D 3.3: Generic assessment of treatment trains concerning their environmental impact and risk reduction potential

The project "Innovation Demonstration for a Competitive and Innovative European Water Reuse Sector" (DEMOWARE) has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration, theme ENV.2013.WATER INNO&DEMO-1 (Water innovation demonstration projects) under grant agreement no 619040

Deliverable Title	D 3.3: Generic assessment of treatment trains concerning their environmental impact and risk reduction potential
Related Work Package:	WP3
Deliverable lead:	Kompetenzzentrum Wasser Berlin gGmbH (KWB)
Author(s):	Fabian Kraus, Christian Remy, Wolfgang Seis, Ulf Miehe
Contact for queries	KWB: Ulf Miehe Kompetenzzentrum Wasser Berlin gGmbH Cicerostr. 24 D-10709 Berlin T +49 30 53653 821 E ulf.miehe@kompetenz-wasser.de
Dissemination level:	Public
Due submission date:	31/10/2016 (M34)
Actual submission:	31/12/2016 (M36)
Grant Agreement Number:	619040
Instrument:	FP7-ENV-2013-WATER-INNO-DEMO
Start date of the project:	01.01.2014
Duration of the project:	36 months
Website:	www.demoware.eu
Abstract	This report describes different options for tertiary treatment of secondary effluent from municipal wastewater treatment plants for the purpose of water reuse. For each of the treatment trains, associated environmental impact (represented by energy demand and related global warming potential) and risk reduction potential (i.e. removal of chemical and microbial contaminants) are described based on the results of the DEMOWARE case studies. This should inform water professionals about impacts and benefits of different options for producing reclaimed water, enabling an informed decision on an adequate treatment train depending on the water quality targets for the respective reuse purpose.

Versioning and Contribution History

Version	Date	Modified by	Modification reason
v.01	02/12/2016	Fabian Kraus	First draft
v.02	20/12/2016	Christian Remy	Final draft after review by Raquel Iglesias

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Glossary

GAC	Granular Activated Carbon
LCA	Life Cycle Assessment
MBR	Membrane bioreactor
PAA	Peracetic acid
PFA	Performic acid
RO	Reverse Osmosis
SAT	Soil-Aquifer Treatment
UF	Ultrafiltration
UV	Ultraviolet disinfection
WWTP	Wastewater Treatment Plant

Executive Summary

This report describes different options for tertiary treatment of secondary effluent from municipal wastewater treatment plants for the purpose of water reuse. For each of the treatment trains, associated environmental impact (represented by energy demand and related global warming potential) and risk reduction potential (i.e. removal of chemical and microbial contaminants) are described based on the results of the DEMOWARE case studies. This should inform water professionals about impacts and benefits of different options for producing reclaimed water, enabling an informed decision on an adequate treatment train depending on the water quality targets for the respective reuse purpose.

After an introductory overview of all trains and the related type of water reuse, the report summarizes details on process description, flow scheme, consumptives (electricity and chemicals required for operation) and their associated primary energy demand and global warming potential, removal rates for contaminants, and additional remarks for operation and maintenance. The final chapter gives an overview of existing uncertainties of this generic assessment and a comprehensive comparison of all options for tertiary treatment in their environmental efforts (= associated global warming potential) and benefits for water quality (= removal of contaminants). A short checklist elaborates on key questions for operators and regulators of water reuse systems from an environmental and risk management point of view.

1 Introduction

The reuse of purified wastewater for other purposes can help to mitigate water stress both in terms of quantity and quality. Water reuse can provide water for agriculture, irrigation of parks and gardens, street cleaning, other non-potable uses such as toilet flushing in households, and even serve as a water resource for indirect or direct potable reuse. However, purified wastewater which is usually treated in a wastewater treatment plant (WWTP) with mechanical and biological stage will in most cases not fulfil the specific quality requirements of the intended reuse purpose. Hence, secondary effluent of the WWTP has to be further treated ("tertiary treatment") to guarantee that quality requirements in terms of microbial and chemical parameters are met in relation to the local regulations and guidelines for the intended type of water reuse. Quality of reused water has to be within defined limits to minimise potential risks of water reuse for human health and ecosystem quality, and tertiary treatment serves as a measure for risk reduction.

Naturally, different types of water reuse need specific levels of risk reduction, i.e. the removal of microorganisms or organic and inorganic substances from the source water. Combining these goals of tertiary treatment for water reclamation with the range of different water qualities of secondary effluent, a variety of treatment options for tertiary treatment can be applied in water reuse systems to enable safe operation of the water reuse scheme and control associated risks. Higher targets in water quality often lead to higher efforts in water treatment with technical processes, leading to rising investment and operational costs, but also to higher environmental impacts of water reuse in terms of energy demand and associated emissions (e.g. greenhouse gases). Finally, an optimum tertiary treatment scheme should provide sufficient risk reduction in relation to the type of reuse without over-spending on energy, chemicals and infrastructure and associated environmental impacts. Moreover, economic feasibility of water reuse will also be affected by the decision for a specific process train for tertiary treatment.

1.1 Objectives

This report gives a short overview on the technical principles of selected process trains for tertiary treatment of secondary WWTP effluent in relation to the target pollutants and the type of water reuse application. In particular, the report characterizes these treatment trains regarding:

- their demand for consumptives (= electricity and chemicals)
- their environmental impact related to operational efforts (= cumulative energy demand of non-renewable resources [1] and global warming potential [2] calculated with LCA [3])
- their risk reduction potential (= removal of microorganisms or chemical contaminants)
- main technical advantages and limitations

This report should help to inform planners and operators of water reuse system about the available trains for tertiary treatment and their characteristics in environmental impact and water quality improvement.

The target group of this report consists of both regulators and practitioners; they can use this document for a first assessment of planned water reuse schemes and compare alternative treatment trains with each other if certain water quality targets or equivalent removal rates for pollutants or microbial parameters are obligatory for operation. Based on technical boundaries and limitations of specific technologies, practitioners may also optimize their upstream treatment in the WWTP (primary, secondary or sludge treatment) to improve operation of the tertiary treatment itself.

1.2 Methodology

Process data in this document is compiled from case studies of water reuse schemes in DEMOWARE and previous research projects of KWB, supplemented with literature data. Data for consumptives, environmental impact scores and treatment performance is given in ranges for each train, as site-specific conditions at a WWTP can have an impact on performance and efforts for treatment. These ranges are based on optimum influent quality for each train, as defined for each technology in the "comments" section. In general, data ranges are kept as small as possible to reduce uncertainty in the prediction of process performance, but as wide as necessary to reflect different case studies and boundary conditions (e.g. composition of secondary WWTP effluent as source water).

1.3 Overview of treatment trains for water reuse

Different processes for water treatment are available to reach specific goals for water quality in water reuse. In principle, the following four treatment goals are relevant for the water reuse schemes assessed within DEMOWARE, which can be realized by the listed technologies:

1) Disinfection/removal of pathogens:
    - Filtration
    - UV
    - Performic acid (PFA)
    - Chlorination
    - Soil-Aquifer-Treatment
    - Ultrafiltration membranes (UF)
2) Removal of particles/suspended solids:
    - Filtration (optional with upstream coagulation)
    - Membrane bioreactor (MBR)
    - Soil-Aquifer-Treatment
    - Ultrafiltration membranes
3) Removal of organic (micro-) pollutants:
    - Membrane bioreactor
    - Granular activated carbon (GAC)
    - Ozonation
    - Reverse Osmosis membranes (RO)
4) Removal of salinity and other dissolved substances (e.g. metals)
    - Reverse Osmosis membranes

Since some of these single technologies work only in combination with other processes, the generic assessment in this report focusses on entire treatment trains (Table 1). These treatment trains reflect specific case studies of DEMOWARE at water reuse sites in Europe and Israel, where they have been tested in pilot-scale or implemented in full-scale systems. A site-specific assessment of environmental impacts and risk management aspects has been carried out for each site, and is reported in another document (Deliverable 3.2 [4]).

Data in this report is mainly based on information and results of the case study assessments, although some adaptations have been made to allow generalisation of figures. For environmental impact, scores for cumulative energy demand and global warming potential for each train have been recalculated with LCA datasets representing the EU mix for electricity and chemicals production [5]. Removal rates for water quality parameters are based on data from pilot or full-scale trials collected within DEMOWARE or related projects of KWB. Since this data is extrapolated from concrete demo sites with defined water quality, direct transferability of the specific figures to other case studies should be carefully checked. Nonetheless, the presented data offers a first idea about consumptives, energy demand, greenhouse gas emissions and risk reduction potential of the different treatment trains for water reuse.

