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Life cycle assessment as decision support tool for water reuse in agriculture irrigation

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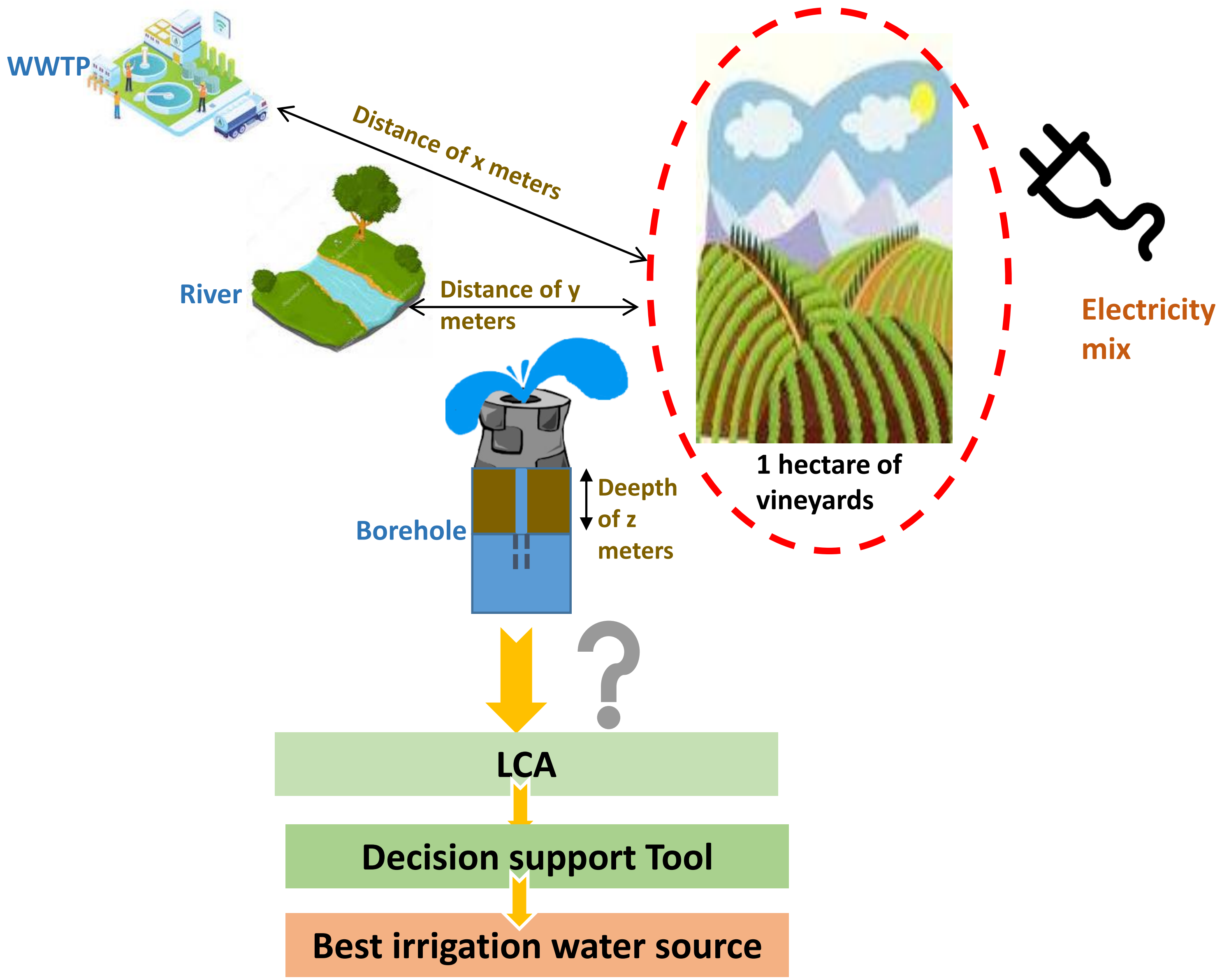
Abstract:

This study presents a decision support tool that evaluates the environmental efficiency of reusing treated wastewater for agricultural irrigation, among other options. The developed tool is published as open source at https://doi.org/10.18167/DVN1/YLP1BA. The objective of this decision support tool is to facilitate the interpretation of the Life Cycle Assessment (LCA) results by progressively reducing the non-discriminatory impacts to solve the difficulty of making a decision with a large number of criteria. This framework was applied to a representative case of reuse of reclaimed water for vine irrigation at the Murviel-Les-Montpellier experimental site (Hérault, France). It was then generalized through modeling assumptions to consider different reuse scenarios.

Graphical Abstract

When Can Recycled Water Benefit Us?



WWTP

Distance of x meters

River

Distance of y meters

Borehole

Deepth of z meters

1 hectare of vineyards

Electricity mix

?

LCA

Decision support Tool

Best irrigation water source

To highlight situations in which the supply of recycled water for irrigation may or may not provide significant environmental benefits, four main parameters were varied: (i) tertiary treatment technologies, (ii) availability of conventional water sources, (iii) energy mix composition.

The results show that the environmental impact of treated wastewater reuse depends directly on the type of tertiary treatment technology and the location of the treatment plant in relation to the field and other water sources. The decision support tool has identified where wastewater reuse is clearly an environmentally beneficial source of irrigation among surface and groundwater sources (e.g., WWTP closer to field than river, groundwater too deep, tertiary treatment environmentally beneficial). However, there are many situations where the decision support process cannot distinguish between reuse of treated wastewater for agricultural irrigation and conventional water sources, especially when the nutrient content of treated municipal wastewater is insufficient to offset the negative effects of high energy requirements and chemicals of tertiary treatment.

Keywords: environmental assessment; public decision support; reuse, irrigation, water sources, agriculture

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1. Introduction

Agricultural production is highly dependent on water and increasingly subject to water risks. Indeed, irrigated agriculture is the largest user of water in the world. Globally, about 70% of freshwater resources are consumed for crop irrigation [1]. By 2050, irrigated food production is expected to increase by more than 50% due to population growth [1]. However, freshwater resources continue to decline due to climate change, groundwater pollution, and aquifer salinization.

In the context of water scarcity, agriculture plays an important role in sustainable management of freshwater resources and mobilization of alternative water such as treated wastewater and desalinated water. Reclaimed water is a key alternative water source that has the advantage of being available most of the time, especially during drought periods [2]. Moreover, the nutrient content (nitrogen and phosphorous) in reclaimed water can reduce the use of chemical fertilizers and enhance crop productivity [3]. Reclaimed water reuse in agriculture is a common practice in the Mediterranean countries and other arid and semi-arid regions where freshwater resources are scarce [3, 4]. For example, in Italy and Spain, between 8 and 12% of treated municipal wastewater is reused for irrigation [5]. In Tunisia, reuse of treated water for agricultural purposes is promoted by the government and accounts for 20% of wastewater effluents [6].

