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REPORT

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HYBRID CONCEPTS FOR MAR WITH RECLAIMED WATER FOR NON-POTABLE REUSE

Project acronym: Oximar-1

by

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Colophon

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Abstract (English)

Wastewater reuse is increasingly considered as possible alternative water source for diverse non-potable uses. Among the major questions, defining which water quality for which reuse is required is crucial. If the demand for reclaimed water is seasonal, the question of reclaimed water storage is also essential. Aquifer recharge for further non-potable reuse can be a solution to address many final reuse applications, including indirect agricultural or landscape irrigation, saltwater intrusion barriers, subsidence mitigation/aquifer replenishment or other non-potable reuses. Most of the aquifer recharge applications of wastewater reuse so far rely on high-pressure membrane systems or even double-membrane combined with advanced oxidation processes. However, when non-potable reuse is targeted, or the replenishment of a threatened aquifer is planned, recharge with high-quality non-potable water could be envisaged as acknowledged by the legislation of several countries.

In this report, the performance of hybrid disinfection/filtration and recharge schemes is assessed in comparison to a high-pressure membrane system working under similar conditions. Among the portfolio of available disinfection and filtration technologies, five treatment trains were chosen – combinations of ozone or UV treatment with sand filters or UF membrane and final infiltration or injection – and compared to a double-membrane system (UF+NF). A synthetic secondary effluent (SE) was considered for this conceptual study on the basis of a worldwide survey of typical SE water qualities. The major legislations from the WHO, the USEPA and Australian guidelines were considered to define the water quality to be reached by these hybrid treatment schemes. The low targeted value in suspended solids (10 mg/L) and microbiological contaminants (1 fecal coliform / 100 mL) requires extensive disinfection and filtration processes. The proposed schemes were selected on the base of a large review of typical pollutant removal efficiencies found in the literature. To perform a comparative Life-Cycle Assessment of the different treatment trains, similar assumptions were made in all cases for a hypothetical case study of a 50,000-PE reuse plant downstream of a secondary sewage treatment plant.

All five proposed hybrid treatment trains are capable of supplying very high non-potable water quality, and the combination of disinfection, filtration and aquifer passage proved to be an efficient combination for removing suspended solids, residual BOD and microbiological contaminants. The environmental performance of the treatment trains was compared in terms of carbon footprint, but also energy demand, human toxicity, acidification impact and land footprint. Both the energy demand and carbon footprint of hybrid schemes was found to be considerably lower than for a double-membrane system, besides offering an additional storage solution in the aquifer. Thus, there is a significant margin for lowering the environmental impact, energy demand and operational costs if non-potable water quality is sufficient for the reuse goal. However, the legal context and social acceptability may represent barriers for this intended recharge of non-potable water to the aquifer.

This conceptual study has shown the potential of hybrid solutions to provide high-quality non potable water for aquifer recharge and further reuse. A large portfolio of solutions was proposed to reach the intended non-potable uses. To assist the selection of adequate treatment trains, the strengths and weaknesses of the solutions can be summarized in a decision tree taking into account the reuse goal, aquifer type and space availability, and selecting the least energy-intensive solution for a given legal and socio-cultural context.

Kurzfassung (Deutsch)

Wiederverwendetes Abwasser wird in steigendem Maße als mögliche alternative Wasserressource für diverse Brauch- oder Bewässerungsanwendungen betrachtet. Dabei ist eine der Hauptfragen, welche Wasserqualität für welche Anwendung benötigt wird. Für den Fall eines saisonal schwankenden Wasserbedarfs ist auch die Frage der Wasserspeicherung von großer Wichtigkeit. Grundwasseranreicherung kann eine Lösung für viele Anwendungen, wie beispielsweise die indirekte Nutzung für Bewässerung in der Landwirtschaft oder im urbanen Raum, für den Aufbau von Salzwasserintrusionsbarrieren, für die Unterstützung des Landschaftswasserhaushaltes und andere Brauchwasseranwendungen sein. Bislang stützen sich die meisten Grundwasseranreicherungssysteme mit gereinigtem Abwasser auf Hochdruckmembranen oder mehrstufige Membransysteme in Kombination mit weitergehenden Oxidationsverfahren. Wenn jedoch keine Trinkwasserverwendung angestrebt wird, ist die Versickerung von weitergehend gereinigtem Abwasser möglich, wie dies auch bereits durch Gesetze verschiedener Staaten vorgesehen ist.

Im vorliegenden Bericht wird die Leistungsfähigkeit von verschiedenen Hybrid-Desinfektions- / Filtrations- und Infiltrationssystemen im Vergleich zu unter ähnlichen Bedingungen arbeitenden Hochdruckmembranen abgeschätzt. Aus bekannten Desinfektions- und Filtrationstechnologien wurden fünf Behandlungskombinationen ausgewählt – Kombinationen aus Ozon- oder UV Behandlung mit Sandfiltern oder Ultrafiltrationsmembranen, die einer Infiltration oder Injektion vorgeschaltet sind – und einem Doppelmembransystem gegenübergestellt. Auf der Basis einer Literaturrecherche zu weltweit typischen Ablaufqualitäten von Kläranlagen wurde ein Modellabwasser als Eingangsqualität für diese Konzeptstudie definiert. Gesetze und Richtlinien der WHO, der US-EPA und aus Australien wurden berücksichtigt, um die anzustrebende Wasserqualität zu definieren. Eine geringe Zielkonzentration an suspendierten Stoffen (10 mg/L) und mikrobiologischer Indikatorparameter (fäkale coliforme Keime 1 /100 mL) macht eine umfangreiche Desinfektion und Partikelentfernung notwendig. Eine vergleichende Ökobilanz (Life-Cycle-Analysis, LCA) basierte auf einer hypothetischen Fallstudie einer 50,000-PE Wasserwiederverwendungsanlage im Abstrom einer konventionellen Kläranlage.

Alle fünf vorgeschlagenen Behandlungskombinationen können qualitative hochwertiges Brauch- oder Bewässerungswasser zur Verfügung stellen, und die Kombination von Desinfektion, Filtration und Untergrundpassage erwies sich als eine effiziente Möglichkeit, suspendierte Stoffe, den CSB und mikrobiologische Kontaminationen zu reduzieren. Die Umweltwirkung der Behandlungskombinationen wurde verglichen bezüglich CO_2-Emmission aber auch im Hinblick auf Energiebedarf, Humantoxizität, Versauerungswirkung und Flächenverbrauch. Sowohl der Energieverbrauch also auch die CO_2-Emmissionen stellte sich für die betrachteten Hybridsysteme im Vergleich zu einem zweistufigen Membranverfahren als deutlich geringer heraus. Zusätzlich ergibt sich der Vorteil eines saisonalen Mengenpuffers. Hindernisse sind noch im Bereich der Gesetzgebung und der öffentlichen Akzeptanz zu berücksichtigen.

Die vorliegende Konzeptstudie zeigt das Potential von Hybridlösungen, qualitative hochwertiges Brauch- und Bewässerungswasser für die Grundwasseranreicherung und spätere Wiederverwendung zu nutzen. Ein Portfolio von Lösungen wird vorgeschlagen um verschiedene Ziele der weiteren Nutzung zu erfüllen. Um die Auswahl zu erleichtern wurde schließlich ein Entscheidungsbaum entwickelt, der die Vor- und Nachteile berücksichtigt sowie die Art der Wiederverwendung, den Aquifertyp sowie die Flächenverfügbarkeit um die optimale Lösung im Hinblick auf den Energieverbrauch innerhalb eines bestimmten gesetzgeberischen und sozio-ökonomischen Rahmens auszuwählen.

Résumé (Français)

La réutilisation des eaux usées est de plus en plus considérée comme une source d'eau alternative envisageable pour divers usages non potables. Parmi les enjeux les plus importants, la définition de la qualité de l'eau pour chaque type de réutilisation est primordiale. Si la demande pour l'eau récupérée est saisonnière, alors la question du stockage de l'eau récupérée paraît également essentielle. La recharge de nappes à des fins de réutilisation non potable peut offrir une solution aux nombreuses applications de récupération finale, comme l'irrigation indirecte des cultures agricoles ou des paysages, la mise en *place* de barrières de confinement contre les intrusions salines, comme solution contre le risque d'affaissement ou pour la réalimentation des aquifères, par exemple. La plupart des applications de recharge de nappes avec des eaux traitées utilisent jusqu'ici essentiellement des systèmes à membrane haute pression ou à double membrane combinés à des processus d'oxydation avancée. Toutefois, si l'objectif est la réutilisation non potable, ou bien la réalimentation d'une nappe menacée, une recharge d'aquifère avec de l'eau non potable de bonne qualité est une solution envisageable, comme le reconnait déjà la législation dans plusieurs pays.

Dans ce rapport, la performance des dispositifs hybrides de désinfection/filtration et de recharge est comparée à celle d'un système à membrane haute pression fonctionnant dans des conditions analogues. Parmi toutes les techniques de désinfection et de filtration disponibles, cinq procédés de traitement ont été retenus – des combinaisons de traitement à l'ozone ou aux ultraviolets avec des filtres à sable ou des membranes UF avant l'infiltration ou injection finale – et comparés à un système à double membrane (UF+NF). Dans cette étude conceptuelle, un effluent secondaire (ES) synthétique a été défini après un examen approfondi de la littérature existante sur les qualités des effluents types de stations d'épuration dans le monde. Les principales directives de l'OMS et textes législatifs de l'Agence de protection de l'environnement américaine (US-EPA) et de l'Australie ont servis de base pour définir la qualité d'eau recherchée pour ces dispositifs de traitement hybrides. Une valeur cible faible de matières en suspension (10 mg/l) et de contaminants microbiologiques (coliformes fécaux 1 /100 ml) présupposent des modalités de désinfection et de filtration poussées. Les dispositifs proposés ont été retenus après un examen approfondi des performances d'élimination des polluants dans la littérature. Afin de réaliser une analyse du cycle de vie des divers procédés d'épuration, des hypothèses analogues ont servies de point de départ pour tous les cas de figure dans l'étude d'une installation hypothétique de réutilisation d'eaux usées de 50 000 PE en aval d'une station d'épuration d'eaux résiduaires conventionnelle.