Table 1 Treatment trains for water reuse analysed in this report

No	Train	Target contaminants	Reuse site	Type of reuse	Size
1	UV or performic acid (PFA)	Pathogens	Braunschweig (DE)	Agricultural irrigation (restricted)	Pilot
2	Filtration + UV + Chlorination	Particles, Pathogens	El Port de la Selva (ES)	Private/public irrigation	Full
3	Filtration + GAC + UV	Particles, Bulk organics, Trace organics, Pathogens	El Port de la Selva (ES)	Artificial groundwater recharge (indirect potable reuse)	Full
4	Membrane bioreactor + GAC + Chlorination	Particles, (Bulk organics), (Nutrients), Pathogens	Old Ford Water Recycling Plant (UK)	Urban reuse (toilet flushing, park irrigation)	Full
5	Soil-Aquifer Treatment (SAT)	Particles, (Bulk organics), Nutrients, Pathogens	Shafdan (IL)	Agricultural irrigation	Full
6	Filtration + Ozonation + SAT	Particles, Bulk organics, Nutrients, Trace organics, Pathogens	Shafdan (IL)	Agricultural irrigation	Pilot
7	Ultrafiltration	Particles, Pathogens	Shafdan (IL)	Side-stream treatment (agricultural irrigation)	Pilot
8	Ultrafiltration + Reverse Osmosis	Particles, Bulk organics, Nutrients, Trace organics, Pathogens, Salinity	Torreele (BE) Shafdan (IL)	Indirect potable reuse/ agricultural irrigation	Full Pilot

Fact sheets for each treatment train contain information on:

- Main treatment target of this process train
- Process description and flow scheme
- Water recovery rate, relating product volume to influent volume [%]
- Electricity and chemicals demand [per m^3 influent]
- Cumulative energy demand of non-renewable resources [MJ/m^3 influent]
- Global warming potential [kg CO2-eq/m^3 influent]
- Treatment performance for selected water quality parameters: log removal for microbial paramters [log], and relative removal for chemical parameters [%]
- Additional information on operation and maintenance

2 Train 1: UV or performic acid (PFA)

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
				X	

2.1 Short description

Disinfection is one of the major goals of water reuse trains, as different types of pathogens can be present in raw wastewater or secondary effluent of a WWTP and may pose a serious health threat to users of reclaimed water. The simplest way to realize a disinfection of wastewater is the addition of a disinfection stage downstream of the traditional WWTP [6]. While the use of chlorine or hypochlorite (Cl_2 or NaOCl) as strong disinfectant is widely applied in many countries, the formation of potentially harmful disinfection by-products via the reaction of chlorine and residual organic matter poses additional risks for downstream use and limits the use of Cl_2 as disinfectant in water reuse. In contrast, the use of UV lamps with an irradiation maximum at 254 nm can effectively inactivate many pathogens, while eco-toxic or inhibitory effects of potential by-products are not reported [7]. Naturally, UV transmission of the water matrix, particle content and UV dose all influence the performance of UV disinfection. In recent years, the addition of peracetic (PAA) or performic acid (PFA) as an alternative chemical oxidant has been tested for disinfection of secondary effluent [8]. Although effective for microbial inactivation, PFA does not form potentially harmful by-products compared to Cl_2. PFA is not stable and thus is prepared on-site by mixing H_2O_2 and formic acid in a separate reactor, resulting in a solution of 13.5% PFA in water. This PFA solution is dosed depending on the disinfection target (here: 2 ppm) and requires a minimum retention time in a contact tank for a reliable disinfection effect [6].

2.2 Process scheme

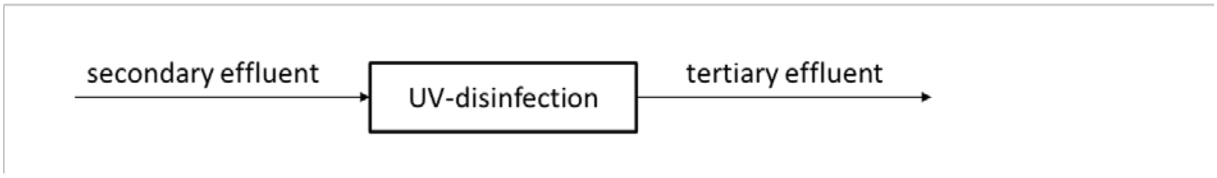

Figure 1 Basic flow sheet for UV disinfection

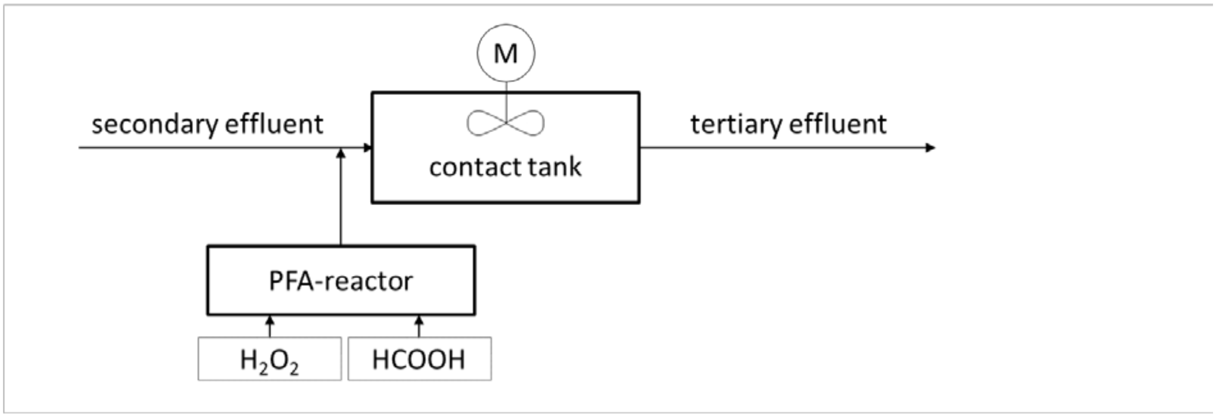

Figure 2 Basic flow sheet for PFA disinfection

2.3 Environmental impact and risk reduction potential

Parameters are reported for a UV dose of 500-900 J/m² and a PFA dose of 2ppm, which are sufficient for restricted agricultural irrigation in the Braunschweig case study (< 2000 cfu/100 mL for E.coli [9]). Minimum contact time for the PFA reactor is 10 min (12-24 min in pilot trials), resulting in a Ct value of at least 20 mg*min/L [6].

Table 2 Operational parameters, environmental impact and risk reduction potential for UV and PFA disinfection

Parameter	Unit	UV (500-900 J/m²)	PFA (2 ppm)	Source
Recovery rate	%	100	100	
Electricity demand	kWh/m³	0.03-0.05	0.003	[6]
Chemical demand	g H_2O_2 (50 %)/m³	-	15-18	[6]
	g Formic acid (100 %)/m³	-	10-12	[6]
Environmental impact				
Cumulative energy demand	MJ/m³	0.32-0.54	1.06-1.28	[4]
Carbon footprint	kg CO_2-eq/m³	0.01-0.03	0.05-0.06	[4]
Risk reduction potential				
Bacteria (E. Coli)	log removal	1.8-4.7	1.5-3.1	[10]
Viruses (som. Coliphage)	log removal	2.9-4.2	1.5-3.4	[10]
Parasites (*C. Perfringens*)	log removal	0.5-2.3	0.1-0.5	[10]

2.4 Comments

- UV requires a certain water quality to be effective, as the presence of solids and turbidity reduces disinfection efficiency and leads to higher UV doses required for a specific disinfection target. Recommended values are a UV transmission of T > 45% and total suspended solids < 10 mg/L.
- Regular cleaning of UV lamps is mandatory to prevent organic and inorganic fouling which reduces transmission and efficiency. Automated cleaning systems (e.g. wiper once per hour) for UV systems are available to limit fouling of UV lamps in secondary effluent. Lamp performance will decrease by fouling of UV lamps over their lifetime.
- For small UV systems with few lamps, the disinfection efficiency can be heavily affected if one lamp fails [6]. Hence, close monitoring of lamp performance is required to guarantee safe operation and reliable disinfection performance especially in small systems.
- PFA disinfection requires a sufficient contact time with water (usually > 10 min) to be effective.
- By-passes/short-cuts of water should generally be avoided in all disinfection processes to guarantee full disinfection performance (log removal rates). Optimized design of UV reactors and PFA contact tanks helps to minimize potential deterioration of disinfection performance.
- Both UV and PFA are flexible technologies: disinfection performance (log removal) is dependent on PFA dosage [ppm] and minimum contact time or applied UV-fluence [J/m²], which also affects the demand for electricity and chemicals.