While reclaimed wastewater reuse has benefits for environmental sustainability, it also poses risks [3]. In this context, Life Cycle Assessment (LCA) provides a quantitative multicriteria approach to evaluate the environmental performance of processes throughout their life cycle. Numerous LCA studies have been conducted to evaluate the environmental impacts caused by either wastewater treatment systems [7,8] or by crop systems irrigated conventional water [9-12]. However, few evaluate the environmental impacts of total crop systems irrigated with reclaimed water. Recently, Romeiko [9] investigated the impact of irrigating corn, soybean, and wheat crops systems with reclaimed and ground water sources in northern China. Wastewater was treated by biological processes (anaerobic-anoxic-oxic) followed by chlorine disinfection prior to discharge. The author uses a combination of experimental measurements and modeling datasets to reflect the specific regional conditions of the study, and he considers 1 kg of grain as a functional unit (FU). Compared to groundwater resources, reuse showed to be beneficial for the majority of the environmental impacts, such as global warming, acidification, ozone depletion, and harmful for non-cancer impacts. Likewise, Moretti et al. [11], based on experimental data of field work, compared the environmental performance of nectarine orchards irrigated in the Mediterranean coastal region by two different water sources: (i) treated municipal wastewater by membrane filtration and, (ii) surface water. The functional unit used is "1 kg of nectarines". The authors found that replacing groundwater with reclaimed water limited eutrophication. However, reuse performed worse for climate change, humans and freshwater toxicity mainly affected by the wastewater treatment phase. Miller-Robbie et al. [12] evaluated greenhouse gas (GHG) emissions and energy use of spinach crop systems in an Indian urban farm irrigated with three water qualities: Groundwater, untreated wastewater, and treated wastewater. It was showed that reuse in agriculture can reduce GHG emissions. Rodriguez-Garcia et al.[13] evaluated assessed the eutrophication and global warming impacts of six different typologies of WasteWater Treatment Plants (WWTP) coupled with different treated wastewater reuse scenarios (agriculture, industral, groundwater recharge, etc.). The plants that reuse treated wastewater for irrigation include tertiary treatments (UV disinfection or filtration process). The authors used two different functional units, one based on volume (m^3) and the other on eutrophication reduction (kg PO_4^{3-}removed). The results of the two FU were different. For the volumetric FU (m^3), the results showed that the potential eutrophication of agricultural reuse is worse compared to the other scenarios, while it seems to be beneficial for Global Warming Potential (GWP) compared to the acquifer recharge. The study by Meneses et al. [14] compared the environmental impacts of producing, for irrigation purposes, $1m^3$of : non-potable water (for agricultural irrigation and urban uses), potable water and desalinated water. Actual operational data from a WWTP in the Mediterranean region were used. The results showed that the agricultural reuse is the most environmentally friendly option, as it reduces the use of fertilizers and thus the energy consumption for their production. Similarly, Muñoz et al. [15] studied the life cycle impacts of tobacco in Spain irrigated with three different water sources including groundwater, treated municipal wastewater, and desalinated water. They found that irrigation with reclaimed water offred potential environmental benefits, compared to the use of desalinated water, especially in terms of eutrophication, aquatic ecotoxicity and energy use. In the same vein, Azeb et al. [16] analyzed the impact of irrigation with recycled water and farmers' practices in greenhouse cucumber cultivation. Compared to groundwater irrigation, the results show that fertilizers have the highest impact on life cycle analysis in the case of reused water. The authors explain this by the fact that farmers do not use the optimal fertilizer doses in terms of irrigation water quality.

Moreover, among other options , the environmental efficiency of reclaimed water reuse depends on the water-energy nexus, which links local water availability to water treatment impacts (as shown by Maeseele et al. [17]).

These studies [9, 11-16] provided important outcomes that allow a better understanding of the potential benefits and main sources of environmental damage from reuse of treated water in agriculture. However, the results depend on the location and characteristics of the experimental field. There is still a lack of a broad and systematic overview of the potential environmental impacts of reclaimed water reuse in irrigation, including the following aspects: Wastewater treatment technologies, fertilizers reduction, water availability, distance between the WWTP and the field, and energy mix.

The objective of this study is to enhance this knowledge and to highlight the environmental trade-offs between conventional and recycled water as an irrigation source. LCA and decision rules were used in this work to develop an intelligent tool to support decision making for the appropriate irrigation water source depending on the context. The entire system of reuse in agriculture is considered: from wastewater treatment to crop irrigation.

2. Materials and Methods

The methodology of LCA is normalized according to ISO 14040. It is an iterative four-stage process: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation.

2.1. Goal and scope definition

The objective of this study is to introduce LCA as an analytical tool to identify the conditions under which reclaimed water reuse for irrigation is environmentally efficient. Therefore, we compare a reference situation in which reclaimed water was used to irrigate the vineyard (scenario #1) in the experimental platform of Murviel-Les-Montpellier (Hérault, France) with two other virtual irrigation options: River water (Scenario #2) and Groundwater (Scenario #3), as described below and in Figure 1:

- Scenario #1: Municipal wastewater is treated by a lagoon and tertiary treatment. The treated wastewater is reused for vine irrigation from June to September. For the rest of the year, the wastewater is treated only in the lagoon and discharged into the river. The crop system irrigated by reclaimed water at the agricultural experimental station in Murviel-Les-Montpellier, Hérault, France (see below) was used as a representative case study.
- Scenario #2: River water is used to irrigate the vines in summer (from June to September). Nevertheless, the wastewater is treated in the lagoon throughout the year and discharged into the natural environment.
- Scenario #3: The vines are irrigated with groundwater from June to September and, in parallel, the wastewater is treated in the lagoon throughout the year before being discharged into the natural environment.

In LCA, the functional unit aims to provide a reference for comparison. In our study, 1 ha of vineyards is used as a functional unit to compare the environmental impacts of different irrigation scenarios. We did not use mass-based functional units as used in previous agriculture LCA studies because this study did not aim to identify the water source that maximizes yield, but to compile and evaluate the environmental consequences of different water sources used to irrigate 1 ha of vines.

The lagoon treatment plant was excluded from the system boundary (Figure 1) because the lagoon treatment plant was operated regardless of whether its effluent was used for irrigation. In order to be reused for irrigation (Scenario #1), the lagoon discharge undergoes tertiary treatment. In addition, the same amount of water was used for all scenarios: 500 m^3/ ha/ production cycle. However, the impact of avoided discharge of treated wastewater to the sea was considered in the reuse scenario (Scenario #1).