Les cinq combinaisons de traitement proposées sont susceptibles de produire des eaux d'irrigation et sanitaire de très bonne qualité. La combinaison de désinfection, filtration et passage souterrain s'est avérée efficace pour éliminer les matières en suspension, la demande biochimique en oxygène (DBO) résiduelle et les contaminants microbiologiques. L'impact environnemental des procédés de traitement a été évalué par rapport à l'empreinte carbonique, mais aussi à la consommation d'énergie, à la toxicité humaine, aux effets d'acidification et d'utilisation des terres. Tant la consommation énergétique que l'empreinte carbonique des systèmes hybrides se sont révélées considérablement inférieures en comparaison avec un dispositif à membrane double, sans compter qu'ils offrent une solution de stockage saisonnier dans la nappe supplémentaire. Ainsi, il y a une marge significative pour réduire l'impact environnemental, la demande en énergie et les coûts d'exploitation, si la qualité de l'eau non potable est suffisante pour être réutilisée. Cependant le contexte juridique et l'acceptabilité sociale peuvent faire obstacle à ce projet de réemploi d'eaux usées traitées pour recharger les aquifères. Cette étude conceptuelle démontre le potentiel des solutions hybrides pour la production d'eau non potable de bonne qualité pour la réalimentation des aquifères et réemploi ultérieur. Un éventail de solutions est proposé

pour satisfaire aux exigences des différents usages non potables visés. Un arbre de décision récapitule les avantages et inconvénients en fonction de l'objectif de réutilisation, du type d'aquifère, de l'espace disponible afin de faciliter le choix de procédés de traitement, et d'opter pour la solution la moins énergivore et la mieux adaptée au contexte juridique et socio-culturel.

Content

Chapter 1
Introduction

1.2 Scope and focus of this report

This report concludes a conceptual study carried out within the project "Oximar" which addresses the combination of disinfection/oxidation solutions and Managed Aquifer Recharge (MAR) for wastewater reuse. Managed Aquifer Recharge may indeed offer an interesting storage solution for further reuse, especially for countries with low land availability and high evaporation losses. In the context of climate change and increasing pressure on water resources, wastewater reuse and its sustainable storage could be indeed a solution to address water stress challenges.

The purpose of this document is to investigate which "hybrid" solutions – involving a disinfection step, a filtration step and finally aquifer recharge (see Fig. 1) – may be technically and economically sound for water reuse involving MAR. Thus, it is built as a sequence of key questions and answers rather than an extensive manuscript-like report. In total, **19 questions are addressed in detail**.

In the following, a "hybrid scheme" (or "hybrid solution") is understood, in opposition to high-energy membrane solutions, as the association of a disinfection and filtration step with aquifer storage for a further use of the recharged water. Different solutions can be envisaged depending on the technology used, and will be the object of in-depth discussions hereafter.

This document should provide a scientific basis for discussing the relevance of hybrid solutions. It reviews different possible treatment trains for non-potable reuse and compares them in terms of energy efficiency, environmental impact and other local constraints, in order to provide recommendations for their implementation.

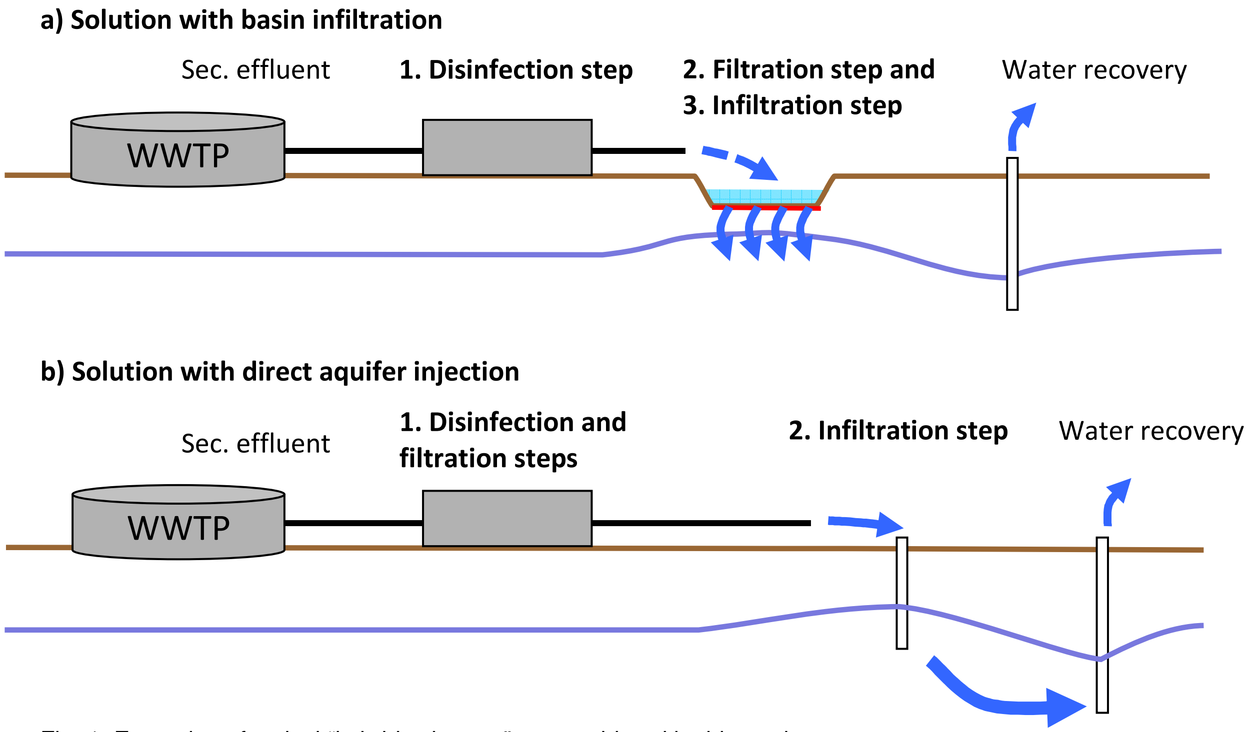


Fig. 1: Examples of typical "hybrid schemes" as considered in this study.

1.3 Structure and keys to this report

This report is structured in different thematic sections: while Chapter 2 focuses on the scientific and technical discussion for selecting relevant hybrid treatment trains, Chapter 3 proposes a comparison of the selected solutions and of possible alternatives, with recommendations for given local conditions. Chapter 4 concludes this report with some questions that remain open and final conclusive remarks.

Following symbols are used to help the user of this report finding relevant information:

- this bullet point precedes *general statements and definitions*. These are then used in the following answers of the report.

- this bullet point precedes *useful recommendations or conclusions*. They indicate information that may support the implementation of given water reuse solutions.
- this bullet point is related to *additional information* written in *BOXES*. In general, this information is useful to detail some particular points of interest, and it usually goes somewhat beyond the addressed question or topic.

➲**Q** this symbol is a *cross-reference to another question of this report*, where the corresponding issue is addressed in detail.

Chapter 2
Framework for the implementation of hybrid solutions

2.1 Water quality and water reuse in the context of this study

Q1. What source water quality for reuse was considered?

The source water quality considered here is Secondary Effluent (SE) from municipal Wastewater Treatment Plants (WWTP), not disinfected prior to reuse. This water is supposed to have been treated mechanically and biologically, without tertiary filtration. Within this study, as a conservative approach, no nutrient removal at the WWTP is considered.

A survey of SE qualities was done for selected countries of all continents (Fig. 2). Quality parameters for SE differ sometimes by a factor 4 or 5 (Total Suspend Solids - TSS, Chemical Oxygen Demand - COD), or even 30 (Biochemical Oxygen Demand after 5 days – BOD_5). Even among developed countries, the SE quality parameters may differ significantly (e.g. Germany vs. Spain). There are also notable differences between developed countries and emerging countries (e.g. Germany vs. Tunisia or Bolivia). However, due to the various different treatments worldwide, and to the limited availability of information for some countries, these figures should rather be considered as indicative than as real benchmarks.

Based on this global survey, and to follow a conservative approach, the statistical 75^{th}-percentile of the collected data is used in the following as input SE – influent for the reuse schemes (Table 1).

Table 1: Treated Wastewater quality parameters as calculated from the global survey (rounded numbers). Turbidity was back-calculated from TSS for the sake of consistency with other parameters.

	EC µS/cm	TSS mg/L	Turb. NTU	DOC mg/L	COD mg/L	BOD_5 mg/L	N-NH_4 mg/L	N-NO_3 mg/L	P-PO_4 mg/L	TCF n/100mL	E.Coli n/100mL
Median	1700	14	6	13	53	14	5	6	2	2.10^5	4.10^4
75^{th} ile	**2000**	**19**	**9**	**16**	**61**	**19**	**7**	**9**	**6**	**5.10^5**	**10^5**
Max.	2500	34	16	19	297	61	10	16	9	7.10^5	2.10^5

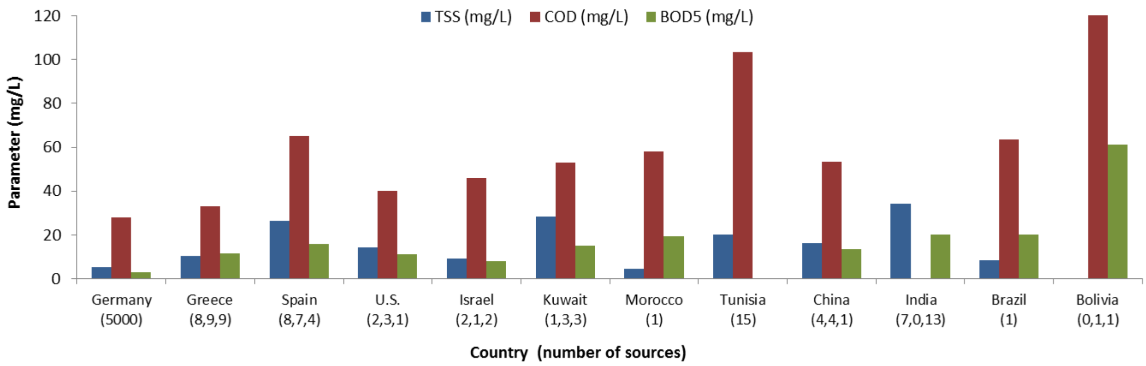


Fig. 2: Global survey of some Secondary Effluent quality parameters.

Q2. What final reuse applications were considered?