3 Train 2: Filtration, UV and Chlorination

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X				X	

3.1 Short description

The primary target of filtration in water reuse trains is the removal of residual suspended solids in secondary effluent upstream of additional disinfection steps. It can also be used to compensate for high variability of secondary effluent quality (e.g. in case of hydraulic overload of clarifier and sludge outflow with peak events for suspended solids).

Filtration is a well-known process in water treatment, and several types of filters are available. In gravity filters, water flows through filtration media (e.g. sand, anthracite) only driven by gravity, and water has to be lifted on top of the filter bed before. They usually work with filter velocities of 5-10 m/h and regular backwash (e.g. 12-24h), using sand or anthracite particles of 0.5-4 mm to minimize head loss. In contrast, pressurized filters work in closed tanks and allow for higher filter velocities (5-30 m/h) and more compact design, although they also require higher pressure (0.2-2 bar) and thus more pumping energy to move the water through the filter bed. Chemical dosing before filtration (e.g. coagulation with Fe/Al) can be used to achieve higher removal of dissolved solids (e.g. bulk organics) in filtration which enables a more effective UV disinfection.

After filtration, water can be effectively disinfected with UV treatment at 254 nm due to improved transmission and low content of solids. If a multi-barrier approach for disinfection is required or some residual disinfection capacity should be provided (e.g. to secure water quality in the distribution network), final chlorination with sodium hypochlorite is an option after filtration and UV treatment. Addition of NaOCl requires a minimum contact time in a reactor or storage tank to be effective for disinfection. The use of hypochlorite as disinfectant is more safe in operation, as the liquid is easier to handle than gaseous Cl_2.

3.2 Process scheme

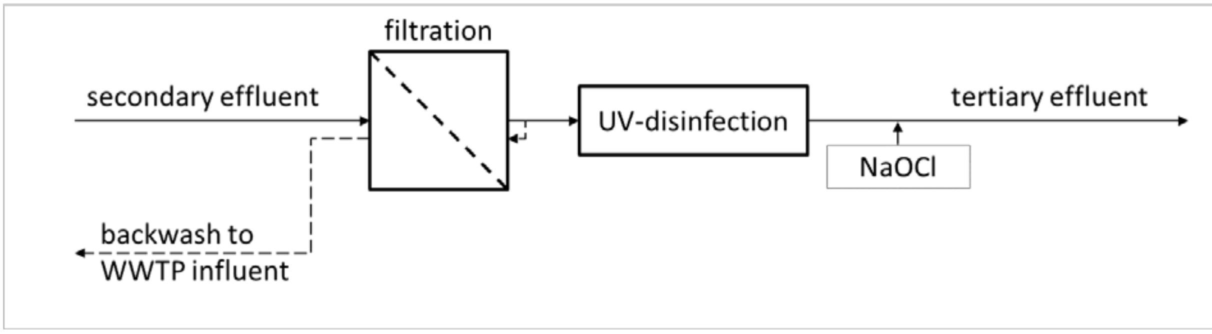

Figure 3 Basic flow sheet for filtration, UV disinfection and chlorination

3.3 Environmental impact and risk reduction potential

Parameters are reported for a UV dose of 500-900 J/m² and a final dosing of NaOCl with approx. 8 ppm of total Cl_2 (contact time > 10 min, residual Cl > 0.4 mg/L, ct > 4 mg*min/L). The data for UV and NaOCl is based on the water reuse system in El Port de la Selva, while information for energy demand of gravity filtration is adopted from previous studies.

Table 3 Operational parameters, environmental impact and risk reduction potential for filtration, UV disinfection and chlorination

Parameter	Unit	Gravity filtration	UV	Cl	Source
Recovery rate	%	> 95 %	-	-	
Electricity demand	kWh/m³	0.04-0.06	0.03-0.05	negligible	[6, 11, 12]
Chemical demand	g NaOCl (15 %)/m³	-	-	60-120	[11, 13]
Environmental impact					
Cumulative energy demand	MJ/m³	0.90-1.49			[4]
Carbon footprint	kg CO_2-eq/m³	0.05-0.08			
Risk reduction potential					
Solids	removal	60-90 %			
Bacteria (E. Coli)	log removal	3.8-10.7			[14]
Viruses (som. Coliphage)	log removal	3.9-7.2			[14-16]
Parasites (*C. Perfringens*)	log removal	2.2-4.3			[14-16]

3.4 Comments

- Filtration is used as pre-treatment for downstream disinfection to remove solids and increase UV transmission (e.g. by removing dissolved solids such as bulk organics) to support UV performance.
- Chlorination needs network/ storage tank/ contact tank for residual disinfection, compared to UV which provides on-site direct disinfection but no residual effect.
- As a chemical disinfectant, disinfection performance of chlorination can be improved by increasing the applied dose, providing flexibility of treatment in case of higher water quality targets.
- Disinfection by-products originating from chlorination can be potentially hazardous for some re-use purposes, e.g. with potential exposure of humans in public/private irrigation, or non-potable applications in households (e.g. toilet flushing), or indirect and direct potable reuse.

4 Train 3: Filtration, GAC filtration and UV

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X	X		X	X	

4.1 Short description

As in train 2, filtration of secondary effluent removes residual suspended solids and acts as a polishing treatment to protect downstream processes. If the type of water reuse requires an enhanced removal of trace organic compounds (e.g. pharmaceuticals, personal care products, and industrial chemicals) from secondary effluent, ozonation or adsorption on activated carbon can be added to the tertiary treatment. In principle, activated carbon can be continuously dosed as powdered activated carbon (PAC), but sufficient contact time for PAC has to be realized, and PAC has to be removed via downstream filtration. In addition, spent PAC cannot be regenerated and has to be disposed. Simpler in operation is a filter filled with granular activated carbon (GAC, 0.6-2.4 mm), which is operated with low filtration velocity (6 m/h) with sufficient contact time (20 min) in a normal filter bed. GAC can also be regenerated after adsorption capacity is reached, which decreases costs and energetic efforts for activated carbon production.

In the present train, GAC filtration is added for the removal of trace organics, targeting a minimum removal of the indicator substance Gabapentin to 50%. In the present study, this target results in a predicted treatment time of 7’000 bed volumes (BV) before exchange of GAC is required. The GAC filter is operated as a gravity filter with periodic backwash. After the GAC, water is disinfected with UV treatment, which is usually more effective downstream of GAC due to improved UV transmission of the water matrix with bulk organics removal (DOC).

4.2 Process scheme

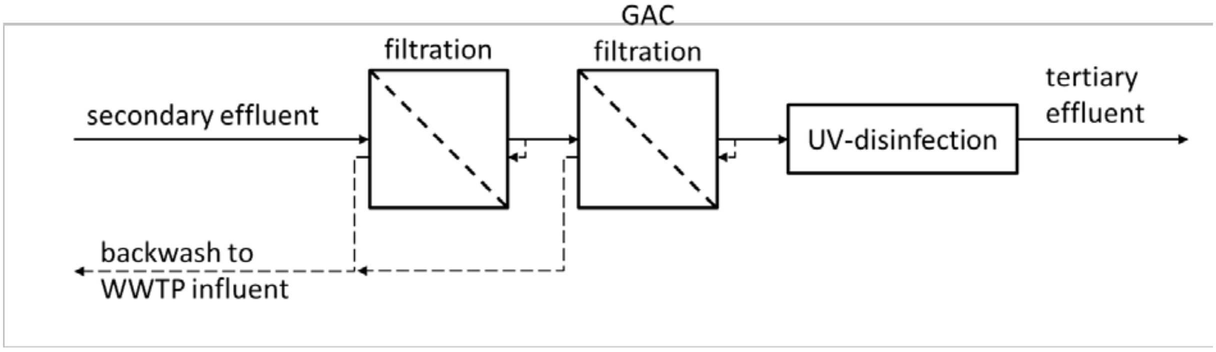

Figure 4 Basic flow sheet for filtration, GAC filtration and UV disinfection

4.3 Environmental impact and risk reduction potential

Parameters are based on the data of case study in El Port de la Selva, considering the local targets and respective operating conditions (e.g. regeneration cycle of GAC). For UV disinfection, a UV dose of 500-900 J/m^2 is assumed.