2.2. General description of the field experiment

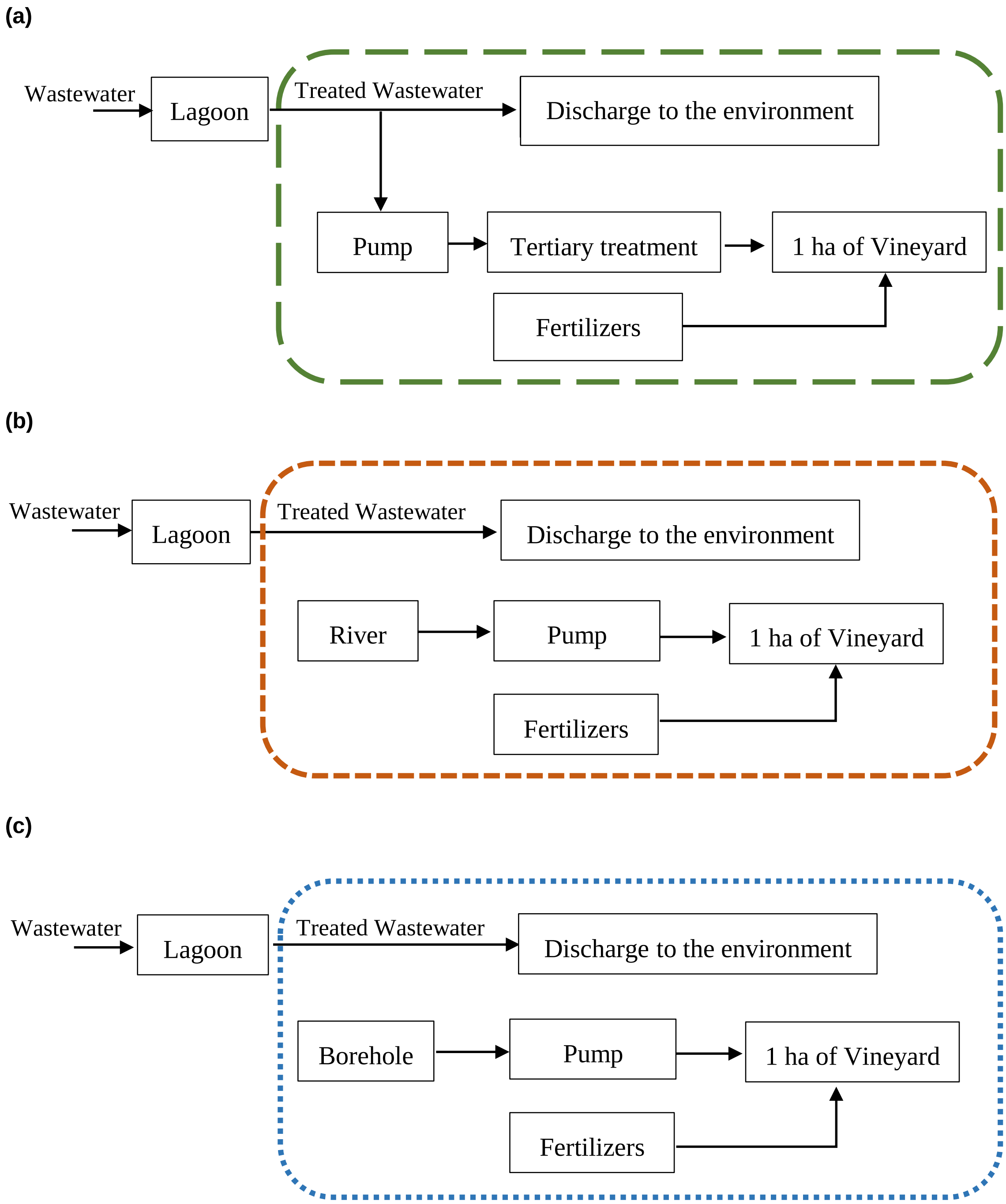

Figure 1. Systems boundaries studied (**a**) Scenario #1: reclaimed water treatment and reuse for vine irrigation. Part of the treated wastewater is discharged to the environment (b) Scenario #2: Irrigation of vines with river water and discharge of the reclaimed water to the environment (**c**) Scenario #3: Groundwater irrigation of vines and discharge of the treated wastewater to the environment.

The study is based on the experimental work carried out on the experimental platform of Murviel-Les-Montpellier (Hérault, France). This case study is the reference situation in the LCA analysis where reclaimed water is reused in agriculture irrigation. The experimental platform consists of (i) a lagoon treatment plant with tertiary treatment composed of a sand filter and UV disinfection, (ii) a 0.5 ha cultivated area with young vines located 600 m from the treatment plant. The plant serves a population of about 1500 inhabitants. In 2017, this plant treated about 200 m^3. d^{-1} (73000 m^3. $year^{-1}$) wastewater from urban collectors. The cultivation area was arranged in 4 rows of 50 m each with 200 vines. The spacing between rows was 2 m and the distance between plants was 1 m. Figure 2 depicts the location of the experimental platform.

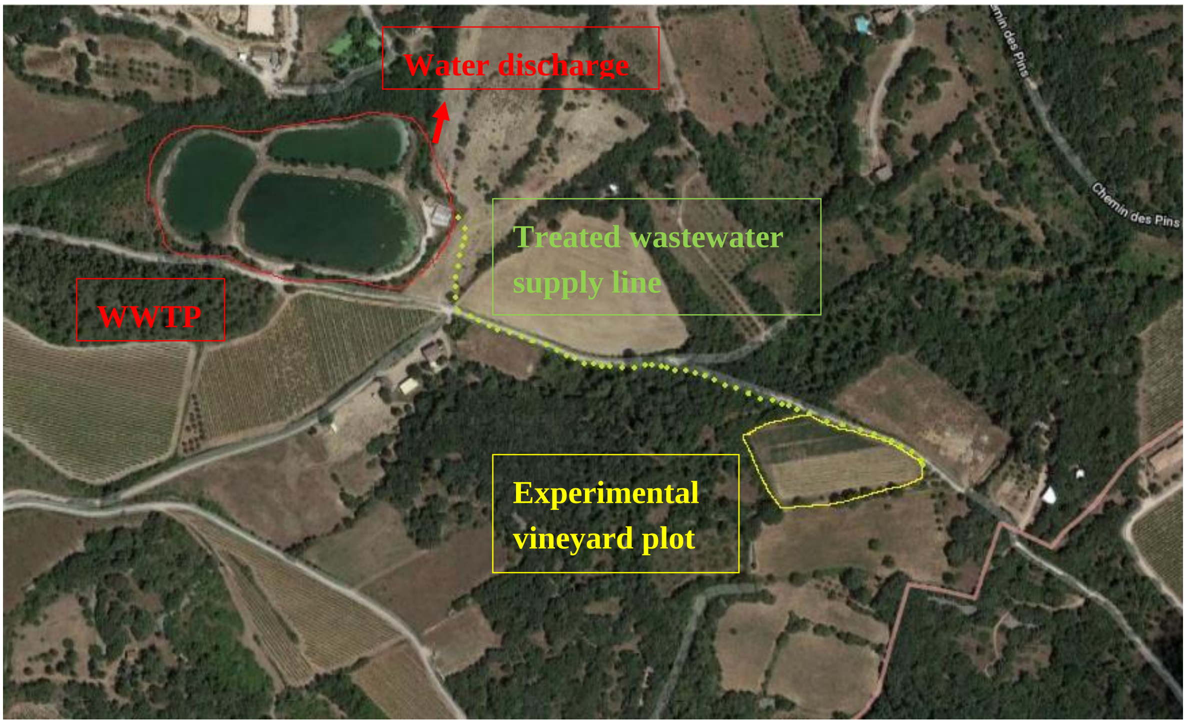

Figure 2.Experimental platform for the reuse of treated wastewater for the irrigation of vineyards, “Murviel-lès-Montpellier”, Hérault.