In this study, all non-potable reuses of Secondary Effluent (SE, ➲**Q1**) except industrial reuses are considered, i.e.:

- *Non- potable urban* reuses like street cleaning, toilet flushing,
- *Agriculture irrigation*,
- *Environmental and recreational irrigation* and *landscaping.*

Many authors consider groundwater recharge as an additional category at the same global reuse level (USEPA 2004; Friedler, Lahav et al. 2006; Hochstrat, Wintgens et al. 2008), however groundwater recharge is usually not a final objective *per se*, but only a way to store water prior to further reuse after pumping. This is the current definition for groundwater recharge (for further reuse) adopted in the present report. As for classification, we will consider groundwater recharge as an application of environmental reuse here, although the final water use may be urban or agricultural (see Table 2).

Potable reuse is not considered in this project because of a very stringent regulation, imposing energy-intensive and high-end treatment schemes. Industrial reuse, though possible using hybrid schemes, is not considered because of the very specific requirements for industrial processes, which should be considered on a case-by-case study. Based on a large survey of different literature sources on reuse, the reuse applications considered are listed in Table 2. However, rather than final reuse application, usually it is the water quality for given reuse applications which will be the limiting factor for a given treatment solution (see also ➲**Q4**).

Table 2: Main water reuse categories considered for this study, and examples of applications (Davis and Hirji 2003; Wintgens, Melin et al. 2005; Bixio, Thoeye et al. 2006; Friedler, Lahav et al. 2006; Asano, Burton et al. 2007; WHO 2007; Hochstrat, Wintgens et al. 2008; Huertas, Salgot et al. 2008). As indicated, groundwater recharge may concern other reuse applications.

Category	Application	Examples
Urban	Unrestricted/High contact	Air conditioning, fire fighting, toilet flushing, *park irrigation, car wash, sidewalks, snow melting**
	Restricted/Low-medium contact	
	Controlled access	Subsurface irrigation
Agriculture	Unrestricted/High contact	Vegetables, orchards
	Low-medium contact, processed food	Cereals
	No contact, non-food crops	Sylviculture, turf, cotton, energy crops
	Crops for animal feeding	Pasture/fodder for dairy and grazing animals without withholding period
Environment and recreational	Unrestricted/Incidental and full-body contact	Golf courses, bathing and recreational ponds/streams
	No primary contact	Fountains, aesthetic ponds, snow making, *wetlands, marshes, streams**
	Restricted/No contact	
	Non-potable aquifer recharge	Groundwater replenishment, saltwater intrusion control, land subsidence control, *all other abovementioned, non-potable reuses*

**applications in italics* may be unrestricted or partially restricted, depending on the degree of exposure of the general population and/or workers.

Q3. What recurrent parameters are mentioned in the main reuse guidelines?

The main purpose of this project is to evaluate the feasibility of recharging treated wastewater to aquifers for further reuse. While reuse guidelines and legislations exist only in selected countries, guidelines for groundwater recharge with reclaimed water are even rarer. Some examples include the U.S.-states of California, Florida and Washington (USEPA 2004), the Australian state of Tasmania (GWI 2012), China (Feng 2008) and Mexico (GWI 2012). However, in most of the cases, the standards are set on a case-by-case approach (USEPA 2012), which is not helpful for a global assessment of the feasibility of recharge.

Due to the lack of existing guidelines or regulations on *groundwater recharge with reclaimed water*, it was chosen here to use the guidelines or regulations for the intended application, as suggested e.g. by (Aertgeerts and Angelakis 2003). It must be underlined that:

- the respect of guidelines or legislation *for the final reuse application* does not guarantee that *permits to infiltrate reclaimed water will be issued*;
- recharge of reclaimed water should *never jeopardize groundwater resources*.

As stated by the USEPA, groundwater recharge for non-potable reuse, especially with infiltration systems (spreading basins, percolation ponds, infiltration basins) is generally *allowed by most state regulations even for relatively low quality water (i.e., secondary treatment with basic disinfection) based on the fact that these systems have a proven ability to provide additional treatment* (USEPA 2012). Within the project OXIMAR, *the highest non-potable reuse quality is targeted*, thus maximising the chances to get infiltration permits. Moreover, several recharge applications may even need water of relatively poor quality to prevent an even more dramatic evolution (e.g. saltwater intrusion control, subsidence mitigation, sustainment of endangered river flow, etc.).

The WHO “Guidelines for the safe use of wastewater, excreta and greywater” (WHO 2007), the American guidelines (California 2001, Florida 1999-2002, national guidelines 2004) and Australian guidelines (EPA Victoria 2002; EPA Queensland 2005) are often considered as references for wastewater reuse (Asano 1998; USEPA 2004; Asano, Burton et al. 2007). In addition to these three generally accepted guidelines, the Chinese guidelines (2002-2005) were also considered, due to the significance of this country (Feng 2008). Although reuse is an ancient practice, all the above-mentioned guidelines and legislations were issued in the past decade. The comparison of these major guidelines shows that the main considered parameters are:

- Particulate pollution, assessed by the *Total Suspended Solids* (TSS) or *turbidity*;
- Biological pollution, assessed mainly by the *Biochemical Oxygen Demand* after 5 days (BOD_5), or sometimes by the *Chemical Oxygen Demand* (COD);
- Microbiological contaminants, assessed by *Total Coliforms* or *Faecal Coliforms*.

Other parameters are considered in some national or state legislation, but there is to date no international consensus on additional quality parameters (*BOX 1*).

- In a first approach, based on similarities in legislation, it seems thus sufficient to consider only *TSS/Turbidity*, *BOD_5* and *Faecal Coliforms* to assess the reclaimed water quality compliance with legislation.

Box 1: Other parameters included in guidelines or legislations

Several country legislations stipulate specific thresholds for additional quality parameters. However, these are often inconsistent from one country to another, which is the reason why there were not considered in a first step. Other main parameters include – but are not limited to (Asano 1998; USEPA 2004; DWA 2008; Angelakis 2012; GWI 2012):

- *helminths and viruses* (WHO, France, Morocco, Saudi Arabia, Tunisia, United Arab Emirates, AUS-Queensland),
- *TDS/salts* (Egypt, Morocco, Tunisia, China, AUS-Queensland),
- *nutrients* (Italy, Egypt, Tunisia, China, Korea, US-Florida),
- *heavy metals* (Greece, Italy, Poland, Egypt, Kuwait, Saudi Arabia, Tunisia, United Arab Emirates, China, Korea, Mexico),
- *pesticides* (Egypt, Mexico).

Due to the numerous legislations, the evaluation of these parameters must be carried out on a case-by-case approach. Moreover, additional aspects such as recommended processes/technologies, monitoring, distance from wells or public area may sometimes be included in recommendations.

Q4. What quality classes can be derived from the main guidelines?

Based on the main legislations on reuse worldwide (➲**Q3**), it was obvious that, irrespectively of the final reuse application (urban, agriculture etc.), groups (or clusters) of water qualities could be identified. As discussed earlier, it seems to be more relevant to discuss water quality classes than end use categories.

Depending on the legislation, up to 3 or 4 groups of water qualities can be defined. These groups “I-II-III” correspond more or less to the quality groups “A-B-C” as defined in many legislations. An additional “Group IV” was added to take into account some legislations on crops for animal feed, as in Queensland’s guidelines (water of quality “D”) (EPA Queensland 2005). The water reuse quality groups and the corresponding quality thresholds are given in Table 3 and Table 4 respectively. Potable reuse is not mentioned and would require higher water quality than the proposed “Group I”.

Table 3: Main non- potable water reuse groups considered for this study, and examples of applications. The quality groups are derived from the US, Australian and Chinese legislations.

Group	Category	Application
Group I (unrestricted non-potable reuse)	**Urban**	Unrestricted/High contact/ Incidental and full-body contact
	Agriculture	
	Environment and recreational	
	Groundwater recharge	Potable aquifer
Group II (restricted non-potable reuse)	**Urban**	Restricted/Low-medium or no primary contact/ Processed food
	Agriculture	
	Environment and recreational	
	Groundwater recharge	Non-potable aquifer
Group III (highly restricted non-potable reuse)	**Urban**	Controlled access/ Restricted/No contact/ Non-food crops
	Agriculture	
	Environment and recreational	
Group IV (animal feed)	**Agriculture**	Crops for animal feeding

Table 4: Maximal acceptable concentrations for selected parameters in reclaimed water according to the water reuse group. The quality groups are derived from the US, Australian and Chinese legislations.

Group	TSS (mg/L)	Turbidity (NTU)	BOD_5 (mg/L)	Fecal CF (n/100mL)
Group I	10	5	20	1
Group II	30	10	30	200
Group III	30	10	30	1,000
Group IV	-	-	-	10,000

2.2 Pre-requisites for aquifer recharge

Q5. What aquifer conditions are favourable for managed aquifer recharge?

Suitable subsurface properties are the major pre-requisite to any managed aquifer recharge (MAR) project. This includes, among others (Gale 2005):

- Hydrogeological properties of the aquifer and of overlying formations,
- Depth to aquifer and aquifer thickness,
- Aquifer mineralogy/texture,
- Groundwater quality.

There are no general guidelines available for selecting an aquifer recharge site. However, some lessons have been learned from experiences:

- Aquifer recharge is relevant for permeable subsurface, and thus mostly concerns sandy unconsolidated aquifers. According to a survey within the project TECHNEAU, typical hydraulic conductivities (K_f values) of recharge sites range from 10^{-3} to 10^{-2} m/s (Grützmacher, Hülshoff et al. 2009). In case of confined aquifers, recharge is only possible though injection wells (USEPA 2012). Very careful management needs to be provided in case of fractured hard rock and carbonate aquifers, which may provide fast pathways for pollutants (Gale 2005).

- In general, aquifer recharge is possible even at great depths, however for depths below 100-200m the recovery of water may be economically inefficient (approx. 0.5-1.0 kWh/m^3 energy for pumping (Staub 2011), which is in the range of magnitude of brackish water desalination for instance). In general, aquifer thicknesses do not exceed 100m for most recharge sites (Grützmacher, Hülshoff et al. 2009). The existence of a vadose zone is required to eliminate most efficiently organic pollutants, especially dissolved organic carbon (DOC) (Sharma, Harun et al. 2008).

