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Environmental analysis of a domestic rainwater harvesting system: A case study in France

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ABSTRACT

Life cycle assessment methodology along with water footprint analysis was used to assess the environmental impacts of a domestic rainwater harvesting system (RWH) in France. Firstly, the relevance of substituting drinking water (DW) with rainwater in a private individual household was studied. Secondly, the effect of several parameters namely construction of infrastructures, building scale and disinfection were evaluated. The quantification of environmental impacts was performed using Ecoinvent inventory data and Impact 2002+ evaluation method. The water footprint was assessed through the water stress indicator (WSI). From an environmental standpoint, the RWH system has only slightly higher impact than the DW system. The consumption of electricity for pumping generates the strongest impact. The analysis of the WSI showed that the RWH system can relieve a stress on water resources where it exists. Consideration of infrastructures and disinfection turns environmental impacts significantly higher in all impact categories. Setting up the RWH system at bigger scale, i.e., building scale, is a bit less favoured than the RWH system at household scale. This study aims at pointing out areas of improvement which need to be further studied to make RWH systems more sustainable.

1. Introduction

Similar to the rest of the world, France must conserve natural resources, in particular fresh water. Among the existing solutions for such conservation, the use of roof-collected rainwater has recently sparked major interest (Li and Zhang, 2010). The main idea of this solution is to avoid using valuable drinking water by substituting it with collected roof runoff.

In France, despite reluctance from sanitary authorities (CSHPF, 2006), the increasing demand from private customers leveraged the reconsideration of rainwater harvesting. Since 2008 a new decree authorises rainwater use inside buildings (French Official Journal, 2008). Currently, French law still prohibits the use of harvested

rainwater for drinking, showering or bathing, though it allows its use for toilet flushing, cleaning the ground and under certain conditions, washing clothes.

Nevertheless, this practice remains a controversial issue. On the one hand, benefits are many: harvested rainwater is a free water source for non-potable water use that reduces water stress and environmental pollution, helps to prevent floods caused by soil permeability and is perceived as an adaptive strategy to deal with the reduction of water availability due to climate change (Angrill et al., 2011; Schudel, 1996). On the other hand, researches have already highlighted an increased energy consumption due to the necessity of pumps (Anand and Apul, 2011; Crettaz et al., 1999). In addition, there may be hygienic issues with collected rainwater. As a result, rainwater used for domestic activities requires minimal treatments involving matter and energy consumption (Jolliet et al., 2010).

In this paper, life cycle assessment methodology was used along with water footprint analysis (Boulay et al., 2011a), and data on the RWH system were collected from case studies. First, the substitution of drinking water with rainwater was considered from an environmental standpoint. Second, sensitive parameters, namely infrastructures, scale and disinfection were assessed. Problematic issues that need to be further studied have been identified. This

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study complements the existing literature on rainwater harvesting targeting areas of improvement.

2. Materials and methods

LCA was performed according to the ISO 14040 (AFNOR, 2006a) and the ISO 14044 (AFNOR, 2006b) standards.

2.1. Goal and scope

This study aims at quantifying the environmental impacts of systems that use rainwater in France. It should be noted that this study was restricted to rainwater use for toilet flushing. The RWH system and the DW system have been modelled through a “cradle-to-grave” approach. The study takes place in the Garonne watershed.

2.1.1. Functional unit

The functional unit was defined as “the supply of 30 L of water per day per person for toilet flushing”. It corresponds to the average consumption per day per person for toilet flushing in France (CIEau, 2013).