Irrigation is carried out from June to September by drip irrigation in accordance with the Decree of 25 June 2014 amending the Decree of 2 August 2010 on the use of water from urban wastewater treatment for crop irrigation. In the off-season, treated wastewater is discharged into the nearest river to the experimental site (see Figure 2). Water samples were collected monthly to analyze the composition in terms of Biochemical Oxygen Demand (BOD5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), total phosphorus, nitrogen: Total nitrogen, Total Nitrogen Kjeldahl (TKN), ammonium (NH_4^+), Nitrogen dioxide (NO_2), nitrate(NO_3). Table 1 shows the average composition of the waste water and the reclaimed water for the year 2017.

Table 1. Average data of the physico-chemical water quality at the inlet and outlet of the WWTP

Water Quality	**Waste water (g.m^{-3})**	**Reclaimed Water (g.m^{-3})**
BOD5	302.8	37.5
COD	689,7	171,4
TSS	284	57.8
Total phosphorus	10.3	5.8
Total nitrogen	102.4	41
Total Nitrogen Kjeldahl	102.37	39.4
NH_4^+	74.9	29.9
NO_2	0.04	0.03
NO_3	0.33	0.29

2.3. Sensitivity analysis

The objective of the sensitive analysis is to assess the impact of the variation of certain parameters on the decision making about the irrigation source. Among the key parameters, we selected: (i) tertiary wastewater treatment technology, (ii) electricity energy mix and, (iii) geographic context (distance between the field and WWTP for Scenario #1, distance between the field and the river for Scenario #2; drilling depth for Scenario #3):

- Tertiary wastewater treatment technology: tertiary treatment is required to ensure that reclaimed wastewater meets microbiological standards. Available technologies for wastewater reclamation include from simple sand filtration to advanced oxidation processes and reverse osmosis. The choice of the most appropriate technology or combination of technologies depends on the quality requirements and the expected application of the reclaimed wastewater. Three different tertiary treatment processes were investigated in the study. The first option is a UV disinfection system. The second option is an UltraFiltration (UF) process with two UF membrane lifespans (3 and 5 years). The third option is a chlorination system.

- Electricity production mix: the electricity processes in the ecoinvent database version 3.6 – which is included in SimaPro 9.1.1.1 - are specific to the geography. They contain the sources for electricity generation, the transmission network, loss due to going between the electricity types (e.g. from high to medium voltage), and direct emissions. Ecoinvent specifies the geography of the electricity process within the name. This study examines the results for different electricity generation mixes in the following countries: France, China, and Spain.
- Geographic context: to see if the geographic characteristics of the reference case affect the results, we performed a sensitivity analysis for the three scenarios compared, as shown in Table 2.

Table 2: Geographical contexts parameters considered for the sensitivity analysis

Scenario	Varied parameter	Value [m]
Scenario #1	Distance between the field and the STEP	100
		1000
		5000
Scenario #2	Distance between the field and the nearest river	100
		1000
		5000
Scenario #3	Drilling depth	30
		70
		110

2.4. Inventory analysis

Tertiary treatment options

Tertiary treatment becomes increasingly necessary to provide a water quality that conforms to the highest standard of French reuse regulations. The following paragraphs describe the different modeling assumptions for the tertiary treatment processes under consideration (Figure 3):

- UV disinfection: this option includes a disk filter (400 µm), a sand filter, a disk filter (130 µm) and an ultraviolet (UV) system. The sand filter weighs 34 kg of steel and it contains a weight of 330 kg of filter sand. The disk filter (400 µm) is an Amiad FILTOMAT M100 filter, consisting of 25 kg of steel. This type of filter has a water-activated self-cleaning mechanism that does not require an external power source to operate. The modeled UV unit was assumed to be a single lamp (300 to 750 W) system. The material data for the UV lamp, vessel reactor, quartz sleeve, sleeve wipers and main electronics were taken from the work of Carré et al. [18]. The lamps run only during demand for irrigation with a power consumption of about 0,01 kwh/m^3 [18]. The UV Lamp Life Expectancy is considered to be 10000 hours, according to [19].

- UF filtration: this option consists of a disk filter (400 µm), a sand filter, a disk filter (130 µm) and the UF pilot AQUAMEM UF80-12. The sand filter and the disk filter are the same as in the option 1 (UV disinfection). The AQUAMEM UF pilot consists of 12 modules, which contain hollow fibers made of polyethersulfone, accounting for a total surface area of 42 m^2 per module. Each fiber has a porosity of 0.01µm. The maximum admissible water flow in the UF pilot is 25 m^3/h. It is assumed that 20% of the pilot plant power consumption is used in hydraulic membrane backwash and chemical wash is negligible.

- Chlorination: the chlorine disinfection alternatives includes a disk filter (400 µm), a sand filter, a disk filter (130 µm), a 10 m^3 chlorine contact basin where the sodium hypochlorite is added to the water and allowed to contact the contaminants for 30 minutes, a 2 m^3 chlorine tank, and a metering pump to inject the chlorine from the chlorine tank into the contact basin.. The amount of process material, sodium hypochlorite, and energy consumption was quantified using the equations and information given in [19]. The chlorine storage tank is made of propylene and the chlorine contact basin is made of concert.