- Concerning aquifer mineralogy and texture, the abovementioned criteria for hydrogeological properties limit aquifer recharge mostly to sand or sand-gravel subsurfaces (Grützmacher, Hülshoff et al. 2009), although lime karst grounds or fractured rocks may also be used. In terms of aquifer treatment, poorly graded sand, pure silica sand and silty sand were found to have less DOC removal efficiency, while sandy loam showed better removal efficiencies (Sharma, Harun et al. 2008).

Q6. What type of treatment is necessary to fulfil the requirements for recharge of reclaimed water?

As presented in ➲**Q4**, groundwater recharge is expected to require high-quality water that could be used in any unrestricted reuse applications. This is due to the fact that recharge with reclaimed water should never degrade the groundwater quality (Aertgeerts and Angelakis 2003). In some countries, specific legislation may even require water fulfilling the drinking water quality standards. On the contrary, countries facing acute saltwater intrusion or other groundwater problems may accept water of poorer quality for aquifer recharge.

Here, based on the main legislations on reuse worldwide, a "Group I" water quality is targeted. Table 5 summarizes the influent quality and target effluent quality according to Group I and, for information, Group II quality.

According to this first assessment, *disinfection* of raw secondary effluent alone is not sufficient for recharging the aquifer, a further reduction of *TSS/turbidity* is at least required. Moreover, a further reduction of BOD_5 could be necessary since the level in secondary effluent is just reaching the target level.

Box 2 additionally shows some technical constraints that must be taken into account for the design and operation of reuse treatment trains. According to what is usually defined as "tertiary treatment", the hybrid treatment trains within the project OXIMAR can be assimilated to *tertiary treatment* prior to *aquifer recharge for wastewater reuse*.

Table 5: Comparison of influent water quality (Table 1), target quality (Table 4) and necessary removal efficiency for selected parameters.

Group	TSS (mg/L)	Turbidity (NTU)	BOD_5 (mg/L)	Fecal CF (n/100mL)
Influent quality	20	9	19	10^6
Group I target	**10**	**5**	**20**	**1**
Req. reduction	*50%*	*45%*	*0%*	*5 logs*
Group II target	**30**	**10**	**30**	**200**
Req. reduction	*0%*	*0%*	*0%*	*3 logs*

Box 2: Technical constraints for selected treatment steps and technologies

Apart from the regulative constraints, technical constraints also influence the choice of reuse treatment steps. In particular,

- *for injection wells*, in general a water of very high quality is required. As an example, at the Bolivar site in Australia, the TSS contents is below 6 mg/L and BOD below 3 mg/L (AQUAREC 2006). Similar water qualities are recommended for *slow sand filters* (Thouement 2012). On the other hand, *infiltration ponds* are less influenced by the quality of the water to be infiltrated, but it has of course an impact on clogging effects and the necessary cleaning frequency.
- *for disinfection*, high suspended solids concentration lower the disinfection efficiency. Thus, it is recommended to be below 10 mg/L TSS. However, other parameters such as BOD do not significantly influence the disinfection efficiency (EPA Victoria (2002)).

Thus, these technical recommendations need also to be considered, especially for long-term operation and maintenance of given treatment trains.

Based on these results, the considered hybrid treatment train is supposed to satisfy three basic “functions” to fulfil the desired water quality (➲**Q4**), namely:

- *Disinfection* for at least a 5 log units removal of fecal coliforms;
- *Filtration* for at least a reduction of 50% of the suspended load;
- *Subsuface/aquifer storage* for later reuse of secondary-treated wastewater.

The final water quality is to be fit for unrestricted reuse. Since the objective of the project is to evaluate the feasibility of reuse options with low energy intensity, to achieve these goals following treatment technologies were considered as part of a portfolio of processes and technologies:

- For *disinfection*: Ozone and UV disinfection;
- For *filtration*: Sand filters (granular media filtration) and membrane filtration;
- For *subsurface storage*: subsurface passage treatment processes (short term and long-term subsurface passage).

Other more technology-intensive solutions will be later compared to these solutions, however the project focuses rather on affordable (lower cost), alternative solutions than on high-technology solutions.

2.3 Treatment efficiencies of tertiary treatment steps

Q7. What are the typical pollutant removal efficiencies of tertiary steps?

The typical pollutant removal efficiencies of the different treatment steps were assessed on the basis of a large literature review, and on experts' review. The collection of data from the literature followed the following methodology:

- Collection of experimental data from water reclamation plants for Secondary Effluent (case studies based on highly treated SE were discarded);
- Comparison of the collected experimental values with ranges provided by previous studies and further examination of outliers (often explained by optimized conditions or technical issues, thus discarded);
- Selection of the **rounded lowest experimental value** (conservative approach) to characterize the potential removal efficiency of a technology for one parameter;
- Confrontation of the collected data to the review of experts from different Veolia divisions (correction and completion of the table).

The choice to use the **lowest of the experimental values collected** aims to reduce the impact of the technologies used, as the design of the treatment and other technical parameters might have an influence on the removal efficiencies. Table 6 is thus providing *conservative values*. Different experts from Veolia divisions reviewed and validated the table. The German Association of Water and Waste Utilities DWA made a similar collection of removal efficiencies, which is well in line with the results of this study (DWA 2008).

The main conclusions of this survey are:

- Sand filters offer mostly *particle removal*, but *poor disinfection*;
- Subsurface passage offers *particle removal* and removes some *organic matter* while offering a *fair degree of disinfection*; its *performance is quite similar to low-energy membranes* (MF/UF);
- Disinfection is quite complementary to filtration or subsurface passage to increase the *microbiological removal*; it should be noted here that only disinfection doses have been considered, but ozone and UV may be used for oxidation purposes;
- High-energy membranes (NF/RO) offer the *most complete removal of pollutants*, with the additional possibility to treat *water with high salinity*.

Table 6: Summary of minimum treatment / pollutant removal efficiencies for the considered treatment steps on Secondary Effluent. Green values are removal efficiencies higher than 80% or 4 Ulog, red values are below 40% or 2 Ulog (thresholds defined just for visualization purposes).

Parameter Removal unit	TSS %	Turb. %	BOD_5 %	COD %	DOC %	FCF Ulog	Viruses Ulog
Sand filters							
Rapid Sand Filter	40	45	0	0	0	1	0
Slow Sand Filter	50	50	0	50	30	2	2
Infiltration-percolation	65	65	50	35	50	3	2
Subsurface passage							
Short-term MAR (<2 months)	90	90	50	80	50	4	4
Lomg-term MAR (>6 months)	90	90	80	70	75	4	3
Disinfection							
Ozonation	0	0	0	0	0	3	3
Ultraviolet	0	0	0	0	0	3	2
Membranes							
Micro Filtration (MF)	95	95	75	75	0	2	2
Ultra Filtration (UF)	95	95	80	80	0	4	2
NF/MF or NF/UF	95	95	80	80	90	4	3
RO/MF or RO/UF	95	95	80	80	95	6	5
Activated carbon							
Actiflo® Carb	80	80	30	30	30	1	1
Granulated AC filter	80	80	30	35	50	2	1

Q8. How complementary is disinfection / oxidation with filtration?

The complementarity of disinfection with a further filtration and/or subsurface passage has been investigated in detail in the project OXIRED carried out by KWB. On the whole, disinfection and especially oxidation enhance the biodegradability of dissolved organic carbon (DOC) and removes some trace organics (Amy, Carlson et al. 2006). The combination of oxidation and subsurface passage is particularly promising for several – but not all – trace organics (Miehe, Hinz et al. 2009; Miehe, Staub et al. 2011). While disinfection / oxidation enhances biodegradability of given compounds and decreases drastically the microbiological load, filtration / subsurface passage degrades the biodegradable compounds and filters the remaining particulate matter.

Moreover, the technical advantage of disinfecting water prior to injection is that it is expected to limit bacterial regrowth and thus algal blooms and fouling. This allows:

- Higher flow rates for filters and infiltration ponds, reducing their land footprint;
- Thinner clogging layers ("schmutzdecke") on the top of the filters or ponds, which saves operational expenditures

The abovementioned were validated with oxidation, however, it is expected that disinfection may also have, to a smaller extent, comparable positive effects for infiltration systems. Additionally, thanks to the disinfection, a better public acceptance and regulation compliance is expected.

→ *Please refer also to D1.1b of the project OXIRED-1 (Miehe, Hinz et al. 2009) and to D3.4 of the project OXIRED-2 (Miehe, Staub et al. 2011) for further information about the benefits of combined oxidation and aquifer recharge*

Q9. Which technologies can achieve high-quality non-potable water?

Estimates of the water quality reachable with several combinations of technologies suggested by the OXIMAR technical committee were calculated, based on the assessment of pollutant removal efficiencies for several treatment steps (Table 6). The combinations of treatment steps were then evaluated with regard to the final water quality for the quality groups. Table 7 shows the result of this evaluation.

Table 7: Summary of compliance (✓) or non-compliance (✗) for the reuse quality groups I-III with a typical wastewater input (75th-ile, see Table 1). Quality group IV was not shown for concision.

Quality compliance	**Treatment steps or combination of treatment steps**				
	Sand filters and Subsurface passage				
	SSF	RSF	S-T SP	L-T SP	I-P
Group I	✗	✗	✗	✗	✗
Group II	✗	✗	✓	✓	✓
	Disinfection		***Membranes***		
	O_3	UV	MF	UF	UF+NF
Group I	✗	✗	✗	✓ *	✓
Group II	✓ **	✓ **	✗	✓	✓
	Disinfection with Sand filters or Subsurface passage***				
	Dis+SSF	Dis+RSF	Dis+S-T SP	Dis+L-T SP	Dis+I-P
Group I	✓	✗	✓	✓	✓
Group II	✓	✓	✓	✓	✓
	Membranes or Activated carbon and Subsurface passage				
	UF+S-T SP	UF+I-P	Dis+AFC+I-P	Dis+RSF+GAC	
Group I	✓	✓	✓	✓	
Group II	✓	✓	✓	✓	

*assuming no membrane failure
**however, limit values for TSS and turbidity, because they are not removed
***similar conclusions for both disinfection technologies, Ozone and Ultraviolet

SSF: slow sand filter, RSF: rapid sand filter, S-T SP: short-term subsurface passage, L-T SP: long-term subsurface passage, I-P: infiltration percolation, O_3: ozonation, UV: ultraviolet, MF: microfiltration membrane, UF: ultrafiltration membrane, NF: nanofiltration membrane or low-pressure RO, Dis: disinfection, AFC: Actiflo® Carb, GAC: granular activated carbon.