Table 4 Operational parameters, environmental impact and risk reduction potential for filtration, GAC filtration and UV disinfection

Parameter	Unit	Gravity filtration	GAC[1]	UV	Source
Recovery rate	%	> 95 %	> 95 %	-	
Electricity demand	kWh/m^3	0.04-0.06	0.03-0.05	0.03-0.05	[6, 11, 12]
Chemical demand	g GAC/m^3	-	50-55	-	[4, 11]
Environmental impact					
Cumulative energy demand	MJ/m^3	2.46-3.24			[4]
Carbon footprint	kg CO_2-eq/m^3	0.20-0.24			
Risk reduction potential					
Solids	removal	60-90 %			[11]
Gabapentin	removal	min. 50 %			
Bacteria (E. Coli)	log removal	1.8-4.7			[14]
Viruses (som. Coliphage)	log removal	2.9-4.2			[14-16]
Parasites (*C. Perfringens*)	log removal	0.5-2.3			[14-16]

4.4 Comments

- Filtration is used as pre-treatment to remove solids upstream of GAC and UV disinfection.
- Pre-treatment with the GAC filter before UV reduces DOC and increases UV transmission of the water matrix, leading to lower energy demand for UV (e.g. by reducing required UV dose by 30%) and/or better disinfection performance
- GAC needs to be exchanged and regenerated after a specific operating time. The exchange interval will have a major impact on the amount of required activated carbon and thus on the resulting carbon footprint of the treatment. An optimized two-stage GAC configuration is useful to control breakthrough of substances and maximize use of GAC before regeneration/disposal

[1] Hypothetic calculated dosage of GAC based on an empty bed contact time of 20 min and a treated bed volume of 7'000 before exchange of GAC material.

5 Train 4: Membrane bioreactor and Chlorination

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X	(X)	(X)		X	

5.1 Short description

This train includes a membrane bioreactor (MBR) for clarification of effluent from the activated sludge tank of a WWTP, together with downstream treatment for disinfection and colour removal. The MBR process substitutes the final clarifier of a WWTP, thus integrating aspects of secondary and tertiary treatment. MBR are more compact than traditional clarifiers and achieve a higher and more constant removal of solids, providing a high effluent quality for downstream treatment or use. However, MBR operation also required considerable demand for electricity and also chemicals for frequent cleaning and fouling prevention. MBR processes assessed in this report are operated as submerged UF membranes with aeration to prevent membrane blocking by particle layers ("air scouring"). Water is driven through the membrane with a suction pump on the permeate side. Downstream of MBR, water is treated with GAC filtration and residual disinfection via dosing of NaOCl in one option. In this scheme, GAC is operated mainly for colour removal, which results in long operation before GAC exchange.

5.2 Process scheme

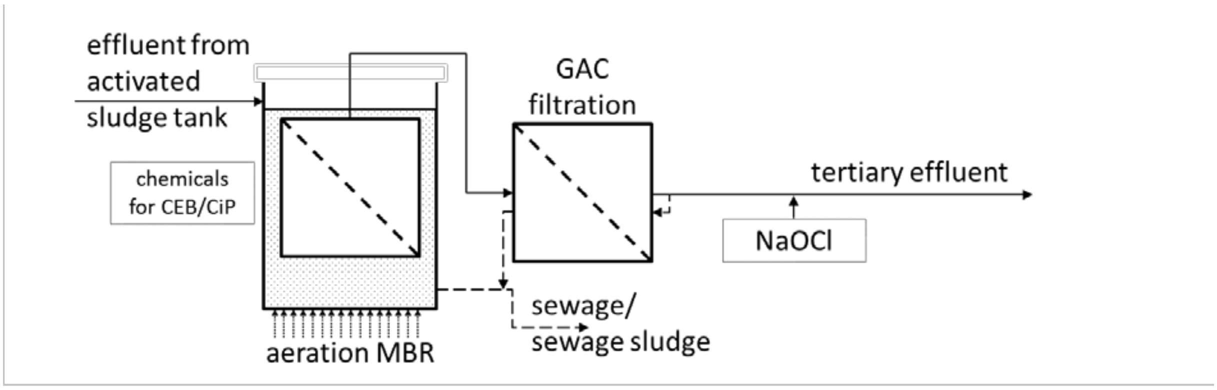

Figure 5 Basic flow sheet for aerated MBR, GAC filtration for colour removal and chlorination

5.3 Environmental impact and risk reduction potential

Process data is based on the reuse train operated at Old Ford Water Recycling Plant. MBR is operated as a second step after activated sludge tank, while GAC is primarily targeting colour removal only (= long re-generation cycles). Final chlorination yields a residual disinfection capacity in the distribution network.

Table 5 Operational parameters, environmental impact and risk reduction potential for aerated MBR, GAC filtration for color removal and chlorination

Parameter	Unit	MBR	GAC[2]	Cl	Source
Recovery rate	%	> 95 %	> 95 %	-	
Electricity demand	kWh/m^3	0.32	0.03-0.05	negligible	[13]
Chemical demand	g GAC/m^3	-	ca. 5	-	[13]
	g NaOCl (15 %)/m^3	20-25	-	60-120	[11, 13]
	g Citric acid (100 %)/ m^3	6-8	-	-	[13]
Environmental impact					
Cumulative energy demand	MJ/m^3	4.21-4.63			[4]
Carbon footprint	kg CO_2-eq/m^3	0.22-0.25			
Risk reduction potential					
Solids	removal	> 95 %			
Bacteria (E. Coli)	log removal	6.0-12.0			[14]
Viruses (som. Coliphage)	log removal	5.0-8.0			[14-16]
Parasites (*C. Perfringens*)	log removal	4.0-8.0			[14-16]

5.4 Comments

- MBR is a compact process for wastewater treatment and secondary clarification, but requires more energy (+50-100%) than conventional activated sludge tanks with sedimentation or filtration. It can be used to upgrade/extend an existing WWTP.
- MBR shows higher and more stable solids removal than conventional secondary clarifiers.
- MBR removes bacteria and partially viruses, although loss of membrane integrity can quickly lead to a partial loss of disinfection performance. Hence, a multi-barrier system with final disinfection is required to guarantee microbial quality of reclaimed water.
- If GAC is used primarily for colour removal, GAC filters can be operated longer (here: 5a) before GAC regeneration is required. Trace organics removal will be limited with this operational mode.
- GAC provides surface for growth of microorganisms and biofilms, which will require a final disinfection downstream to guarantee microbial quality of reclaimed water.
- Downstream of MBR, lower dosage of NaOCl may be required compared to direct disinfection of secondary effluent due to higher quality of MBR effluent (particle-free)

[2] GAC only for color removal, hypothetic dosage calculated based on long regeneration cycle (5a)

6 Train 5: Soil-aquifer-treatment (SAT)

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X	X	(X)		X	

6.1 Short description

Using the natural treatment capacity of an underground passage of water in an aquifer, a wide variety of water contaminants can be removed, namely particles, microorganisms, nutrients, and bulk or trace organics. Soil-aquifer-treatment (SAT) exploits the natural barrier of an unsaturated soil passage and the subsequent travelling of water through the aquifer, relying on physical, chemical, and biological degradation processes. The SAT process can be subdivided into three steps: (I) surface infiltration via infiltration ponds, (II) percolation through the unsaturated soil passage and (III) slow transport through the aquifer [17]. Infiltrated water and native groundwater is recovered downgradient of the infiltration ponds by abstraction wells. The performance of this SAT treatment is strongly related to (a) the characteristics of the unsaturated soil and aquifer passage and (b) the characteristics of infiltrated water. SAT treatment requires soil and aquifer material with moderate water retention capacity (e.g. sandy soils), while high shares of gravel and coarse material decrease treatment efficiency due to high flow velocity and low retention times in the SAT system. On the other hand, soils with high clay or loam fraction prevent sufficient water infiltration. SAT systems are often operated in alternating dry/wet cycle in order to maintain aerobic conditions in the soil and allow for regular maintenance (e.g. removal of clogging layer).

