated to a higher degree in cases of (i) high quality aquifer water, (ii) end uses with high quality requirements (e.g. drinking water) and (iii) the use of fine-grained aquifers in order to avoid clogging of recharge basins, galleries or wells (Dillon et al., 2009a). Figure 2 shows possible pre- and post-treatment processes dependent on water source and end-use. Choice of the right pre-treatment allows recovery of recharged groundwater from any water source and for any end use.

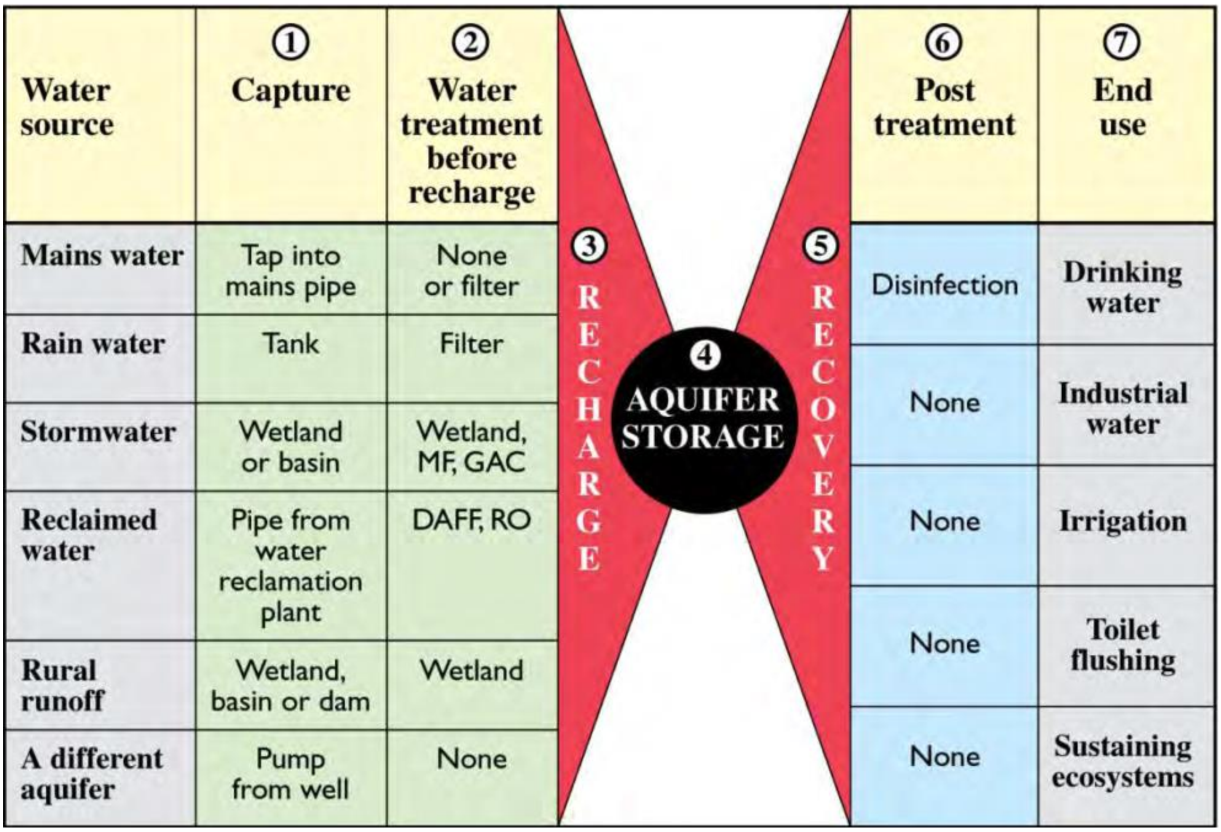

Figure 2: **Typical water sources, capture and pre-treatment methods for MAR (Dillon et al., 2009a). MF: Microfiltration, GAC: Granular Activated Carbon, DAFF: Dissolved Air Flotation and Filtration, RO: Reverse Osmosis**

Dependent on the system determining parameters, MAR systems can have pre-treatment, post-treatment or both (Sharma et al., 2015b). Where river or lake water of low turbidity is diverted to infiltration basins to augment groundwater supplies, no treatment may be necessary (Dillon et al., 2009a). When reclaimed water or other polluted water sources for use as potable water are recharged, adequate treatment is imperative to avoid health risks to consumers. Of main concern are (i) microbiological quality, (ii) total mineral content (total dissolved solids), (iii) presence of heavy metal toxicants and (iv) concentrations of stable and possibly harmful organic substances. Primary treatment of waste water and dissolved air flotation can be sufficient for a SAT system whereas direct injection into the aquifer will require advanced upstream sewage treatment (Asano & Cotruvo, 2004).

Common pre-treatment methods for MAR systems are sedimentation, filtration and disinfection. Primary sedimentation and sand filtration are basic and low cost measures that are used for TSS and turbidity reduction. High TSS concentrations are critical, because they exert strain on the distribution system, cause clogging, reduce the flow length and travel times in the groundwater and reduce treatment efficiencies (e.g. of nitrogen removal). TSS can also act as carriers for heavy metals. Reverse osmosis (RO), ion exchange and biological denitrification are used to reduce nitrogen concentrations from high fertilizer use and insufficient sewage treatment, activated carbon, oxidation-filtration or membrane processes for the reduction of emerging pollutants (Sharma, 2015b).

Some pre-treatment filters incorporate additional layers of adsorbents for the removal of heavy metals or other specific contaminants from source water before recharge. Further pre-treatment processes include pre-screening, skimming, decantation, coagulation and flocculation, dissolved air flotation, microsieving, activated sludge, biofilters and wetlands (Table 1) (Van der Hoek et al., 2000; Balke & Zhu, 2008; Dillon et al., 2009b). Investigation of ASR in a fine grained aquifer showed that pre-treatment of the recharge water with microfiltration (MF) and granular activated carbon (GAC)in order to prevent clogging of the well was a more stringent condition than meeting groundwater and end water quality requirements (Dillon et al., 2009a).

2 Brief description of main treatment steps

Engineered treatment processes are designed for specific flow conditions, water quality (i.e. concentrations of specific species and constituents) and flow rate. Highly variable water quality can lead to difficulties in process operation. Therefore, several pre-treatment steps can be necessary to reach a more or less uniform water quality for the next treatment step to work efficiently (Dillon et al., 2008). A roughing filter, for example, is often used to provide sufficient water quality for biofiltration to work economically (Page et al., 2006). In conventional waste water treatment physical, chemical and biological processes are combined to remove solids, organic matter, nutrients and other constituents. Treatment of municipal waste water is often followed by a disinfection step to guarantee pathogen inactivation (Al-Rekabi et al., 2007). The treatment steps used in (waste-)water treatment are shortly described in chapters 2.1 to 2.5.

An overview of pre-treatment steps for MAR systems is given in Table 1. Listed are pre-treatment steps used in MAR systems in Europe (as described in chapter 4 and 5) supplemented by methods described in literature (Dillon et al., 2008).