In most cases, the microbiological pathogen removal was the limiting factor, explaining why disinfection methods performed better than most granular filtration systems. In this study, only treatment trains obtaining water quality matching the Group I (unrestricted reuse, as described in ➲**Q4**) were selected. Thus, sand filters, disinfection alone, simple membrane filtration or rapid sand filters (RSF) combined with disinfection could not be considered (✕ in Table 7).

In total, five treatment trains were selected based on these results (#1-5). The combination of treatment steps (i.e. treatment trains) enabling a Group I reclaimed water quality are listed in Table 8. Additional treatment trains including

- a high-pressure membrane (#6) (typical high-end reuse solution);
- two solutions involving ozone disinfection and activated carbon: an Actiflo® Carb system (#7) and a rapid sand filter followed by a granulated activated carbon filter (#8).

are also included for illustration purpose in the assessment. However, only treatment train #6 was assessed in detail in the life-cycle assessment, while treatment trains #7-8 were only assessed roughly using indirect calculations (deductions from other LCA results) and expert validation.

Table 8: Final selection of the treatment trains. Please note that treatment train #6 is given for comparison, but provides higher quality water, and that it does not include aquifer recharge / storage.

Treatment train	Filtration	Disinfection	Storage	Water quality
#1	Infiltration pond	O_3 (+infiltration pond)	Aquifer (via vadose z.)	Group I
#2	UF + screening	UF	Aquifer (direct)	Group I
#3	SSF	O_3 (+SSF)	Aquifer (direct)	Group I
#4	UF + infiltration pond	UF	Aquifer (via vadose z.)	Group I
#5	Infiltration pond	UV (+infiltration pond)	Aquifer (via vadose z.)	Group I
#6	UF + NF*	UF (+NF*)	NO STORAGE, Direct reuse	Better than Group I
#7	Actiflo® Carb	O_3 (+infiltration pond)	Aquifer (via vadose z.)	Better than Group I
#8	RSF + GAC	O_3 (+GAC)	Aquifer (direct)	Better than Group I

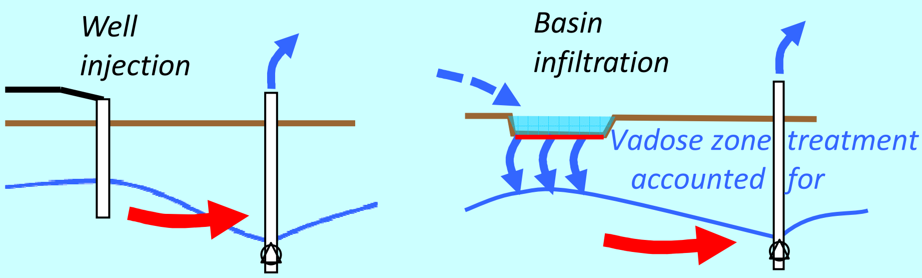
*NF or low-pressure RO.

It must be underlined at this stage that, in order to provide conservative conclusions regarding health hazards, the additional treatment in the saturated aquifer is not considered and the final water quality is considered when the water *reaches the aquifer* (*BOX 3*). Indeed, this additional treatment is specific to the nature of the subsurface and total travel time, and cannot be considered always fully reliable (Aertgeerts and Angelakis 2003).

The comparison of treatment trains #1-5 with treatment #6 is given only for illustration purpose. While treatment trains #1-5 can be assimilated as tertiary treatments, *treatment train #6 is a quaternary treatment*, resulting in a higher final water quality.

BOX 3: TREATMENT IN THE VADOSE ZONE AND TREATMENT IN THE AQUIFER

In the following, the treatment occurring in the aquifer is neglected (subsurface passage within the saturated aquifer), and the treatment occurring in a recharge system using infiltration ponds is assumed of the same quality than in infiltration-percolation systems. In this approach, the potential negative impacts of the aquifer (notably dissolution of salts) are also neglected. Mixing, dilution, are not considered either.



Aquifer treatment not included in the assessment (additional benefits)

Chapter 3
Comparative assessment of hybrid solutions

3.1 Methodology for the comparative assessment

Q10. What tool is used to compare the different treatment trains?

To compare the different hybrid solutions, a life-cycle assessment was conducted. Life-cycle assessment (LCA) is a normalized method to quantify various environmental impacts of a process or product. LCA enables to monitor all impacts of a given process and avoid the shift of environmental burdens to other elements of the environment and to other geographic areas. The life cycle of a system is the "consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (ISO 14040 2006).

Applied to water and wastewater systems, the LCA evaluates the different stages of the life of the plant (mainly construction, use and decommissioning) and includes the linked activities, such as electricity production, transport and chemicals used (Renou 2006). For assessing the life-cycle impacts of a given process, indicators are used – here, only climate change (carbon footprint), human toxicity and terrestrial acidification are presented. The LCA of the hybrid treatment trains is assessed using the software "umberto®" by IFU Hamburg, which enables to describe in detail processes for assessing their life-cycle impacts. The considered emission factors as presented in this report are the VWS&T emission factors used for the Carbon Footprint assessments within the Veolia group.

Additionally to LCA indicators, the land footprint (m^2/m^3) and the energy intensity (kWh/m^3) of the different treatment trains will be assessed.

→ *Please refer also to the MSc. Thesis of Héloïse Thouement (Thouement 2012) for further information on the different environmental impacts of the treatment trains*

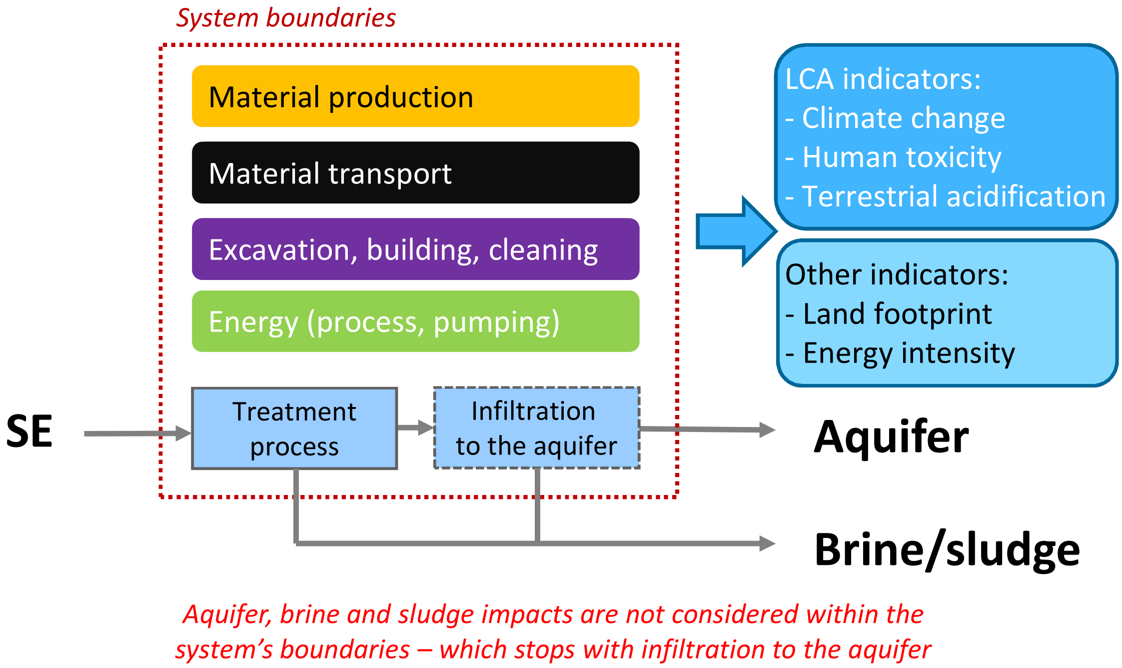


Fig. 3: Energy demand of the selected hybrid solutions.

Q11. What are the operating conditions of the hypothetical case study?

Due to the expected market for the Mediterranean region, a hypothetical case study was proposed in accordance with the project's Technical Committee members with following characteristics:

- Case study located in *Morocco* – this choice impacts the emission factors as well as the distances for raw and engineered material supply (the impact of choosing another similar location have been discussed by (Thouement 2012) for Tunisia;
- Plant size of *50,000 PE*, thus the considered design wastewater flow is 6,250 m^3/d (2.3 Mm^3/y) based on a 125 L/day/PE wastewater generation;
- Wastewater quality based on the 75th percentile of the Secondary Effluent quality review performed (➲**Q1**), as listed in Table 1 (TSS: 19 mg/L, Turbidity: 9 NTU, BOD_5: 19 mg/L, Faecal Coliforms: 1.10^5/100 mL);
- The considered treatment trains have been listed in ➲**Q9** and are the following:
  - *Ozone disinfection* combined with aquifer recharge with *infiltration ponds* (#1) or *slow sand filtration and direct aquifer injection* (#3);
  - *Ultrafiltration* combined with *direct aquifer injection* (#2) or aquifer recharge via *infiltration ponds* (#4);
  - *Ultraviolet disinfection* combined with aquifer recharge via *infiltration ponds* (#5);
  - *Ultrafiltration* combined with *Nanofiltration* (or low-pressure Reverse osmosis) for direct reuse (#6).

  As discussed earlier, treatment trains #7-8, which involve the use of activated carbon, have not been assessed by the detailed LCA, but only roughly using indirect calculations (deductions from other LCA results) and expert validation.

Q12. What are the main design parameters for the hypothetical case study?

The hypothetical case study consists of a tertiary water reclamation and aquifer recharge facility next to an existing wastewater treatment plant. The possibility to recharge the aquifer and sufficient land availability are taken for granted.

Most of the parameters were estimated from the literature or expert feedback at KWB and within the Veolia Group. More detail to all the different parameters can be found in (Thouement 2012).

- The main design parameters of the *treatment steps* are given in Table 9.

Table 9: Main design parameters of the treatments steps for the detailed LCA.