2.1.2. System description and boundaries

2.1.2.1. Rain water harvesting baseline system (RWH). A commercially available domestic rainwater collection system (Sotralentz Habitat) was studied on a household of four persons. This system which permits to benefit from a tax-credit is common in France. Details of this site are provided in Table 1. Rainwater is channelled through gutters and downpipes to a wire mesh filter before entering an underground high density polyethylene (HDPE) storage tank, which moves through a calm inlet. In the event of an overflow, excess water is fed into a nearby canal. A submerged intake with an inlet filter attached to a float is used to pump water into the house. Prior to use, collected rainwater is treated by passing through a physical filter (25 µm) and an activated carbon filter. When insufficient water is available in the tank, a probe activates a valve to allow for pumping from a backup tank containing drinking water. Rainwater that is collected is available to flush 9-L flush toilets. Water physicochemical and microbiological quality was studied over one year (Vialle, 2011; Vialle et al., 2011a, 2013). The rainwater volumes collected, overflowed or used for flushing toilets were also available from a one-year monitoring campaign (Vialle, 2011; Vialle et al., 2011b). This period corresponds to a rainfall of about 766 mm distributed among 174 days and 40% of these rainy days presented precipitations inferior to 2 mm. A 5 m³ storage tank leads to a water saving efficiency of 87%. This means 87% of the water consumption for toilet flushing can be provided by the roof runoff collected. Elements considered in the system boundaries are presented in Fig. 1.

2.1.2.2. Drinking water production system (DW). The water production plant considered for the life cycle assessment is the plant that supplies potable water to the individual house studied. This plant supplies 1,400,000 m³ of potable water per year and its annual electricity consumption is 1.2 GWh. Surface water pumping is performed with three pumps (3 × 20 kWh). The process entails clarification (flocculation with 40 g of polyaluminium chloride per m³ of feed water and decantation with 10 kg of sand per day), filtration in sand filters (80 t of sand renewed every ten years), filtration in granular activated carbon filters (25 m³ renewed every five years), pH re-adjustment (1 g of sodium hydroxide per m³; 0.5 g of sulphuric acid per m³), sterilisation/ozonation (three UV reactors renewed every eight years, each containing twelve low-pressure lamps renewed every three years, with ozone produced on site) and finally, disinfection (0.5 g of gaseous chlorine per m³).

The supply is performed with three pumps (75 kWh). The different steps of the water treatment process are summarised in Fig. 2.

In the present case, the rainwater harvesting system and the water production plant are supposed to run for 50 years without renovation; therefore, dismantlement has not been integrated. The reference year is 2010.

2.1.3. Sensitive parameters

The RWH system and the DW system described previously are baseline systems. However, according to the local context, some optional processes might be added to these baseline systems in order to better suit people's needs. The different parameters assessed in this article are (i) construction of infrastructures I, (ii) building scale B and (iii) disinfection step D. Building scale and disinfection have only been studied on the RWH system, as the DW system does not depend of the scale and contains necessarily a disinfection step. More details on these parameters are described in Table 2.

The construction of infrastructures (scenario called RWH/I and DW/I) can be taken into account to assess the whole life cycle of both systems. Transportation of inputs and wastes is also included. Moreover, the RWH baseline system is set up at the household scale. In densely populated areas, buildings are predominant over household. Thus, a higher scale, i.e., building scale with a 30 m³ storage tank which leads to a water saving efficiency of 95% has also been studied and compared to the household scale. Sub processes are the same regardless the scale. This scenario is called RWH/B. A disinfection step can also be added to the RWH baseline system. Disinfection is not required by legislation when rainwater is used to flush toilets. Yet, disinfection is recommended for rainwater used inside households, in order to avoid any sanitary risks (Vialle et al., 2011a). This scenario is called RWH/D.

A first-flush diversion could have been envisaged. Such a system would without doubt result in an improvement of the quality of harvested rainwater but it would not have a major impact on LCA results as it does consume neither electricity nor consumables.

2.2. Life cycle inventory

2.2.1. Data collection

First, flowcharts were constructed for the RWH baseline system and the different options that can be added to this system (RWH/I, RWH/D, Fig. 3) as well as for the DW system (Fig. 4). Sub-processes do not depend on the scale. Flowcharts represent the stages taken into account and describe the indirect inputs and outputs as well. Data were collected for all the unit processes. Regarding the RWH system, data were supplied by the provider of the system, Sotralentz Habitat. With respect to the drinking water production, the operation phase of the plant was subdivided into the treatment steps presented in Fig. 4. First, subdividing data were collected from the plant manager. Second, all orders of magnitude were checked by water production experts. Infrastructures data of the DW system were extracted from the Ecoinvent database.

