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Risk management and environmental benefits of a prospective system for indirect potable reuse of municipal wastewater in France

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ABSTRACT

This paper presents the assessment of a planned scheme of indirect potable reuse (IPR) in the Vendée region of France in its potential risks for human health and ecosystems, and also in its overall environmental impacts. Methods of risk assessment (quantitative microbial and chemical risk assessment) and life cycle assessment (LCA) are used to characterize the risk associated with the use of reclaimed water for IPR, but also the environmental benefits compared with other options for additional drinking water supply. The LCA results show that IPR is competitive with other options of water supply in its energy demand and greenhouse gas emissions. Pathogens as the main health hazard are controlled effectively by existing and planned preventive measures. For chemicals the number of potentially relevant substances could be reduced substantially by the assessment. A demonstrator phase should now be implemented to validate the outcomes of this prospective assessment by improving data quality of the initial state and by monitoring effective impacts in an operating mode.

Key words | chemical risk assessment, environmental impacts, indirect potable reuse, life cycle assessment, quantitative microbial risk assessment

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INTRODUCTION

In France, indirect potable reuse (IPR) of municipal wastewater has not been realized in practice so far, and there are no specific regulations in place to guide operators and regulators during its implementation (Sanz & Gawlik 2014), especially concerning the mitigation of potential hazards for human health or ecosystems. Hence, starting the implementation of IPR schemes in France requires a transparent dialogue with local regulators and the general public to promote IPR and prove that an adequate risk management is in place which controls potential risks for human health and the environment to an acceptable level.

This study presents the methods and results of this process for the region of Vendée. Situated on the Atlantic Coast, this region exhibits high water demand in summer due to extensive touristic activity. The entire region relies on surface water reservoirs for drinking water production, which are fed by small rivers with very low or even zero discharge in late summer. For the reservoir of Le Jaunay, dry years have led to low water levels and related threats of water shortages. Hence, alternative sources of future water supply have been assessed, namely water imports via pipeline, seasonal storage of water in an old mining quarry to augment the reservoir in summer, seawater desalination, and IPR of municipal wastewater treatment plant (WWTP) effluent after tertiary treatment and pumping to the reservoir (Figure 1). Technical details of reuse trains A and B are available in the full project report (Seis & Remy 2016). Vendée Eau is the local non-profit public body in charge

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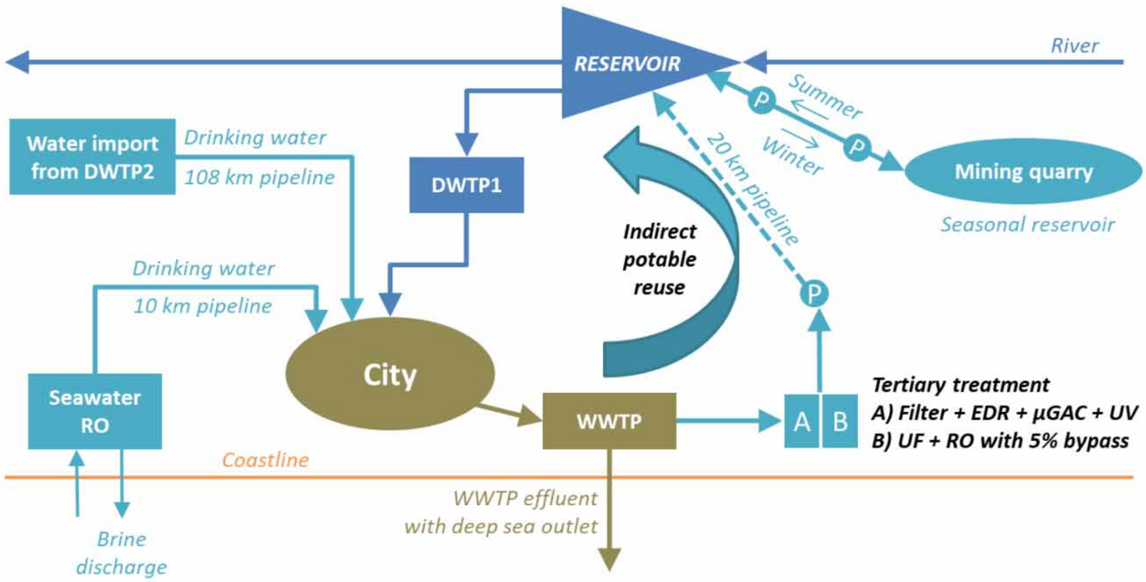