Treatment step unit	Lifetime	Flow*	Number of units	Energy**	Other	
Ozonation unit	15 y	6250 m³/d (100% flow recov.)	1 O_3 generator	0.19 kWh/m³	O_3 dose: 0.6 mg/mg of DOC	
Ultraviolet lamps	3 y		49 UV lamps	0.05 kWh/m³	UV dose: 1000 J/m²	
UF membrane units	7 y	57 m³/d/module (90% flow recov.)	217 modules	0.17 kWh/m³	Coagulant used: $FeCl_3$ Cleaning agents: NaOH, H_2SO_4, NaOCl, HCl, Citric acid, Tenside	
NF membrane units	7 y	13 m³/d/module (90% flow recov.)	391 modules	0.65 kWh/m³		
Slow sand filters	20 y	2.4 m/d infiltration rate	4 SSF (+1 backup)	-	Filter thickness: 1 m, tot. surface 2,600 m² Cleaning frequency: 12 times/year	
Infiltration ponds	30 y	0.43-0.86 m/d infiltration rate	4 IP (+2 for rotations)	-	Sand layer: 0.30 m, tot. surface 1.3-2.8 ha Cleaning frequency: 2-6 times/year***	
Injection wells	30 y (pump: 12 y)	1265-1563 m³/d	4 wells	0.02 kWh/m³	Pump TDH: 4m	Well depth: 20 m Well diameter: 10”
Recovery wells				0.11 kWh/m³	Pump TDH: 25m	

O_3: ozone, UV: ultraviolet, IP: infiltration pond, UF: ultrafiltration membrane, SSF: slow sand filter, NF: nanofiltration membrane.
*flow recovery is also indicated whenever relevant, i.e. the percentage of inflow that can be reclaimed at the outflow of the unit. Membranes do not enable full flow recovery because of backwashing.
**per cube meter reclaimed water.
***sand cleaned on site using a sand washing machine.

→ *Please refer also to the MSc. Thesis of Héloïse Thouement (Thouement 2012) for further information on the design parameters*

3.2 Results of the comparative assessment

Q13. What is the energy demand of selected hybrid solutions?

Additionally to the LCA, the energy demand of the selected treatment trains was assessed. For a better comparison, it was normalized to the cubic meter of reclaimed water at the plant's outflow. Fig. 4 shows the results for the analysed treatment trains. The energy related to pumping was displayed separately.

- The energy demand of the treatment trains #1-4 and #7-8 is approximately 0.20-0.25 kWh/m³, *up to 5 times less than combined Ultrafiltration and Nanofiltration* (#6). The combination of UV with infiltration ponds (#5) reaches even lower energy demand levels with 0.08 kWh/m³.

- It is noteworthy that *water pumping from the recharged aquifer* can increase significantly the energy demand of the treatment trains. Here, a 25 m pump total dynamic head was considered (Table 9), and the wells' energy demand may amount to up to 30% (#1-4) or even 60% of the total energy demand (#5). Thus, storing the water into deep aquifers will not be economically favourable compared to using more shallow or surface water resources.

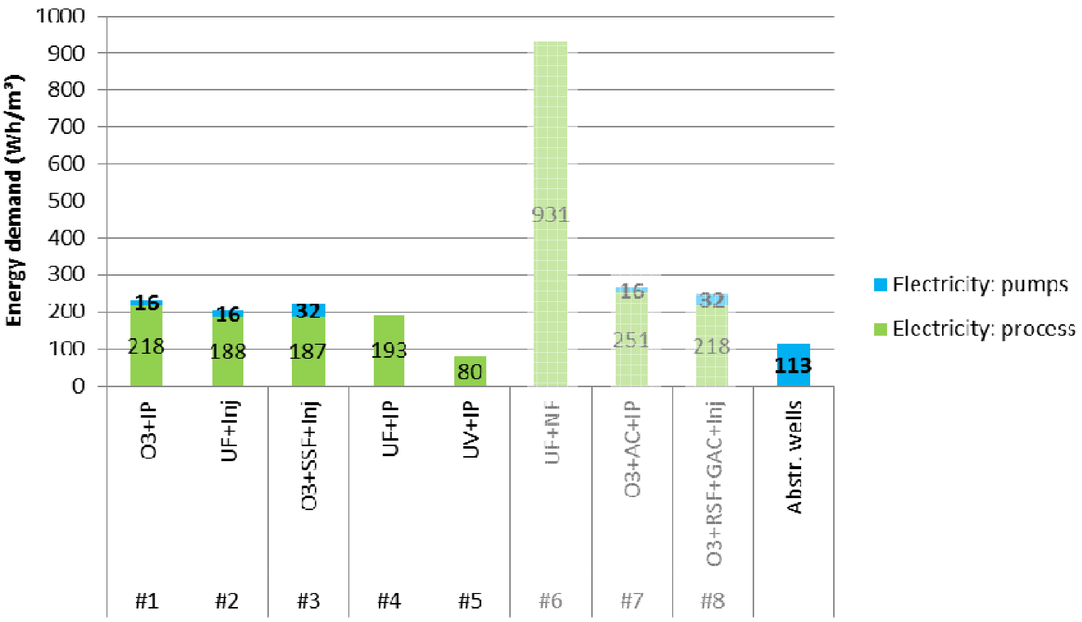


Fig. 4: Energy demand of the selected hybrid solutions.

Fig. 5 shows the results of the hybrid treatment schemes in comparison with other data from the literature (Sala and Serra 2004; Pearce 2008; Vince, Aoustin et al. 2008; Dillon, Pavelic et al. 2009; Argo, Veerapaneni et al. 2010; Godskesen, Hauschild et al. 2012; Ihara, Ueyama et al. 2012).

In comparison to other water supply or reuse options, the results are quite promising: while surface water is less energy demanding due to the absence of pumping, **recharging reclaimed water may be more economical than abstracting deep groundwater, and it is in any case more economical than brackish water or seawater desalination.** The energy demand of the Orange County Water District "Water Factory 21", a typical example of high-tech reuse for groundwater recharge and saltwater intrusion, is given as example – and well above the energy demand of the hybrid schemes (Argo, Veerapaneni et al. 2010).

The results however need to be interpreted carefully, since literature sources may not consider the same boundary conditions as considered within the study of the hybrid treatment trains (e.g. aquifer depth). In particular, groundwater abstraction from shallow aquifers, if involving no treatment, can be more energy-efficient than wastewater reuse for managed aquifer recharge.

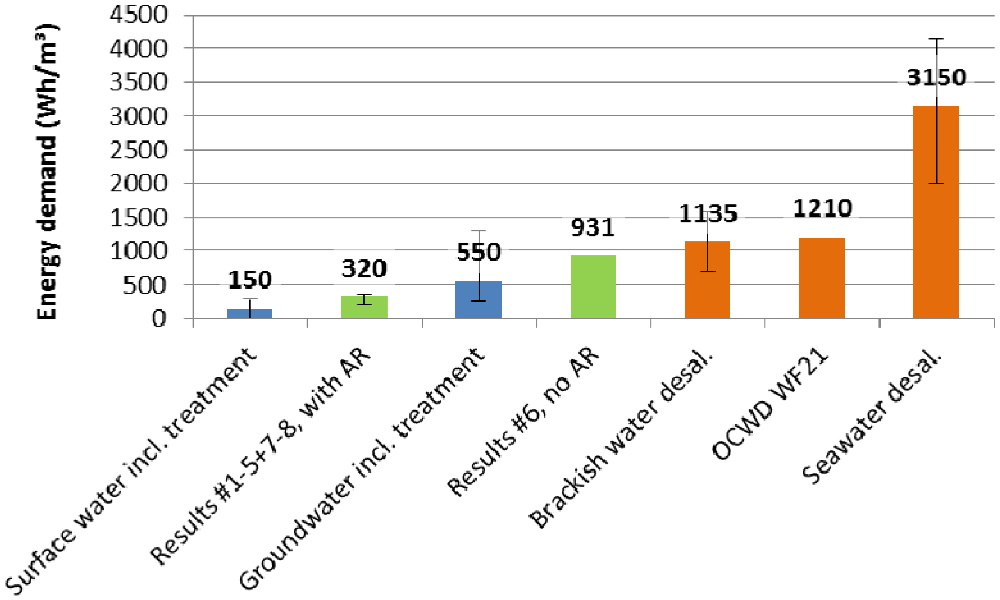


Fig. 5: Comparison of energy demands for selected water supply options.

Q14. What is the carbon footprint of selected hybrid solutions?

Within the life-cycle assessment (➲**Q10**), the carbon footprint of the hybrid treatment trains is assessed using the software "umberto®". As described earlier, the considered emission factors were taken from the VWS&T emission database. Fig. 6 shows the equivalents CO_2 life-cycle emissions of the selected treatment trains. Please note that these results apply to a given setting, and may not be applicable to other context (water quality, geographical parameters…). It is noteworthy that:

- *Most hybrid treatment trains have comparable CO_2 emissions* of around 0.20 kg CO_2eq/m³, with UV disinfection and infiltration (#5) being the less CO_2-emittent (around 0.1 kg CO_2eq/m³). Nanofiltration (#6) increases the CO_2 emissions 3-5 fold (around 0.7 kg CO_2eq/m³).

- *Electricity* is clearly the dominant factor for CO_2 emissions related to these treatment trains. It represents 70-75% of the total life-cycle carbon footprint of the treatment trains, except for UV disinfection and infiltration (#5) where it represents only 51% of the total carbon footprint, and Nanofiltration (#6), with 94% of life-cycle emissions.

- *Construction* is also an important CO_2-emitting source for the treatment trains with infiltration ponds (#1, #4 and #5) – up to 46% for UV disinfection and infiltration (#5). *Chemicals* represent also a significant source of CO_2 emissions for the treatment trains involving membranes (#2, #4 and #6).