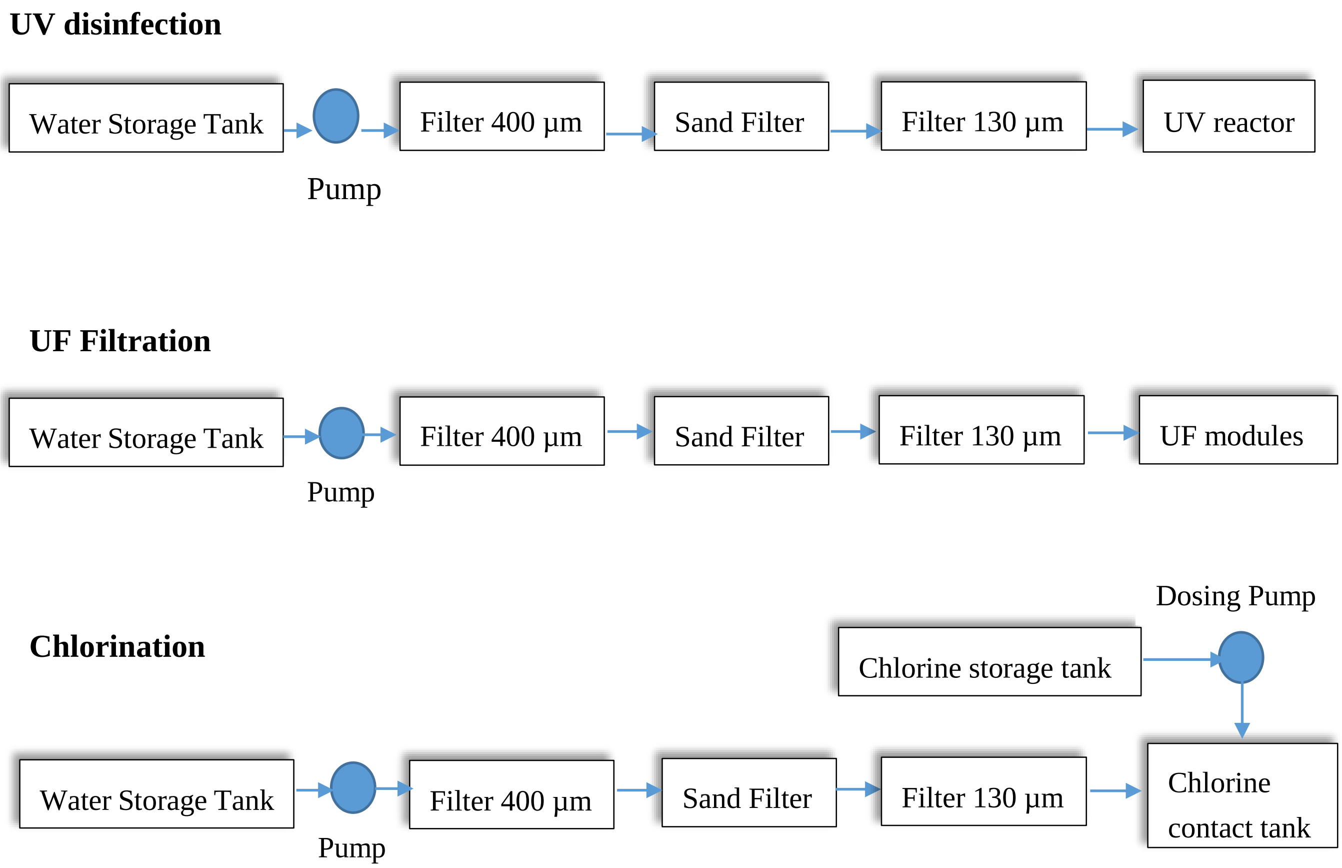

Figure 3. Individual components of the three investigated tertiary treatment scenarios: tertiary treatment with UV disinfection, tertiary treatment with UF filtration and tertiary treatment with chlorination.

Infrastructure water transport

The infrastructure for water transport from the source to the field consists of: (i) a centrifuge pump and (ii) PVC pipes for water transport from the water source to the field and (iii)) PVC pipes for field irrigation.

The field irrigation system is excluded, as the same crop system was considered in the different scenarios. However, the pump characteristics and the length of the transport pipes depend on the type of water source and the distance to the field. For scenario #1, the reclaimed water was transported via plastic pipes from the adjacent WWTP and stored in a pond. For scenario #2, river water was transported via plastic pipes from the adjacent river and used directly for irrigation without prior storage. In the scenario #3, groundwater for irrigation was obtained from the on-site groundwater well.

The water flow rate delivered to the field by the centrifugal pump is fixed at 20 m^3/h, regardless of the type and location of the irrigation water source. The pump must deliver a certain pressure, called the total head, which depends on the suction and discharge conditions. In any case, the selection criterion for the centrifugal pump is the total head of the system (THS), since the flow rate is the same in the field. Following the THS calculations, the Zanni pumps listed in Table 3 were selected for Scenario #1 (reuse) and Scenario #2 (surface water):

Table 3: Centrifuge pumps for water feeding for scenario #1 and #2

River/Field or WWTP/Field distance [m]	Pump Type	Weight [kg]	Efficiency [%]	Life Expectancy [Year]	ecoinvent LCI unit process name
100	HM 32 A/1	72	57	4	Cast iron {GLO}| market for | Cut-off, S
1000	HM 32 A/1	72			
5000	HM 32 A/2	87			

For the reuse scenario, centrifugal pump drive the lagoon effluent through tertiary treatment (UV, UF or chlorination processes) to the field. For borehole irrigation (scenario #3), the characteristics of the GrundFos submersible pump under consideration are summarized in Table 4:

Table 4: submersible pumps for water feeding for scenario #3

Borehole depth [m]	Pump Type	Weight [kg of cast iron]	Efficiency [%]	Life Expectancy [Year]	ecoinvent LCI unit process name
30	SP-30-4	31	57	4	Cast iron {GLO}| market for | Cut-off, S
70	SP-30-9	62			
110	SP-30-15	78			

Fertilization

Since the objective of this work is not to study the contribution of the irrigation water source to fertilization, the same amount of fertilizer was applied to the crop in the different scenarios. For the reclaimed water plots, the nutrients came from both fertilizer and reclaimed wastewater. The fertilizer schedule was designed to meet the nutrient needs of the plants, considering the average annual chemical properties of the reclaimed water. The same amount of nutrients was applied to the plots with conventional water (Scenario #2 and #3). Moreover, Scenario #1 has been expanded by including the impacts generated by the avoided fertilizers production, since reclaimed water irrigation reduced the requirements of fertilizer.

The composition of NPK fertilizer used per ton of product is 6.7 kg of total Nitrogen, 4 kg of P_2O_5 and 12 kg of K_2O, which corresponds to the theoretical fertilizer requirement of grapevine under similar conditions as recommended by the French Institute of Vine and Wine. Fertilizer production was included in the system boundaries because of its impact on agricultural LCA [11]. The impact of fertilizer application was excluded because it was carried out with the same equipment in different scenarios. Similarly, pesticide production and application were excluded because it is assumed that the same amount of pesticide is applied in all scenarios.

On-field emissions

Irrigation and fertilization of crops causes nitrogen and phosphorus emissions to air, soil, and water. These emissions must be quantified for LCA analyzes. Quantified nitrogen emissions are root uptake, volatilization, and leaching. Phosphate emissions are soil erosion, leaching, and runoff.

In the absence of experimental data for emissions to air and groundwater and inconsistent on-site soil analysis data, these emissions are estimated using mathematical models from the literature. Nitrogen (N_2), ammonia (NH_3), nitrous oxides (N_2O), nitrate (NO^-_3) and nitrogen oxides (NO_x) emissions were estimated using models published in the World Food LCA Database [20]. However, Agribalyse models were used to estimate phosphorus emissions.

End of life phase

The end-of-life stages for materials systems are modeled using the ecoinvent 3 processes, as showen in Table 5. The end-of-life phase includes the dismantling of infrastructures (e.g. storage tanks), recycling of steel as it represents a significant portion of the total waste and recycling, while other materials such as concrete and PVC are sent to final disposal in landfills and/or municipal incineration (e.g., plastics). In our case study, the recycling of plastics was not taken into account, as only a small proportion of plastic waste is recycled in France (< 20%) [18].