Table 1: Overview of pre-treatment steps for MAR systems

Treatment type	Objective	Treatment steps
Mechanical	Particle removal	Screening Sand and oil trap Roughing filter Rapid sand filtration Lamellar decantation Clarification pond Surface filtration Sedimentation
Physio-chemical	Removal of dissolved compounds	Activated carbon filtration Coagulation/flocculation Dissolved air flotation Membrane filtration Cartridge filtration Microsieving Ion exchange
Chemical	Removal of organics and inorganics	Chemical P removal Oxidation/reduction Fe/Mn removal by oxidation

Treatment type	Objective	Treatment steps
	Avoidance of metal leaching	pH adjustment Dissolved oxygen (DO) removal
Biological	Degradation of organic compounds Removal of inorganic compounds (N, P)	Activated sludge digestion Nitrification/denitrification Biological P removal Biofiltration Membrane bioreactor Settling and aeration ponds Wetland ponds Reedbeds
Disinfection	Removal, deactivation or killing of pathogenic microorganisms	UV disinfection Chemical disinfection

2.1 Preliminary treatment

In preliminary treatment, coarse solids and other bulk material is removed by processes like coarse screening, grit removal and comminution. To avoid settling of organic solids flow rates are kept sufficiently high (FAO, 2014; Al-Rekabi et al., 2007).

2.2 Primary treatment

In primary treatment, settleable organic and inorganic solids are removed by sedimentation and floating scum by skimming. The effluent from primary treatment is called primary effluent and is reduced by 25 to 50% in biological oxygen demand (BOD_5), by 50 to 70% in suspended solids (SS) and by about 65% in oil and grease content compared to raw waste water. Parts of organic nitrogen, organic phosphorus, and heavy metals associated with solids are also removed. On colloidal and dissolved constituents in waste water primary treatment has no effect. Settled solids and scum make up the primary sludge and are led to further processing, usually in anaerobic digesters (FAO, 2014; Al-Rekabi et al., 2007).

2.3 Secondary treatment

In secondary treatment, residual organics and suspended solids are removed from the primary effluent. Often, this is done by aerobic biological treatment in activated sludge systems, i.e. treatment involving microorganisms, which are metabolizing the biodegradable dissolved and colloidal organic matter in the presence of oxygen. Products of activated sludge treatment are increased microbial biomass and inorganic end-products (mainly CO_2, NH_3, and H_2O). The excess biomass is removed by sedimentation from the secondary effluent in clarifiers and further processed as secondary or biological sludge, often together with the primary sludge (FAO, 2014; Al-Rekabi et al., 2007). Other methods using microbial degradation include trickling filters or biofilters, rotating biological contactors (RBC), oxidation ditches, treatment ponds and lagoons (FAO, 2014; Drinan &

Spellman, 2013) and, mainly for industrial waste water or in hot climates for municipal waste water, anaerobic digestion (Haandel & Lettinga, 1994). Primary and secondary treatment reduces the largest part of the BOD and suspended solids as well as part of the heavy metals (FAO, 2014; Al-Rekabi et al., 2007).

2.4 Tertiary treatment

Tertiary treatment is part of advanced waste water treatment (see 2.5). Advanced waste water treatment is called tertiary treatment, if it follows conventional secondary treatment. Tertiary treatment often includes filtration for removal of remaining suspended solids or multi-step processes for organics, suspended solids, nutrient removal and disinfection (Al-Rekabi et al., 2007; Tchobanoglous et al., 2002).

2.5 Advanced treatment

In advanced waste water treatment, constituents that cannot be removed by primary and secondary treatment like nitrogen and phosphorus, additional suspended solids, refractory organics, pathogens, volatile organic compounds (VOC), odors, heavy metals and dissolved solids are removed in specialized treatment steps. Nutrient removal is often included in an adapted activated sludge system. There, nitrogen is transformed in a 2-step-process to nitrite and nitrate. In a supplementary anaerobic process step, nitrate is converted to gaseous nitrogen. Phosphate elimination can be achieved biologically or by chemically induced precipitation. Advanced treatment can be applied complementary to primary and/or secondary treatment or replace secondary treatment (FAO, 2014; Al-Rekabi et al., 2007; Tchobanoglous et al., 2002).
Although often primary and secondary treatment provide an adequate water quality, advanced treatment might be required for direct or indirect water reuse, to alleviate pollution loads on receiving waters or for industrial purposes (FAO, 2014; Al-Rekabi et al., 2007). The increasing awareness of the effects of micropollutants in municipal and industrial waste water effluents on aquatic life has recently led to increasing demand for advanced treatment technologies included in conventional WWTPs (FOEN, 2012).

Advanced treatment processes contain methods like coagulation/flocculation, chemical precipitation, depth or surface filtration, biofilters, microstraining, chemical or advanced oxidation, sequenced anaerobic/aerobic bio-processes, chemical treatment, chemical scrubbers, (carbon) adsorption, membrane processes, ion exchange, air stripping and disinfection by chlorine compounds, chlorine dioxide, ozonation or UV radiation(Al-Rekabi et al, 2007; Tchobanoglous et al., 2002).

3 Source water types and main water quality concerns for MAR

Source water quality is one factor, which needs to be considered when choosing an appropriate pre-treatment for MAR systems.

Table 2 summarizes the main water quality concerns for different types of source water, which will be described in more detail in this chapter. In

Table 3 pre-treatment methods applied in MAR systems using reclaimed water and storm water are shown together with their effectiveness on TSS and organics removal.

Table 2: Main water quality concerns by water source

Water Source	Main water quality concern
River and lake water	TSS, DOM, turbidity, nutrients, pathogens, cyanotoxins, heavy metals, micropollutants (i.e. pesticides, EDC, PhAC, PCP), hydrocarbons
Storm water	TSS, nutrients, VSS, COD, heavy metals
Treated waste water	Nutrients, pathogens, mineral content, metals, pesticides, EDC, PhAC, PCP,BOD_5, COD, DO, AOX, TSS, active chlorine, chloride, sulphate, fluor, surfactants, mineral oil, chloride solvents, disinfection by-products, complex-forming substances
Urban run-off	Rubber fragments, heavy metals, sodium and sulphate, pesticides, hydrocarbons, solvents
Agricultural run-off	Nutrients, pesticides, fecal microbes and sediments

Table 3: Pre-treatments for MAR using reclaimed water and stormwater and relative effectiveness of each treatment for removal of TSS and liable organics (Dillon et al., 2008)

Pre-treatment	Reclaimed Water	Stormwater	SS removal	Organics removal
Roughing filter		Y	*	

Pre-treatment	Reclaimed Water	Stormwater	SS removal	Organics removal
Rapid sand filtration		Y	*	
Biofiltration		Y	***	**
Activated carbon filtration	Y	Y	*	***
Chemical coagulation and filtration		Y	**	*
Dissolved air flotation and filtration	Y		***	*
Membrane bioreactor	Y		***	*
MF		Y	***	
RO		Y	***	***
Activated sludge digestion	Y		*	**
Settling/aeration ponds	Y	Y	*	*
Wetland ponds		Y	**	*
Reedbeds		Y	**	*

Y = treatment has been widely applied for this type of source water

Treatment effectiveness: blank = ineffective

* = only partially effective

** = moderately effective

*** = very effective

3.1 Surface water

Surface water is mainly rain water that collects in natural water bodies (i.e. river and lake water) or groundwater that emerges from springs (US EPA, 2011). It is the most common source for MAR systems (Hannappel et al., 2014). Surface water quality can vary considerably depending on geology, soil properties, vegetation, climate, land use, human activity and other factors. The terrain the water is flowing through influences mineral composition, silt content and content of suspended particles. Temperature, content of organic matter and the degree of turbulence determine the oxygen content. Different life forms within and besides water bodies affect the content of organic matter (GE Power & Water, 2012). Natural organic matter (NOM) as such is not toxic to humans, but is a precursor to disinfection by-products (Maeng et al., 2011; Luet al., 2009). Typical impurities are turbidity, hardness, free mineral acid, carbon dioxide, sulfate, chloride, fluoride, sodium, silica, iron, manganese, aluminum, hydrogen sulfide and ammonia (GE Power & Water, 2012). In agricultural areas run-off water often carries nutrients like nitrate and phosphate, pesticides, fecal microbes and sediments into the water bodies. Surface run-off in urban areas can contain rubber fragments, heavy metals, sodium and sulfate, pesticides, hydrocarbons and solvents (Tong & Chen, 2002; EEA, n.d.).