Then, the quantities of materials, energy and transport required for each sub-process were listed in a Microsoft Excel sheet. Subsequently, the data were normalised to obtain reference flows expressed “per functional unit”. Indirect energy and material flows required to produce direct inputs and outputs were extracted from the Ecoinvent Database. It is important to note that electricity required has been accounted for by considering the French average production mix. Life cycle inventory results were obtained by multiplying reference flows by emission or extraction factors from the Ecoinvent database 3.1 (Swiss Center for Life Cycle Inventories, 2014). SimaPro® software version 8.04 was used for inventorying

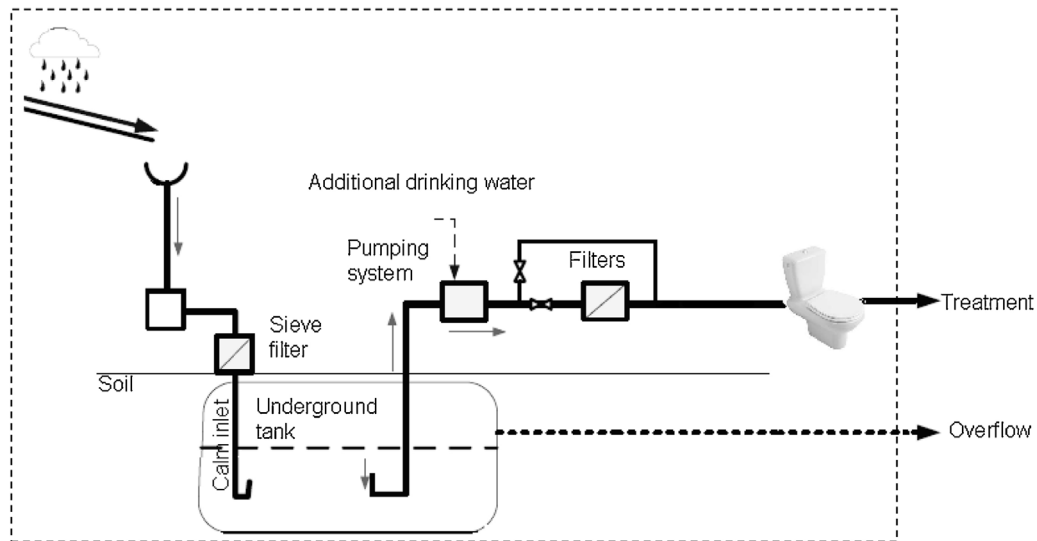


Fig. 1. Rainwater harvesting system boundaries.

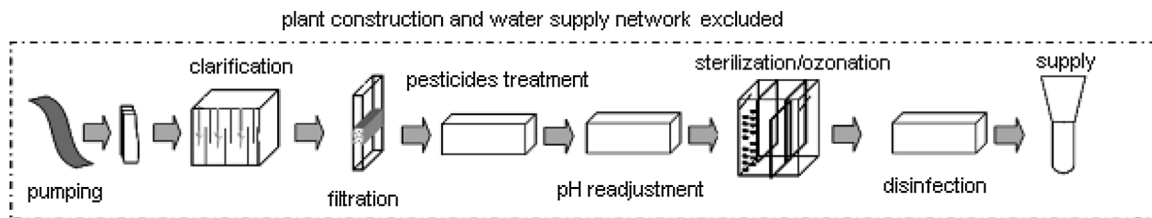


Fig. 2. Drinking water production system boundaries.

Scenarios			Options	Flowchart	
RWHD	RWHD	RWH/I	Infrastructures	<p>diesel for digger → Excavation → emission</p> <p>cement, gravel, HDPE, tank, PVC pipes, diesel → Installation of storage → emission</p> <p>pumps, alternative tank → Installation of pumping → emission</p> <p>filters → Installation of secondary filtration → emission</p> <p>PER pipes, waterworks → Installation of uses → emission</p>	
		RWH baseline system		<p>water from storage tank → Pumping → emission</p> <p>electricity, mains water → Secondary filtration → used activated carbon, used filtering sieve, emission</p> <p>active carbon filtering, sieve →</p> <p>water for toilet flushing → Disinfection → used UV lamp, emission</p> <p>electricity, UV lamp →</p> <p>water for toilet flushing</p>	

Fig. 3. Flowchart for the rainwater harvesting baseline system and options.