In addition, the characteristics of infiltrated water are of importance, since the formation of reductive zones in the unsaturated soil passage can mobilize metals like manganese from parent rock material. To avoid elevated content of metals in the recovered groundwater, the infiltrated water should be in oxic conditions, and the presence of substance with the potential of oxygen depletion (such as ammonium) should be kept to a minimum [17]. If reductive zones are present, post-treatment of recovered water may be required to remove dissolved metals such as manganese or iron. Energy required for the SAT system depends mainly on depth of the recovery wells and is site-specific. Similarly, removal rates for chemical or microbial water parameters in SAT depend on realized retention time of water in the aquifer, local soil type, and also the quality of infiltrated water. Retention time and removal rates should be investigated closely via monitoring of tracer substances to validate treatment performance of the specific SAT system.

6.2 Process scheme

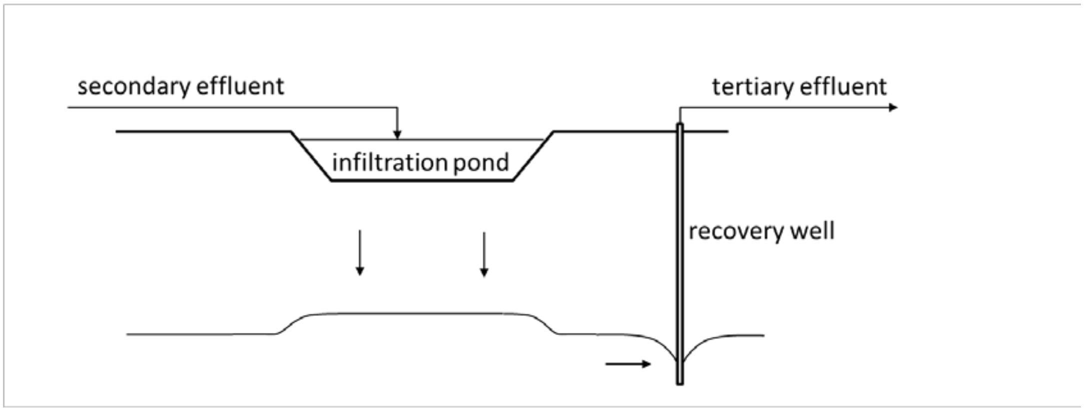

Figure 6 Basic flow sheet for SAT treatment

6.3 Environmental impact and risk reduction potential

Data for SAT system is based on the reuse train operated at Shafdan site in Israel. Recovery of infiltrated water is done with groundwater wells (20-30m depth of water table).

Table 6 Operational parameters, environmental impact and risk reduction potential for SAT treatment

Parameter	Unit	SAT[3]	Source
Recovery rate	%	variable	
Electricity demand	kWh/m³	0.10-0.15	[18]
Environmental impact			
Cumulative energy demand	MJ/m³	1.07-1.61	[4]
Carbon footprint	kg CO_2-eq/m³	0.05-0.08	
Risk reduction potential			
Solids	removal	> 90 %	[18]
Bacteria (E. Coli)	log removal	3.0 per 30d	[14]
Viruses (som. Coliphage)	log removal	0.3 per 30d	[14-16]
Parasites (*C. Perfringens*)	log removal	1.0 per 30d	[14-16]

6.4 Comments

- Pre-treatment of infiltrated water may be required (e.g. removal of residual NH_4, input of oxygen) to prevent anoxic conditions in the aquifer passage and reduce metal input from aquifer material.
- Dedicated management of infiltrations ponds is important to prevent surface or underground clogging in the long-term.
- Long term monitoring along the water flow (transect) recommended to validate removal performance of the SAT system and to check for breakthrough of pollutants.
- Consideration of local hydrogeological situation and proper groundwater management via recovery wells is mandatory for a safe operation of SAT systems.

[3] At recovery well, depth: 20-30m

7 Train 6: Filtration, Ozonation and short Soil-aquifer-treatment (SAT)

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X	X	X	X	X	

7.1 Short description

This treatment train combines an SAT with enhanced pre-treatment of water before infiltration to decrease operational problems in the SAT and introduce a multi-barrier approach for trace organics. A biologically active filter with upstream dosing of a coagulant (PACl) removes particles, residual bulk organics and phosphorus from secondary effluent. In addition, dosing of H_2O_2 introduces oxygen surplus for biological nitrification in the filter, removing residual NH_4-N which may lead to anoxic conditions in the SAT and related problems. Downstream of the filter, an ozonation step provides another barrier for trace organics and microbial contamination and also saturates the water with oxygen before infiltration. Efficiency of ozonation is improved by the upstream coagulation/filtration process, as bulk organics (DOC) are removed which would consume ozone and thus decrease oxidation capacity for the trace organics. In addition, residual H_2O_2 after filtration combines with ozonation into an advanced oxidation process (AOP) with high efficiency for trace organics removal. Downstream of this extensive pre-treatment, travel time in the aquifer could be reduced ("short SAT" = 30-35d) while still providing sufficient water quality due to the multi-barrier approach for microbial and chemical contaminants. In addition, operational problems of SAT with reductive zones and metal remobilization can be overcome.

7.2 Process scheme

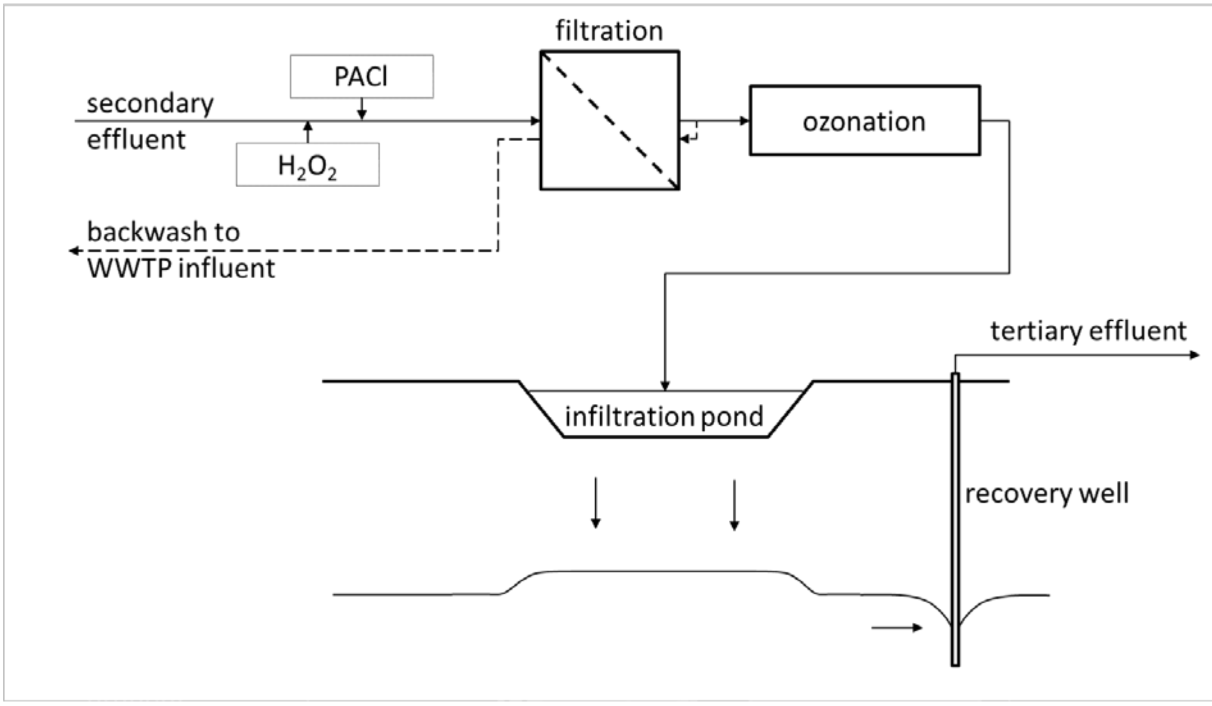

Figure 7 Basic flow sheet for filtration, ozonation/AOP, and SAT treatment

7.3 Environmental impact and risk reduction potential

Parameters are based on the pilot system operated at Shafdan site in Israel in the DEMOWARE project [17].