Table 5: end-of-life stages for materials systems

Material	Used by	End of life (ecoinvent LCI unit process)
Concrete	chlorine contact tank; Water storage tank	Waste concrete {Europe without Switzerland}| market for waste concrete | Cut-off, S
PVC	PVC pipes for water transport from the water source to the field	Waste polyvinylchloride product {Europe without Switzerland}| market for waste polyvinylchloride product | Cut-off, S
Polypropylene	Chlorine storage tank	Waste polypropylene {Europe without Switzerland}| market group for waste polypropylene | Cut-off, S
Steel and iron	Sand filter; Disk filter; Storage Tank; Pumps; UV reactor; UF pilot	Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S
Sand	Sand filter	Inert waste {Europe without Switzerland}| market for inert waste | Cut-off, S

3. Calculation

3.1. LCA Impact analysis

LCA requires the processing, calculation and analysis of a wide range of information. The use of LCA software facilitates these different phases, ensuring transparency and traceability. SimaPro is a calculation software that links inventory data, informed by the LCA producer, to the environmental damage caused by the inventoried substances. It was developed by the Dutch and is a world leader in the implementation of LCA. SimaPro software version 9.1.1.1 integrates several evaluation methods (Recipe, ILCD, Usetox...) and various life cycle inventory databases (ICV) (ecoinvent, ELCD, LCA Food). In this work, the method of International Reference Life Cycle Data System (ILCD) 2011 method [21] was selected. This method is recommended by the European Commission, which has analyzed several methodologies for life-cycle impact assessment to reach a consensus on the recommended method for each environmental topic, both at midpoint and endpoint levels. Because each step of the impact analysis generally involves additional assumptions and uncertainties in characterizing damages, the uncertainty in the results increases as one progresses from the inventory to mid-point category and then from the mid-point category to the damage results. To limit the uncertainties, only the midpoint impact categories from the ILCD method were used in this study. In addition, 8 midpoint impact categories were determined: Climate Change (CC), Ozone Depletion (ODp), Human Toxicity (HT) that regroup human carcinogenic toxicity and human non-carcinogenic toxicity, Ionizing Radiation (IR), Acidification (Ac), Freshwater Eutrophication (FEp), Marine Eutrophication (MEp), Freshwater Ecotoxicity (FEt).

3.2. Decision support tool

Typically, the main difficulty among the LCA use is the interpretation of highly multicriteria results. Indeed, one can conclude that A is better than B only if ALL impacts are lower. Otherwise, it is not possible to discriminate between A and B from an environmental point of view and other criteria must be considered. As a consequence, we developed an LCA calculator in excel that includes the selected LCA impacts categories (the 8 midpoint impact categories) and a simple decision-making procedure inspired from [22]. This LCA decision support tool is published under https://doi.org/10.18167/DVN1/YLP1BA. It consists in reducing, gradually, the number of impacts considered by applying elimination rules. In fact, limiting the number of impacts leads to reduce the complexity of the information transmitted and to guide the decision-maker to a choice.

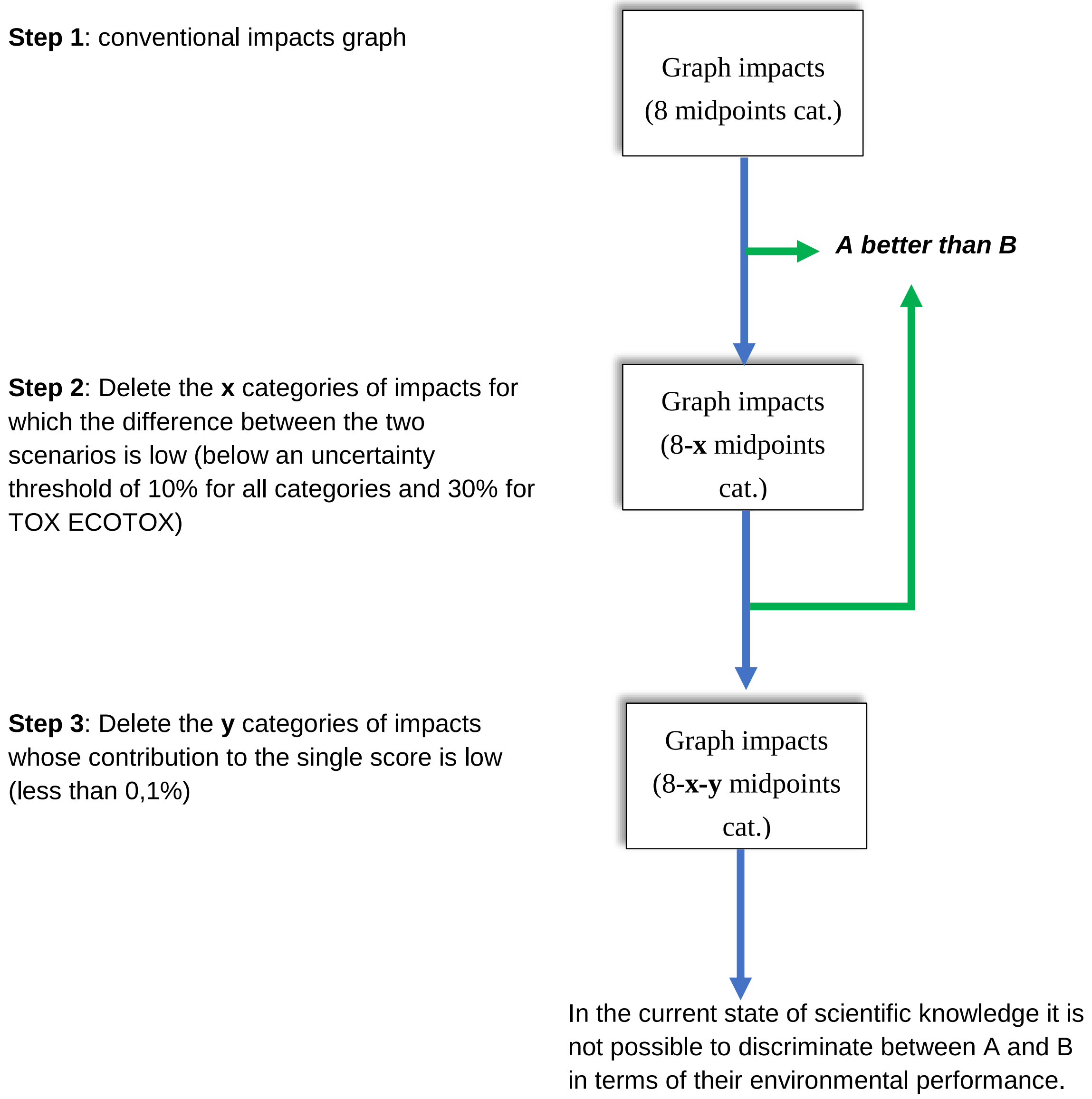

Figure 4: Decision-support tree for the analysis of the LCA results

After displaying comparison LCA results between two scenarios with SimaPro, we guide decision making according to the decision tree presented in Figure 4. In fact, If the scenario A is not better than scenario B on all the considered impacts, then the first elimination step will be applied automatically by excel. The first elimination step consists in the delete of the **x** categories of impacts for which the difference between the two scenarios is below an uncertainty threshold of 10% for all categories and 30% for TOX ECOTOX. The two uncertainty thresholds for the step 2 (10 and 30%) were used, based on Jolliet et al. [23] While it is not always possible to decide between A and B at the step 2, Excel go to step 3. This last consist on the remove of the **y** categories of impacts whose contribution to the single score is low (less than 0,1%) [23]. If it is still unable to choose between A and B, then we can conclude that in the current state of scientific knowledge it is not possible to discriminate between A and B in terms of their environmental performance. In this case, the decision can be based on the other components of sustainability (social & economic).