Physical and chemical characteristics of surface water can vary strongly both short-term, seasonally and long-term due to extreme weather events, seasonal variations and circumstances (GE Power & Water, 2012).

The analytical results of a three-year monitoring program of major river systems, streams tributaries and ditches in Northern Greece (Simeonov et al., 2003) give an overview of concentrations and values of field pH, electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD_5), organic (Kjeldahl) nitrogen (TON), acid-hydrolysable (total) phosphorus (TP), orthophosphate (PO_4^{3-}), nitrite (NO^{2-}), nitrate (NO^{3-}), ammonium (NH^{4+}) and the acid-available fractions of metals and other toxic elements that can be expected in surface waters. They are listed and compared to the standards defined in the EU drinking water directive in Table 4. The EU groundwater directive defines standards for nitrates (50 mg/l) and active substances in pesticides, including relevant metabolites and reaction products (0.1 µg/l for each individual substance and 0.5 µg/l in total). Threshold values for other pollutants are established country-specifically (Council Directive 2006/118/EC).

Table 4 **Analytical results of a three-year monitoring program of the major river systems, streams tributaries and ditches in Northern Greece (Simeonov et al., 2003; Council Directive 98/83/EC)**

Component	Unit	Mean + Std. Dev.	Minimum	Maximum	EU Drinking water standard
pH	---	8.1 ± 0.26	7.7	8.6	≥ 6.5 and ≤ 9.5
EC	µS cm^{-1}	421 ± 193	126	690	2500 (at 20°C)
DO	mg L^{-1}	7.4 ± 1.2	3.7	12.3	---
TSS	mg L^{-1}	17.7 ± 14.4	6.2	45.8	---
COD	mg L^{-1}	12.2 ± 11.6	4.0	94.0	---

Component	Unit	Mean + Std. Dev.	Minimum	Maximum	EU Drinking water standard
BOD_5	mg L^{-1}	11.4 ± 9.3	2.0	8.0	---
TON	mg L^{-1}	0.62 ± 0.71	0.02	2.55	---
TP	mg L^{-1}	0.57 ± 0.63	0.14	1.97	---
PO43-	mg L^{-1}	0.22 ± 0.26	0.06	0.53	---
NO2-	mg L^{-1}	0.21 ± 0.27	0.01	1.56	0.50
NO3-	mg L^{-1}	0.38 ± 0.34	0.3	10.2	50
NH4+	mg L^{-1}	1.22 ± 1.06	0.03	3.08	0.5
Ag	µgL^{-1}	1.1 ± 0.02	1.0	3.0	---
As	µg L^{-1}	Less than 0.1	Less than 0.1	Less than 0.1	10
Cd	µg L^{-1}	0.26 ± 0.19	0.1	0.6	5.0
Cr	µg L^{-1}	6.5 ± 5.5	1.0	18.0	50
Cu	µg L^{-1}	4.2 ± 2.4	2.0	7.0	2000
Fe	µg L^{-1}	326.6 ± 211.9	113	833	200
Hg	µg L^{-1}	Less than 0.2	Less than 0.2	Less than 0.2	1.0
Mn	µg L^{-1}	155.4 ± 102.3	45	291	50
Ni	µg L^{-1}	4.1 ± 2.9	2.0	12.0	20
Se	µg L^{-1}	Less than 0.1	Less than 0.1	Less than 0.1	10
Zn	µg L^{-1}	57.2 ± 44.8	20	157	---

3.1.1 River and lake water

In addition to the factors described above (3.1), industrial or domestic discharges and the remobilization of contaminants in sediments or soil can have a strong effect on the water quality of rivers and lakes. Along the flow of a river (from spring to mouth), the water quality can decrease significantly (US EPA, 2011). Typical contaminants found in surface water bodies are suspended solids, dissolved organic matter (DOM), nutrients, pathogens, mainly from waste water effluents, cyanotoxins, heavy metals and micropollutants such as pesticides, pharmaceuticals, hydrocarbons and endocrine disrupting compounds (EDC) (Sprenger et al., 2011; Turgut, 2003).

Industrial waste water is an important source of water pollution. Depending on the industry, waste water contaminants differ. Table 5 lists typical contaminants produced by different industries.

Table 5: Water pollutants by industrial sector (Hanchang, n.d.)

Industrial Sector	Pollutant
Iron and steel	BOD, COD, oil, metals, acids, phenols, cyanide
Metal working industry	Metals (Cr, Ni, Zn, Cd, Pb, Fe, Ti)
Textiles and leather	BOD, solids, sulfates, chromium
Pulp and paper	BOD, COD, solids, chlorinated organic compounds, dioxin
Petrochemicals and refineries	BOD, COD, mineral oils, phenols, chromium
Chemicals	COD, organic chemicals, heavy metals, SS, cyanide
Non-ferrous metals	Fluorine, SS
Microelectronics	COD, organic chemicals
Mining	SS, metals, acids, salts
Photo processing	Silver
Dry cleaning	Solvents
Car repair	Solvents
Printing plants	Inks, dyes

Contaminants from municipal waste water plants that can impact river and lake water quality are described in chapter 3.2, impacts from agriculture and urban areas in chapter 3.1.

Effluents from fish farms can also contribute to fresh water pollution. They contain low concentrations of pollutants, but have high flow rates leading to high nutrient inputs (N and P) into water bodies (Naylor et al., 2003; Foy & Rosell, 1991). They can further lead to an increase in alkalinity, total hardness, BOD_5, TSS and mesophilic bacteria and a decrease in DO concentration. Often, chemicals and drugs against parasites and pathogenic bacteria also are introduced (Boaventura et al., 1997).

3.1.2 Stormwater

Stormwater is water from rainfall or snowmelt. In areas with impervious surfaces or in the case of exceeded intake capacity of the soil, stormwater flows off as surface run-off (US EPA, 2014). In urban areas, stormwater management is an integral part of civil engineering and is necessary to prevent flooding, erosion and water quality problems (Adams, 2000). Stormwater often is an abundant and relatively unused resource that can make a valuable contribution to city water supplies while reducing impact on the waterways it is currently led into. Since storage is often the limiting factor of stormwater harvest and usage, MAR offers a viable and economical solution for its storage and treatment (Dillon et al., 2009a; CSIRO, n.d.).

Stormwater can be drained to aquifers via infiltration basins, sumps or wells for subsequent reuse as drinking water or irrigation supply (Dillon, 2005). Storage inside an aquifer for a year, has allowed stormwater to be used as drinking water without any further treatment. In other cases, for example when recharging a brackish limestone aquifer, constructed wetlands have been used as suitable pre-treatment for recovery as irrigation water without any further treatment (Dillon et al., 2009a).