Figure 1 | Situation at the reuse site: regular drinking water supply from the reservoir with drinking water treatment plant (DWTP1) and options for augmenting water supply in summer (importing from DWTP2, seasonal storage in mining quarry, seawater reverse osmosis (RO), indirect potable reuse with process train A or B using filtration, reverse electrodialysis (EDR), micro-granular activated carbon (µGAC) and UV treatment (train A) or ultrafiltration (UF) and reverse osmosis (RO) with 5% bypass (train B)).

of the water supply for 264 of the 267 municipalities in the Vendée region. Within the EU demonstration project DEMOWARE (www.demoware.eu, FP7 #619040), the case study of Vendée Eau was elaborated as an example of how the technical development of this 'greenfield' site for IPR can be supported by risk and environmental assessment.

Recent studies in the literature have reported on life cycle assessment (LCA) of water reuse trains (e.g. Carré *et al.* 2017; Schoen *et al.* 2017) and microbial risk assessment of water reuse and IPR (e.g. Barker *et al.* 2013; Amha *et al.* 2015). However, IPR has not been assessed so far with an integrated system perspective, using both LCA and chemical and microbial risk assessment to analyze and compare different reuse alternatives, including also the environmental compartment (reservoir) and final drinking water treatment. Hence, the present study provides valuable experience in applying these tools for a prospective IPR system in the planning process (i.e. using a limited amount of data) and in a context where regulatory requirements are lacking.

MATERIALS AND METHODS

Risk assessment was applied to the two IPR scenarios depending on two different options for tertiary treatment, subsequent pumping of the treated water into the reservoir, and final drinking water treatment. Building on existing data from three monitoring campaigns for hygienic parameters as well as organic and inorganic pollutants, a quantitative estimation of the hygienic and environmental risk was conducted. Given the small available data set of only three measurements per substance and parameter, the use of complex models for chemical and microbial behavior within the environmental buffer is not justified. Instead, simple but transparent assessment strategies have been given preference with worst case and realistic but conservative assumptions as a way to cope with existing uncertainties. More details of the assessment can also be found in the project report (Seis & Remy 2016).

Chemical risk assessment

A single substance approach was applied for chemical risk assessment of organic pollutants, following the European Union Technical Guidance Document for risk assessment of new and existing substances (TGD). Risk for freshwater organisms and human health is expressed in terms of risk quotients (RQ), stating the ratio between an endpoint specific benchmark and predicted substance concentration. Benchmark values were collected from the literature (see Supporting Information (SI) Tables 1–3, available with the online version of this paper). If more than one potential benchmark was found, both have been used for the assessment and compared.

Following previous studies (Etchepare & van der Hoek 2015), preference has been given to existing legally binding limit values. If these are not available, benchmarks based on toxicological information are derived or – if these are not available – default precautionary values are used. For environmental endpoints, values for predicted no-effect concentrations (PNEC) are used as benchmarks. Since short-term chronic effects of emerging compounds are considered unlikely, chemical risk assessment was based on an estimation of the average effluent concentration. To implement a realistic but conservative scenario, the upper bound of the 95% confidence interval for detected concentrations has been used for the assessment (see SI Table 4, available online).

Moreover, an incremental approach is used by first assessing risk without considering any preventive measures (i.e. in WWTP secondary effluent). If the RQ fell below a value of 1, the substance was not considered in the further assessment steps. The next step included dilution and adsorption in the reservoir, again checking substances against the benchmark. The next step included effects of tertiary treatment and considered the remaining concentration in the reservoir.

As the system is still at a planning stage, removal rates for organic substances in tertiary treatment are based on available literature data and expert knowledge (see SI Table 5, available online), using a min–max approach for removal in both treatment trains during the assessment.

