Decision trees for MAR impact evaluation:

Identification of optimum conditions to face emerging pollutants removal in MAR systems

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Title: Decision trees for MAR impact evaluation, Identification of optimum conditions to face emerging pollutants removal in MAR systems.

Summary: This report compiles the results found in a comprehensive bibliographic review on trace organic removal rates in different Managed Aquifer Recharge (MAR) sites. The elimination of 12 selected emerging pollutants is classified and evaluated based on previously selected key parameters of MAR systems to identify the optimum conditions that will determine the design and operation of infiltration facilities in terms of water quality impacts. The aim is to provide guidance to the authorities and water suppliers to evaluate the trace organic removal in an existing or a new designed MAR facilities and, as a consequence, to identify those trace organics that need some special legislation. This report includes also a review of the existing European legislation regarded to MAR activities.

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1 Introduction

1.1 Background

Managed Aquifer Recharge (MAR) with reclaimed waste water combines natural water treatment during infiltration with subsurface storage and has shown to be a cost-effective wastewater reclamation technology that can improve wastewater effluent to drinking water quality levels (Kazner et al., 2012). However, concerns about trace organic compounds constitute one of the main drawbacks of this technology.

The EU Water Framework Directive (2000/06/EC) stipulates that MAR can be a supplementary measure to reach good quantitative and qualitative water status by regulating the water cycle on basin scale within an integrated water resource management. On the other hand, the EU Groundwater Directive prohibits any actions that may deteriorate groundwater quality – a demand which needs to be evaluated site-specifically.

When recharging aquifers with reclaimed water, member states authorities use to follow a conservative approach denying authorization of new sites due to the lack of information related to impacts on groundwater quality. On the other hand there is a long-term experience in many EU countries with river- or lake water infiltration, which may contain relevant shares of treated wastewater (and related trace organics). Several European research initiatives have identified the lack of harmonized and adequate regulation at European level as a key barrier for the deployment of water reuse schemes in Europe in general and MAR in particular.

Micropollutants are of special concern as some have shown to be poorly degradable or may be removed only under specific conditions. MAR enables storage of water in periods of good resource quality and it offers natural degradation of some pollutants while others have been shown to persist in the subsurface limiting the widespread of MAR technology if the behavior of these contaminants is not described.

1.2 Objectives and work

The aim of the overall project is to demonstrate MAR benefits and limitations with a special focus on emerging pollutants and to draw recommendations for its optimal design and operation in compliance with the European Directives.

This specific task intends to develop a European approach for MAR authorization through the identification of the optimum MAR characteristics to ensure a minimum environmental impact related to trace organics and other pollutants.

The original purpose pretended to develop a decision tree to evaluate MAR impact onto groundwater systems at existing or new sites. The aim was to relate the % of removal with some determinant key parameter and to classify these parameters in a hierarchal way in order to build a decision tree. Decision tree models are well suited to represent the complexity of interactions between different factors. Decision trees are hierarchical structures of rules or conditional statements based on different classes. The construction of a decision tree involves searching for the set of questions that is most efficient at distinguishing between the classes on the basis of the observed attributes. The process of decision trees

induction involves the formulation and comparison of rules for discriminating between members of different classes. As a consequence the influence of the different classes in the results has to be well-known and, furthermore these classes has to be independent as the discrimination of a value in a class should no limit the existence of the following class in the hierarchal structure.

Instead the compiled information has shown that in the most of the cases the results depend on a suite of variables or can also be site-dependent (Heberer et al., 2008; Kyu et al., 2011, Massmann et al., 2006; Wiese et al., 2011). Additionally, available information in most of the sites is not enough to identify the most determinant parameter or to categorize their role in the compound removal. In these cases it is no possible to classify the key parameters in a hierarchal structure. As a consequence, an Influencing Parameters Matrix has been elaborated in order to relate the results with the suite of parameters and values that allow these results. This matrix offers a tool to identify the optimum configurations to achieve the best removal rates for each compound.

Other specific objectives that have been also studied in this task:

- Identification of key parameters that determines environmental impacts related to emerging pollutants.
- Influence of key parameters on attenuation of selected trace organics during subsurface passage.
- Evaluation of national regulations in European countries that can limit MAR authorizations.
- Identification of characteristics that source water quality has to accomplish to fulfill with existing regulations.

The work carried out to achieve the objectives has included the conduction of the following tasks:

- Bibliographic research of all MAR sites where trace organic compounds have been analyzed an evaluated in terms of attenuation capacity during subsurface passage.
- Bibliographic research of trace organic intrinsic characteristics.
- Evaluation of the most determinant key parameters in each of the compiled investigation sites.
- Definition of key parameters that characterize MAR systems in general and are of relevance for groundwater impacted by MAR with treated waste water at long term, based on literature data.
- Data-driven approach to assess the impact of MAR on ambient groundwater quality.
- Revision and compilation of different European legislations that can limit or control MAR authorizations.
- Comparison of different characteristics that different European countries require for recharging water.
- Evaluation of legislation and limits fixed by other non-European countries.

1.3 Structure of the document

This document consists of two main parts:

- The first part of the document describes the methodology followed to develop an approach for assessing MAR impact on emerging pollutants removal. As a consequence the bibliographic research is described together with the selection of trace organic compounds and the key parameters that might

influence trace organic compounds attenuation. To conclude, the attenuation conditions are evaluated separately for each compound to finally indicate the optimum characteristics of the recharging facility for emerging pollutants removal.

- The second part of the document includes the revision and comparison of different existing legislations that controls MAR authorizations in selected European countries. The regulations of different countries are described with emphasis in water quality threshold values and trace organics. Furthermore, the limits of the different legislations are compared in a table and a description of the recommendations for possible points of compliance with the European Groundwater is included.

2 Removal Conditions Matrix for the impact assessment of organic trace compounds during MAR

2.1 Objective and methodology

As an approach for assessing impacts of MAR systems onto groundwater resources, a matrix, Removal Conditions Matrix, has been developed focusing on selected emerging substances and defined key parameters that might influence removal rates.

The objective of the Removal Conditions Matrix is to be able to predict the attenuation or persistence of specific emerging substances in MAR systems in function of the range of values of key parameters. This matrix can be used as a decision support tool for new MAR sites authorization or to define monitoring and control practices.

The first step consisted in the selection of the compounds representing emerging contaminants and the key parameters that might be related to their attenuation in MAR systems. This selection of parameters has been conducted at a project level to ensure homogenization among different working areas. In the second phase of the work, an extensive literature research and review has been done taking into account the selected compounds and key parameters. All key information and findings of the literature review has been assembled in a table (site results table) in order to organize all the data, to keep the details of the information sources and to summarize the results of these investigations. Finally, the analyses of these investigations results and the corresponding conclusions have been summarized in the Removal Conditions Matrix for each compound. The matrix enables to determine, for each emerging substance, which are the conditions influencing their attenuation in MAR systems and which degree of removal would be expected under these conditions.

2.2 Selection of compounds and key parameters

The project consortium selected more than 40 compounds representing emerging substances. From these pollutants 12 have been selected for this study based on the following criteria:

- commonly found in wastewater / drinking water supplies
- environmental relevance
- broad spectrum of chemical and physical properties
- cover the range from good to bad elimination by O_3 and/or UV/H_2O_2
- existence of analytical method by project partners

These pollutants have been selected once analytical capabilities of the project team has been taken into consideration and after identifying the most commonly found in the sites of interest. All final selected compounds can be analyzed by most of the partners with analytical capabilities. Those compounds that are site-specific (not always analyzed in all samples) and those of difficult analysis, irregular input (varying concentration in source water) and not very persistent have been excluded from this selection.

Table 1: DEMEAU selected compounds

Compound
Benzotriazole
Bezafibrate
Carbamazepine
Epoxi-carbamazepine
Diclofenac
Gemfibrozil
Iopromide
Metroprolol
Phenazone
Primidone
Sulfamethoxazole
Trimethoprim

The bibliographic research has been focused to these compounds. With the aim to evaluate common aquifer behaviors, in a first instance only data from existing sites where these compounds have been studied have been included in the analysis. The compilation has also considered data from laboratory tests but these examples have been used only for comparison purposes.

To classify the published results of different MAR techniques, a first list of key parameters to be studied was elaborated. Key parameters where those considered to be governing the attenuation of emerging substances:

- Residence time
- Redox conditions
- Organic Carbon in sediment and water
- Attenuation/sorption capacity of the sediment
- Existence of an unsaturated zone
- Temperature

After the literature review, it was considered the other key parameters should be included as indicators of influencing removal of emerging substances as explained and detailed afterwards.

The final selected key parameters are:

- MAR type
- Aquifer type

- Redox conditions
- DOC/TOC
- Residence time
- Concentration of the emerging substance in source water (initial concentration)
- Temperature
- Percentage of attenuation
- Compound characteristics

2.3 Literature review

An extensive literature review has been done related to attenuation of emerging substances during MAR. From the scientific papers and books reviewed, a more detailed review has been done on those articles with relevant information related to the trace organic substances considered in this study.

From the detailed review, key information as the attenuation percentage (% of removal) and the influencing conditions (key parameters) has been gathered in the Sites Results Table for each selected compound (Annex-C). The reviewed studies encompass different MAR types as direct injection (ASTR) and infiltration systems as infiltration pond, soil aquifer treatment (SAT), bank filtration, etc. from 6 different countries (Germany, Spain, USA, Italy, Israel and China). All the data incorporated in the table includes the source of reference where this result has been obtained.

2.4 Development of the Site Results Table and Compound Specific Attenuation capacity table

In a first stage, the Site Results Table (Annex_C) has been organized by each emerging substance in alphabetical order. For each compound, information has been structured by article or reference source and by differentiating the specific site. When appropriate, various specific cases per each site have been distinguished in the table. This is when in the same site coexists different type of MAR, different characteristics of the aquifer (upper or lower aquifer) or if seasonal changes evidence variations in the results (summer or winter). Most of the cases are real cases of field MAR devices; only one column experiment has been taken into consideration for comparison purposes and because was a compound with low available information. The Sites Results Table is included in the Annex-C.

An effort has been made on keeping the objectivity of the information gathered in the Site Results Table, transcribing the original data from the articles into the table. Standardization of units has been carried out for better comparison. When table values have been extracted from paper graphics or figures instead of being read in a table or in the text, these values have been indicated in the table (blue color).

Available information in the literature review is not the same for each compound, neither for each site; consequently an effort has been made to compile all data representative of the key parameters. The Sites Results table gathers article's available information on the following factors:

- Ref.: Indicates the literature reference. The number included in the table is indicated in the corresponding article of the references chapter in order to identify the source of information.
- MAR type: briefly describes the MAR devices, making a major difference between injection and infiltration MAR types. Injection MAR devices include Aquifer Storage Treatment and Recovery systems (ASTR), and infiltration systems are represented systems as bank filtration, infiltration pond, irrigation,

surface spreading basins, etc. In some cases, in the same site there is an infiltration pond and an injection and recovery well. Data from two different types of MAR has been differentiated in the table.

- Aquifer type: summarizes basic information of the aquifer type (confined/unconfined), the type of flow in this aquifer as porous/karst/fractured, other details as shallow/deep and if available data indicates the unsaturated zone thickness.
- Redox conditions: describes the main redox condition during the subsurface passage as oxic conditions, nitrate reducing, manganese reducing, iron reducing, sulfate reducing, etc.
- Organic carbon concentration in source water and during recharge: indicated by the concentration of Dissolved Organic Carbon (DOC) or by the concentration of Total Organic Carbon (TOC, etc.).
- Residence time: residence time of groundwater in the aquifer indicated either by residence time itself or by travel time, hydraulic conductivity, hydraulic retention time, etc.
- Concentration of the concerned emerging substance: indicates the initial concentration (in source water) and the final concentration (in aquifer during recharge, or from the observation well). This is because differences have been observed at different initial concentrations and for taking into account potential errors when initial concentrations are close to the limit of quantification (LOQ).
- Limit of quantification of analysis of the concerned emerging substance (LOQ).
- Temperature: temperature of groundwater.
- Percentage of removal: percentage of compound removed comparing the concentration in the aquifer in the observation point with the concentration of the source water.

Percentage of removal is the parameter of most concern for this study. In the literature review, removal rates of compounds are presented and interpreted differently. To standardize the results of different papers and the removal rates of each case it has been necessary to make some assumptions:

- The first analysis have been done over the potential water dilution that can mask real removal:
    - When dilution factor is specified in the paper, then this value is considered in the final removal rate and if it is necessary the percentage of removal has been recalculated accordingly.
    - In some papers, dilution factor is not taken into consideration but the site description suggests that there may be some dilution. As this factor is unknown, then it is described and specified in the Site Results Table.
    - When dilution is not known neither specified in the paper but there are data of removal in several observation wells and in pumping well, then data from the last observation point before to pumping well is preferred and included in the table in order to minimize dilution factor. It is assumed that pumping well has higher dilution factor due to its pumping cone.
- In some papers the percentage of removal is not estimated. The initial and final concentration of the concerned compound is presented (in a table or a graphic), and then percentage of removal has been calculated from these values:
    - The results of the removal rates in some papers are reported in box-plot graphics where maximum, minimum and mean values are displayed. In these cases, the value of final concentration considered in the Table is the mean concentrations of the concerned compound.

- In some recalcitrant compounds is quite common to find higher concentration in the observation point than in the injection point. This is related to the analytic method error and to mix with different groundwater. Then removal rate is considered to be negligible.
- The percentage of removal is not always linear or progressive along an observation line from the injection point. In some sites it has been observed that the removal rates are not always higher in the further point. This can be attributed to a mix of different water types or to a different infiltration time (water from different infiltration concentrations):
    - If residence time range is significantly wide then the two extreme values (maximum and minimum) are considered in the table indicating their respective residences times,
    - In some cases the average value is the one considered by the author in the text. Then this is the value considered as removal rate for that compound in the table.

Basic information on the solubility and mobility and the acid strength of each compound has been summarized in a separated table, as the acid dissociation constant, octanol water partition coefficient, soil organic carbon coefficient, etc. This information was not available for all compounds (Table 2). This table also includes the reference (Ref.) of the source of information which is detailed in the references chapter.