Of concern is the content of contaminants that can be found especially in urban run-off. While flowing off, run-off can collect debris, chemicals, sediment and other pollutants (US EPA, 2014). Common constituents include different forms of nitrogen and phosphorus, TSS, volatile suspended solids (VSS), COD and heavy metals like lead and zinc (Brezonik & Stadelmann, 2002).

3.2 Treated waste water

Treated waste water is an abundant water source in urban areas, which, with proper treatment, can be used as drinking water, for industrial use, irrigation and environmental purposes (Dillon et al., 2009a). In direct reuse treated waste water is introduced directly, either with or without an engineered storage buffer, into a water treatment plant. In indirect reuse treated waste water is used for augmentation of a water source like surface or groundwater, thereby providing an additional environmental buffer before water treatment (USEPA, 2012).

Water stress due to water quality degradation and water scarcity is a matter of serious concern to municipalities, industries, agriculture and the environment in many countries. With appropriate treatment for the intended end-use, reclamation and reuse of municipal waste water can present a sustainable alternative water source (Wintgens et al., 2008; Asano & Cotruvo, 2004) that is additionally reducing nutrient loads on recipient water bodies (US EPA, 2012). Several treatment facilities exist for the reuse of reclaimed water. The Torreele Plant in Belgium is an established water reclamation plant using waste water effluent for aquifer recharge and subsequent drinking and environmental purposes. In contrast to the use of stormwater for aquifer recharge, reclaimed water offers the advantage of very stable flows (Dillon et al., 2009a).

Aquifer storage can serve as temporary storage for reclaimed water providing additional treatment during soil and sub-soil passage, especially in the vadose zone, and/or by aquifer residence time (Dillon et al., 2009a; Ternes et al., 2007) with the additional benefit of increasing public acceptance (Asano et al., 2007; Leviston et al., 2006). Several types of viruses, protozoa and bacteria as well as DOC, nitrogen and labile organic matter can be degraded by microorganisms present in the soil and the aquifer. Their degradation is strongly influenced by the redox state in the aquifer and by the presence of microorganism populations. Although attenuation is also achieved by adsorption, this mechanism is not considered sustainable, because contaminants and pathogens are not retained once the sorption sites become fully occupied (Dillon et al., 2008; Amy & Drewes, 2007; Ternes et al., 2007).

In a SAT system with suitable hydrogeological conditions primary treatment, a stabilization pond and dissolved air flotation can suffice as pre-treatment for municipal waste water, if retention time is kept long enough and only part of the natural aquifer is used for recharge. The pre-treatment processes need to ensure low algal concentrations in the influent in order to avoid clogging of the infiltration basins. Direct injection of reclaimed water requires extensive pre-treatment including MF, RO and disinfection processes to avoid contamination of the aquifer and to ensure adequate end water quality (Dillon et al., 2009a; Asano & Cotruvo, 2004).

Of special concern in MAR projects are pathogens, mineral content, nutrients, metals, pesticides, EDC, pharmaceutically active compounds (PhAC), personal care products (PCP) and other stable and potentially toxic organic substances (WRRF, 2007; Asano& Cotruvo, 2004). Other parameters that have to be taken into consideration with the use of reclaimed water are pH, EC, BOD_5, COD, DO, adsorbable organic halogen compounds (AOX), TSS, active chlorine, chloride, sulphate, fluor, surfactants, mineral oil compounds, chloride solvents, disinfection by-products andcomplex-forming substances (Salgot et al., 2006). Concentrations of viruses and protozoa are of particular concern and need to be controlled and monitored, even if the product water meets the microbiological requirements for drinking water. This is mainly due to the fact that typical microbiological indicators are not adequate for reclaimed water, in which pathogen concentrations are much higher than even in heavily polluted natural waters (Asano & Cotruvo, 2004).

Of further concern for human and environmental health is the content of organic matter in waste water effluents. Effluent organic matter (EfOM) is composed of (i) refractory compounds, (ii) residual degradable substrates, (iii) intermediates, (iv) complex organic compounds and (v) soluble microbial products (SMP) (Barker & Stuckey, 1999). SMP are biodegradable products from substrate metabolism and biomass decay, which are major membrane foulants (Jarusutthirak & Amy, 2006), can lead to bacterial regrowth in the water distribution system and to the formation of disinfection by-products (Amy & Drewes, 2007). EfOM also contains micropollutants like PhAC, EDC and PCP, many of which are not or only partly transformed during municipal waste water treatment. They require advanced treatment, for example with advanced oxidation processes (AOP), in order to prevent accumulating concentrations in drinking water supplies and in the environment (Maeng et al., 2011).

The socio-cultural context needs also be considered with regard to the choice of appropriate technical solutions for the use of reclaimed water (Bixio et al., 2005; Asano et al., 2007).

4 Pre-treatment methods during MAR in relation to source water and end-use

Table 6 shows possible pre-treatment steps and their removal efficiencies for contaminants of main concern as well as removal efficiencies in the MAR systems for artificial recharge and recovery (ARR) and SAT as described by Sharma et al. (2015a). This table is intended for the selection of appropriate pre-treatment steps with ARR and SAT. Its use as well as possible post-treatment steps are described in detail by Sharma et al. (2015a). The list of pre-treatment steps for ARR systems has been supplemented with additional steps and preventive measures as suggested in the Australian Guidelines for Managed Aquifer Recharge (NRMMC, EPHC, & NHMRC, 2009).

Table 6: Matrix for selection of appropriate pre-treatment options for ARR and SAT (Sharma et al., 2015a; NRMMC, EPHC, & NHMRC, 2009)

Pollutants to be removed	Pre-treatment and preventive measure		Removal efficiency for ARR	Removal efficiency of SAT**		
	Type	Removal Efficiency				
Pathogens	Chlorination	1-4 Log	1-<8.3 Log (regulated by residence time)	PE	>1 - 6.9	
	UV	1-4 Log		SE	0 - 6.5	
	Ozonation	1-4 Log		TE	0.4 - 4.0	
	MF/UF	0-7 Log	n.a.			
Hardness	Lime softening	60%	-	PE	-	Only post-treatment
	NF	85-99%		SE	-	
				TE	-	
Turbidity	Sedimentation + Aeration + Rapid Sand Filter /Slow Sand Filter	>95-100%	50-100%	n.a.		
	MF	>98%				
	Wetlands	n.s.				

Pollutants to be removed	Pre-treatment and preventive measure			Removal efficiency for ARR		Removal efficiency of SAT**		
	Type	Removal Efficiency						
	UF	>98%				PE	50-100%	
						SE	50-100%	
	Coagulation+ Sedimentation	>95%				TE	50-100%	
TSS	Sedimentation + Aeration + RSF/SSF	100%		90-100%		n.a.		
	UF	85-99.9%				PE	86-100%	
	Coagulation+ Sedimentation	50->85%				SE	>90-100%	
	Aeration+RSF	70-80%		n.a.		TE	>90-100%	
Iron/ Manganese	Aeration + RSF	Fe	92-97%	-		PE	-	Only post-treatment
		Mn	17-79%			SE	-	
	Aeration + RSF + Aeration + RSF	Fe	>99%			TE	-	
		Mn	31-96%					
	Coagulation + Flocculation + Filtration	n.s.						
	Ph and Eh adjustment in source water	n.s.						
Fluoride	-	-		-	Only post-tr.	n.a.		