4. Results and Discussion

First, we consider the French electricity mix and compare the environmental impact of irrigation with reclaimed water and river water for different scenarios: different tertiary treatment and different distance between field and river and field and STEP. Second, for the same mix and reuse scenarios, we compare irrigation with reclaimed water and drilling water for different drilling depths. Finally, the electricity mix is varied to evaluate the impact of the energy source on the choice of the appropriate irrigation water source.

Table 6 shows the results of the Excel calculator based on LCA for the different scenarios assessed, so that the reader can simultaneously observe the relative impact of the different circumstances on the irrigation water source decision.

4.1. Reclaimed water VS Surface water for the French mix

Sub-table 6-A presents the comparison LCA results between scenario #1 (irrigation with TWW) and scenario #2 (surface irrigation) for different tertiary treatments, different geographic contexts (field/WWTP and field/river distances), and for the French electricity mix.

Table 6: Results of the decision support tool comparing reclaimed water reuse to river irrigation (A,C,D) and reclaimed water reuse to borehole irrigation (B,D,F)

The adjusted parameters are: (i) three tertiary treatments (chlorination, UF filtration with two different membrane life spans of 3 and 5 years, UV disinfection), (ii) three distances between field and WWTP (100 m, 1000 m, 5000 m), (ii) three distances between field and River (100 m, 1000 m, 5000 m) , (iii) three borehole depths (30 m, 70 m, 110 m), (iv) three electricity mixes (France, China, Spain).

No conclusion means that, under the considered conditions, the decision-making procedure cannot easily distinguish between the two compared options.

River means that, under the considered conditions, irrigation with surface water is more environmentally friendly than the reuse option.

Borehole means that, under the given conditions, groundwater irrigation is more environmentally friendly than the reuse option.

Reuse means that, in this situation, supplying reclaimed water for irrigation offers significant environmental benefits.

REUSE versus RIVER

French mix

(A)

Tertiary treatement	Chloration			UF membrane			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

Chinese mix

(C)

Tertiary treatement	Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

Spanish mix

(E)

Tertiary treatement	Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE
5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

REUSE versus Borehole

French mix

(B)

Tertiary treatement	Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Borehole depth	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

Chinese mix

(D)

Tertiary treatement	Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Borehole depth	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

Spanish mix

(F)

Tertiary treatement	Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Borehole depth	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

UV disinfection

Analysis of the results in sub-table 6-A showed that the reuse scenario is more beneficial than irrigation from surface water (river) only in the case of UV tertiary treatment and when the field is closer (or at the same distance) to the WWTP than to the river. In the latter cases, scenario #1 with UV treatment generates lower impacts in all considered impacts categories except acidification where the difference between the two-compared scenarios is not significant at about 3% (10% is the defined uncertainty threshold for the percentage of significant difference between two non-toxicity impacts [22]). For this reason, the choice of the reuse scenario was obvious. In this case, field irrigation with TWW generates a net benefit resulting from:

- the avoided discharge of TWW into the environment
- the replacement of fertilizers with the nutrients provided by TWW
- the reduction in electricity used to pump the water, since the field is closer to the WWTP than to the river

UF filtration

In this case, the tertiary treatment of the reclaimed water is an ultrafiltration process composed of 12 polysulfone filtration membranes. Based on the decision rules, the environmentally preferred irrigation scenario in this case is scenario #2: river or surface irrigation (see sub-table 6-A). In fact, the reclaimed water scenario showed higher life cycle impacts than the surface water scenario, regardless of the distance of the field from the WWTP and the nearest river (Table 2). Analysis of the contribution of scenario #1 with UF tertiary treatment shows that the production of polysulfone, the membrane material, is the largest contributor to the total impact (Figure.5). The other sub-systems are not shown in the figure, because their contribution to the total environmental impact is small (about 0.04%).

Extending the membrane lifespan from three to five years reduces the magnitude of the different impact categories but does not change the decision. In fact, the surface water source is still better than reuse with UF tertiary treatment. In addition, it was assumed that there is no chemical cleaning of the membranes, which could affect the results.

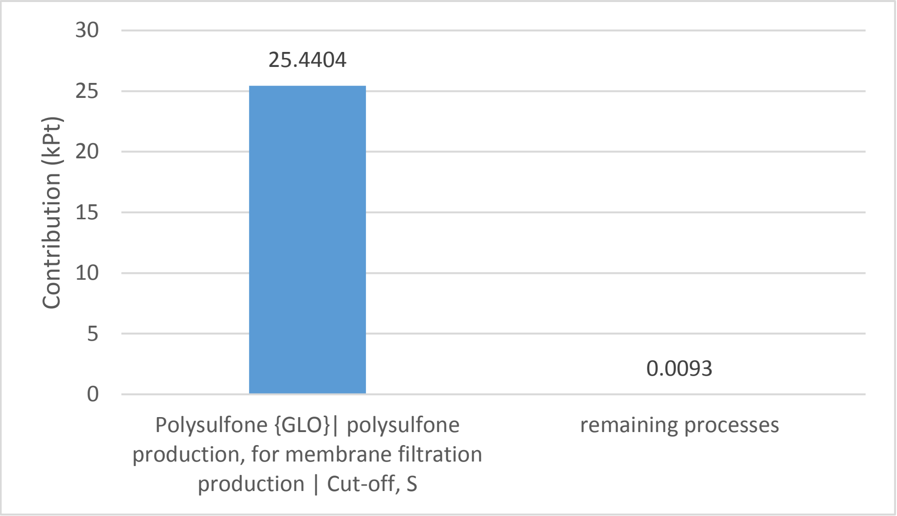

Figure 5: Contribution analysis to the single score of scenario #1 with UF tertiary treatment for a distance of 100 m between the field and the WWTP and a membrane lifetime of 3 years.

Chlorination

If the tertiary treatment is a chlorination train, the decision tool shows that it is not possible to distinguish between reuse with chlorination tertiary treatment and surface irrigation (river irrigation) in terms of environmental performance. The same trend is observed for all geographical situations considered (Table 2). If we look more closely at the results of the impact categories, we can see that reuse is the worst option in terms of ozone depletion, acidification and ionizing radiation. The pollutant with the greatest contribution to the ozone depletion category is the sodium hypochlorite (NaOCl), which is used to disinfect reclaimed water. NaOCl is produced by reacting a dilute caustic soda solution with liquid or gaseous chlorine. Ionizing radiation is mainly affected by the energy required to pump water followed by NaOCl production. In the same way, hypochlorite production and field emissions were most significant in acidification impact categories. However, reclaimed water reuse reduces climate change, eutrophication and ecotoxicity impact categories due to avoided fertilizers uses and fewer nutrient emissions into the natural environment.