Microbial risk assessment

For microbial risk assessment, we conducted an entry-level probabilistic risk assessment, which included several conservative to worst-case assumptions. Thus, if under the made assumptions the risk stays below tolerable thresholds we can conclude that the treatment train, consisting of wastewater and drinking water treatment (WWT + DWT), is likely to provide sufficient protection against microbial hazards. For risk assessment, drinking water concentrations of reference pathogens are estimated based on assumed/measured wastewater concentrations and assumptions about the expected pathogen reduction during WWT and DWT. *Rotavirus* was chosen as reference pathogen for viral pathogens, *Campylobacter jejuni* for bacterial pathogens and both *Cryptosporidium parvum* and *Giardia intestinalis* for parasitic pathogens. Measured data were available for *Cryptosporidium* and *Giardia* in the effluent of the wastewater treatment plant. For *Rotavirus* and *Campylobacter* effluent concentrations were calculated from WWTP influent concentrations (see SI Table 6) and log removal rates (see SI Table 7). (SI Tables 6 and 7 are available online.)

Drinking water concentrations are combined with assumptions about the daily water consumption (worst-case 1–2 L) and available dose–response relationships from the literature to calculate the daily and annual probability of infection and illness. Illness probability estimates are multiplied by pathogen-specific average severity factors leading to an estimation of DALYs, which was used as the final risk indicator. Risk was considered acceptable below a limit of 10^{-6} DALYs per person per year (pppy) (Australian reuse standard, WHO recommended), since no level of acceptable risk is defined in France. Pathogen reduction within the environmental reservoir was neglected, thus the present calculations assume a virtual 'direct potable reuse' setup as a worst-case scenario for human pathogens in WW. We neglected potential wildlife contamination in the reservoir, because DWT does provide sufficient protection against wildlife-induced pathogens already today.

For each individual step in the system we collected the reported log-removal performance (LRV) from international guidelines (see Table 7 in SI). For WWT and DWT LRVs the Australian guidelines for water recycling (NRMMC-EPHC-AHMC 2006) and the WHO drinking water guidelines (WHO 2011) were used, respectively. We interpreted min and max values as the uncertainty between treatment systems. If guideline documents provided min–max values, we described this range in terms of a triangular distribution, with the mode being set realistically but conservatively to the arithmetic mean of the reported LRVs. Since details for oxidation processes (chlorination, ozonation) in the DWTP were unknown, a lower limit was set to 0, which can also be regarded as conservative. Calculations have been conduction via Monte-Carlo-simulation sampling 10,000 samples from each distribution.

Life cycle assessment

The LCA follows the framework of ISO 14040 (ISO 14040 2006; ISO 14044 2006) with the goal to quantify the potential environmental impacts of different options for drinking water supply in the Vendée region (see SI Table 8, available online).

The functional unit relates to 'the provision of 1 m³ of drinking water' or [m³]-1 ready to be fed into the local drinking water network. LCA scenarios are outlined in SI Table 8 and Figure 1. The system boundaries include all relevant processes for water treatment and transport up to the drinking water network (water distribution excluded), starting from the raw water source. Operational efforts include electricity and chemicals for water treatment and transport (pumping), and sludge disposal. Infrastructure of water treatment and pipelines is included. For the quarry, constructional efforts for preparing the quarry for water storage are neglected. Background processes include production of electricity, chemicals, and materials for infrastructure related to construction and operation of the systems under study.

Data for the life cycle inventory for electricity and chemical demand and water recovery is collected from full-scale data of existing plants and pipelines, feasibility or design studies, and literature in close cooperation with the operator and related subcontractors (see SI Table 9, available online). Background datasets are taken from the LCA database ecoinvent v3.1 (Ecoinvent 2014) using the French electricity mix. For activated carbon, production of virgin carbon and regeneration is modelled according to our own datasets (DWA 2016). LCA indicators are selected as cumulative energy demand (CED) of fossil and nuclear resources (VDI 2012), global warming potential (GWP) of 100a (IPCC 2007), and water availability footprint (WAF) (ISO 14046 2014) using the water scarcity factors of AWARE (WULCA 2015).