Pollutants to be removed	Pre-treatment and preventive measure		Removal efficiency for ARR	Removal efficiency of SAT**	
	Type	Removal Efficiency			
Arsenic	Control of Eh during recharge	n.s.	90%	n.a.	
Nitrate	Ion exchange	90%	50-100%	PE	57-100%
				SE	3 - >90%
	RO	65 - >95%	n.a.	TE	0-22%
	Activated sludge	n.s.	50-100%	n.a.	
	Biofiltration	n.s.			
	Wetlands	n.s.			
Ammonium	Chlorination	100%	53-90%	n.a.	
	Aeration + RSF	40-50%			
	NF/RO	90-98%	n.a.	PE	25-99%
				SE	0-99%
				TE	17-100%
Organic micro-pollutants (highly dependent on type of pollutant)	Ozonation	50->90%	≥50%	n.a.	
	GAC	0-70%			
	Exclude prone sub-catchments	n.s.			
	UF	>90%	n.a.	PE	75-100%
	RO	70-99.9%		SE	20-100%
				TE	10-100%

<table>
<tr><th rowspan="2">Pollutants to be removed</th><th colspan="2">Pre-treatment and preventive measure</th><th rowspan="2" colspan="2">Removal efficiency for ARR</th><th rowspan="2" colspan="3">Removal efficiency of SAT**</th></tr>
<tr><th>Type</th><th>Removal Efficiency</th></tr>
<tr><td rowspan="2">Colour</td><td>Aeration + Coagulation + RSF</td><td>>60-64%</td><td rowspan="2" colspan="2">50-100%</td><td rowspan="2" colspan="3">n.a.</td></tr>
<tr><td>GAC</td><td><55%</td></tr>
<tr><td rowspan="3">Salinity</td><td rowspan="3">Increase volume of recharged fresh water</td><td rowspan="3">n.s.</td><td rowspan="3">-</td><td rowspan="3">Only post-treatment</td><td>PE</td><td>-</td><td rowspan="3">Only post-treatment</td></tr>
<tr><td>SE</td><td>-</td></tr>
<tr><td>TE</td><td>-</td></tr>
</table>

** PE = primary effluent; SE = secondary effluent; TE = tertiary effluent

n.a. = method not applied to this recharge system

n.s. = values not specified

Only post-treatment = parameter reduction is performed only in post-treatment steps

Pre-treatment methods during MAR improve the quality of water prior to recharge. Their choice and necessity is determined by the factors described above. Pre-treatment steps applied by MAR sites in Europe for different water sources and water end-uses will be described in chapters 4.1 to 4.3. In Table 7, Table 8 and Table 9, the European sites are summarized and an overview of the different pre-treatment methods is given.

4.1 MAR sites producing water mainly for environmental benefits

Environmental benefits are here defined in a broad sense and include MAR sites without a clear recovery concept. Recovery of the recharged water takes place by various end-users, which may include agriculture, ecology, industry or drinking water supply.

Llobregat aquifer, Spain –Basin infiltration

With the growth of the Barcelona area, the Llobregat Delta Aquifer, an important water supply in times of dry periods, has been exceedingly used, leading to decreasing groundwater levels and sea water intrusion into the aquifer. In the last 40 years, several projects have been launched to guarantee good groundwater quality and the sustainable use of the aquifer. Aquifer recharge allows the storage of excess water to cover water demand in dry periods while at the same time providing water purification by soil passage and aquifer residence time (Hernández et al., 2011).

Infiltration basins have been constructed at three sites along the course of the Llobregat River. Sant Vicenç dels Horts is constructed both for the use of river water and for reclaimed water from the El Prat del Llobregat Tertiary Treatment Plant (Hernández et al., 2011), where secondary effluent of El Prat WWTP is treated by ballasted coagulation-flocculation, lamellar decantation, surface filtration and UV and chemical disinfection (Cazurra, 2008; Aguiló et al., n.d.). Secondary treatment at the WWTP includes screening, elimination of sand and oil in desanders-deoilers, primary clarification, activated sludge with anaerobic, anoxic and oxygenation processes and secondary clarification (Acciona Agua, n.d.). Currently, the recharge sites are operated only with river water. Sole pre-treatment before infiltration is sedimentation in clarification ponds. An automated system regulates the recharge volume according to river water flow rate. To minimize clogging, water quality is monitored for turbidity, conductivity and ammonium. Estimated recharge volume is 6 to 10 Mio. m^3 per year.

Llobregat aquifer, Spain – Deep well injection

In the Llobregat Delta in Spain, intensive groundwater exploitation and excavation of part of the confining layer of the aquifer has led to increasing sea water intrusion since the 1960s into an aquifer, which is used for industrial, agricultural and drinking water purposes (Custodio, 1981, 2008, 2010; Irìbar, 1992; Irìbar & Custodio, 1992). As one of the measures to mitigate water scarcity and ameliorate aquifer quality, an injection hydraulic barrier was constructed (Ortuño et al., 2008), injecting reclaimed water from the Baix (El Prat) Llobregat waste water treatment and reclamation plants (WWTP and WRP) (Cazurra, 2008; Aguiló et al., n.d.). At the WWTP municipal waste water is treated by screening, elimination of sand and oil in desanders-deoilers, primary clarification, activated sludge with anaerobic, anoxic and oxygenation processes and secondary clarification (Acciona Agua, n.d.). The secondary effluent is further purified in the El Prat WRP by ballasted coagulation-flocculation, lamellar decantation, surface filtration and UV and chemical disinfection (Cazurra, 2008; Aguiló et al., n.d.). At the hydraulic barrier plant, the WWTP effluent is treated by UF, RO and UV disinfection prior to injection. UF is applied to maintain stable microbiological water quality, to prevent clogging of the injection wells and to reduce fouling of the RO membranes. RO is needed to reduce salinity mainly due to former and current upstream potash mine activity. According to Spanish law, EC, pH, temperature, ammonia, turbidity, biological and chemical parameters, major elements, metals, volatile organohalogenated and organochlorine compounds are monitored.

The treated water is injected into the confined, lower sand and gravel aquifer through 15 wells, which are placed 1 km inland and parallel to the shore and which cover the whole depth of the aquifer. Abstracted water is mainly used for urban and industrial supply. At the same time, it serves as an emergency water supply for the city of Barcelona.

The project was successful in rising groundwater levels and reducing salt concentrations in the aquifers without experiencing any negative effect on injection capacity due to clogging up to date (Ortuño et al., 2012; Hernández et al., 2011).

