

Part of D12.1: Decision trees for MAR impact evaluation



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Title: Decision trees for MAR impact evaluation

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.

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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 O₃ and/or UV/H₂O₂
- 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):
 - o 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,
 - o 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 taken into account for analyzing the attenuation of Iopromide on MAR systems. These sites cover 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 shows 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 taken 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	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		The removal depends on DOC at short residence times
	16 days	Porous. Shallow anoxic aquifer	no data	<12	no data	Not removed	[14]	
	16 days	Porous. Shallow anoxic aquifer	NO3 reduction	>12	no data	85% of removal	[14]	
GEMFIBROZIL	INJECTION					No data		High removal rates. Is quite a rapid process, but removals higher than 50% are always expected. DOC is not relevant.
	16-25 days	Porous shallow	Oxic to/and NO3 and Mn reduction	3-12	72-375	58%-73% of removal	[3], [14]	
	1-5-15 days	Porous shallow.	Oxic and NO3-Mn	8	500-880	97%-100%	[3], [7], [15]	

MAR TYPE	Residence time water	AQUIFER	REDOX	DOC (mg/l)	Initial concentration	RESULTS	REF	REMOVAL	
		Temp.>20 °C	reduction			of 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).
		30 -120 days	Porous shallow	NO3 and Mn and Fe reduction	7	150-300	Not removed	[8], [21]	
	INFILTRATION	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]	
TRIME THOPR IM 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.

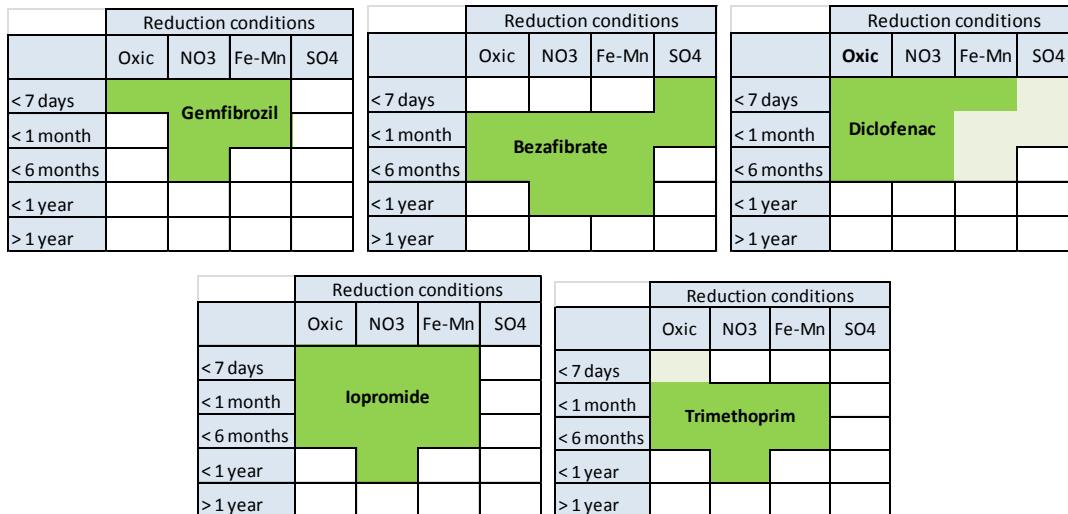


Figure 1: Trace organic compounds with high removal rates (in green)

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.

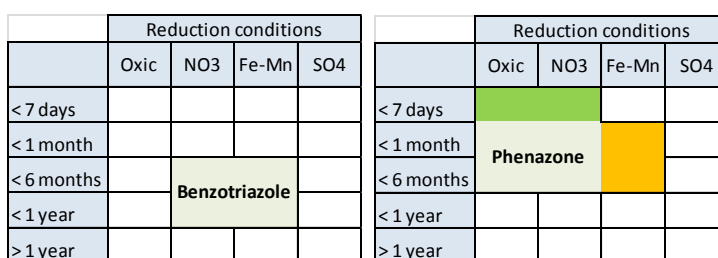


Figure 2: Benzotriazole and Phenazone removal conditions (in light green significant removal rates)

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.