Table 2: Solubility and mobility information of each selected trace organic compound.

	pKa	LogDow (pH=7)	LogKow	LogKoc	LogKd	Ref
Bezafibrate	6.00	0.85	4.25	0.78	1.48	[10]
Carbamazepine	13.93	2.40	2.45	1.93	0.33	[10]
		2.63	2.67			[3], [18]
Diclofenac	4.15	1.65	4.06	1.37	1.37	[10]
		1.06	4.06			[3], [18]
Gemfibrozil	4.80	2.19	4.39			[3], [18]
Metoprolol	9.60	-0.80	1.90	-0.44	-2.70	[10]
Primidone	12.30	0.40	0.40			[18]
			-0.84	-0.84		[3]
Sulfamethoxazole	5.70	-0.43	0.89	-0.17	-2.43	[10]
Trimethoprim	6.60	0.51	0.91	0.53	-1.73	[10]

Abbreviation

pKa: acid–base dissociation constant
Log Kow: octanol water partition coefficient
LogDow(pH=7): octanol water distribution coefficient
Log Koc: soil organic carbon coefficient
LogKd: Distribution coefficient (mass-averaged partition coefficient).

2.5 Removal Conditions Matrix for the impact assessment of organic trace compounds during MAR

A matrix has been built up on the bases of the Site Results Table. In the latter, the % of removal has been related with values and characteristics of the different key parameters.

The matrix has grouped those cases with similar results on attenuation of emerging substances (similar % of removal) indicating in additional columns in which conditions occurred (redox conditions, residence time, organic carbon concentration, etc.).

A range of percentage removal has been classified and indicated by colors:

Not removed (0-20%)
Partially removed (20-50%)
Significantly removed (50-90%)
Removed (90-100%)

The more or less optimum conditions for MAR installations are defined by residence time, aquifer type, redox conditions, DOC in recharging water and the initial concentration of the compound in the source water. Injection and infiltration MAR types are considered separately. The number of references that meet the same removal range is also indicated in order to show the consistency of the results.

2.6 Summary of findings

Summary of findings per each compound are described below:

2.6.1 Attenuation of Benzotriazole during MAR

Available information on Benzotriazole removal on MAR is represented only by sites with anoxic conditions with residence times from 20 days to 1 year. Removals rates around 75%-85% are found in infiltration ponds and bank filtration sites with residence time above 4 months and in Iron/Manganese reduction conditions. All examples of injection MAR systems with short residence time show low removal rates.

2.6.2 Attenuation of Bezafibrate during MAR

Relevant information about Bezafibrate attenuation in MAR devices is been found in 10 different sites characterizing different conditions as different MAR types, Different redox conditions (from oxic to most reductive zone) and different residence time ranging from days to 1 year. In most of the cases, Bezafibrate is completely removed in MAR. Low removal rate (40%) was only obtained in an injection device with less than 3 months and under nitrate reduction conditions.

2.6.3 Attenuation of Carbamazepine during MAR

Data from 14 different sites has been considered for analyzing Carbamazepine behavior through a MAR device. Available information encompasses different MAR types as injection well, SAT, bank filtration, infiltration pond, different conditions as oxic and reductive conditions and different residence time (ranging from hours to 1 year). Carbamazepine is found to be recalcitrant in MAR devices in both oxic and in Nitrate and Manganese conditions, with no significant removal. Nevertheless, high removal rates up to 99% have been obtained in strictly anoxic conditions with long residence time.

2.6.4 Attenuation of Diclofenac during MAR

Available information on Diclofenac removal in MAR is characterized by 12 different sites representing different MAR devices, different redox conditions and residence time from days to several months. In most of the cases Diclofenac is highly removed in MAR systems under both oxic and anoxic conditions. In opposition, there are a few cases, under nitrate and manganese reduction conditions, with no significant removal.

2.6.5 Attenuation of Epoxi-Carbamazepine during MAR

There is only one site with relevant information on Epoxi-Carbamazepine behavior on MAR. Results on this site show how removal rates increase from 0 up to 85% when there is presence of an organic layer at short residence time.

2.6.6 Attenuation of Gemfibrozil during MAR

Relevant information about Gemfibrozil removal in MAR systems is represented by 5 different sites encompassing different infiltration devices, both oxic and reducing conditions and different residence time from 1 day to 3 months. Gemfibrozil is rapidly significantly removed in all conditions, with best results under high temperatures (97%-100%).

2.6.7 Attenuation of Iopromide during MAR

Information from 7 sites has been taking into account for analyzing the attenuation of Iopromide on MAR systems. These sites covers different MAR devices as ASTR, injection well, bank filtration and infiltration basins, both oxic and anoxic conditions and residence time ranging from 1 day to several months. All conditions show high removal rates, as in both oxic and reducing conditions and short and long residence time.

2.6.8 Attenuation of Metoprolol during MAR

There is few data available on removal of this compound in MAR systems. Available data show high removal (100%) after long residence time (more than 6 months).

2.6.9 Attenuation of Phenazone during MAR

Relevant information about Phenazone removal in MAR systems is characterized only by 2 sites but with different cases representing different redox conditions and different residence time (from 2 to 120 days). Phenazone show good removal rates and best results are under oxic conditions (91%). In some cases there is no consistency on removal behavior, high removal rates are obtained with short residence time and afterwards concentration of Phenazone increases with longer residence in the same aquifer.

2.6.10 Attenuation of Primidone during MAR

Information from 8 sites has been taking into account for analyzing the attenuation of Primidone on MAR systems. These different sites cover MAR infiltration sites as bank filtration, infiltration ponds and spreading basins and different redox conditions and residence time. Primidone is not removed in most of the cases in both oxic and reduction conditions and it is considered recalcitrant in MAR systems. Nevertheless, there is some example with long residence time where removal rates of 30% are obtained.

2.6.11 Attenuation of Sulfamethoxazole during MAR

Available information on Sulfamethoxazole removal in MAR is characterized by 13 different sites representing different MAR devices, different redox conditions and residence time ranging from days to 1 year. This compound show good removal rates from 80 to 99% under anoxic conditions (nitrate, manganese, iron and sulphate reduction conditions). Removal rates are as well significant under most of the oxic conditions (from 50% to 80%) but some cases show low removal (26%).

2.6.12 Attenuation of Trimethoprim during MAR

Information from 5 sites has been taking into account for analyzing the attenuation of Trimethoprim on MAR systems. These sites cover injection and infiltration MAR systems, Both oxic and anoxic conditions and residence time ranging from 1 day to 1 year. Removal rates from 90% to 100% are obtained from 1 month residence time in both oxic and anoxic conditions. In some example with short residence time (less than 3 days) no removal was observed.

In most cases, there is consistency on the attenuation conditions of each compound.

Removal Conditions Matrix is included in Table 3.

Table 3: Removal Conditions Matrix

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
BENZOTRIAZOLE	INJECTION	< 90 days	Porous shallow	NO3 reduction	10	550-2300	21%-35 % of removal	[9]	Only partially removed. Best results seems to be obtained in infiltration MAR types and with long residence times where redox conditions are Fe-Mn. ASTR with short distances no removal has been observed. Persistent in less favorable conditions.
	INFILTRATION	120-365 days	Porous shallow	Fe - Mn reduction	8-10	200-2300	75-86% of removal	[9], [13]	
BEZAFIBRATE	INJECTION	60 days	Porous	NO3 reduction	10	510	40% of removal	[9]	Significant removal in most of the conditions. Best results in infiltration MAR types with reduction conditions; no influence of residence time. Worst results in injection type MAR with less than 60 d of residence time in NO3 redox conditions.
	INFILTRATION	no data	Porous shallow	no data	no data	80	67% of removal	[9]	
		> 7 days	Porous	Any (oxic and NO3-Mn-SO4 reduction)	no data	20-60	100% of removal	[6], [20]	

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
		> 180 days	Porous	Anoxic	10	no data	100% of removal	[9]	
CARBAMAZEPINE	INJECTION	< 60 days	Porous	NO3 reduction	10	280	Not removed	[9]	Not removed in most of the conditions, considered recalcitrant in MAR. Nevertheless in some projects with surface infiltration, anoxic conditions and long time residence some removals have been reported but groundwater dilution can occur in these sites -there is no data about it- and there is some uncertainty about concentrations in recharge water.
	INFILTRATION	20 - 180 days	Porous shallow. Karst	Oxic and NO3- Mn reduction	3-10	175-900	Not removed	[3], [6], [7], [9], [14], [15], [21]	
		7-80 days	Porous shallow	Any (oxic and NO3-Mn reduction)	7	260-850	<40-50% of removal	[5],[20]	
		120 -365 days	Porous shallow and confined aquifers	Fe reduction	6	175-610	>50%	[10], [15], [21]	
		15 -365 days	Porous shallow	Strictly anoxic conditions	10	no data	91%-99% of removal	[9], [20]	
DICLOFENAC	INJECTION						No data		High removal rates in both oxic and anoxic conditions and short and long residence time. Nevertheless, in some cases low
	INFILTRATION	< 60 days	Porous. Shallow	NO3-Mn reduction	7	15-25	Not	[6]	

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
			aquifer				removed		removal rate is obtained. Removal is not influence by redox conditions either residence time. Site specific behaviour is considered.
		5 -15 -120 days	Porous shallow. Karst	Fe-Mn reduction	no data	125-250	55%-85% of removal	[9], [20], [21]	
		> 5 days- 60 -120 -180 days	Porous. Shallow and confined deep aquifer	Oxic and NO3 and Mn reduction	7-10	24-120	91%-100% of removal	[3], [7], [10], [15], [20], [21]	
EPOXI-CARBAMAZEPINE	INJECTION						Not data		
	INFILTRATION	16 days	Porous. Shallow anoxic aquifer	no data	<12	no data	Not removed	[14]	The removal depends on DOC at short residence times
	INFILTRATION	16 days	Porous. Shallow anoxic aquifer	NO3 reduction	>12	no data	85% of removal	[14]	
GEMFIBROZIL	INJECTION						No data		
	INFILTRATION	16-25 days	Porous shallow	Oxic to/and NO3 and Mn reduction	3-12	72-375	58%-73% of removal	[3], [14]	High removal rates. Is quite a rapid process, but removals higher than 50% are always expected. DOC is not relevant.
	INFILTRATION	1-5-15 days	Porous shallow. Temp.>20 °C	Oxic and NO3-Mn reduction	8	500-880	97%-100% of removal	[3], [7], [15]	

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
IOPROMIDE	INJECTION	< 90 days	Porous shallow	no data	no data	200	64% of removal	[9]	Removed in both oxic and anoxic conditions. Best results in infiltration sites rather in injection systems.
		> 60 days	Porous shallow	NO3 reduction	8	4100 ng/l	100% of removal	[9]	
	INFILTRATION	1 - 90 - 180 days	Porous shallow. Karst	Oxic conditions and NO3 to Fe-Mn reduction	7-9	350-3000	91%-100% of removal	[2], [7], [9], [10], [21]	
METOPROLOL	INJECTION						No data		Few data available. Good removal in long residence time.
	INFILTRATION	180-240 days	Porous shallow	no data	no data	1700	100% of removal	[10]	
PHENAZONE	INJECTION						No data		Best results under oxic conditions. Removal can be inexistent in anoxic conditions indeed at long residence times. In some cases not consistent along flow path (high removal at short residence time and worst at long residence time).
	INFILTRATION	30 -120 days	Porous shallow	NO3 and Mn and Fe reduction	7	150-300	Not removed	[8], [21]	
		15 - 50 days	Porous shallow	Oxic and NO3-Mn reduction	7	220-770	41%-66% of removal	[5], [8], [21]	

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
		2-120 days	Porous shallow	Oxic conditions	7	300	91% of removal	[21]	
PRIMIDONE	INJECTION						No data		Not removed in most of the conditions. Recalcitrant in MAR. Nevertheless in some projects with long Rt and locally confined aquifers, removals of around 30% have been reported.
	INFILTRATION	20 - 60 days	Porous shallow and deep confined aquifers. Karst	Oxic to/and NO3 and Mn reduction	7-10	50-225	Not removed	[3], [6], [7], [9], [12], [15]	
		> 1 year	Porous shallow and deep confined aquifers	no data	5	202	31%-50% of removal	[15]	
SULFAMETHOXAZOLE	INJECTION	60-90 days	Porous shallow	no data	no data	150	Not removed	[9]	In injection projects, with residence times < 90 days it seems that redox conditions and initial concentrations can have relevant influence of % of removal. In infiltration projects best results are found in anoxic conditions in Fe and Mn reduction conditions. Low removal rates in oxic
		20-60 days	Porous	NO3 reduction	10		80% of removal	[9]	
	INFILTRATION	682 m/d	Karst	no data	no data	195	Not removed	[9]	

MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
	7-60 days	Porous shallow and deep confined aquifers	Oxic and NO3 reduction	7	460	26%	[7], [20]	conditions.
	30-60 -180 days	Porous shallow	Oxic conditions	7	120-620	53%-82%	[1], [2], [9], [10], [21]	
	120 days	Porous shallow	NO3 to Fe-Mn reduction	7	485	80%	[2]	
	< 30 days	Porous shallow	Anoxic	no data	150	99%	[1]	
	120- 180 days	Porous shallow	Fe and SO4 reduction. Strictly anoxic conditions	10	290	92%-99%	[9], [20], [21]	
TRIMETHOPRIM INJECTION	< 60 days	Porous shallow	NO3 reduction	10	150	100% of removal	[9]	Best results at long term in both oxic and anoxic conditions. Worst removal rates

	MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL
	INFILTRATION	< 3 days	Porous shallow	Oxic to NO3 reduction	7	50	Not removed	[7]	have been observed in infiltration of 60 h of residence time (and oxic conditions)
		30-60-180 days	Porous shallow	Oxic to/and NO3 and Mn reduction	7-10	10-50	90%-100% of removal	[1], [7], [9], [21]	

2.7 Recommendations for MAR systems related to emerging pollutants removal

Following the same classification as the Removal Conditions Matrix, the 12 trace organic compounds have been categorized by their removal rates taking into account retention time and redox conditions as:

	Removed (90-100% of removal)
	Signaficantly removed (50-90% of removal)
	Partially removed (20-50% of removal)
	Not removed (0-20% of removal)
	Partially removed or Not removed depending on the site (*)

(*) this category has been included as there are differences in removal rates that can be attributed to site specific characteristics.

The only key Parameters that have been taken into account in these recommendations are Redox Conditions and Residence Times. This is because these are the key parameters that are studied in most of the sites are there is enough available data to conduct this analysis. Instead, DOC content in recharging water and in the aquifer can be also an important key factor but the Site Results Table shows that in most of the compiled sites this value is very similar, there are only few sites with enough different values that would allow to extract conclusions about related removal rates. More specifically, the DOC content has been analyzed in 55% of the sites. What it can be observed is that the 95% of the sites have registered concentrations of DOC in recharging water from 7 to 10 mg/l and in 97% of the sites the DOC content in the aquifer is between 1 and 5. Similar observation can be made in Aquifer Type Key parameter. Nearly 90% of the sites are alluvial, shallow porous or sandy aquifers.