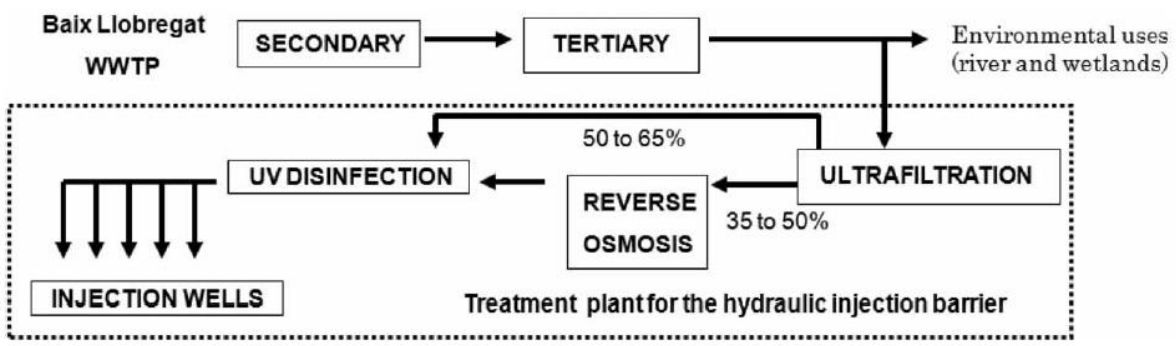

Figure 3: Waste water treatment system prior to injection into the aquifer of Baix Llobregat WWTP and WRP (Ortuño et al., 2012)

<u>Hessisches Ried, Germany – sprinkler irrigation and various infiltration techniques</u>

At the "Hessisches Ried" area in Germany treated Rhine River water is used for sprinkler irrigation and groundwater replenishment. Groundwater replenishment takes place through a series of recharge shafts, infiltration wells and open channels. Groundwater replenishment aims at i) compensating seasonally occurring groundwater deficits ii) realizing ecological benefits and iii) securing drinking water supply (WHR, 2008). Through a sequence of technical treatment steps the infiltrated water quality meets drinking water standards.

Table 7: Overview of pre-treatment methods used for MAR types producing water for multi purposes without managed abstraction scheme

MAR type	Source water type	Pre-treatment	Case study	References
Pond **infiltration**	(1) River water (Llobregat River); (2) Reclaimed water	(1) Clarification pond (2) Screening, desanders-deoilers, primary clarification, activated sludge, secondary clarification Coagulation-flocculation, lamellar decantation, surface filtration and UV, chemical disinfection	Llobregat Delta, Spain	Acciona Agua, n.d.; Aguiló et al., n.d. ; Cazurra, 2008; Hernández et al., 2011; Ortuño et al., 2009
Deep well injection	Reclaimed water	Screening, desanders-deoilers, primary clarification, activated sludge, secondary clarification	Barrera hidraulica del Llobregat, Barcelona (Spain)	Acciona Agua, n.d. ; Aguiló et al., n.d.; Cazurra, 2008 ; Hernández et al., 2011;

		Coagulation-flocculation, lamellar decantation, surface filtration, UV and chemical disinfection UF, RO, UV disinfection		Ortuño et al., 2012; Teijòn et al., 2009;
Different infiltration techniques (recharge shafts, infiltration wells and open channels)	River water	Screening, pre-ozonation, flocculation, sedimentation, ozonation, secondary flocculation, filtration, activated carbon	Hessisches Ried (Germany)	WHR 2008

4.2 MAR sites producing water mainly for agricultural purposes

Nardò, Italy – Sinkhole infiltration

In Nardò, MAR is used for further treatment of secondary effluent from municipal waste water treatment plants. The waste water is treated with activated sludge and the effluent is transported to the MAR area by an open channel (Asso channel) and infiltrated into the unconfined karstic aquifer by a sinkhole with an average flow rate of about 150 l/s (La Mantia et al., 2008). The water is extracted through recovery wells at distances of 600 to more than 3'000 m from the injection area, resulting in an average residence time of 20 to 25 days. With 1.7 Mio.m^3 per year about 1/3 of the injected water is recovered and is used for unrestricted irrigation without post-treatment. In Nardò, the MAR system is the critical barrier for the limitation of human health risks due to viruses, bacteria and protozoa. Acceptable risk levels with regard to aerosol ingestion could be reached only by replacing sprinkler by drip irrigation (Ayuso-Gabella et al., 2011).

Valld'Uixó, Castellon (Spain) – Well injection

The recently constructed reservoir in la Valld'Uixó allows the storage of 2 Mm^3 of surplus water of the Belcaire River to be injected into the aquifer in drought periods. Public and private entities joined efforts to carry out the first pilot test by injecting 310'000 m^3 in 2013 and 2014 using two injection wells of 100 m depth. DEMEAU project collaborated in the assessment of 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. The area is subject to salinity ingress and the main objective of well injection is to counteract salinity ingress. Main end-user is the local agriculture (Morell et al., 1996).

Table 8: Overview of pre-treatment methods used for MAR types producing water for (restricted) agricultural purposes

MAR type	Source water type	Pre-treatment	Case study	Reference

Sinkhole infiltration	Reclaimed water	Activated sludge, sedimentation	Nardo, Italy	Ayuso-Gabella et al., 2011 La Mantia et al., 2008
Well injection	River water	Clarification pond	Valld'Uixó, Castellon	Morell et al. (1996)

4.3 MAR sites producing drinking water

Lange Erlen, Basel, Switzerland – Forested soil infiltration

Since 1964 water has been diverted from the river Rhine to augment groundwater supplies in Basel for subsequent extraction as drinking water. The system covers about half of the drinking water demand of the city of Basel. The water is caught above the power plant Birsfelden and led onto embanked natural forest sites on former alluvial soils. After passing a coarse screen, the water is treated by rapid sand filtration, which removes about 95% of suspended solids. An average of 60'000 m^3 per operating day of the pre-filtered water is led onto several of the 11 watering infiltration sites (total size about 13 ha) inside of the forest. The system is operated during 9 months per year. In general, a watering site is flooded for 10 days followed by a 20 day drying period. By passing the different soil horizons the river water is purified, but in contrast to slow sand filter systems no biofilm is generated. After a horizontal flow distance of about 200 to 800 m in the aquifer, the water is recovered by11 wells. It is of high drinking water quality and only adjusted for pH and treated with chlorine dioxide to prevent re-growth of microorganisms before it is fed into the distribution network.

On a yearly basis, the extracted volume is about equal to the infiltrated volume. Infiltration and purification capacities (i.e. removal of dissolved organic carbon) have remained constant and satisfactory since establishment of the system. Apart from the drying phases, no regeneration or maintenance measures are necessary (Rüetschi, 2004).

The Hague, The Netherlands – Dune filtration and ASTR

A main source of fresh groundwater is found in the sandy dunes along the coast, where it has been used for drinking water purposes since 1854. Fresh water occurs in the dunes in reservoirs, which are fed by infiltration of rain water that, due to density differences, forms a fresh water lens on the sea water that infiltrates further below. Because of over-use of these water reserves, several water utilities have started recharging the reservoirs with river or lake water.

The Dune Water Company of South-Holland (DZH) uses pre-treated water from the river Meuse for dune infiltration through open ponds or deep wells and subsequent drinking water supply in the region of the Hague, providing a total of about 83 Mio. m^3 per year through three facilities.

Waternet uses pre-treated Rhine water from the Lekkanaal in Nieuwegein to replenish dune fresh water supplies through 40 infiltration ditches, providing the city of Amsterdam with about 70 Mio. m^3 per year of drinking water.

PWN in the North-Holland province uses pre-treated raw water from the Lekkanaal and from Lake IJsselmeer in Andijk for infiltration through open ponds or deep wells. The abstracted water (about 47 Mio. m^3 per year) is treated and mixed with hyperfiltration water from a membrane filtration plant using pre-treated surface water for supply of consumers in the region.

Pre-treatment includes microsieving to remove suspended solids and mussel larvae, coagulation, flocculation and sedimentation for removal of suspended solids, phosphates, heavy metals, microorganisms and organic matter, and rapid sand filtration for removal of further suspended solids and reduction of organic matter, iron, manganese, ammonium and algae concentrations. Organic micro-pollutants are monitored or removed by activated carbon filtration at one site of the DHZ.