Table 7 Operational parameters, environmental impact and risk reduction potential for filtration, ozonation/AOP, and SAT treatment

Parameter	Unit	Filtration	Ozone	SAT	Source
Recovery rate	%	> 95 %	-	variable	
Electricity demand	kWh/m³	0.04-0.06	0.07-0.15	0.10-0.15	[12, 18, 19]
Chemical demand	g PACl (18 %)/m³	3	-	-	[18]
	g H_2O_2 (50 %)/m³	50-60	-	-	[18]
	g O_3/m³	-	5-10	-	[18, 19]
Environmental impact					
Cumulative energy demand	MJ/m³	3.82-4.74			[4]
Carbon footprint	kg CO_2-eq/m³	0.20-0.24			
Risk reduction potential					
Solids	removal	> 90 %			[18]
Gabapentin	removal	60-95 %			[20]
Bacteria (E. Coli)	log removal	3.0-7.0 + 3.0 per 30d HRT in SAT			[14]
Viruses (som. Coliphage)	log removal	3.0-6.0 + 0.3 per 30d HRT in SAT			[14-16]
Parasites (*C. Perfringens*)	log removal	2.0-8.0 + 1.0 per 30d HRT in SAT			[14-16]

7.4 Comments

- Ozonation enables oxygen input into the unsaturated soil and aquifer by supersaturation of water with oxygen.
- Removal of oxygen-depleting substances by coagulation/filtration optimizes downstream ozonation and increases capacity of SAT.
- Ozonation provides another barrier for trace organics and pathogens (disinfection).
- SAT can be built with shorter travel times (~ 30d) due to increased capacity of pre-treatment and multi-barrier approach.

8 Train 7: Ultrafiltration (UF)

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X				X	

8.1 Short description

Ultrafiltration (UF) membranes can completely remove particles and pathogens due to their physical filtration of solids at the membrane surface. UF membranes as tertiary treatment of a WWTP are usually operated in dead-end mode, using both outside-in and inside-out flow regimes in hollow-fibre modules depending on the type of membrane. Dead-end operation enables a high recovery rate of 85-95 % and relatively low energy demand. In comparison, higher recovery usually leads to higher energy demand of the system. Air scouring of membranes can also be used with outside-in hollow fibres to prevent build-up of a particle layer and blocking of membranes. However, use of air should be minimized as this is an important driver for the total energy demand of the UF system.

To prevent biofouling of the membrane, sodium hypochlorite is added upstream of the membrane stage for disinfection. Citric acid combined with hydrochloric acid is used for regular chemically enhanced backwash and cleaning in place.

8.2 Process scheme

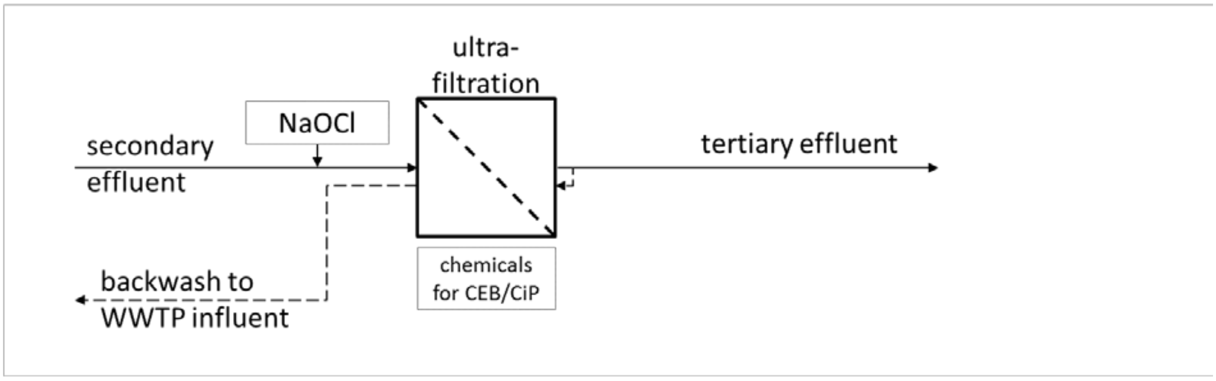

Figure 8 Basic flow sheet for ultrafiltration (UF)

8.3 Environmental impact and risk reduction potential

UF operational parameters are based on pilot data from Shafdan and full-scale data of Torreele reuse system.

Table 8 Operational parameters, environmental impact and risk reduction potential for ultrafiltration (UF)

Parameter	Unit	UF	Source
Recovery rate	%	85-92	[18, 21]
Electricity demand	kWh/m³ filtrate	0.12-0.28	[18, 21]
Chemical demand	g NaOCl (15 %)/m³	10-40	[18, 21]
	g Citric Acid (40 %)/m³	0.5-1.5	[18, 21]
	g HCl (32 %)/m³	0-0.4	[18, 21]
Environmental impact			
Cumulative energy demand	MJ/m³	1.64-3.36	[4]
Carbon footprint	kg CO_2-eq/m³	0.08-0.17	
Risk reduction potential			
Solids	removal	> 90 %	[18, 21]
Bacteria (E. Coli)	log removal	4.0-6.0	[14]
Viruses (som. Coliphage)	log removal	4.0-5.0	[14-16]
Parasites (*C. Perfringens*)	log removal	4.0-6.0	[14-16]

8.4 Comments

- UF backwash in higher quantities (given a lower recovery rate of 85-90 %) is usually recycled to the inlet of the WWTP.
- Upstream disinfection is recommended to limit fouling and formation of biofilms on membrane, but chlorine-resistant membranes may then be required.
- Monitoring of performance and membrane integrity is recommended for successful operation.
- Cleaning strategy needs to be optimized if performance of UF is decreasing.
- Constant operation of the UF system is recommended, which adds complexity to operational management for sites with seasonal operation of the reuse system.
- Membrane systems usually require trained staff and may need higher maintenance efforts.

9 Train 8: Hybrid-membrane treatment with Ultrafiltration (UF) and Reverse osmosis (RO)

Particles	Bulk organics	Nutrients	Trace organics	Pathogens	Salinity
X	X	X	X	X	X

9.1 Short description

A hybrid membrane scheme with ultrafiltration and reverse osmosis (RO) can be used for removal of variety of chemical and biological contaminants from secondary effluent. In addition to the UF, RO provides another barrier for microorganisms and removes many organic and inorganic substances, e.g. bulk and trace organics, nutrients, metals, and also salinity. The latter effect leads to high energy demand for RO treatment, as osmotic pressure has to be overcome to drive the water through the tight RO membrane. Recovery of RO systems fed with secondary effluent is usually between 80-85% if a two stage RO configuration is used. It should be underlined here that RO treatment of secondary effluent (with salinity of 1’000-1’500 µS/cm) is significantly less energy-intensive than desalination of seawater (ca. 50’000 µS/cm) and can also be operated with higher recovery.

RO systems are usually operated in combination with a UF membrane upstream to protect the RO modules from particles and high microbial loads. However, high dosages of chemicals for antifouling and antiscaling are still required upstream of the RO membrane to enable constant operation and prevent loss of capacity. High dosing of acid is used to lower the pH and prevent scaling of minerals on the membrane, and pH has to be corrected to neutral after RO treatment by dosing of caustic.

9.2 Process scheme

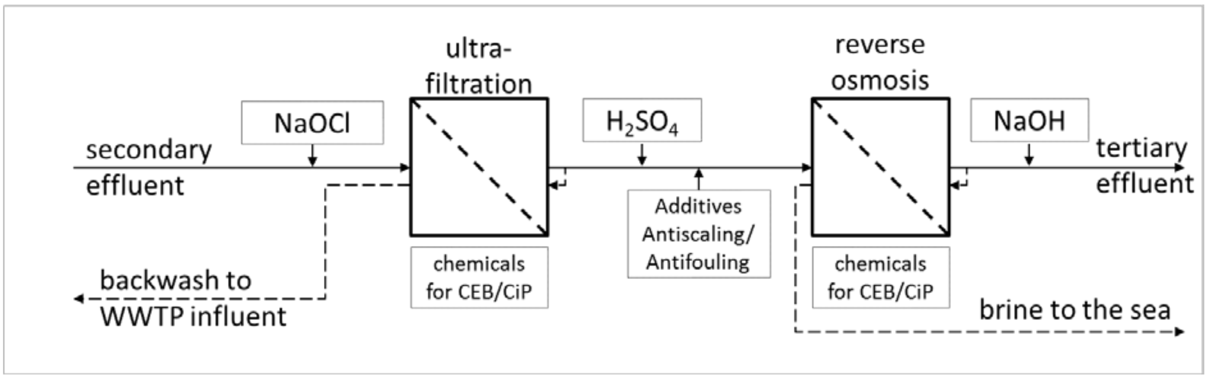

Figure 9 Basic flow sheet of Ultrafiltration (UF) and reverse osmosis (RO)

9.3 Environmental impact and risk reduction potential

UF and RO operational parameters are based on data from Shafdan and Torreele reuse sites.