RESULTS AND DISCUSSION

The calculated risk of microbial hazards for human health is over five orders of magnitude below the acceptable level of 10^{-6} DALYs per person per year (pppy) for both alternatives of tertiary treatment (Figure 2). With the estimated pathogen concentrations in secondary WWTP effluent, removal rates for microbial groups of bacteria, viruses and parasites during tertiary treatment and drinking water production

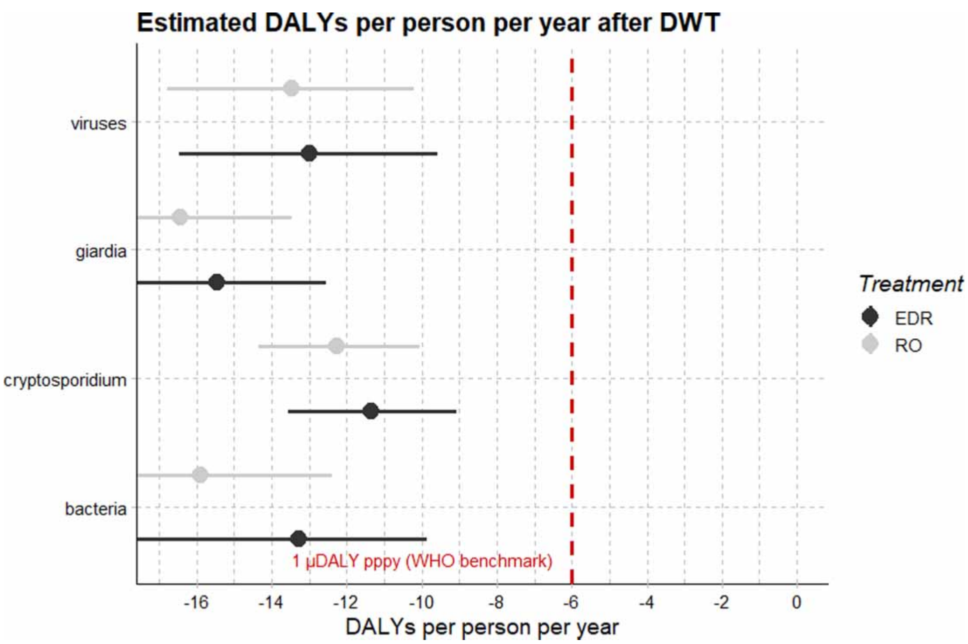

Figure 2 | Calculated health risk in µDALYs per person per year for different reference pathogens and treatment trains for tertiary treatment of wastewater and subsequent drinking water treatment. Points: median of Monte-Carlo samples, lines: 95% of Monte-Carlo samples.

are suitable to control the risk to an acceptable level. From a hygienic perspective, the IPR system poses a very low risk of not achieving the applied health target.

For chemical risk assessment, the results show that for both treatments the expected concentrations in raw water fall below the toxicologically derived thresholds (ADI, TDI, RfD). However, for some chemicals, existing precautionary benchmarks (HPV) may potentially be exceeded (Figure 3) in the reservoir. Additionally, if the EU guideline value for pesticides of 0.1 μg/L is applied to Glyphosate and its degradation product AMPA, concentrations of these substances are likely to be above this benchmark. While the HPV is specific for Germany, the potential elevation of pesticides may pose an operational risk to the planned system.

Figure 4 shows the resulting additional treatment performance of the DWTP required to reduce concentrations below all applied legal, toxicological and precautionary health benchmarks in the final product for human