Deep well infiltration (ASTR) is used for recharge of confined aquifers. These aquifers are without contact to the phreatic water, which reduces environmental impact due to eutrophication. This method needs close control of infiltration water quality to prevent clogging of the wells. After a residence time of about 30 to 60 days the water is extracted using closed systems such as wells, drainage and transport pipes except for one Waternet plant, where a closed system is not feasible. There, an open abstraction, collection and transport system is used.

The abstracted water is aerated and softened. A rapid sand filtration is used to remove oxidized species of iron and manganese resulting from the aeration process, suspended solids and algae. Activated carbon is used in final treatment before sand filtration in the plants without activated carbon in the pre-treatment, reducing concentrations of organic micropollutants and taste and odour. Waternet applies an additional ozonation step for oxidation of organic micropollutants and as disinfection for the open abstraction system. Finally, slow sand filtration decimates bacteria and viruses and removes remaining suspended solids (Tielemans,2007).

<u>Berlin-Tegel, Germany – Bank filtration and basin infiltration</u>

In Berlin, all drinking water is produced from local groundwater resources, which are being recharged by bank filtration and basin infiltration (Ziegler, 2001). About 70 % of the drinking water is produced via bank filtration (56%) and artificial groundwater recharge (14%) (BWB, 2003). Because of the high content of waste water effluent in some of the used water bodies, the drinking water system in Berlin can be partially considered an indirect waste water reuse system (Ziegler, 2001).

Tegel Water Treatment Plant (WTP Tegel) is one of the largest water treatment plants in Berlin extracting about 50 Mio. m^3 per year (1998). With 14 to 28%, drinking water of WTP Tegel has the highest fraction of reused wastewater among Berlin's WTPs. Waste water effluent from the WWTP Schönerlinde is discharged into the Nordgraben upstream of Lake Tegel, resulting in lake water with a waste water portion of 10 to 30% and a partially closed water cycle (Fritz et al., 2002; Ziegler, 2001). The waste water of WWTP Schönerlinde is treated in a traditional nitrification/denitrification activated sludge process with phosphate elimination. In 1985, a surface water treatment plant (SWTP Tegel) with flocculation, sedimentation and filtration processes was installed upstream of Lake Tegel to add to the purification processes of the WWTP for the removal of phosphorus by $Fe_2(SO_4)_3$ flocculation and of remaining filterable compounds resulting in very clean water entering Lake Tegel (BWB, n.d.).

Water is extracted through eight well galleries around Lake Tegel with a total of 130 vertical and one horizontal well. Three of the galleries are affected by artificial groundwater recharge, which is infiltrated via infiltration basins (30'069 m^2 total) (BWB, 2014; Ziegler, 2001). About 80% of the groundwater abstracted consists of bank filtrate and artificially recharged water (Ziegler, 2001).

Pre-treatment for groundwater recharge consists of microsieving to reduce clogging of the infiltration basins. Nevertheless, the top layer of the sandy soil needs to be removed from time to time, to guarantee sufficient permeability. The infiltration basins are usually cleaned once a year by drying up the basins and removing the upper sand layer for washing (Ziegler, 2001). The retention time in the aquifer is about 50 days, which allows recovery of the groundwater without any microbiological problems and distribution without disinfection. After extraction the groundwater is only aerated for iron and manganese oxidation and filtered by rapid filtration (Grünheid et al., 2005). The long-lasting and stable purification capacity and low energy and maintenance requirements result in a very sustainable water supply system. Problems with regard to the self-purification capacity of the system can emerge related to persistent, polar organic compounds, though (Ziegler, 2001).

Torreele, Belgium – Dune filtration

In the Veurne region in the Northern part of Belgium, dune water has been used since World War I. Dune water extraction is limited, though, because of the presence of salt water north and south of the dunes. Over-extraction of dune water will lead to saline water intrusion into the dunes. To comply with the increasing drinking water demand in the region, the Torreele project was started, using treated, mainly domestic waste water for groundwater recharge.

The Torreele plant, operated by the Intermunicipal Water Company of Veurne-Ambacht (IWVA, n.d.) since 2002, has a treatment capacity of 2.5 Mio. m^3 infiltration water per year, which corresponds to about 40% of the drinking water demand of the region. Infiltration water is taken directly from the local waste water treatment plant (WWTP) Wulpen (Van Houtte et al., 2005; IWVA, n.d.). The waste water is treated in a conventional pre-denitrification activated sludge process with mechanical pre-treatment and P and N removal (Kazner et al., 2012). The WWTP effluent is treated with a prescreening, MF, cartridge filter, RO with subsequent chemical re-mineralization and UV radiation (Figure 4) before it is fed into the sandy unconfined aquifer through an infiltration pond of 18'200 m^2 in the catchment area. To completely capture the infiltrated water, the 112 extraction wells are placed around the infiltration area. Residence time is a minimum of 40 days. After extraction, the water is aerated and filtered by sand filtration for removal of iron and manganese.

To protect the dune area, strict environmental standards are applied and no untouched dunes were accessed (Van Houtte et al., 2005; IWVA, n.d.).

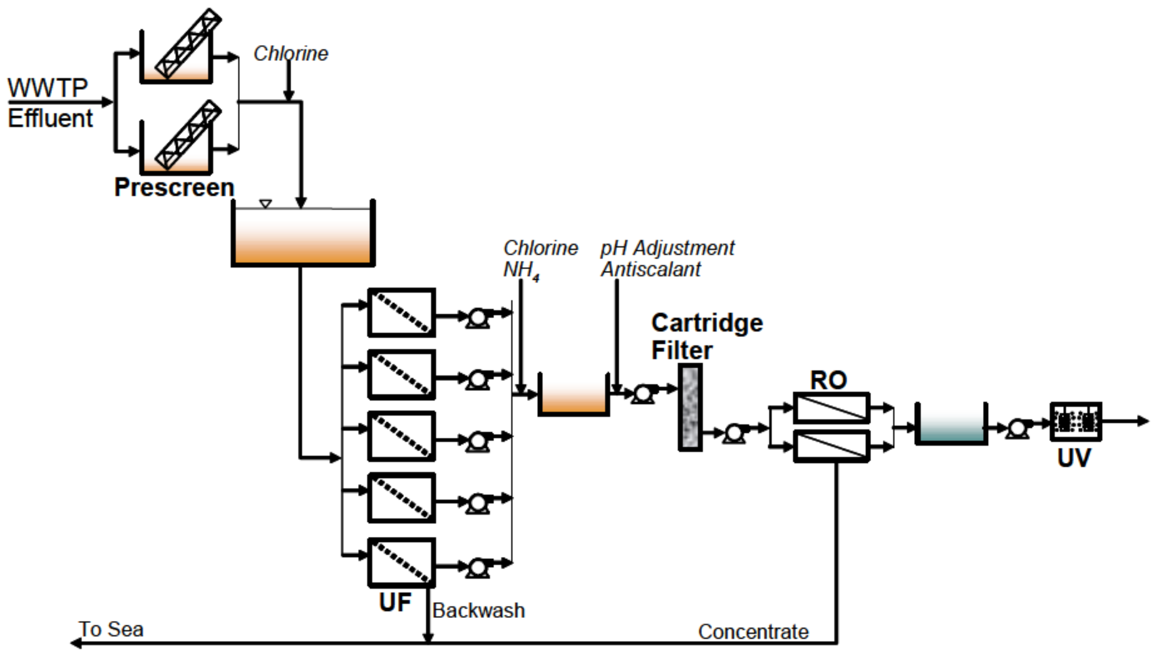

Figure 4: Process scheme of pre-treatment at Torreele plant (van Houtte and Verbauwhede, 2008)