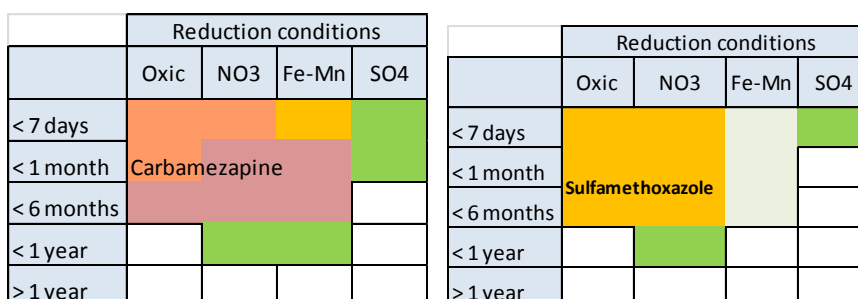


Figure 3: Carbamazepine and Sulfamethoxazole removal conditions (in green high removal rates; in red low removal rates)

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.

	Reduction conditions			
	Oxic	NO3	Fe-Mn	SO4
< 7 days	Primidone			
< 1 month				
< 6 months				
< 1 year				
> 1 year				

Figure 4: Primidone low removal rates (in red)

There is not enough information on Epoxi-Carbamazepine 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 identify 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

Annex-A 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 NO ₃ 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 Btr 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	

Compo und	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)	

Compo und	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 (denitrification 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	

Compo und	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	

Compo und	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	shallow 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 (denitrification 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

Compo und	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 (denitrification 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	

Compo und	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=0.2 4-26.5 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	

Compo und	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)	

Compo und	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 (reactive layer) DOC = 12 mg/L	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,16m)=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.	

Compo und	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)	

Compo und	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	shallow 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 (denitrification 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%)	

Compo und	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) <i>2 m unsat. zone</i>	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=0.2 4-26.5 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 <i>7 m unsaturated zone</i>	n.a.	n.a.	n.a.	low residence times (days)	125	<i>25 (43 if dilution taken into account)</i>	10-20	<i>65%</i> removed (58% dilution factor is taken into account)	

Compo und	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	

Compo und	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=0.0 9-0.7 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	shallow 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

Compo und	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=0.2 4-26.5 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)	

Compo und	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.	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.	Aeobic	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 (NO ₃ 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

Compo und	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=0.2 4-26.5 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)	

Compo und	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)	

Compo und	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 sandy 1,6 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	

Compo und	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 sandy 1,6 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

Compo und	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) NO ₃ reduction, Mn reduction and Fe reduction	DOC=7.05 mg/L	DOC=4.95 mg/L	$k=8.64 \times 10^{-2}$ - 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 NO ₃ reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	300	n.a.	50	O ₂ : 91% removed NO ₃ : 73% 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	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	shallow 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	

Compo und	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) <i>2 m unsaturated zone</i>	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=0.2 4-26.5 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 <i>7 m unsaturated zone</i>	n.a.	n.a.	n.a.	n.a.	50	<i>25 (43 if dilution taken into account)</i>	10-20	<i>13% removed (58% dilution factor is taken into account)</i>	

Compo und	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/L DOC (MAU, 16m)=1.16 mg/L	k(UAU)= 6-86 m/d k(MAU)= 1.7 - 17 m/d From 6 months to 8 years	202	90-160 (lower concentrations in long Rt samples but other processes can occur)		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= 8.6×10^{-2} to 8.6 m/d [4]	151	38 (oxic, 60-120d)	1	In oxic conditions only 75% removed, 2-4 months	<14°C

Compo und	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

Compo und	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=0.2 4-26.5 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	

Compo und	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)	

Compo und	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	

Compo und	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 NO ₃ reduction	DOC= 7.2 mg/L	DOC= 4.7 mg/L	2-130 d	290	n.a.	1	O ₂ : 41% removed NO ₃ : 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=0.2 4-26.5 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 sandstone 15 m	AnaerobicNO3 reduction	DOC=10 mg/L	DOC=2 mg/L (80% removed)	20-60 d	150	< LOQ	25	100% removed at short term	

Compo und	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: Chemical 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