Table 9 Operational parameters, environmental impact and risk reduction potential for UF and RO

Parameter	Unit	UF	RO	Source
Recovery rate	%	85-92	75-80	[18, 21]
Electricity demand	kWh/m³ filtrate	0.12-0.28	0.58-0.60	[18, 21]
Chemical demand	g NaOCl (15 %)/m³	10-40	0-4	[18, 21]
	g Citric Acid (40 %)/m³	0.5-1.5	1.0-1.8	[18, 21]
	g HCl (32 %)/m³	0-0.4	-	[18, 21]
	g NaOH (40 %)/m³	-	0-6	[18, 21]
	g H_2SO_4 (40 %)/m³	-	15-75	[18, 21]
	Additives for antifouling		0.5-5	[18, 21]
	Additives for antiscaling		2.5-4	[18, 21]
Environmental impact				
Cumulative energy demand	MJ/m³	10.21-12.21		[4]
Carbon footprint	kg CO_2-eq/m³	0.51-0.63		
Risk reduction potential				
Solids	removal	>99%		[18, 21]
Gabapentin	removal	60-85 %		[22]
Bacteria (E. Coli)	log removal	> 10		[14]
Viruses (som. Coliphage)	log removal	> 10		[14-16]
Parasites (*C. Perfringens*)	log removal	> 10		[14-16]

9.4 Comments

- This train produces significant volumes of UF backwash and RO brine (total recovery rate only 60-75 %). UF backwash can be recycled to the inlet of the WWTP, while brine is usually discharged to freshwater or the ocean (causing potential problems of nutrient input and eutrophication).
- Additional brine treatment may be required to be meet legislative requirements.
- Disinfection prior to UF can be useful to limit fouling and formation of biofilms on membrane.
- pH-adjustment before RO mandatory to prevent mineral scaling (high consumption of chemicals)
- Use of antifouling and antiscalant chemicals and cleaning strategies has to be adapted for the particular water quality and membrane type (type of chemicals, dosing).
- Monitoring of performance recommended for successful operation
- Constant operation of membrane systems is recommended, complex for sites with seasonal tertiary treatment and reuse

10 Discussion and conclusions

10.1 Limitations of generic assessment data

As already mentioned in the introduction of this report, the direct transferability of extrapolated data from DEMOWARE case studies to other specific reuse sites is limited. This is related to a number of different aspects:

Site-specific process data

Performance of water treatment processes is usually depending on actual influent water quality and site-specific operating conditions. Hence, realistic data for consumptives will cover a wider range for electricity and chemical demand due to specific characteristics and variability of secondary WWTP effluent, maintenance strategies and site-specific operational strategies.

Country-specific LCA data

In addition, LCA indicator scores for environmental impact of electricity consumption were calculated based on a "European" electricity mix, considering the gross electricity shares of 23[4] EU member states in 2014 [23] and the respective electricity mix of these member states in 2010 [5]. Related impact scores for chemical production were calculated for European averages as reported in DEMOWARE Deliverable D3.2 [4]. When transferring the LCA indicator scores to specific case studies, the local electricity mix should be taken into account, as electricity is a major contributor to energy demand and global warming potential. Within European countries, these indicators can vary heavily (factor 2-15) between member states:

- Non-renewable cumulative energy demand of electricity mix for EU-23 = 10.7 MJ/kWh, for Austria = 5.9 MJ/kWh, and for Greece = 16.2 MJ/kWh
- Global warming potential of electricity mix for EU-23 = 0.54 kg CO_2-Eq/kWh, for Sweden = 0.06 kg CO_2-Eq/kWh, and for Poland = 1.11 kg CO_2-Eq/kWh

Variation in treatment performance

Treatment performance of the different treatment trains is associated with uncertainty with regards to removal ratios and resulting potential for risk reduction. Mean relative removal rates [%, log removal] are depending on actual process configuration and operation at the specific WWTP, and also on influent concentrations of pollutants and pathogens. For some processes (e.g. UF or RO membranes), a fixed effluent concentration may be more appropriate, but was difficult to report from the case study results. Hence, relative removal rates reported in this document can be regarded as representative for the respective treatment train ("generic"), but they may vary depending on local conditions and operational strategy.

10.2 Discussion

Process trains for tertiary treatment of reclaimed water described in this report are characterized by different efforts (= environmental impact) and benefit (= removal of pollutants or pathogens). In general, higher targets in water quality will most likely lead to higher efforts for water treatment. Taking into account the limitations of the generic assessment as discussed above, treatment trains can be compared in their efforts and benefits to illustrate this trade-off between higher water quality and higher environmental impact from electricity and chemicals demand. Figure 10 presents a comparative overview of all trains for global warming potential (as proxy for effort) and removal pathogens (bacteria or viruses), while Figure 11 shows the relation between GWP and removal of solids or trace organics (gabapentin as proxy).

[4] All member states, excluding Cyprus, Malta and the Baltic states (no electricity mix in EcoInvent 3.1 available)

Disinfection systems via UV or PFA disinfection (train 1) show the lowest GWP of all investigated treatment schemes, while risk reduction for bacteria and viruses ranges between 2-5 log units. Both options can be considered as feasible "low-cost" disinfection options for non-potable reuse schemes (e.g. agricultural irrigation, restricted irrigation). Comparing UV with PFA disinfection, UV is favourable due to lower GWP and higher pathogen reduction according to the DEMOWARE trials. It should be mentioned here that PFA disinfection might achieve similar removal rates for pathogens when different operational setups are considered (e.g. higher PFA dose, longer HRT) [8].

Combining UV disinfection with filtration prior to the disinfection step, performance of UV disinfection can be optimised due to solids removal in the filter and simultaneous increase of UV transmission of filtered water. Nonetheless, the need of filtration as pre-treatment for UV disinfection may not be generalized, as it depends on the quality and variability of secondary effluent (= performance of the secondary clarifier). Treatment train 2 includes also disinfection via chlorine, which significantly improves the removal of bacteria (and partly viruses) and thus increases the log-removal credits of the entire treatment train. In addition, chlorine provides residual disinfection capacity in the distribution network without a major additional effort in energy demand and GWP, resulting in a final GWP of < 0.1 kg CO_2-Eq/m^3. This treatment train can be considered as expansion of the single-stage UV option for non-potable reuse schemes with increased demand for disinfection, e.g. public irrigation.

Treatment train 3 (Filtration + GAC + UV) combines the benefits of solids removal and pathogen removal with a barrier for trace organics. However, additional GAC filtration results in significantly higher energy consumption and GWP (0.2-0.24 kg CO_2-Eq/m^3) compared to train 2. Here, the GAC stage is designed for a removal rate of > 50 % for gabapentin as a proxy compound for trace organics. Effectively, the actual removal rate will be significantly higher with fresh/regenerated GAC and will decrease with increasing operating time of the GAC filter.

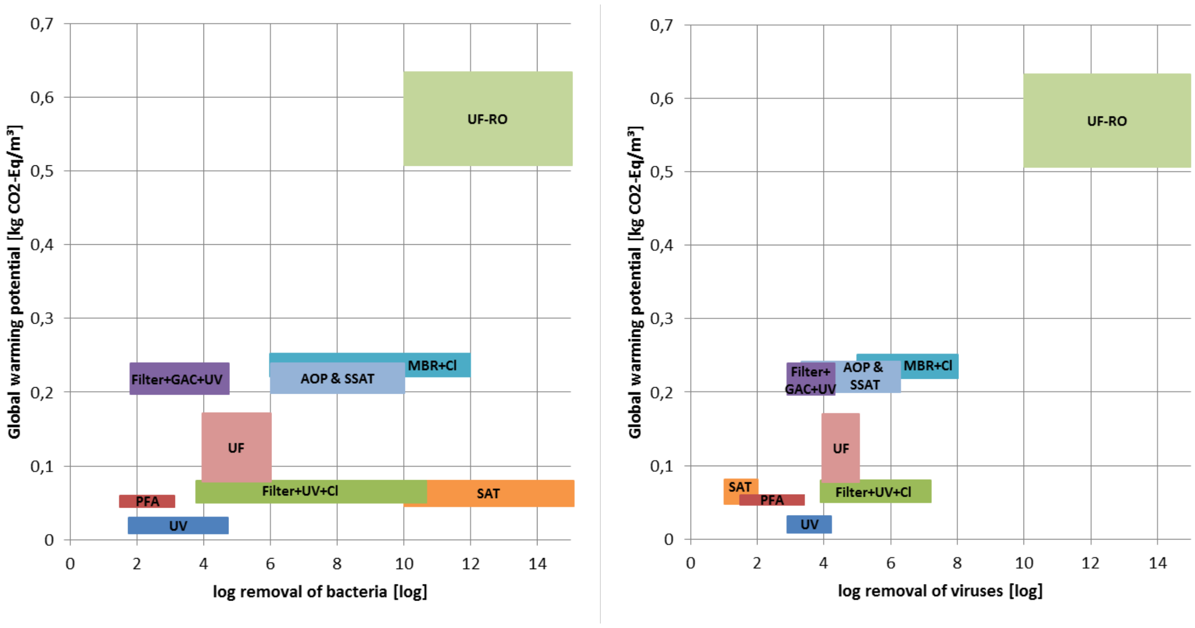

Figure 10 Range in global warming and risk reduction potential for selected treatment trains
Llog removal of bacteria (left) and viruses(right) for selected treatment trains. Assumed travel time for SAT: 100-200 d and for SSAT: 30-35 d.