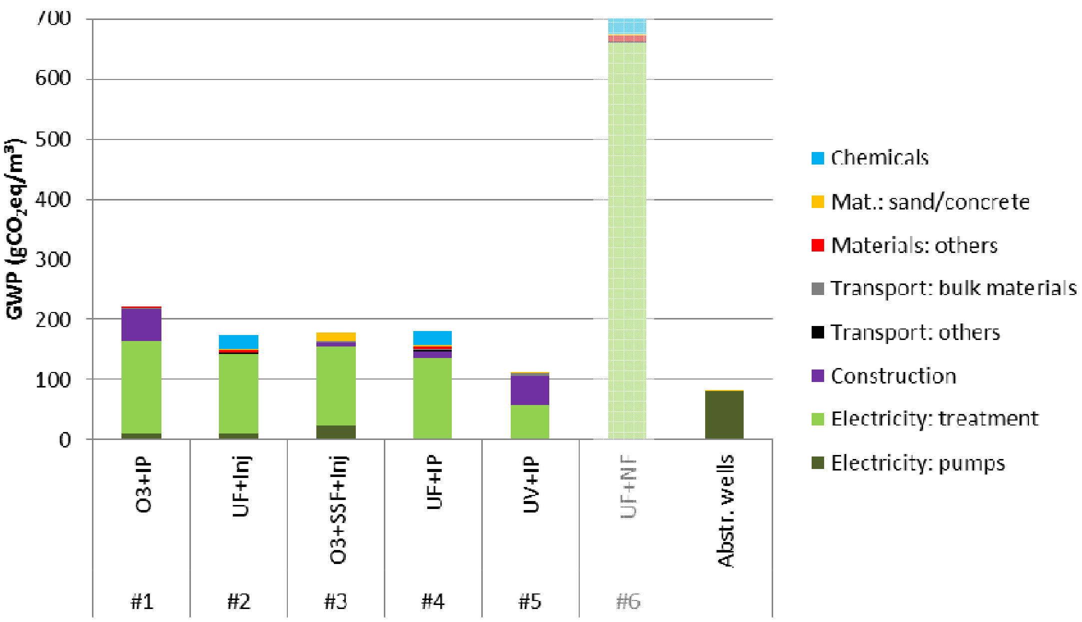


Fig. 6: Global warming potential (CO_2-equivalent emissions) of the selected hybrid solutions. Treatment trains #7-8 are not included, as no detailed LCA was performed.

When water abstraction is included, on average, the hybrid treatment schemes had an emission of 253 gCO_2eq/m³ for #1-5. A rough assessment gives emission estimates for solutions with activated carbon (#7-8) of 350-400 gCO_2eq/m³. Although life-cycle assessments cannot be compared between different locations (due to, e.g., different water qualities and emission factors), it can be said that these values are very comparable to the emissions related to groundwater abstraction for drinking water (280 gCO_2eq/m³ after (Godskesen, Hauschild et al. 2012)), and well below the emissions related to sea water desalination (1950-2460 gCO_2eq/m³ after (Muñoz, Rodríguez et al. 2009; Godskesen, Hauschild et al. 2012).

Q15. What are the other environmental impacts of selected hybrid solutions?

The software “umberto®” enables to describe other life-cycle impacts of processes in addition to the carbon footprint. Among these, human toxicity and acidification potential were considered, to limit the analysis to two indicators that could be interpreted at the operational level.

To compare the relative impacts of climate change, human toxicity and acidification, it is possible to normalize the impacts to the average yearly impacts of a population equivalent (PE) – expressed in milli-PE-year per cube meter of reclaimed water (mPE*a/m³). Fig. 7 shows the normalized emission of the selected treatment trains. Again, please note that these results apply to a given setting, and may not be applicable to other context (water quality, geographical parameters…). It is noteworthy that:

- *The order of magnitude of all impacts is low*, since it represents less than 1/10000 of a population equivalent per cubic meter (<0.1 mPE*a/m³). With a plant design flow of 2.28 Mm³/y, this would mean an annual impact of up to 50 PE for most treatment trains (#1-5), and 150 PE for the Nanofiltration treatment train.
- *The Acidification potential* is highly correlated with the energy demand and thus with the *Climate change impact*. Again, from an environmental point of view, solutions with a lower energy demand should be preferred.
- *The Human toxicity impact* is related to the use of chemicals, and it even surpasses the other impacts for some of the treatment trains involving membranes (#2 and #4). Thus, the impact of chemicals, though not important for the carbon footprint, is nevertheless significant.

Additionally, Fig. 8 shows the land footprint of each proposed scheme. If space availability is an issue, solutions involving membranes (#2 and #6) or slow sand filters (#3) should be preferred. On the whole, highly urbanized areas may anyway not be the primary target of hybrid reuse schemes, which will probably choose high-technology, high-energy demanding equipment providing reclaimed water of potable quality.

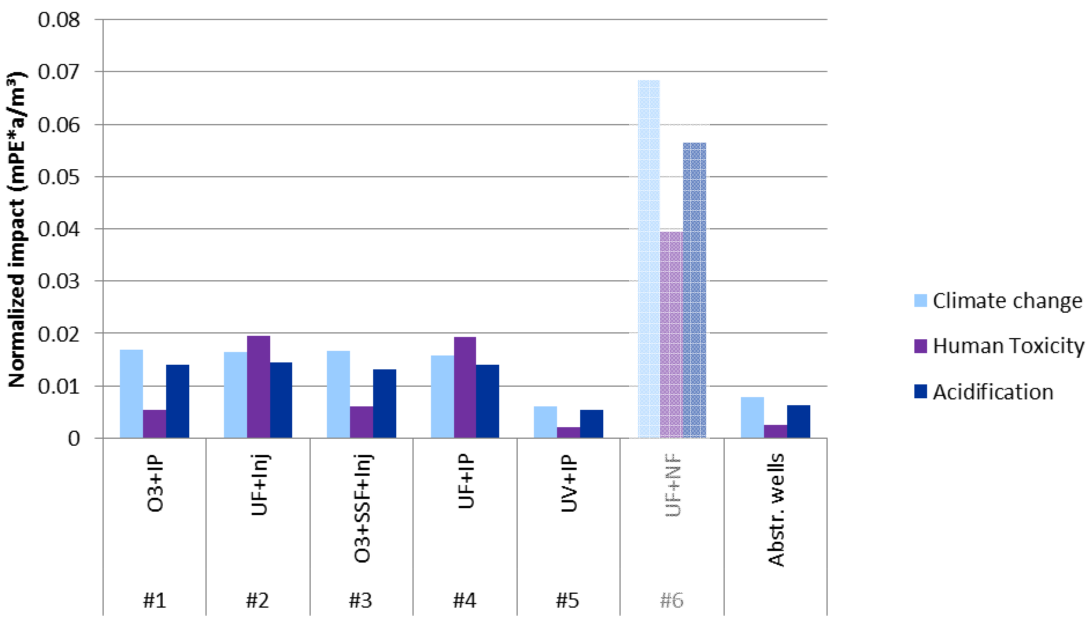


Fig. 7: Normalized Climate change, Human toxicity and Acidification impacts of the selected hybrid solutions. Treatment trains #7-8 are not included, as no detailed LCA was performed.

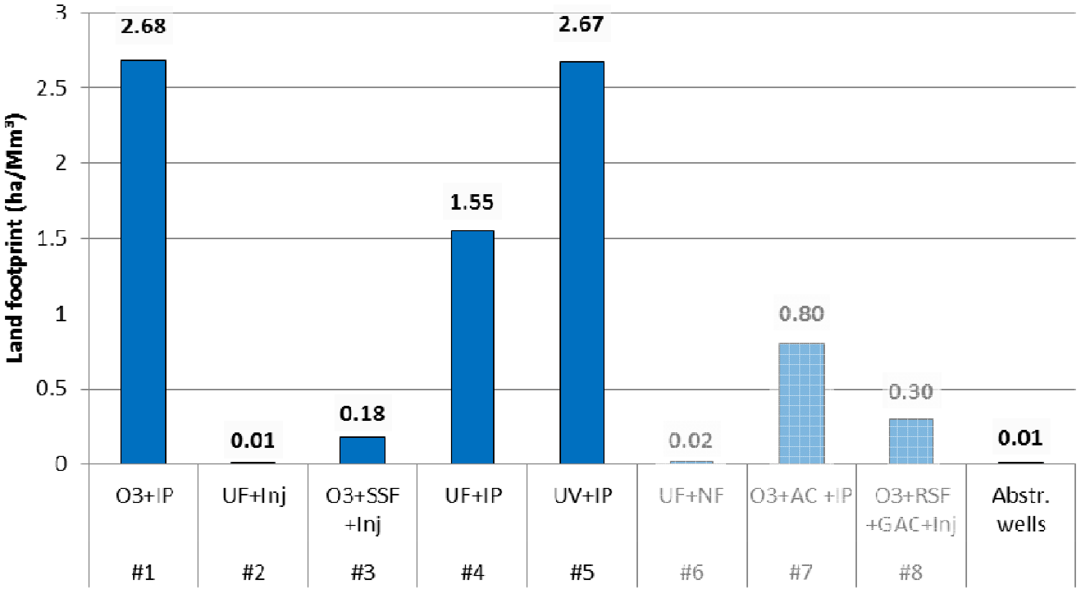


Fig. 8: Specific land footprint of the selected hybrid solutions.

→ *Please refer also to the MSc. Thesis of Héloïse Thouement (Thouement 2012) for further information on the different environmental impacts of the treatment trains*

Q16. What are the strengths and weaknesses of the selected hybrid solutions – and where could they be recommended?

The different treatment trains were already compared in terms of energy intensity, carbon footprint, human toxicity impact, acidification potential and land footprint. Additionally, they can be evaluated with respect to their possibility to provide advanced trace organics removal. To support the decision process, a simplified decision-tree is proposed in Fig. 9. Given the fact that the objective should be to minimize operational costs and environmental footprint (considered as a base condition), the main variables that influence decision from the operator side are:

- The final water quality – if indirect potable reuse via aquifer recharge is targeted, then *high-tech schemes* should be chosen;
- The necessity to remove trace organics – which is possible with treatment trains including *Ozonation, Nanofiltration* units or *Activated Carbon* systems, or other high-tech alternatives;
- Space availability – if it is an issue, *membrane solutions* or more *compact filters* (SSF) should be preferred.

Table 10 summarizes advantages and disadvantages of the investigated schemes and a comparison to some alternative high-tech schemes. The portfolio of solutions can be widened to these alternatives, or even other combinations, in order to satisfy the local needs and quality requirements.

Advanced solutions involving high-pressure membranes (#6), ozonation and Actiflo® Carb (#7), RSF and activated carbon (#8) have been proposed. In general, they obtain excellent water qualities, but it must be however noted that they involve much more technology than most of the proposed hybrid treatment trains. These are actually quaternary treatment steps, and thus cannot be directly compared to the hybrid schemes #1-5.