As concluded from the Removal Conditions Matrix, 5 of the 12 trace organic compounds studied show high removal rates in both oxic and anoxic redox conditions and in short and long residence time after passage through MAR infiltration systems (Figure 1). These compounds are Bezafibrate, Gemfibrozil, Diclofenac, Iopromide and Trimethoprim. Then no specific considerations are needed for ensuring removal of these compounds.

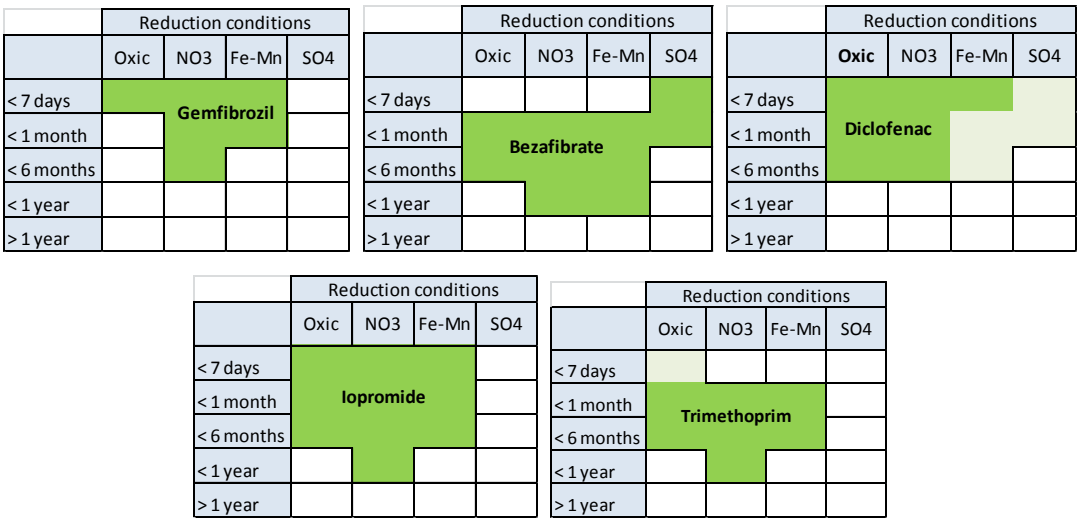

Figure 1: **Trace organic compounds with high removal rates (in green)**

The rest of the studied compounds require specific conditions to achieve best removal rates in MAR systems. For example, Benzotriazole shows some attenuation in nitrate and iron-manganese reduction conditions when residence time is longer than 6 months (Figure 2). On the other hand Phenazone reaches 100% removal rates in oxic to anoxic conditions at short residence times in MAR infiltration systems.

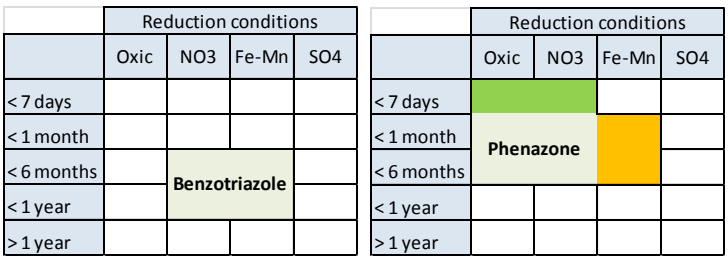

Figure 2: **Benzotriazole and Phenazone removal conditions (in light green significant removal rates)**

Carbamazepine and Sulfamethoxazole show very low removal rates with some specific exceptions (Figure 3). Carbamazepine or Sulfamethoxazole needs very long residence time (at least 6 months) and anaerobic conditions or strictly anaerobic conditions (sulfate redox conditions) to be removed.

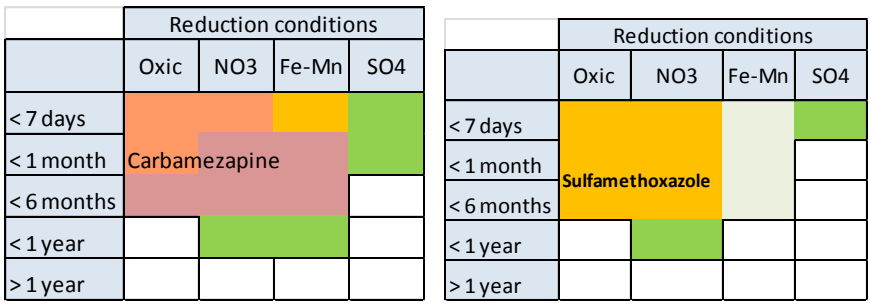

Figure 3: **Carbamazepine and Sufamethoxazole removal conditions (in green high removal rates; in red low removal rates)**

In all compiled sites, Primidone shows no removal in any circumstance (Figure 4). Then this compound can be used as a tracer in MAR systems. Other technologies will be needed to be considered in order to ensure removal of Primidone.

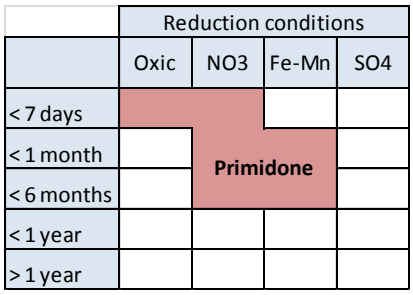

Figure 4: Primidone low removal rates (in red)

There is not enough information on Epoxi-Carbamazapine and Metoprolol in order to summarize which best MAR characteristics ensure their removal. Furthermore, no recommendations are made for injection MAR devices since few information is available. More studies should be needed in order to conclude best conditions for emergent pollutants removal in injection MAR systems.

2.8 Summary for planners and operators of MAR infiltrating systems

Previous analysis has revealed those compounds that are easily removed under certain conditions and those that will require additional water treatments to Soil Aquifer Treatment. Operators can use these results in MAR operations design and planning. If aquifer conditions are known are recharging water is characterized, the conclusions of this work will allow to identificate if potential additional water treatments are needed or if soils treatments can ensure the removal of those compounds. These findings are summarized in Table 4. For each compound, it is indicated which are the optimum aquifer conditions to ensure their removal.

Table 4: Summary for MAR operators

COMPOUND	AQUIFER CONDITIONS
Benzotriazole	In nitrate and iron-manganese reducing conditions and with residence time between 3 and 12 months the maximum expected natural removal is between 50 and 90%.
Bezafibrate	All aquifer conditions ensure > 90% removal
Carbamazepine	Removal rates >90% are only expected in aquifer with very long residence time (at least 6 months) and anaerobic conditions (sulfate reducing conditions).
Diclofenac	All aquifer conditions ensure > 90% removal except more reducing conditions where the removal is above 50%.

COMPOUND	AQUIFER CONDITIONS
Epoxi-Carbamazepine	Not enough information to identify removal conditions.
Gemfibrozil	All aquifer conditions ensure > 90% removal.
Iopromide	All aquifer conditions ensure > 90% removal.
Metoprolol	Not enough information to identify removal conditions.
Phenazone	Phenazone reaches 100% removal rates in oxic to slight anoxic conditions and short residence times.
Primidone	It is not removed at any aquifer conditions.
Sulfamethoxazole	Removal rates >90% are only expected in aquifer with very long residence time (at least 6 months) and anaerobic conditions or strictly anaerobic conditions (sulfate redox conditions).
Trimethoprim	All aquifer conditions ensure > 90% removal

3 Overview of Managed Aquifer Recharge legislation

3.1 European legislation

To foster the implementation of Managed Aquifer Recharge (MAR) it is important to ensure that MAR does not compromise any of the protective goals or threshold values given in European and national legislation. The present European water directives do not specify requirements for MAR schemes and only define a broad frame in which MAR may be developed. At a regional or national level some additional legislation or guidelines regulates specific concepts to achieve the protection of human health.

Hence, the European directives do not provide a dedicated approach or guidance along which managed aquifer recharge may be implemented. In the absence of dedicated legislation concerning MAR in Europe, especially with reclaimed water as source water, the projects have to consider different points of compliance. As a consequence, different aspects have to be taken into account in order to fulfill all potential legislations:

- Characteristics of the source water (e.g. reclaimed water) to be injected/infiltrated
- Groundwater and pore water quality (saturated and unsaturated zone)
- End-use of recovered water (depending on the intended end-use different requirements may have to be met)
- Environmental impacts (e.g. groundwater dependent ecosystems)

This report provides an overview of most relevant European and partners national legislative framework in the context of MAR implementation. The scope of most relevant European directives and possible relations to MAR are highlighted in the following.

3.1.1 Water Framework Directive (2000/60/CE)

Within the European water framework directive (WFD) surface water bodies are required to meet “good ecological and chemical status” and groundwater (GW) bodies “good chemical and quantitative status” by 2015. The WFD demands that no deterioration in water status by any activity over the territory may occur. The WFD mentions artificial recharge/managed aquifer recharge as a possible supplementary measure and indicates that this activity will require periodic controls and previous authorization. The article 11(3f) states that “controls, including a requirement for prior authorisation of artificial recharge or augmentation of groundwater bodies are mandatory. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater. These controls shall be periodically reviewed and, where necessary, updated“.

The WFD does not fix quality limits for recharged water but specifies that the activity cannot compromise the achievement of environmental objectives related to water bodies. Artificial recharge/managed aquifer recharge is explicitly mentioned as a supplementary measure to reach the “good status” objectives, but no particular measures are mentioned to implement such measures.

3.1.2 Groundwater Directive (2006/118/EC)

The objective of the groundwater directive (GWD) is to protect groundwater against pollution and deterioration through the establishment of specific measure to protect and control GW pollution. The directive requires identifying the chemical status of GW:

- The directive fixes the limits for nitrates and pesticides concentration.
- The directive requires to the member States the establishment of threshold values of As, Cd, Pb, Hg, NH4, Cl, SO4, PCE, TCE and electrical conductivity. These threshold values have to take into account the intrinsic or natural concentrations.

According to WFD, the member States have to elaborate specific measures (Article 11) to prevent or to limit the input of contaminants with the aim to ensure that the status of groundwater is not deteriorated and the concentrations do not show an upward trend. The contaminants to be controlled and limited are listed in WFD Annex VIII: Organohalogen compounds, Organophosphorous compounds, Organotin compounds, substances which have been proved to possess carcinogenic or mutagenic properties or properties, persistent hydrocarbons as well as bioaccumulable organic toxic substances, cyanides, metals and their compounds, arsenic and its compounds, biocides, materials in suspension, nitrates, phosphates and substances which have an unfavourable influence on the oxygen balance and other contaminants of concern for each state member. The limits have to include the attenuation capacity of the unsaturated zone.

In this context, the Article 6 (3d) specifies that without prejudice to any more stringent requirements in other Community legislation, Member States may exempt from the indicated measures inputs of pollutants that are result of artificial recharge or augmentation of bodies of groundwater authorised in accordance with Article 11(3)(f) of Directive 2000/60/EC. This Article indicates the characteristics of “Basic Measures” of the general Program of measures and indicates that in case of artificial recharge or augmentation of groundwater bodies a prior authorisation will be required.

As a consequence, in case of artificial recharge the allowed concentration of contaminants can be adapted to each situation by the correspondent environmental authority avoiding the violation of other regulations.

3.1.3 Urban Wastewater Treatment Directive (91/271/EEC)

The urban waste water treatment directive (UWWTD) aims to protect the environment from any adverse effect due to the discharge of wastewater. The directive indicates the wastewaters that have to be collected and stipulates the minimum treatment level thus giving a first rough estimate of the quality parameter of wastewater treatment plant effluents (Table 5 and Table 6). At the same time it stipulates water reuse when stating "Treated waste water shall be reused whenever appropriate" (Article 12 UWWTD), but it remains unclear how ”appropriate” is defined in this context.

Table 5: **Requirement for discharges for urban wastewater treatment plants subject to articles 4 and 5 of the Directive. The values for concentration or for the percentage of reduction shall apply (91/271/EEC, UWWTD).**

Parameters	Concentration	Minimum percentage of reduction (1)	Reference method of measurement
Biochemical Oxygen Demand, BDO5 at 20º (without nitrification (2))	25 mg/l O_2	70-90 40 under article 4 (2)	Homogenized, unfiltered, undecanted sample. Determination of dissolved oxygen before and after five-day incubation at 20ºC±1ºC, in complete darkness. Addition of a nitrification inhibitor.
Chemical Oxygen Demand (COD)	125 mg/l O_2	75	Homogenized, unfiltered, undecanted sample potassium dichromate.
Total suspended solids	35 mg/l (3) 35 under article 4 (2) (more than 10000 p.e.) 60 under article 4 (2) (2000-10000 p.e.)	90 % (3) 90 under article 4 (2) (more than 10000 p.e.) (4) 70 under article 4 (2) (2000-10000 p.e.)	- Filtering of a representative sample through a 45 µm filter membrane. Drying ant 105ºC and weighing. - Centrifuging of a representative sample (for at least five minutes with mean acceleration of 2800 to 3200 g), drying at 105ºC and weighing.

(1) Reduction in relation to the load of the influent

(2) The parameter can be replaced by another parameter: TOC or TOD if a relationship can be established between BOD5 and the substitute parameter

(3) This requirement is optional

(4) One population equivalent (p.e.) means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day

Table 6: **Requirement for discharges for urban wastewater treatment plans to sensitive areas are subject to eutrophication as identifies in Annex II.A (a). One or both parameters may be applied depending on the local situation. The values for concentration or for the percentage of reduction shall apply (91/271/EEC, UWWTD).**

Parameters	Concentration	Minimum percentage of reduction (%) (1)	Reference method of measurement
Total phosphorous	2 mg/l P (10000 – 100000 p.e.) (4) 1 mg/l P (more than 100000 p.e.)	80	Molecular absorption spectrophotometry
Total nitrogen (2)	15 mg/l P (10000 – 100000 p.e.) 10 mg/l P (more than 100000 p.e.)	70-80	Molecular absorption spectrophotometry

(1) Reduction in relation to the load of the influent.
(2) Total nitrogen means: the sum of total Kjeldahl-nitrogen (organic N + NH_3), nitrate (NO_3)-nitrogen and nitrite (NO_2)-nitrogen.
(3) Alternatively, the daily average must not exceed 20 mg/l N. This requirement refers to a water temperature of 12ºC or more during the operation of the biological reactor of the waste water treatment plant. As a substitute for the condition concerning the temperature, it is possible to apply a limited time of operation, which takes into account the regional climatic conditions. This alternative applies if it can be shown that paragraph 1 of Annex 1.D is fulfilled.
(4) One population equivalent (p.e.) means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day

Planning aspects of the Directive to designate sensitive areas (sensitive water bodies) and less sensitive areas are:

- Freshwater bodies, estuaries and coastal waters which are eutrophic or which may become eutrophic if protective action is not taken;
- Surface freshwaters intended for the abstraction of drinking water which contain or are likely to contain more than 50 mg/l of nitrates;
- Areas where further treatment is necessary to comply with other Council Directives

Regulation aspects:

Establish systems of prior regulation or authorisation for all discharges of urban wastewater and industrial wastewater into urban sewage collecting systems to ensure that no adverse effect on the environment (including receiving waters) will occur.