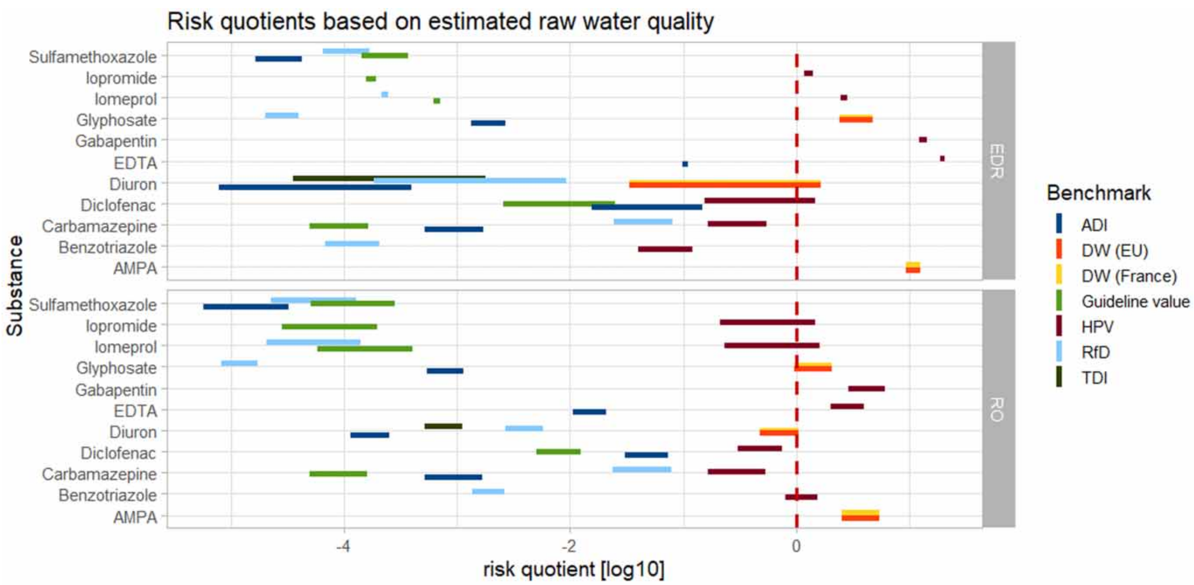

Figure 3 | Calculated risk quotients for reclaimed water in the reservoir in relation to health targets (ADI: acceptable daily intake, DW (EU): drinking water standards for Europe, DW (France): drinking water standards for France, Guideline value: WHO or Australian guidelines on water reuse, HPV: health-based precautionary value (Germany), RfD: reference dose, TDI: tolerable daily intake).

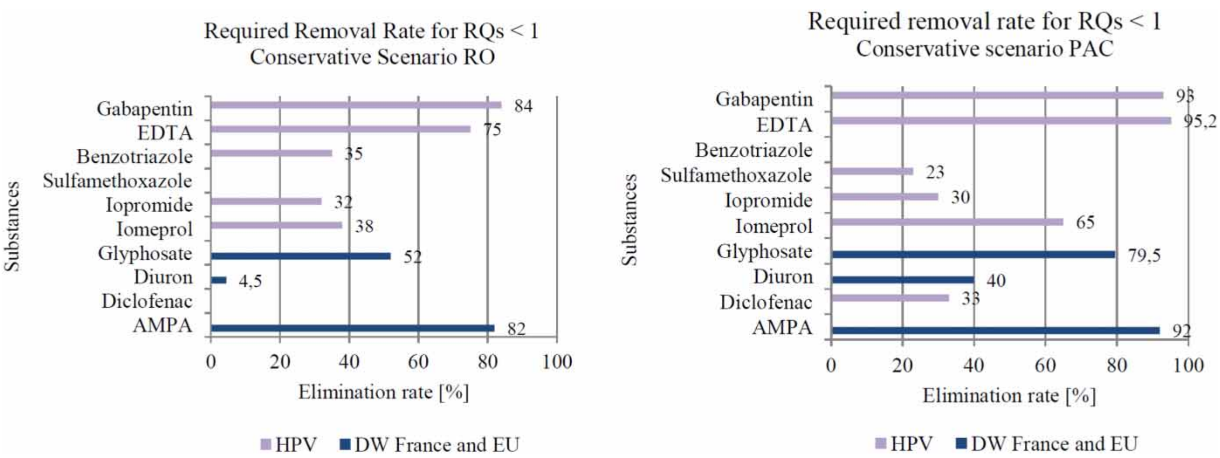

Figure 4 | Necessary additional removal required by DWTP to reduce concentrations in drinking water below benchmark value (HPV: health-based precautionary value, DW: drinking water standards) using conservative estimates for removal in tertiary treatment via RO (left) and EDR + μGAC (right).

consumption. For Glyphosate and AMPA, a review conducted by Jönsson *et al.* (2013) indicates that both substances are effectively removed by ozonation and chlorination, which are both implemented in Le Jaunay, allowing concentrations to be reduced below the legal benchmarks. For other substances such as EDTA and Gabapentin, which are considered to be less removable by either oxidation or adsorption processes, an exceedance of the collected precautionary health benchmarks cannot be excluded und should be subject to further monitoring efforts.

For environmental endpoints (Figure 1 in the Supporting Information, available with the online version of this paper), no additional treatment barrier exists before the reservoir, thus potentially harmful effects cannot be excluded for those substances with an RQ > 1 (e.g. Diclofenac, Clarythromycin). However, this risk should also be seen on a relative scale: existing inland WWTPs discharge secondary effluent into rivers upstream of the reservoir, and this potentially harmful effect is accepted as long as requirements of the authorization order are fulfilled. Thus, the present risk of IPR for ecosystems does not seem unacceptable compared with existing WWTP standards for discharge into the environment.