Table 1
Characteristics of the site under study.

Site	Collection surface		Storage		Use	
	Type	Area (m ²)	Volume (m ³)		Occupants	Toilets
Household	Tiles sloping roof	204	5		4 people family	2×

Table 2
Sensitive parameters summary.

RWH Rainwater harvesting baseline system	Option I : construction of infrastructures included					
	Option B : larger scale : building scale					
	Site	Type	Area (m ²)	Volume (m ³)	Occupants	Toilets
	Part of an engineer school	Bituminous Flat roof	1 650	30	~ 60 researchers	x 8
DW Drinking water system	Option D : disinfection step included					
	Option I : construction of infrastructures included					

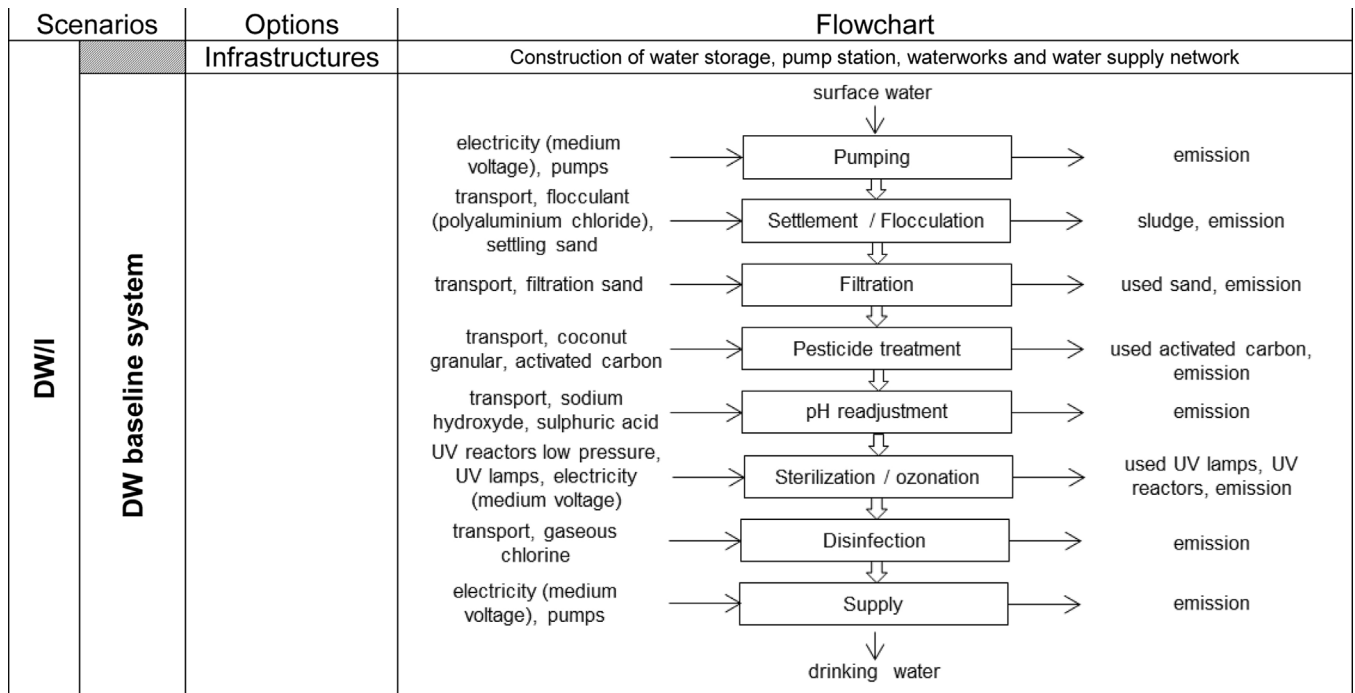


Fig. 4. Flowchart for the drinking water system and option.

elementary flows (Pré consultants, 2014). All numerical data used for calculation in this study are available elsewhere (Vialle, 2011).