Monitoring aspects:

Member States are required to ensure that both discharges from urban wastewater treatment plants and receiving waters are monitored.

3.1.4 Drinking water directive (98/83/EC)

The requirements of the recharge installation will depend on the water end use. WFD includes most of the uses through its objective of ecological quality for surface waters. Other uses have to be checked with national regulations. Drinking water directive is the most restrictive and it is used as a reference in most Member States to ensure that human health is protected. This Directive includes mandatory indicator values for most of the contaminants and covers microbial, chemical and physical water characteristics (Table 7).

Table 7: Suggestion for target values for raw water for drinking water production (IAWR, 2008).

Anthropogenic non-natural substances with known biological effects	Target value (µg/L) maximum permissible values
Pesticides and their metabolites per individual substance	0.1 [*, a]

Endocrine active substances per individual substance	0.1 *
Pharmaceuticals (incl. antibiotics) per individual substance	0.1 *
Biocides per individual substance	0.1 *
Other organic halogen compounds per individual substance	0.1 *
Substances with low biodegradability per individual substance µg/L 1.0	1.0[b]
Synthetic complexing agents per individual substance µg/L 5.0	5.0

*Unless toxicological information needs a lower value

[a] Equal to the drinking water standard

[b] If other non-natural organic substances have passed proper toxicological screening and are regulated as harmless, a target value of 1 µg/L is justified, similar to other official precaution targets. Only for complexing agents is a temporary value of 5 µg/L acceptable for technical reasons.

When dealing with drinking water uses, an additional consideration is to conduct a risk assessment following the procedures of water safety plans (WHO 2005 and 2007) as it is stated in the directive. The Water Safety Plans provides information on improved strategies for the control and monitoring of drinking-water quality.

Table 8: Summary of main European legislation

Directive	Limits
WFD	No limit values for reclaimed water. Chemical status of GW (baseline characterization) Elaboration of specific measures and monitoring
GWD	No GW deterioration is allowed: limit to input concentration of some substances. Limit of nitrates, pesticides Threshold values of As, Cd, Pb, Hg, NH4, Cl, SO4, PCE, TCE and electrical conductivity
UWWTD	Discharges to collecting systems receive at least secondary treatment (primary in coastal and estuaries) Discharges will not affect adversely the environment Regulates N, P, DBO, COD y TDS based on area type (sensitive areas)

3.2 National legislations

As it has been indicated, when European legislations are published, each Member State have to adopt it in its national legislation coherently with these existing regulations.

According to WFD, the member States have to elaborate specific measures and they have also to adapted the allowed concentration of contaminants avoiding the violation of other regulations.

In the following paragraphs, it is described how different countries have regulated the Artificial Recharge in their respective national regulations (if this is the case) in accordance with complementary European legislations.

The analysis includes also Switzerland legislation. As this country is not a member of the European Union, the European legislation is not transposed to their national regulations. Nevertheless, Switzerland was involved in the Coordination Group of the WFD and they do take part in cooperation on international river basins, such as the Rhine. Furthermore, Switzerland is one of the partners of the DEMEAU partners.

3.3 Spain – Royal Decree 1620/2007

This decree defines the conditions for water reuse authorization. It specifies different types of reuse and indicates the quality criteria for each different uses. In this decree groundwater recharge is classified as environmental use either by percolation or well injection (Table 9).

Table 9: Maximum admissible values for reuse of water used for aquifer recharge (UFC: Colony-forming units per milliliter; UNT: Nephelometric Turbidity Unit)..

Maximum admissible value for:	Aquifer Recharge by percolation (indirect recharge)	Aquifer recharge by well injection (direct recharge)
Nematode eggs	Not specified	1 egg/10 L
Escherichia Coli	1000 UFC/100 mL	0 UFC/100 mL
Total Suspended Solids	35 mg/L	10 mg/L
Turbidity	Not specified	2 UNT
Other Criteria	Total N= 10 mg N/L NO3= 25 mg NO3/L (Art. 257 to 259 of RD 849/1986)	Total N= 10 mg N/L NO_3= 25 mg NO3/L (Art. 257 to 259 of RD 849/1986)

The different uses that this decree regulates are: urban uses (residential areas and communal services), agriculture (irrigation of different type of crops or vegetables and with specific methods), industrial uses (process waters, cleaning waters, refrigeration towers…), recreational uses (golf courses, springs…) and environmental uses (aquifer recharge, wetlands, river discharges, irrigation…).

3.4 Netherlands

3.4.1 Water Act

The Water Act of Netherlands came into force in 2010. This document integrated the eight previous sectorial water acts existing at that time in the country. Nowadays, all water related issues are addressed by this Act, which defines which authorities are due to care about water management as well as permits,

registers and taxes of groundwater recharge.

3.4.2 Groundwater Act

The Groundwater Act contains rules for the extraction of groundwater and artificial infiltration of water in the soil. The objective of the Groundwater Act (1981) is to balance the interests involved with the development of groundwater resources. The provinces have the primary responsibility for groundwater management. The Groundwater Act provides the administrative framework and legal instruments (permits and general rules) to regulate abstraction of groundwater and artificial recharge of aquifers. Based on the Groundwater Act provinces may put a levy on groundwater extraction to pay investigations related to groundwater management and for financial compensation in case of withdrawal of permits and unaccounted damages. The Groundwater Act sets quality requirements with respect to the infiltration of water into groundwater. Abstraction of groundwater or infiltration of water in groundwater requires a license issued by provincial authorities (sect. 14) and such activities shall be notified to those authorities on a monthly basis.

Drinking water in the Netherlands is supplied by companies, which are government owned, because drinking water supply is considered to be of a public and not a private interest (Kuks, 2002).

In this Directive, quality aspects are mainly related to protection of recharge areas. Other groundwater-quality issues are dealt with in the Wet Bodembescherming (Soil Protection Act) of 1987, which includes regulations for prevention of subsurface pollution and for remediation of contaminated soils. Within this legislation, the provinces are obliged to set up the water monitoring and water management plan.

3.4.3 Soil Protection Act

The Soil Protection Act (1987; fully revised in 1999) includes groundwater in the definition of the soil as a liquid component. This Act aims to prevent, and if necessary, clean-up soil and groundwater pollution. The Soil Protection Act states that the general protection level is filled in via General Administrative Orders (GAO's) which are set on a national level and include the artificial recharge of aquifers (1993), containing rules and standards for water infiltration into the soil.

Netherland's trace organic pollutants requirements for infiltration recharge are shown in Table 10:

Table 10: Decision Infiltration Soil Protection, Appendix 1 (corresponding to Article 3, first paragraph).

PARAMETER	VALUES
Organochlorine pesticides	
som (organochlorine pesticides)	0.1 µg/L
endosulfan	0.05 µg/L
α-HCH	0.05 µg/L
-HCH (lindane)	0.05 µg/L

DDT (incl.DDD en DDE)	0.05 µg/L
dichloropropene	0.05 µg/L
aldrin	0.05 µg/L
dieldrin	0.05 µg/L
endrin	0.05 µg/L
heptachlor	0.05 µg/L
hexachlorobutadiene	0.05 µg/L
hexachlorobenzene	0.05 µg/L
organophosphate pesticides	
azinphos-methyl	0.1 µg/L
dichlorvos	0.1 µg/L
dimethoate	0.1 µg/L
mevinphos	0.1 µg/L
parathion	0.1 µg/L
triazines/ triazinonen/ aniliden	
atrazine	0.1 µg/L
simazine	0.1 µg/L
metolachlor	0.1 µg/L
chloorfenoxyherbicide	
2-methyl-4-chlorophenoxy acetic acid (MCPA)	0.1 µg/L
mecoprop	0.1 µg/L
2,4-dichloro-phenoxy-acetic acid (2,4 D)	0.1 µg/L
urea herbicides	
chlorotoluron	0.1 µg/L
isoproturon	0.1 µg/L
metoxuron	0.1 µg/L
linuron	0.1 µg/L

chlorophenols	
trichlophenol	0.1 µg/L
tetrachlophenol	0.1 µg/L
pentachlophenol	0.1 µg/L
various	
dinoseb	0.1 µg/L
2,4 dinitrophenol	0.1 µg/L
bentazon	0.1 µg/L
Oil	
mineral oil	200 µg/L
Polycyclic Aromatic Hydrocarbons (HAP)	
naphthalene	0.1 µg/L
anthracene	0.2 µg/L
phenanthrene	0.2 µg/L
cryseen	0.2 µg/L
fluoranthene benzo (a) anthracene	Σ 0.1 µg/L
benzo (k) fluoranthene benzo (a) pyrene	
benzo (ghi) perylene	
indeno (l23cd) pyrene	
HALOGENATED HYDROCARBONS	
trichloroethene	0.5 µg/L
tetrachlorethylene	0.5 µg/L
trihalomethanes (THMs)	2 µg/L
chlorinated phenols	0.5 µg/L
Active ingredients in Pesticides and biocidal products, including relevant	0.1 µg/L 0.5 µg/L (sum

metabolites	of pesticides)

3.4.4 Environmental Management Act

The Environmental Management Act (1993) does not make specific reference to artificial groundwater recharge but establish the rules to protect the groundwater quality. The provincial administration is forced to develop and bring into force provincial legislation for groundwater protection.

3.4.5 Water Management Act

The Water Management Act (1989) refers specially to surface water. This law holds planning system that includes elements as the groundwater management policy to be pursued in accordance with the Groundwater Act.

3.5 Switzerland

3.5.1 Federal law and Ordinance of water protection (LEaux and OEaux)

Two main directives regulate water sources in Switzerland, the "Federal law of water protection" (LEaux) from 1991 and the "Ordinance of water protection" (OEaux) from 1998, both revised in 2011. Both pieces of legislations make reference to MAR as "installation of artificial supply to groundwater", which it applies mainly the same regulations for water catchments.

On this document, "installation of artificial supply" will be referred as "artificial recharge facilities".

There is no specific article about water quality used on MAR but it is clearly stated in LEaux Article 6 that infiltration of substances potentially able to cause contamination are forbidden.

Section 1 of LEaux makes references to discharge, introduction and infiltration of substances related to water quality. In LEaux Article 7 and in OEaux Article 8 related to waste water, it is mentioned that infiltration of contaminated water must be previously treated and authorized by the Canton authorities. Canton authorities might permit infiltration of reclaimed water in specific cases.

As stated in Article 21 of OEaux, general requirement on groundwater quality are:

- The concentration of substances for which requirements are set in Table 6 should not continually increase in groundwater.
- The quality of groundwater must be such that they do not pollute surface water during withdraw or flow.
- Water temperature fluctuations are limited to 3°C.
- The infiltration of discharged water shall not have an impact on groundwater regarding:
    - any nuisance alteration of odor compared to the natural state;
    - lack of oxygen or any alteration of water pH;
    - no turbidity or water color, except in the case of water present in the solid rock.

- The infiltration facilities, water withdrawals and other construction-related interventions should as much as possible not damage the protective cover layers or change the hydrodynamics to the point of causing adverse effects on water quality.

Groundwater quality supplementary requirements (Annex 2 OEaux) if to be used or with potential of use as drinking water are summarized in Table 11.

Table 11: Supplementary requirements for groundwater to be used or with potential of use as drinking water. OEaux.

Parameter	Requirement
Organic dissolved carbon (ODC)	2 mg/l C
Ammonium (sum of N-NH_4- and N-NH_3)	In oxidant conditions: 0.08 mg/l N (corresponding to 0,1 mg/l ammonium) In anoxic conditions. 0,4 mg/l N (corresponding to 0,5 mg/l ammonium)
Nitrate (N-NO_3^-)	5.6 mg/l N (corresponding to 25 mg/l nitrate)
Sulfate (SO_4^{2-})	40 mg/l SO_4^{2-}
Chloride (Cl-)	40 mg/l Cl^-
Aliphatic Hydrocarbons	0.001 mg/l for each substance
Monocyclic Aromatic Hydrocarbons	0.001 mg/l for each substance
Polycyclic Aromatic Hydrocarbons (HAP)	0.1 µg/l for each substance
Volatile halogenated hydrocarbons (HHV)	0.001 mg/l for each substance
Organic pesticides (biocides and phytosanitary products)	0.1 µg/l for each substance .
Halogenated organic adsorbable compounds (AOX)	0.01 mg/l X
Organic pesticides (biocides and phytosanitary products)	0.1 µg/l for each substance .

Following requirements in Table 12 (Annex 3 OEaux) apply to treatment plants of more than 200 EH (equivalent habitants). The authority set in each case the requirements for treatment plants of less than 200 EH.

Table 12: General requirement for discharge into water of polluted waste communal water.

Parameter	Requirement
Total suspended solids	Installations < 10 000 EH: –concentration in discharged water: 20 mg/l Installations > 10 000 EH and more: – concentration in discharged water: 15 mg/l (filtration with 0,45 mm

	membrane)
BOD5 (with nitrification blockage)	Installations < 10 000 EH: – concentration in discharged water: 20 mg/l O2 and – purification rate from polluted raw water: 90 % Installations > 10 000 EH and more: – concentration in discharged water: 15 mg/l O2 and – purification rate from polluted raw water: 90 %
Organic dissolved carbon (ODC)	Installations < 2000 EH and more: – concentration in discharged water: 10 mg/l and – purification rate: 85 %, expressed as: $100 \times \left(1 - \frac{mg\ ODC\ in\ treated\ water}{mg\ of\ Organic\ Total\ Carbon\ in\ polluted\ raw\ water}\right)$
Transparency (after Snellen method)	30 cm
Ammonium (sum of N-NH4- and N-NH3)	If concentration of ammonium in polluted water might have harmful consequences to a water body, the following values apply if temperature of polluted water is higher than 10° C: – concentration in discharged water: 2 mg/l N and – effectiveness treatment rate: 90 %, expressed as: $100 \times \left(1 - \frac{mg\ N\ in\ treated\ water}{mg\ N - Kjeldahl\ in\ polluted\ raw\ water}\right)$ In this case, nitrification will be required all over the year. Note: Nitrogen from Kjeldahl method is the sum of Nitrogen in Ammonium, Ammonia and in organic nitrogenous substances.
Nitrite (N-NO2-)	0,3 mg/l N (indicative value)
Halogenated organic absorbable compounds (AOX)	0,08 mg/l X

As it is specified in Annex 4 of OEaux, groundwater, natural or after an artificial recharge, in order to be considered as exploitable or suitable for water supply, must:

- Be in a sufficient quantity to be exploited, needs not taken into consideration
- Meet, if necessary after application of a simple treatment, the requirements set for drinking water in the legislation of food products.
- The regulations of groundwater protection areas and perimeters take into consideration MAR installations (Article 20 and Article 21 of LEaux and Article 29, Article 30 and Article 31, and Annex 4 of OEaux).