The LCA results for CED and GWP are shown in Figure 5. Water import and seasonal storage in the quarry have the lowest CED, followed by IPR, which needs around 35–39 MJ/m³ for tertiary treatment, water transport to the reservoir, and drinking water production. For IPR alternatives, the EDR train has slightly higher CED and GWP than the RO train, mainly due to higher total electricity demand of the EDR stage increasing linearly with salinity compared with RO, which is still operated in relatively low osmotic pressure. Seawater RO has by far the largest CED, mainly due to the high electricity demand for operating the RO system. For GWP, all options are within 0.63–0.74 kg CO2-eq/m³ except for seawater RO, which is highest with 1.05 kg CO2-eq/m³. Due to the high share of nuclear power generation in France and the resulting low GWP of electricity production, electricity demand contributes less to GWP than to CED, especially if compared with the contribution of chemicals.

These LCA results show that IPR is competitive in its efforts for drinking water production with the alternative concepts of water import and seasonal storage, and significantly superior to seawater desalination, which has the highest energy demand and related greenhouse gas emissions.

The environmental benefits of IPR are illustrated by the results of WAF (Figure 6): the current water supply is associated with a high WAF of 55 m³ world-eq/m³. All other alternatives have a significantly lower WAF. Water import is associated with a small WAF (7 m³ world-eq/m³) due to lower water scarcity in the local region of DWTP2. In contrast, seasonal storage in the quarry and the IPR options have a neutral WAF, as they supply additional raw water to the reservoir from water sources with marginal or no scarcity (i.e. water stored during high water availability in winter or WWTP effluent which is usually released to the ocean). Seawater RO has no effect in the WAF, as seawater is not

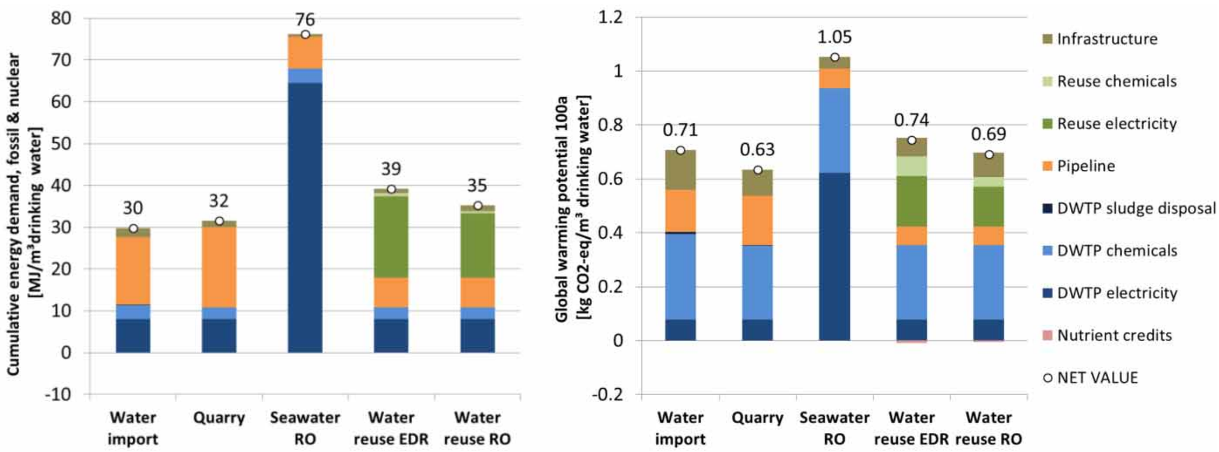

Figure 5 | Cumulative energy demand (fossil + nuclear, left) and global warming potential (right) per m³ drinking water for the different options to augment current drinking water supply.