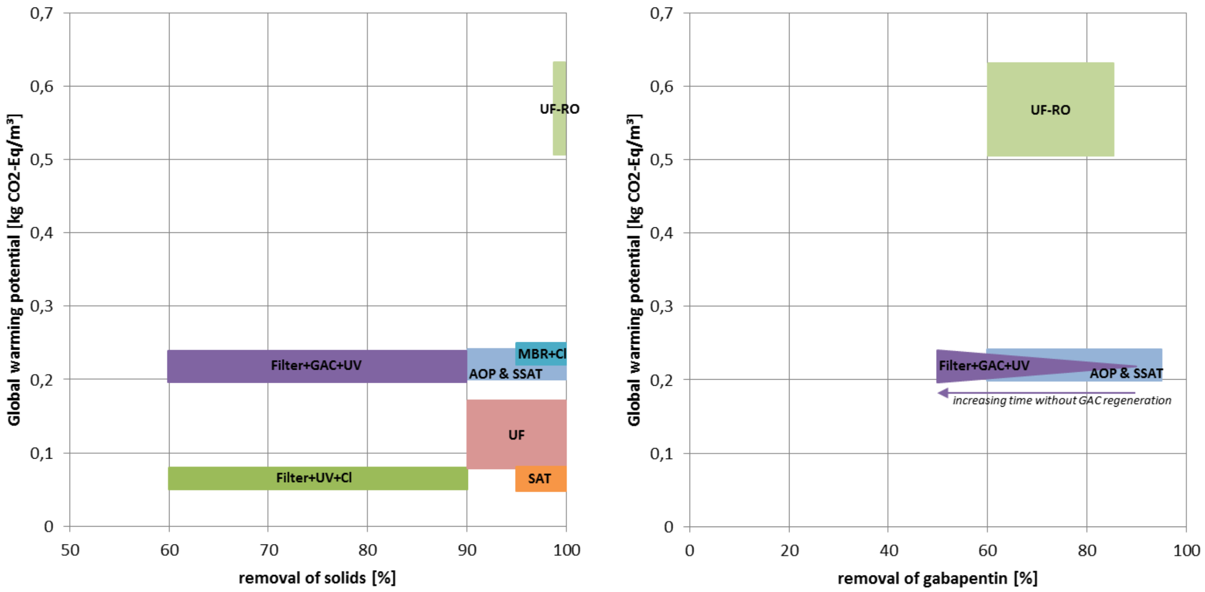

Figure 11 Range in global warming and risk reduction potential (solids and gabapentin as proxy for trace organics) for selected treatment trains

The combination of MBR and chlorination (train 4) yields high log removals for pathogens (bacteria: 6-12 log; viruses: 5-8 log) but also a substantial energy demand and GWP (0.22-0.25 kg CO_2-Eq/m³) mainly due to the electricity required for MBR operation (aeration and pumping). The relative solids removal is comparably high (around 95 %), since the MBR influent is highly loaded with suspended solids compared to "regular" secondary effluent as input to a tertiary treatment stage.

The log reduction of pathogens via soil-aquifer-treatment (SAT) is strongly dependent on the retention time of water in the aquifer. For common SAT travel times of around 100-200 d the log removal for bacteria is high (> 10 log credits), whereas the removal rate for viruses is relatively low (1-2 log credits). Solids removal in SAT is high (usually > 95 %), and the energy consumption and related GWP of SAT is directly related to the depth of the water table in the aquifer (pumping energy for water recovery). For normal operation of SAT (20-30m depth), GWP is below 0.1 kg CO_2-Eq/m³.

Combining filtration and advanced oxidation process via ozonation (AOP) as an advanced pre-treatment before short SAT results in a moderate GWP (0.2-0.24 kg CO_2-Eq/m³) mainly due to electricity and oxygen demand of ozonation. Ozonation removes trace organics and provides an additional barrier for pathogens compared to regular SAT without pre-treatment. Pathogen removal rates for the combined train with short SAT are around 6-8 log units for bacteria (lower than regular SAT with long travel times), and 3-6 log units for viruses (significantly higher than regular SAT due to ozonation). Besides the benefits of increasing SAT capacity and mitigating problems of SAT operation (e.g. oxygen deficiency and dissolution of Mn) with the oxidative pre-treatment, another advantage of this treatment train is the high trace organics removal rates by ozonation (60-95 %). Naturally, this removal rate depends on applied ozone dose and DOC concentration in the influent water. The upstream coagulation/filtration prior to ozonation additionally reduces DOC in the water and consequently required ozone dosage.

A single membrane treatment with ultrafiltration is associated with low to moderate GWP (0.08-0.17 kg CO_2-Eq/m³) and removes >90 % of solids from secondary effluent. The removal of pathogens is increased with UF if compared to single-stage disinfection systems such as UV or PFA disinfection (removal of bacteria in UF: 4-6 log; removal of viruses in UF: 4-5 log).

A hybrid-membrane system with ultrafiltration and reverse osmosis is highly efficient regarding pathogen removal (> 10 log units of bacteria, viruses and protozoa), solids (> 99 %) and also salinity. In addition, the removal of trace organics in RO is very high, although specific removal rates depend on membrane integrity and physico-chemical characteristics of the particular trace organic substance. However, significant water losses via brine discharge (> 20 %) and high energy consumption and related GWP (0.51-0.63 kg CO_2-Eq/m³) are the main drawbacks of this treatment train.

In practice, combinations of the assessed treatment trains are also common for a multi-barrier approach, thus increasing treatment efficiency but also resource consumption. As an example, the scheme for indirect potable reuse in Torreele (BE) combined a hybrid UF/RO system with an SAT stage to provide additional barriers for contaminants and storage/buffer capacity.

10.3 Conclusion and outlook

In summary, this report provides an overview of basic characteristics of different trains for tertiary treatment. It could identify the trade-off between final water quality and related environmental impact due to electricity and chemicals demand. All treatment trains described in this report can be considered useful for their particular goal and type of water reuse, but the choice of an adequate treatment has to take into account water quality targets, but also reasonable effort in terms of environmental and economic aspects. Water professionals are advised to carefully assess and check the required targets for risk reduction (= removal of pathogens and contaminants) related to their specific type of water reuse, and choose an adequate treatment train with can be operated with reasonable effort. Proper choices of technologies for implementation of environmental friendly water reuse schemes have to go beyond the issue of risk reduction only. They should individually search for an acceptable compromise between (i) safety needs by exposed people and environment and (ii) environmentally friendliness compared to other alternatives of water supply (e.g. local water supply, water import or seawater desalination).

To guide this process, a selection of key questions for a successful implementation of water reuse schemes from an environmental point of view may be formulated:

- Is there a defined need for exploitation of additional water resources?
- Which alternatives for additional water supply are available?
- What will be the expected use of the reclaimed water (= type of water reuse)?
- Who is exposed to this reclaimed water?
- What is the required water quality to ensure adequate risk management of water reuse?
- Which treatment steps can achieve the required water quality?
- Do you require a quantitative risk assessment to illustrate existing uncertainties?
- What is the environmental and economic impact of water reuse in comparison to other alternatives for additional water supply (e.g. water import, seawater desalination)?

Some of these questions may be addressed on a first level with the help of the generic information included in this document. However, a site-specific analysis of alternatives and treatment processes with their related environmental and economic impacts is required to prove that the final reuse scheme will operate with suitable risk management and in a sustainable way.

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