The regulations of groundwater protection areas and perimeters take into consideration MAR facilities

(Article 20 and Article 21 of LEaux and Article 29, Article 30 and Article 31, and Annex 4 of OEaux).

Zone S1 (catchment zone) include artificial recharge facility. Zone S1 must prevent damage and contamination of its environment.

Zone 2 must prevent germs and virus to enter into the artificial recharge facilities and must be dimensioned in order to:

- Water flow duration from zone S2 external limit to artificial recharge facilities is at least of 10 days
- Distance from zone S1 ant the external limit of zone S2, in the flow direction, is at least of 100 m; it could be less if hydrogeological studies allow to prove that the artificial recharge facilities are well protected by cover layers with low permeability and intact.
- For groundwater in karst our fractured media, S2 covers the basin areas of the artificial recharge facilities that presents high vulnerability.

Zone 3 must ensure that in case of imminent danger, there is sufficient time and space to take the imposed measures.

Article 43 of LEaux states that Canton authorities have to ensure improvement of groundwater table condition in case of overexploitation or supply reduction by decreasing withdrawal, by managed aquifer recharge or by safe drinking water storage in the aquifer.

3.5.2 DFI Ordinance on drinking water

Drinking water is governed by the food law. This includes the Law on Foodstuffs (LDAI, SR 817.0) which includes the Ordinance on Food Hygiene (OHyg, RS 817.024.1), the Ordinance on Foreign Substances and Components (OSEC, RS 817.021.23), and the Ordinance on drinking water, spring water and mineral water (RS 817.022.102).

The Ordinance on Foreign Substances and Components (OSEC) fix concentrations of foreign substances and components that can be tolerated in food and in particular drinking water. In the field of drinking water, no changes have been made since 2000. From the perspective of a future revision, the Federal Office of Public Health (BAG) conducted a critical review of parameters proposing adaptations.

3.6 Germany

3.6.1 Groundwater Ordinance (Grundwasserverordnung, GrwV)

The German GrwV states the following concerning MAR systems:

- Groundwater systems must be described and reviewed every 6 years according to Appendix 1, No 1, i.e. among others include a review of MAR sites and the recharge processes and connections of the groundwater body to other hydrologic systems
- Endangered groundwater systems must be detailed more thoroughly according to Appendix 1, No 2, i.e. identify all sources of water addition to the aquifer (including the location, volumes of water added, chemical and physical characteristics of the water added). Moreover, the land use of the surfaces where recharge happens must be detailed.

In Annex 2 the following threshold values are defined, above which measures need to be taken to improve

water quality (which would therefore be the minimum water quality, in case of infiltration, at the point of reaching the groundwater surface): NO3: 50 mg/L; Pesticides and relevant metabolites: 0.1 µg/L each (in total: 0.5 µg/L); As: 10 µg/L, Cd: 0.5 µg/L, Pb: 10 µg/L, Hg: 0.2 µg/L, NH4: 0.5 mg/L, Cl: 250 mg/L, SO4: 240 mg/L, Tri- and tetrachlorethene: 10 µg/L. A relevant indicator for groundwater quality is the 90th percentile of substance's frequency distribution in an aquifer complex. In case this value is higher than the previously defined thresholds, this value is valid for further evaluation.

3.6.2 Water Management Act (Wasserhaushaltsgesetz, WHG)

In the Water Management Act (WHG), MAR is never mentioned explicitly, and there is, to me, a very large interpretation possible. However, the following aspects relate to MAR:

- It states that no official agreement is required to infiltrate rain water in aquifers (by whatever means)
- Groundwater management options must ensure that the quality of groundwater is improved, not worsened.

3.7 France

Water policy is administered at three jurisdictional levels conditioned by directives of the European Union: the national, water basin and local water commission levels. National policies are required to simultaneously consider consumptive water use requirements and the non-consumptive needs of aquatic ecosystems, surface and groundwater quantity and quality.

Masterplans for Water Development and Management (Schéma Directeur d'aménagement et de gestion des eaux SDAGE) and Local Water Development and Management Plans (Schémas d'aménagement et de gestion des eaux SAGE) guide both the coordination of diverse and competing water users and operational implementation.

The European directive Eaux Résiduaires Urbaines 1991, transcribed into the French water law of 1992, is the legislative basis for stormwater and aquifer management. French Water law provides for two water management regimes in MAR systems: authorisation and declaration.

Declaration is less constrained than authorization, and applies when the total harvesting surface area ("superficie totale desservie") is greater than 1ha and less than 20ha. Harvesting approval is granted on submission of documentation. The granting of an Authorisation for areas greater than 20 ha is conditional on the results of preliminary environmental studies and assessments complying with prescribed water condition standards.

In France a specific site study is required in order to obtain the permission for MAR installations. The different regulations that have to be taken into account are the following:

3.7.1 Code de l'environnement

The environment law is very complete and the part that describes the protection of water resources is: "Livre II : Milieux physiques; Titre 1er : Eau et milieux aquatiques et marins » (Water and aquatic and marine environments)

3.7.2 LOI n° 2004-338

Loi nº2004-338 du 21 avril 2004 concerning the transposition 2000/60/CE of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water (1)

3.8 SUMMARY of MAR legislation

In summary, European legislations (WFD, GWD, and UWWTD) do not include specifically artificial recharge with treated wastewater. A summary of most relevant European legislation is given in Table 13.

Table 13: Summary of main European legislation

Directive	Limits
WFD	No limit values for reclaimed water. Chemical status of GW (baseline characterization) Elaboration of specific measures and monitoring
GWD	No GW deterioration is allowed: limit to input concentration of some substances. Limit of nitrates, pesticides Threshold values of As, Cd, Pb, Hg, NH4, Cl, SO4, PCE, TCE and electrical conductivity
UWWTD	Discharges to collecting systems receive at least secondary treatment (primary in coastal and estuaries) Discharges will not affect adversely the environment Regulates N, P, DBO, COD and TDS based on area type (sensitive areas)

In the analysed countries there is a lack of harmonisation. European and national directives only give brief comments for MAR systems. These directives state that degradation of groundwater quality it is not allowed and the member states have to authorize the recharge systems and verify the monitoring program. Drinking water quality is the most restrictive legislation and it is currently used in several countries to allow the MAR systems installation.

The only national regulations that takes into account the direct and indirect infiltration of water are Spain and Switzerland. Both countries set the requirements in the same parameters but give different limits. It has to be pointed out that Switzerland has not adopted European legislations and their contamination thresholds are not limited by European requirements.

Nevertheless, emergent contaminants are not regulated at European level. For priority substances Environmental Quality Standards (EQS) have been defined (EC, 2001; EC, 2008) but the list of Annex X of the WFD have not been yet updated. The Netherlands legislate the input concentration of pesticides and herbicides, among others priority substances, but do not includes the trace organic compounds that are being studied in DEMEAU project.

The values that different European countries specify in their respective legislations are included in **Annex A** Table 15**.** This table with all values differentiates the values when the directives indicate water for

recharge, both indirect (e.g. SAT) and direct (e.g. injection wells), and raw water or groundwater. The last refers to the quality limits for that groundwater that is going to be used for drinking purposes.

An analysis of previous research projects has been conducted. AQUAREC project (2006) and afterwards RECLAIM WATER project (2012) published a proposal of quality requirements for groundwater recharge (Table 14).

Table 14: Requirement for indirect groundwater recharge, proposed quality for direct groundwater recharge and drinking water requirements (Kazner et al., 2012- adapted from Bixio & Witgens, 2006)

Parameter	Unit	Polishing goal for indirect infiltration	Polishing goal for direct infiltration	Drinking water quality
pH	-	7-9	>6.5 and <9.5	>6.5 and <9.5
Conductivity	mS/cm	0.7	<0.7	<2.5
Alkalinity*	mg/$CaCO_3$/L			
TSS*	mg/L			
COD	mg/L	70-100	< 5	< 5
TOC*	mgC/L			
Total N	mgN/L	< 25	< 25	
NH_4^+	mgN/L	< 0.2	<0.5	<0.5
NO_2^-	mgN/L		<0.5	<0.5
NO_3^-	mgN/L	< 25	< 25	< 11.3
Total P*	mgP/L			
PO_4^{2-}*	mgP/L			
SO_4^{2-}	mgS/L	30	< 30	< 250
As	µg/L	5	< 10	< 10
B	mg/L	0.2	< 1.0	< 1.0
Cd	µg/L	3	< 5.0	< 5.0
Cl^-	mg/L	100	< 250	< 250
Cr	µg/L	25	< 50	< 50
Hg	µg/L	0.5	< 1.0	< 1.0
Pb	µg/L	5	< 25 < 10 in 2013	< 25 < 10 in 2013
Zn*	µg/L			

Micropollutants	µg/L	< 0.1	Compound specific	Compound specific
Faecal coliforms	CFU/100 mL	$< 10^4$	0	0
Faecal streptococ.*	CFU/100 mL		0	0
Helminthova, Giardia	1/L	< 1	0	0

*not reported

3.9 Recommendations for possible points of compliance with the EU-GWD

A principal requirement of the GWD is to assess the actual or potential impact of the man-made recharge 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) were defined by WFD-CIS (2007a) and can be applied to MAR facilities according to:

- POC 0: this POC is located at the base of the source in the unsaturated zone. It could therefore be situated just below the point/area of recharge (e.g. infiltration pond). The purpose of POC 0 is to assess if a pollutant input takes place, what the pollutants are, and whether the groundwater could be affected.
- POC 1: this POC is located at the point of input into the groundwater; for a direct input (e.g. well injection), POC 0 is the same as POC 1, but the function is different. At POC 1 the actual concentration in the groundwater itself is primarily taken into account, whereas at POC 0 one primarily looks at the properties of the source itself as explained above.
- POC 2: this POC is located hydraulically down gradient from the recharge area in between POC 1 and a receptor. The purpose of this compliance point is to provide an early warning that the receptor might be impacted. It is also used during the risk assessment process for predicting the potential impact of the input.
- POC 3: This POC is used to assess whether the desired groundwater quality is reached and to monitor the impact at the receptor. If a risk assessment shows that the pollutant will exceed the compliance value at this POC, then pollution is likely to occur as a result of the input. Measures/controls will need to be put in place to remove this impact, or the activity should not be permitted.

Specifications at POC 0, POC 1 and/or POC 2 should be defined in a way that compliance values at POC3 are met. Applying this concept on MAR the possible POC in the frame of the GWD are illustrated in Figure 5.

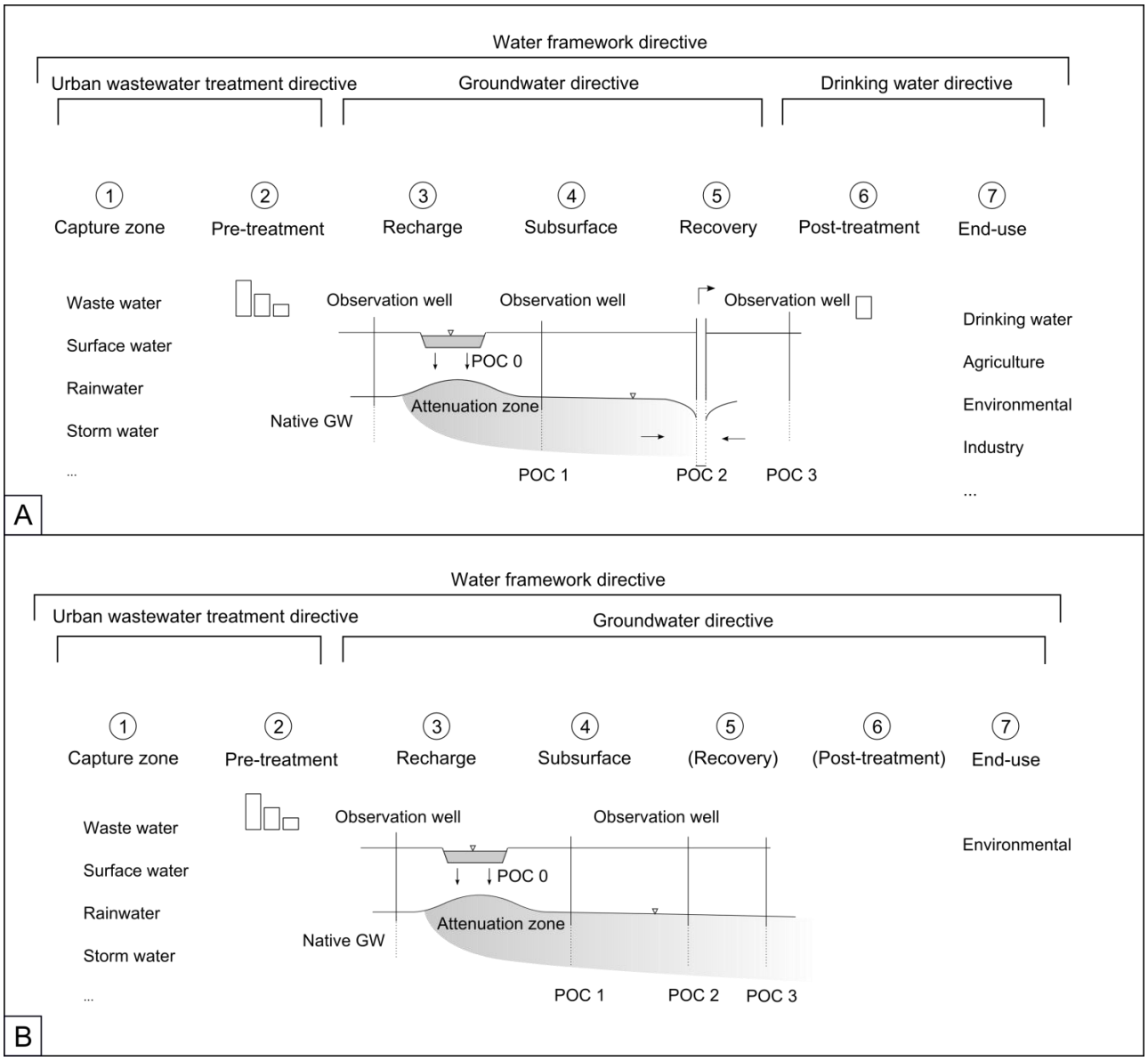

Figure 5: **Components of MAR and possible points of compliance (POC) with most relevant European legislation.**

In 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). The concept of an attenuation zone in the subsurface is an integral part of MAR schemes and is useful to define the treatment barrier. Various models exist to estimate spatial extent of an attenuation zone (NRMMC-EPHC-NHMRC, 2009). If the recharge activity will be stopped the attenuation zone will vanish and previously existing hydrochemical conditions will be re-established in short time. This is in contrast to contamination plumes, where the uncontrolled input of hazardous substances to the aquifer results in long-term contamination, even if the contamination source is removed.