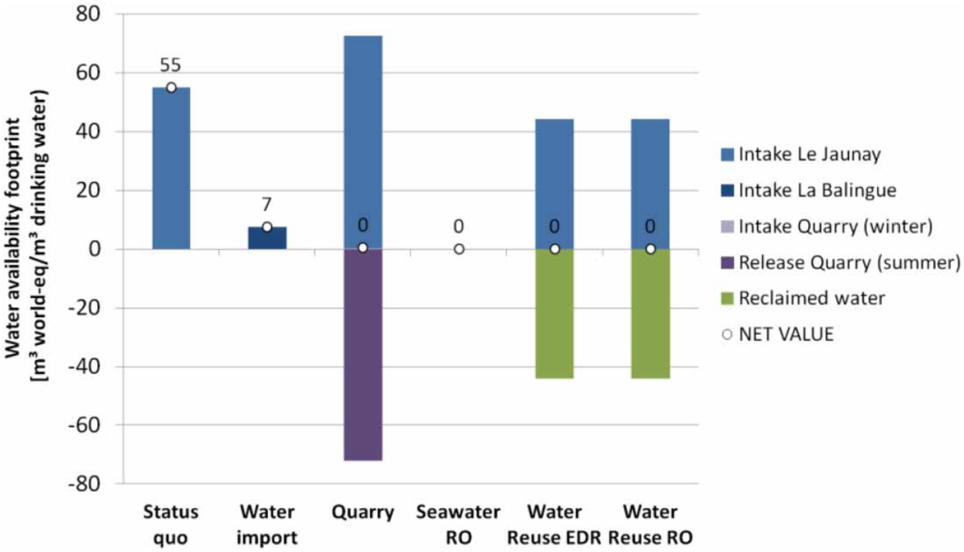

Figure 6 | Water availability footprint per m³ drinking water for the status quo and different options to augment current drinking water supply.

accounted with scarcity in the method applied (WULCA 2015). Hence, WAF is suitable to show the benefits of alternative water resources to augment the existing drinking water supply in the Vendée region without posing major additional water stress for the environment.

CONCLUSIONS

The results of the risk assessment and LCA of the prospective IPR system at Vendée can be summarized as follows:

- From a hygienic perspective, both alternatives for tertiary treatment are expected to achieve the health-based target of 10^{-6} DALYs per person per year if the existing DWTP is included as a barrier to pathogens in risk assessment. Consequently, IPR does not lead to any unacceptable risk from pathogens.
- Chemical risk assessment revealed that an increase of the concentrations of substances of emerging concern in the reservoir has to be expected due to the discharge of reclaimed water.
- Given the current assumptions, both IPR scenarios are expected not to reduce concentrations for all substances below all existing environmental benchmarks, indicating that potential harmful effects on freshwater organisms cannot be fully excluded. However, this additional risk may be seen as comparable to existing WWTPs discharging to rivers in the region without tertiary treatment.
- While the conducted study indicates that the planned reuse system is able to comply with existing, legally binding drinking water thresholds, IPR imposes new operational targets for the DWTP. Given the current state of information, an increase of the concentration in the reservoir cannot be excluded for all investigated organic substances. Thus, although this increase is not expected to pose an unacceptable risk to human health, due to the precautionary character of the applied benchmarks, the existing operation patterns for ozone dosing and exchange rates of activated carbon filters should be reassessed and adapted to the changes in raw water quality. If higher efforts for drinking water treatment are needed (e.g. higher ozone doses), the related environmental impacts of IPR would increase.
- IPR is competitive in its energy efforts and related greenhouse gas emissions with other options of drinking water supply such as water import and seasonal storage. IPR is superior in both aspects to seawater desalination, which requires a significantly higher energy input for water treatment mainly due to the RO process.
- The environmental benefits of IPR are illustrated in a neutral water availability footprint, showing that IPR is an option to augment the local water supply without posing additional water stress on the local freshwater resources.

- Overall, the entire assessment is based on design data and a limited amount of water quality data. It is recommended to validate the results of this prospective assessment in a demonstrator phase with more data on water quality and process design (e.g. oxidant doses, UV doses) and performance. The latter will also reduce uncertainty in the removal rates.

The results of this study will be used by the local operator Vendée Eau in communication with other stakeholders (regulators, public authorities, and the local community) to promote the concept of IPR, showing that chemical and microbial risks due to IPR can, if managed appropriately, be kept within acceptable limits. Environmental impacts are comparable to other options of water supply. In the next phase, a demonstrator of the IPR scheme is planned to confirm the design data of the tertiary treatment and validate the assumptions made during the design study, using additional analytical campaigns to permit an update of the risk assessment approach.

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