4.2. Reclaimed water VS Drilling water for the French electricity mix

This comparison reflects the situation in which the decision-maker must choose between reclaimed water reuse and borehole water irrigation source in different contexts. In this sense, a sensitivity analysis was carried out in order to determine the influence of (i) borehole depth, (ii) distance between field and WWTP and, (iii) tertiary treatment of reclaimed water on the outcomes of LCA. As shown in the sub-table 6-B, these parameters are critical to the choice of irrigation source (reuse or borehole).

UV disinfection

For UV tertiary treatment, reuse is indeed more environmentally efficient than borehole irrigation, unless the WWTP is too far from the field (distance ≥ 5000 m) and the groundwater is at shallow depth (≤ 30m). In this last case, reuse is poor only in IR. It is twice as important as groundwater irrigation because of the electricity consumption, which contributes in IR impact by 98% in the reuse case and 90% in the case of groundwater irrigation. In fact, the electrical energy required to transport the TWW over a distance of 5000 m is higher than that required to pump water from a 30 m deep borehole. However, when the borehole depth is greater than or equal to 70 m, reuse with UV treatment is environmentally beneficial because the nutrient content in the TWW reduces the use and production of fertilizers, mainly affecting CC, ODp, HT, Ac and FEt. For example, when the distance between the field and the WWTP is 5000 m and the borehole depth is 110 m, the contributions of fertilizer use in scenario #3 are 70% for CC, 46% for ODp, 80% for HT, 58% for Ac, and 84% for FEt. The impact of the groundwater irrigation scenario on freshwater and marine eutrophication impacts is mainly caused by the discharge of lagoon effluent, which is partially avoided in the reuse scenario.

UF filtration

Based on the results from LCA, the excel calculator decides that is not environmentally friendly to replace groundwater with TWW for UF tertiary treatment. This is mainly due to the production of membrane material, which strongly affect all the considered environment categories. Although the reuse decreases the lagoon emissions, the UF tertiary treatment with its 12 modules of 42 m^2 of polysulfone per module increases all the environmental impacts of scenario #1 with UF. After polysulfone production, electricity is the process that has the highest impact on all categories, expect for marine and freshwater eutrophication, which are affected by emissions from the lagoon. For marine and freshwater eutrophication, the difference between the two scenarios is not more than 30%, because the amount of recycled wastewater is not very important.

Chlorination

As in the case of surface irrigation, the decision support tool shows that it is not possible to distinguish between the two water sources: Reuse with tertiary chlorination and groundwater. Indeed, reuse with tertiary chlorination reduces climate change, human toxicity, freshwater eutrophication, marine eutrophication, and freshwater ecotoxicity over the life cycle. However, the impact of irrigation with treated water is twice that of irrigation with groundwater and the life cycle of IR is too important. The first life cycle impact factor of ODp in the reuse scenario is sodium hypochlorite used for chlorination of TWW. In addition, no significant difference is found between the two options for freshwater and seawater eutrophication. Consequently, the decision is up to the decision maker, who could rely on other indicators to choose between the compared water sources.

4.3. Electricity mix

The same LCA analysis as in sections 4.1. and 4.2. was reproduced, but the French energy mix was replaced first by the Chinese mix and then by the Spanish mix.

Chinese electricity mix

China is by far the largest producer of electricity from fossil fuels, accounting for nearly 73%. The results presented in Table 6-C and 6-D show that, the conclusions for the Reuse VS River and Reuse VS Borehole scenarios remain the same when we replace the French electricity mix with the Chinese electricity mix. However, analysis of the results from LCA for the last two cases shows that the high ionizing radiation of the French electricity mix is reduced when it is replaced by the Chinese mix, which contains a lower proportion of nuclear electricity. However, the climate change, acidification and ecotoxicity impacts increase because the Chinese electricity mix is mainly generated from fossil fuels. As stated earlier, these changes do not affect the overall conclusions on the reuse.

Spanish electricity mix

Results from LCA show that replacing the French electricity mix with the Spanish electricity mix would reduce IR and ODp but increase climate change, acidification and ecotoxicity impacts, because the Spanish mix contains about 45% fossil energy. However, the difference between the results of the two mixes (Spanish and Frensh) is observed only for River VS Reuse scenario and when the field is 1000 m from the river and 5000 m from the WWTP. In the latter case, the reuse is ecologically beneficial, since the Spanish mix reduces considerably its ODp impact compared to river sceanario.

5. Discussions

The results of the decision support tool has shown that the environmental benefits of agriculture wastewater reuse over conventional water remain case-by-case dependent and no general conclusion can be drawn. The decision on reuse depends on the characteristics of the treatment technology, especially tertiary treatment, and the specifics of the site.

Tertiary treatment of wastewater is not only a disinfection step, but can also prevent operational problems due to clogging of drippers with biofilms. However, the complexity of the technology (e.g., UF treatment) and the use of chemicals (e.g., chlorination) could increase the environmental impacts of the reuse scenarios compared to groundwater and surface irrigation. The environmental benefits of treated wastewater over conventional water sources are related to the reuse of treated wastewater, which reduces the use of fertilizers. If the wastewater is not reused, it will be discharged into the aquatic environment where it will affect freshwater and marine eutrophication. Thus, reuse can be a double-edged sword.

Conventional water sources also have negative impacts on the environment through (i) the energy consumption required to extract and transport water, (ii) emissions from the production and use of fertilizers and (ii) the release of TWW into the environment. In addition, on the one hand, overuse of conventional water sources is the cause of water quality (i.e., salinization) and quantity degradation. On the other hand, surface and groundwater can also be polluted by human activities and wastewater discharges, which can lead to contamination of water resources by pathogens. The problem is not in contrast with wastewater treated by tertiary treatment, which is a disinfection step. The consideration of pathogens in urban water is still relatively complex in LCA, as shown by [24].

The aim of this work is to provide decision makers with a tool to decide on the efficiency of reuse depending on the specifics of the case considered. However, the lack of data on country-specific water scarcity could affect the accuracy of the results. Endpoint indicators could be used to consider the impact of water scarcity, as shown in [17]. Thus, decision makers can improve their decisions by considering water availability at the site in question.

In addition, the local electricity mix can also influence the environmental efficiency of TWW reuse. Likewise, endpoint impact indicators could provide more useful information on the impact of the energy-water mix than midpoint indicators [17]. The integration of endpoint impacts will be the subject of our future work to improve the proposed decision tool.

6. Conclusions

This paper presents an intelligent decision tool that supports the selection of environmentally friendly irrigation water source depending on the context. It uses LCA impacts data generated by SimaPro and predefined decision rules programmed in Excel. This tool is available as open source at https://doi.org/10.18167/DVN1/YLP1BA. The decision support tool identifies the conditions (treatment technologies, geographic context, energy mix) under which reuse is environmentally beneficial. In some situations, the decision support tool is unable to distinguish between conventional and non-conventional irrigation (reuse) from an environmental perspective. This is a first step in facilitating a decision maker's use of LCA with respect to reuse efficiency. In addition, other factors (economics, regulations, etc.) should be considered.

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