2.2.2. Data quality

Uncertainty analysis is applied to all inventory data. Six parameters are qualitatively evaluated on a 1 (best mark) to 5 (worst mark) scale for each data set and an uncertainty factor is attributed to each evaluation using a correspondence table (Weidema and Wesnaes, 1996). As the parameters “sufficiency” and “geographical correlation” do not apply to our data, they were given a value of 1. Afterwards, the variance is calculated (Jolliet et al., 2010). Data collected are of good quality as they are field data established from case studies. Furthermore, Monte Carlo simulations were conducted to

analyse the propagation of uncertainty. These simulations permit to check if differences between scenarios were significant or not.

2.3. Life cycle impact assessment

The inventory results were transformed into environmental impacts with SimaPro® software, using the midpoint/endpoint method Impacts 2002+ (Jolliet et al., 2003). The result of this study may also be influenced by the selection of the impact assessment methodology. Therefore, the ReCiPe methodology (Goedkoop et al., 2009) has been used to check the results obtained with Impact 2002+. The first step of impact assessment is classification, which consists in determining the environmental problems to study. Emissions are attributed to an environmental class or

midpoint category. Then, during the characterisation step, emissions are weighted within each environmental class. The final step is evaluation and determines the relative importance of each class. In essence, midpoint categories are grouped and weighted within each damage or endpoint category.

A water footprint analysis was also performed according to Boulay's methodology, which is one of the only methods that assesses both quantitative and degradative water use by taking into account withdrawn and released water quality and quantity. Boulay's methodology evaluates water stress through the loss of functionality associated with water uses (Kounina et al., 2012). Water footprint was assessed at the midpoint level through the Water Stress Indicator (WSI), which represents the equivalent amount of water ($\text{m}^3\text{-eq}$) generating competition between water users. First, intake and released water have been classified in water categories according to their quality (Boulay et al., 2011a). Then, a water stress index α_i is assigned depending on geographical areas and water categories (Boulay et al., 2011b). Values for water category and α_i are presented in Table 3. At last, Eq. (1) is applied to obtain the WSI.

Eq. (1): Water Stress Indicator calculation according to Boulay's methodology

$$\text{WSI} = \sum_i \alpha_i * V_{i,\text{in}} - \sum_i \alpha_i * V_{i,\text{out}} \quad (1)$$

where WSI (Water Stress Indicator) expresses the impact score at midpoint level, representing the equivalent amount of water ($\text{m}^3\text{-eq}$) generating competition between users, α_i the stress index of water category i (in $\text{m}^3\text{-eq}$ of water per m^3 of water category i withdrawn/released), and V_i the volume of water category i entering or exiting the process of product system.

3. Results and discussion

In this section, results of the characterisation carried out using Impact 2002+ are presented. Very similar results were also obtained with the Recipe method (Goedkoop et al., 2009) and indicate that the choice of methodology has little effect on the eco-profile in this study. The score of the worst scenario is fixed as the reference scenario at 100%.

3.1. Comparison of RWH and DW systems

The substitution of a portion of the potable water with rainwater in the flush toilet was compared to the exclusive use of potable water at the individual household scale. The results are presented with endpoint categories in Fig. 5. Rainwater harvesting practices are slightly less favourable than using potable water for all impact categories.

The WSI for the RWH system is equal to -0.71 equivalent litres of water per functional unit. The negative sign means that stressed water is made available for another user during the process. A RWH system for toilet flush operating in a family of four people during one year would make available around 1 m^3 of stressed water for another user, i.e., 2% of the water consumed. The WSI for the DW system is equals to 0, which means it does not have any impact on the environment. Such a result can be explained by the fact that in the Garonne watershed, there is no stress on rainwater ($\alpha_i = 0$). However, there is a small stress on river water ($\alpha_i = 0.027$). That is why it is better to use rainwater than river water.