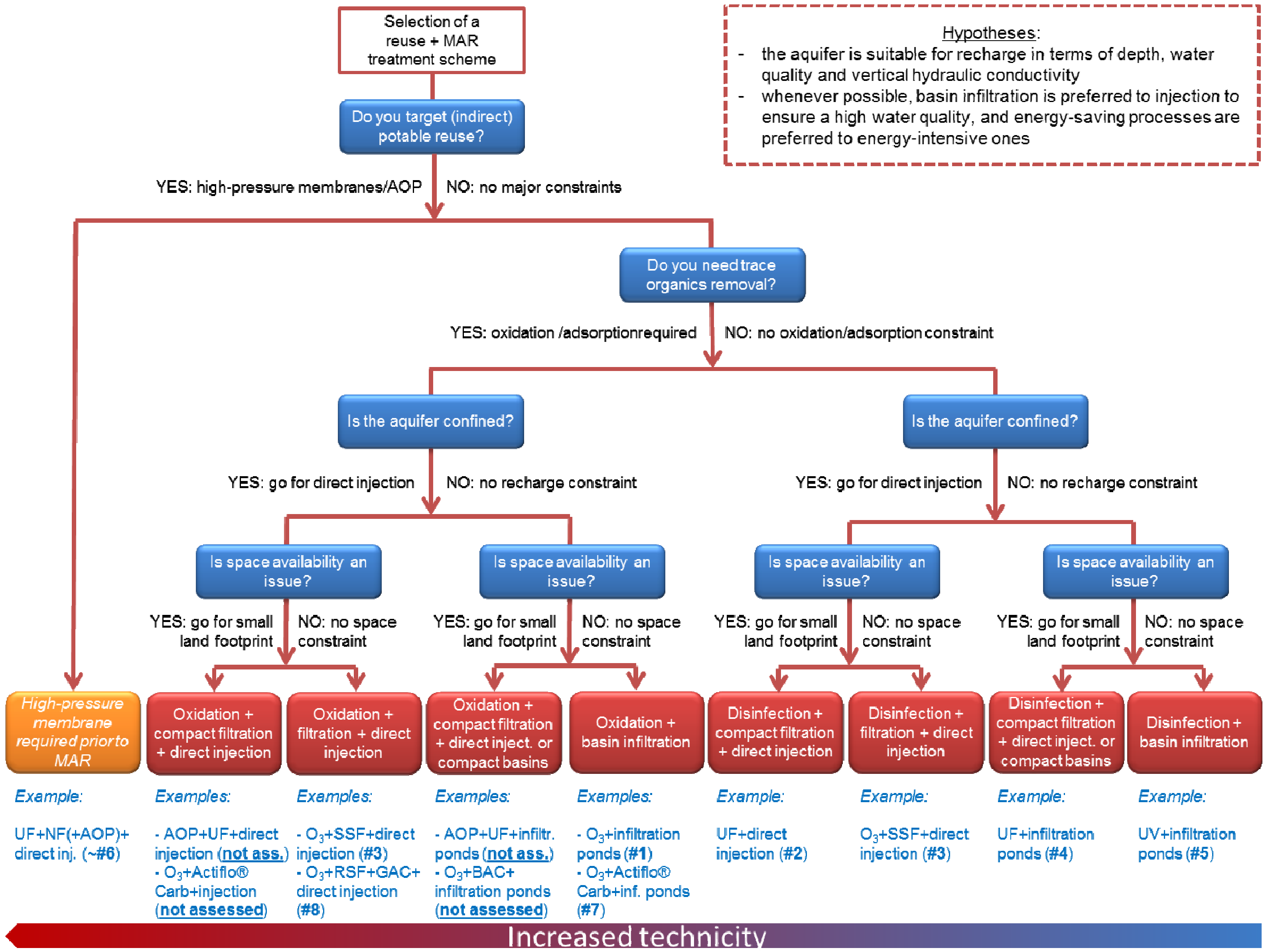


Fig. 9: Proposed simplified decision-tree for selecting treatment trains.

Table 10: Summary of strengths (+) and weaknesses (-) of the selected treatment trains and additional alternatives.

	Treatment trains and alternatives	LCA carbon footprint	LCA human toxicity	Energy demand	Land footprint	Tr. organics removal	Additional issues
Core OXIMAR hybrid schemes	**#1 (O_3 + infiltration ponds)**	+	+	+	-	+	Possible by-products issue Low BOD and COD removal
	#2 (UF + direct injection)	+	+/-	+	++	-	No vadose zone treatment Sludge disposal
	#3 (O_3 + SSF + direct injection)	+	+	+	+	+	No vadose zone treatment Possible by-products issue Low BOD and COD removal Possible clogging at injection well
	#4 (UF + infiltration ponds)	+	+/-	+	+/-	-	Best final water quality (amongst #1-5) Sludge disposal
	#5 (UV + infiltration ponds)	+	++	++	-	-	Low BOD and COD removal
Other OXIMAR options	**#6 (UF + NF)**	-	-	-	++	++	Excellent final water quality Brine disposal Expensive alternative, no storage
	#7 (O_3 + Actiflo® Carb + infiltration ponds)	+/-*	-*	+*	+/-*	++*	Excellent final water quality Higher Carbon footprint (PAC) Sludge disposal
	#8 (O_3 + RSF + GAC + direct injection)	+/-*	+*	+*	++*	++*	Excellent final water quality No vadose zone treatment

UV: ultraviolet, UF: ultrafiltration membrane, SSF: slow sand filter, NF: nanofiltration membrane, O_3: ozonation, RSF: rapide sand filter, GAC: granulated activated carbon.
*source: personal communications of KWB and VERI experts.

Chapter 4
Open questions, summary and conclusions

4.1 Possible drawbacks of hybrid solutions and open questions

Q17. What are the main limitations of the proposed hybrid solutions?

The proposed hybrid solutions associate disinfection, filtration and infiltration of secondary effluent. Despite their relevance and competiveness, following limitations must be underlined:

- Hybrid solutions cannot be used when the salt contents is too high, there NF/RO should be recommended, as the only technologies capable of desalting water.
- Most of the proposed solutions offer only a limited removal of BOD, COD, other nutrients and DOC, trace organics or heavy metals. If there is specific concern on one of these parameters, additional investigations are required. Treatment trains involving activated carbon or high-pressure membranes could help to achieve these additional criteria.
- Prior to recharging an aquifer, an in-depth study and modelling of the subsurface should be conducted. The infiltration potential should not be overestimated, and not evaluated only for the first meters of the subsurface. Moreover, the clogging rate needs to be assessed with care.
- The proposed hybrid schemes highly depend on source water quality and aquifer properties. This makes it difficult to export a return of experience to another different setting, and every solution will need to be tailor-made.
- Most of the treatment steps require limited engineering (in contrast to high-end membranes or disinfection systems), however the competencies required for operating such a plant should not be underestimated, and may sometimes be difficult to find among local personnel. In particular, the operation of recharge wells or the monitoring of groundwater quality are critical points.

Q18. What can be the drawbacks of recharging reclaimed water?

The recharge of reclaimed water to an aquifer may have, under given circumstances, negative effects and potentially lead to the contamination of freshwater aquifers. For instance,

- Some countries exhibit high salt contents in wastewater. This water should only be recharged if salts have been removed by an adequate step, since salts cannot be eliminated by the aquifer.
- Care must be given not to accumulate nutrients, salts, metals or other pollutants in the vicinity of the recharge zone, and to propose an adequate elimination of the residual pollution or dismantlement of the recharge ponds at decommissioning.
- In some areas, such as South Florida and Southern California, naturally occurring arsenic-containing minerals in the aquifer matrix may leach into the groundwater due to changes in oxidation-reduction potential (ORP) during injection, storage, and recovery of water (USEPA 2012). Similar can be said of Iron and

Manganese, which can be present in important concentrations in aquifers. Thus, aquifer mineralogy should be monitored with care for incompatibilities with the source water.

- For direct injection to a highly permeable aquifer, such as the Biscayne Aquifer in South Florida, additional nutrient limits that are stricter than those required for typical direct injection should be set (USEPA 2012). The nutrient requirements address the potential impacts to nearby surface waters, such as rivers, lakes, canals, and wetlands that are hydrologically connected and supported by the aquifer.

In general, the recharge of reclaimed water should of course never jeopardize the initial water quality (Aertgeerts and Angelakis 2003). Although aquifer recharge may have drawbacks, one should however not forget that it may have significant “side benefits” like supplying water to the vegetation, supporting the base flow of rivers, prevent saltwater intrusion or ground subsidence – and the latters may also be a primary goal of infiltration of reclaimed water.

Q19. Why is a demonstration site indispensable and what should it prove?

(At least) two key issues claim for a large-scale demonstration pilot of hybrid solutions:

- The present study is based only on theoretical considerations and on an extensive review of literature and expert’s points of view. Although very detailed investigations have been made, and safety factors have been considered concerning the pollutant removal efficiencies, the real operation of such hybrid treatment trains is subject to challenging conditions, variable pollutant loads and possible failure of treatment systems.
- As indicated as one of the possible drawbacks of hybrid solutions, these can be only “tailor-made” and are highly site-specific (➲**Q17**). In particular, aquifer suitability for recharge of reclaimed water is a critical point.

4.2 Summary and recommendations

On the basis of extensive literature reviews and expert discussions, the proposed hybrid treatment trains for wastewater oxidation/disinfection, filtration and infiltration have proven to be able to deliver high-quality, suitable for most of the non-potable reuses. Moreover, they are expected to be competitive in terms of energy demand and environmental impacts compared to high-technology solutions or alternative water sources (brackish water, seawater or even possibly groundwater).

When assessing the relevance of reuse involving aquifer recharge, one should also not forget the main benefit of water reuse, which enables to virtually augment water resources at a given location – besides from other less-quantifiable benefits like public health improvement, aquatic ecosystem restoration, and local economic development. Moreover, the proposed concept includes a sustainable and long-term storage of reclaimed water for further reuse using aquifers.

In this report, recommendations have been issued to support the implementation of solutions and help identify:

- when these solutions may be considered as alternatives to other reuse schemes,
- under which circumstances they may be more energy-efficient than high-tech solutions, if hybrid solutions already fulfill quality requirements,
- which solutions could be proposed for given settings and local conditions (necessity to provide oxidation, aquifer nature, space availability).

This report validated the concept of hybrid solutions for reuse involving managed aquifer recharge. A large portfolio of solutions was proposed, ranging from low-tech to high-tech schemes for aquifer recharge and recovery of the reclaimed water. The marketability of this concept should however still be evaluated worldwide.

Chapter 5
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