During MAR two different settings can be distinguished: i) MAR with managed recovery (Figure 1A) and ii)

MAR without managed recovery (Figure 1B). During MAR schemes such as deep well injection (direct input) and at many infiltration ponds unsaturated conditions below the pond are not always realized (mixture between direct and indirect input) POC 0 and POC 1 cannot be clearly distinguished. In case of SAT schemes unsaturated conditions below the recharge area are indispensable and POC 0 is important to monitor possible pollutant input from the MAR activity. If the MAR scheme does not include managed recovery, e.g. infiltration ponds for groundwater replenishment or deep well injection to create hydraulic barriers in coastal aquifers, the groundwater directive is valid alone. In this case it is important to meet the environmental value of the target aquifer/receptor. The receptor is considered to be protected if compliance values at POC 3 are met. Hydraulically up-gradient of the recharge site native groundwater monitoring is required to report on unaffected/background values.

The EU-GWD states that the input of hazardous substances to groundwater must be prevented (primarily linked to the prevent objectives in the GWD). An input is considered to have been prevented if the substance is not detectable above natural background concentrations. Procedures to define background concentrations are described in WFD-CIS (2007b). As defined by the European Communities Environmental Objectives (Groundwater) Regulations hazardous substances are “any substances or groups of substances that are toxic, persistent and liable to bio-accumulate, and other substances, or groups of substances, that give rise to an equivalent level of concern” (ECEOGR, 2010). Non-hazardous substances are not defined, but can be seen as all substances other than hazardous. For non-hazardous substances the assessment must ensure that the substances will not exceed previously defined background concentrations (primarily linked to the limit objectives in the GWD) and does not cause a significant upward trend at the receptor.

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Annex-A Maximum admissible values by different European legislations

Table 15: Maximum admissible values by different European legislations.

	EU	Spain	Switzerland	Netherlands	Germany	France

	Raw water (potential to drinking water)/ groundwater						
	Injection recharge						
BOD5 (Biochemical oxygen demand at 25°C without nitrification)	Indirect infiltration recharge	25 mg/L O2	40-300 mg/L (1)	20 mg/L O2 (< 10.000 p.e.) 15 mg/L O2 (> 10.000 p.e.) (1)			
COD (Chemical Oxygen demand)	Raw water (potential to drinking water)/ groundwater						
	Injection recharge						
	Indirect infiltration recharge	125 mg/L O2	160-500 mg/L (1)				
Total Suspended Solids	Raw water (potential to drinking water)/ groundwater						
	Injection recharge		10 mg/L		0,5 mg/L (zwev.stof)		
	Indirect infiltration recharge	60 mg/L (2.000-10.000 p.e.) 35 mg/L (> 10.000 p.e.)	35 mg/L	20 mg/L (< 10.000 p.e.) 15 mg/L (> 10.000 p.e.) (1;7)			
Turbidity	Raw water (potential to drinking water)/ groundwater						
	Injection recharge		2 NTU				
	Indirect infiltration recharge						
Transparency (after Snellen method)	Raw water (potential to drinking water)/ groundwater						
	Injection recharge						
	Indirect infiltration recharge			30 cm (1)			
Organic Dissolved Carbon (ODC)	Raw water (potential to drinking water)/ groundwater			2 mg/L C (3)			
	Injection recharge						

	Indirect infiltration recharge			10 mg/L (1)			
Total phosphorus	Raw water (potential to drinking water)/ groundwater			2 mg/L C (3)			
	Injection recharge						
	Indirect infiltration recharge	2 mg/L P (10.000-100.000 p.e.) 1 mg/L P (>100.000 p.e.)	10-20 mg/L (1)	10 mg/L (1)			
Total nitrogen	Raw water (potential to drinking water)/ groundwater						
	Injection recharge		10 mg N/L				
	Indirect infiltration recharge	15 mg/L N (10.000-100.000 p.e.) 10 mg/L N (>100.000 p.e.)	10 mg N/L				
Ammonium	Raw water (potential to drinking water)/ groundwater			Oxidant cond.: 0,08 mg/L N Anoxic cond.: 0,4 mg/l N Σ (N-NH4+ + N-NH3) (3)		0,5 mg/L (NH4+) (4)	4 mg/L (2)
	Injection recharge				2,5 mg/L N (NH4+)		
	Indirect infiltration recharge			2 mg/l N (T>10°C) Σ (N-NH4+ + N-NH3) (1)			
Nitrate	Raw water (potential to drinking water)/ groundwater	50 mg/L		5,6 mg/L N (25 mg/L NO3-) (3)		50 mg/L (4)	100 mg/L (2)

	Injection recharge		25 mg/L NO3-		5,3 mg/L N		
	Indirect infiltration recharge		25 mg/L NO3-				
Nitrite	Raw water (potential to drinking water)/ groundwater						
	Injection recharge						
	Indirect infiltration recharge			0,3 mg/l N (1)			
Sulphate	Raw water (potential to drinking water)/ groundwater			40 mg/l SO42- (3)		240 mg/L (4)	250 mg/L (2)
	Injection recharge				150 mg/L		
	Indirect infiltration recharge		2000 mg/L (1)				
Chloride	Raw water (potential to drinking water)/ groundwater			40 mg/l Cl- (3)		250 mg/L (4)	200 mg/L (2)
	Injection recharge				200 mg/L		
	Indirect infiltration recharge		2000 mg/L (1)				
As	Raw water (potential to drinking water)/ groundwater					10 µg/L (4)	100 µg/L (2)
	Injection recharge				10 µg/L		
	Indirect infiltration recharge		0,5-1 mg/L (1)				
B	Raw water (potential to drinking water)/ groundwater						
	Injection recharge						
	Indirect infiltration recharge		2-10 mg/L (1)				
Cd	Raw water (potential to drinking water)/ groundwater					0,5 µg/L (4)	5 µg/L (2)
	Injection recharge				0,4 µg/L		
	Indirect infiltration recharge		0,1-0,5 mg/L (1)				
Cr	Raw water (potential to drinking water)/ groundwater						50 µg/L (2)
	Injection recharge				2 µg/L		

	Indirect infiltration recharge		Cr (III) 2-4 mg/L Cr (IV) 0,2-0,5 mg/L (1)				
Hg	Raw water (potential to drinking water)/ groundwater					0,2 µg/L (4)	1 µg/L (2)
	Injection recharge				0,05 µg/L		
	Indirect infiltration recharge		0,05-0,1 mg/L (1)				
Pb	Raw water (potential to drinking water)/ groundwater					10 µg/L (4)	50 µg/L (2)
	Injection recharge				15 µg/L		
	Indirect infiltration recharge		0,2-0,5 mg/L (1)				
Ba	Indirect infiltration recharge				200 µg/L		1 mg/L (2; surface water)
Co	Indirect infiltration recharge				20 µg/L		
Cu	Indirect infiltration recharge				15 µg/L		
Ni	Indirect infiltration recharge				15 µg/L		
Zn	Indirect infiltration recharge				65 µg/L		5 mg/L (2)
Escherichia Coli	Raw water (potential to drinking water)/ groundwater						20.000 /100 mL (2)
	Injection recharge		0 UFC/100 mL				
	Indirect infiltration recharge		1000 UFC/100 mL				
Pesticides (for substance)	Raw water (potential to drinking water)/ groundwater	0,1 µg/L 0,5 µg/L (sum of pesticides)				0,1 µg/L 0,5 µg/L (sum of pesticides)	2 µg/L 5 µg/L (sum of pesticides) (2)
	Injection recharge				0,5 µg/L (sum of pesticides)		
	Indirect infiltration recharge		0,05 mg/L (1)				

Biocides	Raw water (potential to drinking water)/ groundwater			0,1 µg/L (3;6)			
	Injection recharge						
	Indirect infiltration recharge						
Organochlorine pesticides (per substance)	Indirect infiltration recharge				0,05 µg/L		
Organophosphate pesticides (per substance)	Indirect infiltration recharge				0,1 µg/L		
Triazines/ triazinonen/ aniliden (per substance)	Indirect infiltration recharge				0,1 µg/L		
Chlorofenoxy herbicides (per substance)	Indirect infiltration recharge				0,1 µg/L		
Urea herbicides (per substance)	Indirect infiltration recharge				0,1 µg/L		
Other organic halogen substances	Raw water (potential to drinking water)/ groundwater			0,01 mg/l X (3;5)			
	Injection recharge				30 µg/L (5)		
	Indirect infiltration recharge			0,08 mg/l X (1;5)			
Aliphatic Hydrocarbons	Raw water (potential to drinking water)/ groundwater			1 µg/L (3)			
	Injection recharge						
	Indirect infiltration recharge						
Monocyclic Aromatic Hydrocarbons	Raw water (potential to drinking water)/ groundwater			1 µg/L (3)			
	Injection recharge						
	Indirect infiltration recharge						
Polycyclic Aromatic Hydrocarbons (HAP)	Raw water (potential to drinking water)/ groundwater			0,1 µg/L (3)			1 µg/L (2)
	Injection recharge				0,1 µg/L (sum)		
	Indirect infiltration recharge						
Volatile halogenated hydrocarbons (HHV)	Raw water (potential to drinking water)/ groundwater			1 µg/L (3)		10 µg/L (sum; 4)	

	Injection recharge				0,5 µg/L (per substance)		
	Indirect infiltration recharge						
Chlorophenols (per substance)	Indirect infiltration recharge				0,1 µg/L		
Dinoseb, 2,4 dinitrophenol, bentazon (per substance)	Indirect infiltration recharge				0,1 µg/L		
Mineral oil	Indirect infiltration recharge				200 µg/L		

(1): Water as treated wastewater discharge
(2): Water quality limits of waste water used for drinking water production
(3): Groundwater quality if to be used or with potential of use as drinking water
(4): Groundwater quality as Groundwater Act
(5): Halogenated organic adsorbable compounds (AOX)
(6): Organic pesticides (biocides and phytosanitary products)
(7): Filtration with 0,45 mm membrane

Annex-B Priority substances

Article 16 of the Water Framework Directive (2000/60/EC) (WFD) sets out "Strategies against pollution of water", outlining the steps to be taken. The first step was to establish a First list of priority substances to become Annex X of the WFD. These substances were selected from amongst those presenting a significant risk to or via the aquatic environment, using the approaches outlined in Article 16 of the WFD.

This first list was replaced by Annex II of the Directive on Environmental Quality Standards (Directive 2008/105/EC) (EQSD), also known as the Priority Substances Directive , which set environmental quality standards (EQS) for the substances in surface waters (river, lake, transitional and coastal) and confirmed their designation as priority or priority hazardous substances, the latter being a subset of particular concern. As required by the WFD and EQSD, the Commission subsequently reviewed the list and in 2012 it put forward a proposal for a Directive amending the WFD and the EQSD as regards priority substances.

Priority Substances and Certain Other Pollutants according to Annex II of Directive 2008/105/EC

Thirty-three substances or groups of substances are on the list of priority substances for which environmental quality standards were set in 2008, including selected existing chemicals, plant protection products, biocides, metals and other groups like Polyaromatic Hydrocarbons (PAHs) that are mainly incineration by-products and Polybrominated Biphenylethers (PBDE) that are used as flame retardants.

Table 16: List of priority substances in the field of water policy

Number	Name of priority substance (1)	Identified as priority hazardous substance
(1)	Alachlor	
(2)	Anthracene	X
(3)	Atrazine	
(4)	Benzene	
(5)	Brominated diphenyletheriv	X
	Pentabromodiphenylether (congener numbers 28, 47, 99, 100, 153 and 154)	
(6)	Cadmium and its compounds	X
(7)	Chloroalkanes, C10-13 (2)	X
(8)	Chlorfenvinphos	
(9)	Chlorpyrifos	

	(Chlorpyrifos-ethyl)	
(10)	1,2-Dichloroethane	
(11)	Dichloromethane	
(12)	Di(2-ethylhexyl)phthalate (DEHP)	
(13)	Diuron	
(14)	Endosulfan	X
(15)	Fluoranthene (3)	
(16)	Hexachlorobenzene	X
(17)	Hexachlorobutadiene	X
(18)	Hexachlorocyclohexane	X
(19)	Isoproturon	
(20)	Lead and its compounds	
(21)	Mercury and its compounds	X
(22)	Naphthalene	
(23)	Nickel and its compounds	
(24)	Nonylphenols	X
	(4-nonylphenol)	X
(25)	Octylphenols	
	(4-(1,1',3,3'-tetramethylbutyl)-phenol)	
(26)	Pentachlorobenzene	X
(27)	Pentachlorophenol	
(28)	Polyaromatic hydrocarbons	X
	(Benzo(a)pyrene)	X
	(Benzo(b)fluoranthene)	X
	(Benzo(g,h,i)perylene)	X
	(Benzo(k)fluoranthene)	X
	(Indeno(1,2,3-cd)pyrene)	X
(29)	Simazine	
(30)	Tributyltin compounds	X
	(Tributyltin-cation)	X
(31)	Trichlorobenzenes	
(32)	Trichloromethane (chloroform)	
(33)	Trifluralin	

(1) Where groups of substances have been selected, typical individual representatives are listed as indicative parameters (in brackets and without number). For these groups of substances, the indicative parameter must be defined through the analytical method.

(2) These groups of substances normally include a considerable number of individual compounds. At present, appropriate indicative parameters cannot be given. Fluoranthene is on the list as an indicator of other, more dangerous polyaromatic hydrocarbons.

The eight pollutants, which fall under the scope of Directive 86/280/EEC (Amended by Directive 88/347/EEC and 90/415/EEC) and which are included in List I of the Annex to Directive 76/464/EEC, are not in the priority substances list. However, environmental quality standards for these substances are included in the Environmental Quality Standards Directive 2008/105/EC.