Table 9 Overview of pre-treatment methods used for MAR types producing drinking water

MAR type	Source water type	Pre-treatment	Case study	Reference
Forested soil infiltration	River water (Rhine)	Rapid sand filtration	Basel (Lange Erlen), Switzerland	Rüetschi, 2004
Dune infiltration + well injection	River water (Meuse, Rhine),	Microsieving, coagulation, flocculation, sedimentation, (activated carbon filtration), rapid sand filtration	The Hague, Scheveningen-Waalsdorp, The Netherlands	Tielemans, 2007
Bankfiltration, Pond infiltration	Lake water (Lake Tegel) with 10 - 30 % treated effluent	Activated sludge, N and P removal (WWTP) Flocculation, sedimentation and filtration (SWTP) Microsieving	Berlin-Tegel, Germany	BWB, 2003; Fritz et al., 2002; Grünheid et al., 2005; Ziegler, 2001
Dunefiltration, ASTR	Reclaimed water	Screening, sand trap, activated sludge, N and P removal Pre-screening, MF, cartridge filtration, RO with re-mineralization, UV irradiation	Torreele, Belgium	Van Houtte et al., 2005

5 Summary of pre-treatment methods at selected European MAR sites

Figure 5 displays the various pre-treatment methods used in European MAR systems in relation to the different water sources and end-uses of MAR product water for the main categories environmental use (Table 7), agricultural (Table 8) and drinking water (Table 9).

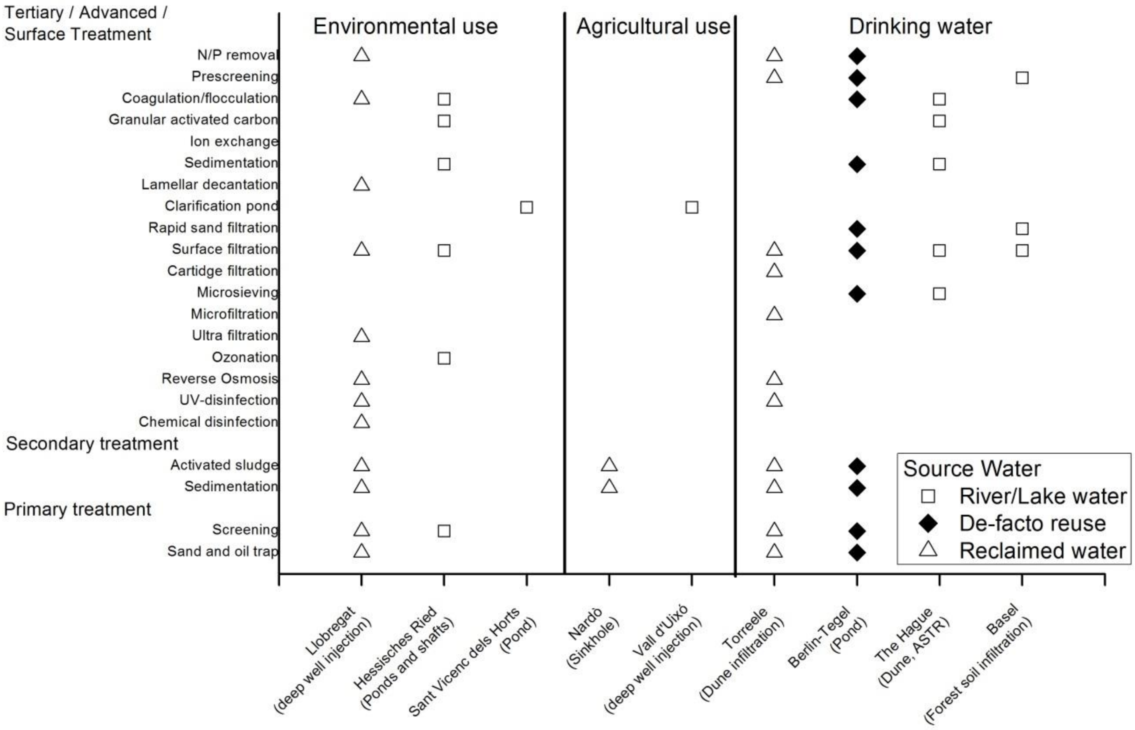

Figure 5: **Typical pre-treatment methods in relation to the water end-use and the source water based on case studies from European MAR sites (Belgium, Germany, Italy, Netherlands, Spain and Switzerland).**

6 Conclusions

River and lake water, stormwater and waste water effluents are suitable, valuable and often sustainable and economical sources for MAR. Depending on source water quality pre-treatment requirements differ. Ambient groundwater quality, hydrogeological conditions, process conditions in the aquifer, intended end-use, the MAR system used, local water quality guidelines and public acceptance are additional factors, which need to be considered when choosing appropriate pre-treatment systems. Often, several treatment steps are necessary to achieve and secure the required product water quality and to provide a uniform water quality for the next treatment step to protect downstream technology (Sharma et al., 2015a; Dillon et al., 2009b; Dillon et al., 2008; Asano & Cotruvo, 2004).

Pre-treatment is necessary to remove critical contaminants from the source water, to enhance system performance and removal efficiencies, to ensure the long-term functioning of the system, to meet regulatory demands in current and future conditions, to ensure beneficial uses of the aquifer beyond as well as, on cessation of aquifer use for water treatment, future beneficial uses within the attenuation zone (Sharma, 2015b; Dillon et al., 2008; Asano & Cotruvo, 2004).

Reclaimed water needs much more advanced pre-treatment than surface water. Higher level pre-treatment is necessary especially in the case of high quality native groundwater, high quality product water and in fine-grained aquifers (Dillon et al., 2009). This is also apparent in the choice of pre-treatment steps at the European MAR sites (Figure 5). MAR systems can provide a certain degree of treatment during soil and sub-soil vadose zone passage and by aquifer residence time (Dillon et al., 2009a; Ternes et al., 2007) resulting in lower pre-treatment requirements. Removal of viruses, protozoa and bacteria, DOC, nitrogen and some trace organics by natural attenuation processes has been shown to be effective (Dillon et al., 2008; Amy & Drewes, 2007; Ternes et al., 2007).

MAR systems can be used as treatment of surface water with only little pre-treatment, as seasonal storage for times of water scarcity and/or to counteract salt water intrusion (Asano & Cotruvo, 2004). Aquifer storage can be part of civil engineering effort in stormwater management to prevent flooding, erosion and water quality problems (Adams, 2000) and reduce the impact on the waterways it is currently led into (CSIRO, n.d.). Under favorable conditions (e.g. long residence times) only little or no additional treatment might be necessary before end-use (Dillon et al., 2009a).

Waste water is an abundant resource with stable flows, which has been successfully used in several MAR systems. It can be reclaimed with appropriate and usually advanced treatment (Dillon et al., 2009a; Wintgens et al., 2008; Asano & Cotruvo, 2004). With the use of reclaimed water the main concerns are microbiological quality, total mineral content, presence of heavy metal toxicants and concentrations of stable and possibly harmful organic substances (WRRF, 2007; Asano & Cotruvo, 2004). With knowledge of source water and intended end-use, appropriate pre-treatment methods can be assessed using Table 6.

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