	Name of other pollutant
(6a)	Carbon-tetrachloride(4)
(9b)	DDT total (4)(5)
	para-para-DDT (4)
(9a)	Cyclodiene pesticides
	Aldrin (4)
	Dieldrin (4)
	Endrin (4)
	Isodrin (4)
(29a)	Tetrachloro-ethylene (4)
(29b)	Trichloro-ethylene (4)

(4) This substance is not a priority substance but one of the other pollutants for which the EQS are identical to those laid down in the legislation that applied prior to 13 January 2009

(5) DDT total comprises the sum of the isomers 1,1,1-trichloro-2,2 bis (p-chlorophenyl) ethane (CAS number 50-29-3; EU number 200-024-3); 1,1,1-trichloro-2 (o-chlorophenyl)-2-(p-chlorophenyl) ethane (CAS number 789-02-6; EU Number 212-332-5); 1,1-dichloro-2,2 bis (p-chlorophenyl) ethylene (CAS number 72-55-9; EU Number 200-784-6); and 1,1-dichloro-2,2 bis (p-chlorophenyl) ethane (CAS number 72-54-8; EU Number 200-783-0).

Annex-C Sites Results Table

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Benzotriazole	[9]	Shafdan, Tel Aviv, Israel	Short term: Hybrid SAT: ultrafiltration + dug well	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic NO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	2300	1500	0.1	35% at short term SAT	
	[9]	Shafdan, Tel Aviv, Israel	Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 2300)	500	0.1	78% at long term SAT	
	[9]	Gaobeidian, Beijing, China	ASTR. Post-wastewater treatment + Injection well	Shallow aquifer (17.5 m) as is injected into a well the non-saturated zone has no effect	The previous ozonation treatment reduced the Btri concentration and no subsequent changes were observed after ASTR.	n.a.	n.a.	60-90 d (passage of 34 m)	550	350	0.1	21% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[13]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy	Anoxic to anaerobic	DOC=8 mg/L	DOC= 5-6 mg/L	120 - 150 d	2300	1000	n.a.	56% removal 86% removal at pumping well (considering dilution)	
		Lake Wannsee, Berlin, Germany	Bank filtration	Sandy	Anoxic to anaerobic	n.a.	n.a.	120 - 150 d	1300	600	n.a.	53% removal 75% at pumping well (not known if considering dilution)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Bezafibrate	[6]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anaerobic and reduced redox conditions (desnitrification and manganese reduction) when T>14°C [5]	n.a.	n.a.	n.a.	20	< LOQ	n.a.	100% removed (Co ≈ LOQ)	
	[6]	Lake Wannsee, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anoxic in summer (high temperatures) [8]	n.a.	n.a.	shallow aquifer: < 60 d	60	< LOQ	n.a.	100% removed (< 60 d)	
	[9]	Shafdan, Tel Aviv, Israel	Short term: Hybrid SAT: ultrafiltration + dug well	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic NO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	510	300	20	40% removed at short term SAT	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Shafdan, Tel Aviv, Israel	Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 510)	< LOQ	20	100% removed at long term SAT	
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	n.a.	80	15 (*26 if dilution is taken into account*)	10	67% (58% dilution factor is taken into account)	
	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields. Digested sludge added to irrigation water	Very sandy 1.6 m unsaturated zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	130	< LOQ	25	100% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[20]	Rhine	Bank filtration	Alluvial	Aerobic	n.a.	n.a.	7-20 days	n.a.	n.a.	n.a.	100% removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic to denitrifying	n.a.	n.a.	12-60 days	n.a.	n.a.	n.a.	100% removed	
	[20]	Elbe	Bank filtration	Alluvial	Denitrifying	n.a.	n.a.	45-80 days	n.a.	n.a.	n.a.	100% removed	
	[20]	Ruhr	Bank filtration	Alluvial	Anaerobic. Sulfate reduction zone at infiltration zone	n.a.	n.a.	5-15 days	n.a.	n.a.	n.a.	100% removed	
	[12], [21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	Sandy	Idem aquifer than [1], [2], [5], [6] & [8]	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2 - 130 d	< LOQ	< LOQ	50	< LOQ (not considered for conclusions)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Carbamazepine	[3]	South Plate River, Brighton, Colorado, USA	Bank filtration	Alluvial sandy	Reduced redox conditions, from oxic to anoxic: denitrification, manganese-reducing	TOC=7.6 mg/L (summer, T=19°C, high flow) TOC=10.5 mg/L (winter, T=9°C, low flow)	3.7 mg/L	shalow aquifer: 10-20 d	245-900	50-885	n.a.	Not removed	
	[5]	Lake Tegel, Berlin, Germany	Infiltration pond	Sands fine to coarse grained. Glaciofluvial sediments 2-3 m unsaturated	Oxic/aerobic when low temperatures Eh (recharging water)=365 mV Eh (aquifer winter)=360-430mV	DOC=7.32 mg/L	n.a.	k= 17-69 m/d (3-25 d)	260 (winter)	180-130 (winter)	60	<50% removed after 50 days (not known if dilution)	<14°C
	[5]	Lake Tegel, Berlin, Germany	Infiltration pond	Sands fine to coarse grained. Glaciofluvial sediments 2-3 m unsaturated	Anaerobic and reduced redox conditions (desnitrification and Mn reduction) when T>14°C Eh (recharging water)=365 mV Eh (aquifer summer)=370-240 mV	DOC=7.32 mg/L	n.a.	k= 17-69 m/d (3-25 d)	850 (summer)	500-640 (summer)	60	<40% removed after 50 days (not known if dilution)	>14°C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[6]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anaerobic and reduced redox conditions (desnitifrication and Mn reduction) when T>14°C [5]	n.a.	n.a.	n.a.	325	200	n.a.	Only partially removed due to dilution	
	[6]	Lake Wannsee, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anoxic in summer (high temperatures) [8]	n.a.	n.a.	shallow aquifer: < 60 d	330	360	n.a.	Not removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	330	302	n.a.	Not removed (either upper and lower aquifer)	20-28°C
	[9] and [22]	Shafdan, Tel Aviv, Israel	Short term: Hybrid SAT: ultrafiltration + dug well	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic NO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	280	380	n.a.	Not removed at short term SAT	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9] and [22]	Shafdan, Tel Aviv, Israel	Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 280)	25	n.a.	91% removed at long term SAT	
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	n.a.	140	75	10	Not removed (58% dilution factor taken into account)	
	[9]	Nardo, Salento, Italy	Infiltration in natural sinkhole	Karst aquifer. Fractured sandstone, limestone and dolomite deposits 32 m unsaturated zone	n.a.	n.a.	n.a.	k= 682 m/d	750	410	10	Not removed (55% dilution factor taken into account)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields	Very sandy 1,6 m unsaturated zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	2100	< LOQ-570	25	Partially removed	
	[14]	Llobregat river, Barcelona, Spain	SAT. Infiltration pond (with organic layer)	Alluvial, sandy-gravel. Unconfined. 4 m unsaturated zone	Anoxic in the unsaturated zone and in the aquifer. Nitrate reduction	DOC = 3 mg/L (infiltration pond)	DOC = 1.8 mg/L DOC = 12 mg/L (reactive layer)	16 d K horiz = 1000 m/d	24	24	3.5	Not removed (with organic layer)	
	[15]	Southwestern USA	Surface spreading bassins	Upper alluvial unconfined aquifer (UAU). Medium alluvial confined aquifer (MAU). Lower alluvial confined aquifer (LAU) 15 m unsaturated zone	n.a.	DOC=5.62 mg/L	DOC (LAU, 6-18m)=1.43 mg/L DOC (MAU,16 m)=1.16 mg/L)	k(UAU)= 6-86 m/d k(MAU)= 1.7 - 17 m/d From 6 months to 8 years	175	85-115 (lower concentrations in long Rt samples but other processes can occur)	n.a.	Not removed at short term. Some potential % removal at long term.	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[15]	Southwestern USA	Surface spreading bassins	Alluvial 35 m unsaturated zone	n.a.	n.a.	n.a.	khoriz= 4.6-19.5 m/d kvert=0.09-0.7 m/d 15-30 days	n.d.	455-610	n.a.	Not removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic	n.a.	n.a.	7-20 days	n.a.	n.a.	n.a.	Slightly removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic to denitrifying	n.a.	n.a.	12-60 days	n.a.	n.a.	n.a.	Slightly removed	
	[20]	Elbe	Bank filtration	Alluvial	Denitrifying	n.a.	n.a.	45-80 days	n.a.	n.a.	n.a.	Slightly removed	
	[20]	Ruhr	Bank filtration	Alluvial	Anaerobic. SO4 reduction zone at infiltration zone	n.a.	n.a.	5-15 days	n.a.	n.a.	n.a.	99% removed (strictly anaerobic conditions)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	Sandy	Oxic conditions and NO3 reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	500	n.a.	5	O2: 14% removed NO3: 8% removed	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	Sandy	Mn and Fe reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	500	n.a.	5	Mn: 20% removed Fe: 50% removed	
	[18]		Experimental column		anoxic (denitrifying)	DOC=7 mg/L	DOC=3 mg/L (25d)	hydraulic retention time =25 d	288	318		Not removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Diclofenac	[3]	South Plate River, Brighton, Colorado, USA	Bank filtration	Alluvial sandy	Reduced redox conditions, from oxic to anoxic: denitrification, manganese-reducing	TOC=7.6 mg/L (summer, T=19°C, high flow)TOC= 10.5 mg/L (winter, T=9°C, low flow)	3.7 mg/L	shalow aquifer: 10-20 d	<10-54	<10	10	100% removed (5 d)	
	[6]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anaerobic and reduced redox conditions (desnitrification and Mn reduction) when T>14°C [5]	n.a.	n.a.	n.a.	15	< LOQ-10	5	Not removed	
	[6]	Lake Wannsee, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anoxic in summer (high temperatures) [8]	n.a.	n.a.	shallow aquifer: < 60 d	25	20	5	Not removed (20%)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsat. zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7,84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	24	10		55% removed (in upper aquifer, 3 days travel time, oxic conditions) 100% removed in lower aquifer (60 days travel time, anoxic)	20-28°C
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	low residence times (days)	125	25 (*43 if dilution taken into account*)	10-20	65% removed (58% dilution factor is taken into account)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Nardo, Salento, Italy	Infiltration in natural sinkhole	Karst aquifer. Fractured sandstone, limestone and dolomite deposits 32 m unsat. zone	n.a.	n.a.	n.a.	3-5 days k= 682 m/d	250	20 (*36 if dilution taken into account*)	10-20	85% removed (55% dilution factor is taken into account)	
	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields	Very sandy 1,6 m unsat. zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	130	< LOQ	25	100% removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic	n.a.	n.a.	7-20 days	<50	< LOQ	n.a.	100% removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic to denitrifying	n.a.	n.a.	12-60 days	75	< LOQ	n.a.	100% removed	
	[20]	Elbe	Bank filtration	Alluvial	Denitrifying	n.a.	n.a.	45-80 days	120	< LOQ	n.a.	100% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[20]	Ruhr	Bank filtration	Alluvial	Strictly anaerobic. Sulfate reduction at infiltration zone	n.a.	n.a.	5-15 days	200-600	< LOQ - 75	n.a.	65% removed	
	[15]	Southwestern USA	Surface spreading basins	Alluvial 35 m unsaturated zone	n.a.	n.a.	n.a.	khoriz= 4.6-19.5 m/d kvert=0.09-0.7 m/d 15-30 days	80	< LOQ	n.a.	100% removed	
	[18]		Experimental column		anoxic (denitrifying)	DOC=7 mg/L	DOC=3 mg/L (25d)	hydraulic retention time =25 d	361	100	n.a.	52%	
	[18]		Experimental column		Aerobic. Hydrophobic acids	DOC=3.1 mg/L	DOC=2.7 mg/L	retention time =0.8 d	604	538	n.a.	Not removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[12], [21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Oxic conditions and NO3 reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2 - 130 d	130	24	5	91% removed under oxic NO3: 85% removed	
	[12], [21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Fe and Mn reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2 - 130 d	130	41	5	Mn: 61% removed Fe: 61% removed	
Epoxi-Carbamezapine	[14]	Llobregat river, Barcelona, Spain	SAT. Infiltration pond	Alluvial, sandy-gravel. Unconfined. 4 m unsaturated zone	Anoxic in the unsaturated zone and in the aquifer. Nitrate reduction	DOC = 3 mg/L (infiltration pond)	DOC = 1.8 mg/L	16 d K horiz = 1000 m/d	n.a.	n.a.	n.a.	Not removed if no organic layer	
	[14]	Llobregat river, Barcelona, Spain	SAT. Infiltration pond with organic layer	Alluvial, sandy-gravel. Unconfined. 4 m unsaturated zone	Anoxic in the unsaturated zone and in the aquifer. Nitrate reduction	DOC = 3 mg/L (infiltration pond)	DOC = 12 mg/L (reactive layer)	16 d K horiz = 1000 m/d	n.a.	n.a.	n.a.	85% removed if organic layer	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Gemfibrozil	[3]	South Plate River, Brighton, Colorado, USA	Bank filtration	Alluvial sandy	Reduced redox conditions, from oxic to anoxic: denitrification and Mn reduction	TOC= 10.5 mg/L (winter, T=9°C, low flow)	3.7 mg/L	shalow aquifer: 10-20 d	375 (winter)	220 (winter)	25	58% removed (low removal in winter, 25 d)	<9°C
	[3]	South Plate River, Brighton, Colorado, USA	Bank filtration	Alluvial sandy	Reduced redox conditions: nitrate reduction (higher than in winter) and Mn reduction	TOC= 7.6 mg/L (summer, T=19°C, high flow)	3.7 mg/L	shallow aquifer: 10-20 d	500 (summer)	5 (summer)	25	99% removed (fast in summer, 5 d)	>19°C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	880	70	n.a.	97% removed (fast; 12h travel time in upper aquifer, oxic conditions)	20-28°C
	[14]	Llobregat river, Barcelona, Spain	SAT. Infiltration pond	Alluvial, sandy-gravel. Unconfined. 4 m unsaturated zone	Anoxic in the unsaturated zone and in the aquifer. Nitrate reduction	DOC = 3 mg/L (infiltration pond)	DOC = 1.8 mg/L	16 d K horiz = 1000 m/d	192	61	n.a.	62%	
	[14]	Llobregat river, Barcelona, Spain	SAT. Infiltration pond with organic layer	Alluvial, sandy-gravel. Unconfined. 4 m unsaturated zone	Anoxic in the unsaturated zone and in the aquifer. Nitrate reduction	DOC = 3 mg/L (infiltration pond)	DOC = 12 mg/L (reactive layer)	16 d K horiz = 1000 m/d	72 (org layer)	19 (org layer)	n.a.	73% (if organic layer)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[15]	Southwestern USA	Surface spreading bassins	Alluvial 35 m unsaturated zone	n.a.	n.a.	n.a.	khoriz= 4.6-19.5 m/d kvert=0.09-0.7 m/d 15-30 days	1235	< LOQ	n.a.	100% removed	
	[18]		Experimental column	n.a.	Aeorbic	DOC=3.1 mg/L	DOC=2.7 mg/L	retention time =0.8 d	373 (C1) 544 (C2) 770 (C3) 721 (C4)	26 (C1) 431 (C2) 336 (C3) 255 (C4)	n.a.	93% (C1: hydrophobic acid) 21% (C2: hydrophilic carbon) 56% (C3: effluent organic matter) 65% (C4: organic colloids)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[18]		Experimental column	n.a.	anoxic (denitrifying)	DOC=7 mg/L	DOC=3 mg/L (25d)	hydraulic retention time =25 d	444	<25	25	100% in anoxic column	
Iopromide	[2]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 3-4 m unsaturated zone	Reduced redox conditions: From anoxic (NO3 reduction) to anerobic (Fe and Mn reduction)	DOC=7.5 mg/L	DOC=4.8 mg/L	120 d (55 m travel distance) k =17-69 m/d	841	< LOQ	20	100% removed (fast; >80% in less than 1 month /2 m travel distance)	10-15°C
	[2]	Lake Tegel, Berlin, Germany	Infiltration bassin	Sandy 2 m unsaturated zone	Aerobic	DOC=7.5 mg/L	DOC=4.7 mg/L	50 d (32 m travel distance) k =17-69 m/d	737	< LOQ	20	100% removed (fast; 85% in 4 days/2m travel distance)	3-24°C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and NO3 reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	2700	60	n.a.	97% removed (fast; 12h travel time in upper aquifer, oxic conditions)	20-28°C
	[9]	Gaobeidian, Beijing, China	ASTR. Post-wastewater treatment + Injection well	Shallow aquifer (17.5 m) as is injected into a well the non-saturated zone has no effect		n.a.	n.a.	60-90 d (passage of 34 m)	200	170	50	15% removed (from graphic) 64% removed (from table)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Shafdan, Tel Aviv, Israel	Short term: Hybrid SAT: ultrafiltration + dug well	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic NO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	4100	< LOQ	50	100% removed at short term SAT	
	[9]	Shafdan, Tel Aviv, Israel	Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 4100)	< LOQ	50	99% removed at long term SAT	
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	n.a.	4200	200	20-60	95% removed (58% dilution factor taken into account)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Nardo, Salento, Italy	Infiltration in natural sinkhole	Karst aquifer. Fractured sandstone, limestone and dolomite deposits 32 m unsaturated zone	n.a.	n.a.	n.a.	k= 682 m/d	350	20	10	91% removed (55% dilution factor taken into account)	
	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields	Very sandy1,6 m unsaturated zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	3000	< LOQ	25	100% removed	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Oxic and NO3 reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	1000	n.a.	20	O2: 94% removed NO3: 95% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Mn and Fe reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	1000	n.a.	20	Mn: 99% removed Fe: 70% removed	
Metoprolol	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields	Very sandy1,6 m unsaturated zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	1700	< LOQ	25	100% removed	
	[19]		Bank filtration									>70% (Lack of data: not considered for conclusions)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Phenazone	[5]	Lake Tegel, Berlin, Germany	Infiltration pond	Sands fine to coarse grained. Glaciofluvial sediments 2-3 m unsaturated	Oxic/aerobic when low temperatures Eh (recharging water)=365 mV	DOC=7.32 mg/L	n.a.	k= 17-69 m/d (3-25 d)	570 (winter)	50-240 (winter)	50	91% removed (< 3days) 58% removed (50 days)	<14° C
	[5]	Lake Tegel, Berlin, Germany	Infiltration pond	Sands fine to coarse grained. Glaciofluvial sediments 2-3 m unsaturated	Anaerobic and reduced redox conditions (denitrification and Mn reduction) when T>14°C Eh (recharging water)=365 mV	DOC=7.32 mg/L	n.a.	k= 17-69 m/d (3-25 d)	220 (summer)	< LOQ-130 (summer)	50	100% removed (<3 days) 41% removed (50 days)	>14° C
	[8]	Lake Wannsee, Berlin, Germany	Bank filtration	Pleistocene, glaciofluvial and fluvial sands Unsaturated zone as [1], [2], [5], [6] & [12]	Seasonal oxic conditions (low temperatures, T<14C) in shore area.	DOC=7.05 mg/L	DOC=5.45 mg/L (shore area)	k=8.64x10^{-2} - 8.64 m/d [4]	150	50	n.a.	66% removed in oxic conditions (winter, < 15 days)	<14° C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[8]	Lake Wannsee, Berlin, Germany	Bank filtration	Pleistocene, glaciofluvial and fluvial sands Unsaturated zone as [1], [2], [5], [6] & [12]	Anoxic in summer (high temperatures) NO3 reduction, Mn reduction and Fe reduction	DOC=7.05 mg/L	DOC=4.95 mg/L	$k=8.64x10^{-2}$ - 8.64 m/d [4]	150	130	n.a.	10% removed when anoxic conditions (summer and winter, < 30 days)	>14° C
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Oxic and NO3 reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	300	n.a.	50	O2: 91% removed NO3: 73% remove	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Mn and Fe reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	300	n.a.	50	Mn: 46% removed Fe: 6% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Primidone	[3]	South Plate River, Brighton, Colorado, USA	Bank filtration	Alluvial sandy	Reduced redox conditions, from oxic to anoxic: denitrification, Mn-reducing	7.6 mg/L (summer, T=19°C, high flow) - 10.5 mg/L (winter, T=9°C, low flow)	3.7 mg/L	shalow aquifer: 10-20 d	75-225	<25-110	25	Not removed	
	[6]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anaerobic and reduced redox conditions (denitrification and Mn reduction) when T>14°C [5]	n.a.	n.a.	n.a.	55	20	n.a.	Not removed (Only partially removed due to dilution in deeper aquifer)	
	[6]	Lake Wannsee, Berlin, Germany	Bank filtration	Sandy 2 m unsaturated	Idem aquifer than [1], [2], [5], [8] & [12]. Sampled May-Oct Anoxic in summer (high temperatures) [8]	n.a.	n.a.	shallow aquifer: < 60 d	60	55	n.a.	Not removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	150	168	n.a.	Not removed (either upper and lower aquifer)	20-28°C
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	n.a.	50	*25 (43 if dilution taken into account)*	10-20	13% removed (58% dilution factor is taken into account)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Nardo, Salento, Italy	Infiltration in natural sinkhole	Karst aquifer. Fractured sandstone, limestone and dolomite deposits 32 m unsaturated zone	n.a.	n.a.	n.a.	k= 682 m/d	120	50 (*90 if dilution taken into account*)	10	24% removed (55% dilution factor is taken into account)	
	[15]	Southwestern USA	Surface spreading basins	Upper alluvial unconfined aquifer (UAU).Medium alluvial confined aquifer (MAU).Lower alluvial confined aquifer (LAU)15 m unsaturated zone	n.a.	DOC=5.62 mg/L	DOC (LAU, 6-18m)=1.43 mg/LDOC (MAU,16 m)=1.16 mg/L)	k(UAU)= 6-86 m/dk(MAU)= 1.7 - 17 m/dFrom 6 months to 8 years	202	90-160 (lower concentrations in long Rt samples but other processes can ocurr)		31% removed at short term (6-18 months) 50% removed at long term (> 8 years)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[15]	Southwestern USA	Surface spreading basins	Alluvial 35 m unsaturated zone	n.a.			khoriz= 4.6-19.5 m/d kvert=0.09-0.7 m/d 15-30 days	110	115-155		Not removed	
	[18]		Experimental column		anoxic (denitrifying)	DOC=7 mg/L	DOC=3 mg/L (25d)	hydraulic retention time =25 d	568	764		Not removed	
	[12], [21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Idem aquifer than [1], [2], [5], [6] & [8]	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2 - 130 d	140	129	5	< 9 %	
Sulfamethoxazole	[1]	Lake Wannsee, Berlin, Germany	Bank filtration	Unconfined. Glaciofluvial and fluvial sands.3-4 m unsaturated zone	Oxic in winter (upper aquifer)	n.a.	n.a.	upper aquifer= 30 dK= 8.6 x10^{-2} to 8.6 m/d [4]	151	38 (oxic, 60-120d)	1	In oxic conditions only 75% removed, 2-4 months	<14° C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[1]	Lake Wannsee, Berlin, Germany	Bank filtration	Unconfined. Glaciofluvial and fluvial sands. 3-4 m unsaturated zone	Anoxic in summer (upper aquifer)	n.a.	n.a.	upper aquifer= 30 d K= 8.6 $x10^{-2}$ to 8.6 m/d [4]	151	2 (anoxic, <30d)	1	99% (at anoxic conditions, < 1 month)	>14° C
	[2]	Lake Tegel, Berlin, Germany	Infiltration basin	Sandy 2 m unsaturated zone	Aerobic	DOC=7,5 mg/L	DOC=4,7 mg/L	k=17-69 m/d	463	*218*	20	53% removed (> 50 days / 32 m travel distance)	3-24°C
	[2]	Lake Tegel, Berlin, Germany	Bank filtration	Sandy 3-4 m unsaturated zone	Reduced redox conditions: From anoxic (NO3 reduction) to anerobic (Fe and Mn reduction)	DOC=7,5 mg/L	DOC=4,8 mg/L	k =17-69 m/d	485	*97*	20	80% removed (117 d /77 m travel distance)	10-15°C

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	460	390		26% removed (60 days travel time in lower aquifer + taking into account dilution) (not removed in upper aquifer)	20-28°C
	[9]	Gaobeidian, Beijing, China	ASTR. Post-wastewater treatment + Injection well	Shallow aquifer (17.5 m) as is injected into a well the non-saturated zone has no effect	The previous ozonation treatment reduced the SMX concentration and no subsequent significant changes were observed after ASTR.	n.a.	n.a.	60-90 d (passage of 34 m)	150	83	25	Not removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Shafdan, Tel Aviv, Israel	Short term: Hybrid SAT: ultrafiltration + dug well	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic NO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	250	50	25	80% removed at short term SAT	
	[9]	Shafdan, Tel Aviv, Israel	Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 250)	< LOQ	25	92% removed at long term SAT	
	[9]	Sabadell, Barcelona, Spain	Bank filtration	Alluvial aquifer. Sand and gravel 7 m unsaturated zone	n.a.	n.a.	n.a.	n.a.	120	25	10	62% removed (58% dilution factor taken into account)	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[9]	Nardo, Salento, Italy	Infiltration in natural sinkhole	Karst aquifer. Fractured sandstone, limestone and dolomite deposits 32 m unsaturated zone	n.a.	n.a.	n.a.	k= 682 m/d	195	110	10	Not removed (55% dilution factor taken into account)	
	[10]	Braunschweig, Germany	SAT (soil aquifer treatment). Irrigation of Agricultural fields	Very sandy 1,6 m unsaturated zone	n.a.	BOD5=9.5 mg/L	n.a.	180-240 aprox	620	< LOQ-110	25	82% removed. Partially removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic	n.a.	n.a.	7-20 days	n.a.	n.a.	n.a.	Slightly removed	
	[20]	Rhine	Bank filtration	Alluvial	Aerobic to denitrifying	n.a.	n.a.	12-60 days	n.a.	n.a.	n.a.	Slightly removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
	[20]	Elbe	Bank filtration	Alluvial	Denitrifying	n.a.	n.a.	45-80 days	n.a.	n.a.	n.a.	Slightly removed	
	[20]	Ruhr	Bank filtration	Alluvial	Anaerobic. Sulfate reduction zone at infiltration zone	n.a.	n.a.	5-15 days	n.a.	n.a.	n.a.	99% removed (strictly anaerobic conditions)	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Oxic and NO3 reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	290	n.a.	1	O2: 41% removed NO3: 47% removed	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Mn and Fe reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	290	n.a.	1	Mn: 74% removed Fe: 89% removed	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
Trimethoprim	[1]	Lake Wannsee, Berlin, Germany	Bank filtration	Unconfined. Glaciofluvial, fluvial sands 3-4 m unsaturated zone	Oxic in winter and Anoxic in summer (upper aquifer)	n.a.	n.a.	upper aquifer= 30 d K= 8.6 $x10^{-2}$ to 8.6 m/d [4]	12	< LOQ	2	100% (at all monitoring wells, also <1month, in both oxic and anoxic conditions)	
	[7]	Montebello Forebay, California, USA	SAT (soil aquifer treatment). Infiltration pond	Sandy. Unconfined upper aquifer, confined lower aquifer (62% reclaimed water + 38% native water) 2 m unsaturated zone	From oxic to anoxic conditions in upper aquifer and nitrate reducing conditions in lower aquifer.	TOC=7.84 mg/L	3.5 mg/L (upper aquifer, travel time <3 days) 1.7 mg/L (lower aquifer, travel time 60 days)	kvert=0.24-26.5 m/d khoriz=7.9-11.6 m/d travel time: 60 h upper aquifer travel time: 60 d lower aquifer	54	58 (upper aquifer) 3.5 (lower aquifer)	n.a.	90% removed (60 days travel time in lower aquifer + taking into account dilution) (not removed in upper aquifer)	20-28°C
	[9]	Shafdan, Tel Aviv,	Short term: Hybrid SAT: ultrafiltration	Unconfined. Mainly sand and sandstone15 m	AnaerobicNO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	150	< LOQ	25	100% removed at short term	

Compound	Ref.	Site location	MAR type	Aquifer type	Redox conditions	O.m. in recharging water	O.m. in aquifer during recharge	Residence time	Co (ng/L)	Cf measured (ng/L)	LOQ (ng/L)	Removal (%)	Temp.
		Israel	+ dug well	unsaturated zone								SAT	
			Long term: conventional by 1 day flooding	Unconfined. Mainly sand and sandstone 15 m unsaturated zone	Anaerobic	DOC=10 mg/L	DOC=1 mg/L (90% removed)	180-365 d	n.a. (at present 150)	< LOQ	25	Removed at long term SAT	
	[21]	Lake Tegel & Lake Wannsee, Berlin, Germany	Bank filtration and infiltration pond	sandy	Oxic and NO3 reduction; Mn and Fe reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	25	n.a.	2	95%-100% in all redox conditions	

Observations

References of each site are identified by a number which is indicated in the references chapter.

Table text in blue color indicates data that has been inferred from figures or estimations from literature data.

Abbreviation

TOC: Total Organic Carbon

DOC. Dissolved Organic Carbon

COD: Cemical Oxygen Demand

BOD5: Biochemical Oxygen Demand (5 days)

LOQ: Limit of quantification

n.d.: not detected

n.a.: not available

Co: Concentration in recharging water

Cf: Concentration in aquifer during recharge

o.m: Organic Matter