Although the RWH system is slightly less interesting than the DW system concerning the impact categories human health, ecosystem quality, resources and climate change, it has a successful water footprint. In case there is a complex treatment process to

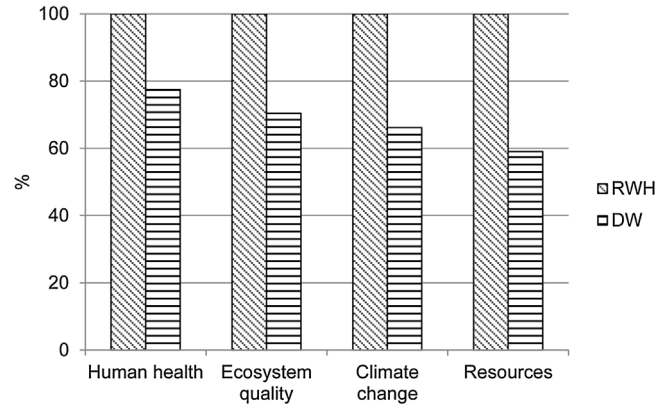


Fig. 5. Impact 2002+ – damage categories – comparison of rainwater and exclusive drinking water to flush toilet. RWH, rainwater harvesting baseline system; DW, drinking water system.

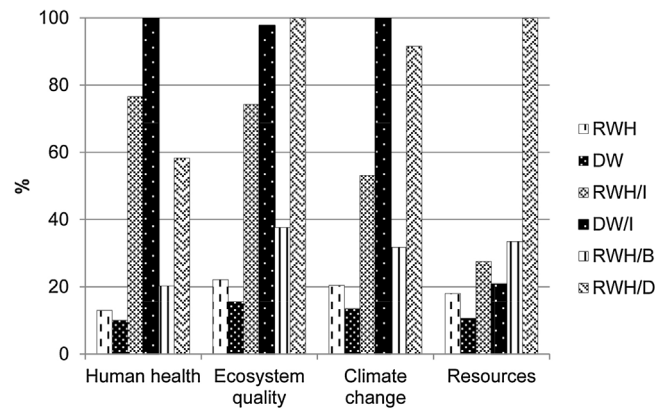


Fig. 6. Impact 2002+ – damage categories – influence of three parameters. DW, drinking water system; RWH, rainwater harvesting system; DW/I, drinking water system with infrastructures included; RWH/I, rainwater harvesting system with infrastructures included; RWH/B, rainwater harvesting system at building scale; RWH/D, rainwater harvesting system with disinfection step included.

produce drinking water, RWH might be even more interesting as environmental impacts of DW system would increase.

3.2. Analysis of sensitive parameters

The influence of three parameters on the RWH system and one parameter on the DW system was assessed. Fig. 6 presents the results in endpoint categories.

3.2.1. Parameter 1: infrastructures included (DW/I and RWH/I)

When the construction of infrastructures is taken into account, environmental impacts increase significantly for both systems. The increase is particularly drastic for the DW system. Although rainwater was considered to substitute potable water used to flush toilet, drinking water remains necessary for other domestic uses. This is why neglecting the construction of drinking water plant and water supply network is closer to reality in France, as the drinking water system is already set up. Yet the same does not apply to RWH system, as it is added to pre-existing houses.

3.2.2. Parameter 2: building scale (RWH/B)

With regard to the RWH system, environmental impacts of the building scale appear to be approximately 10% or 20% higher than the household scale, depending on the damage category considered. This is due to the electricity consumption for pumping which is higher in the building because all eight toilets must periodically

Table 3
Water category and their respective α_i (Boulay et al., 2011b).

	Water category	α_i (m ³ -eq/m ³ withdrawn)
RWH system		
Intake water	Rain	0
Released water	S3: high coliform, medium toxicity	0.027
DW system		
Intake water	S3: high coliform, medium toxicity	0.027
Released water	S3: high coliform, medium toxicity	0.027

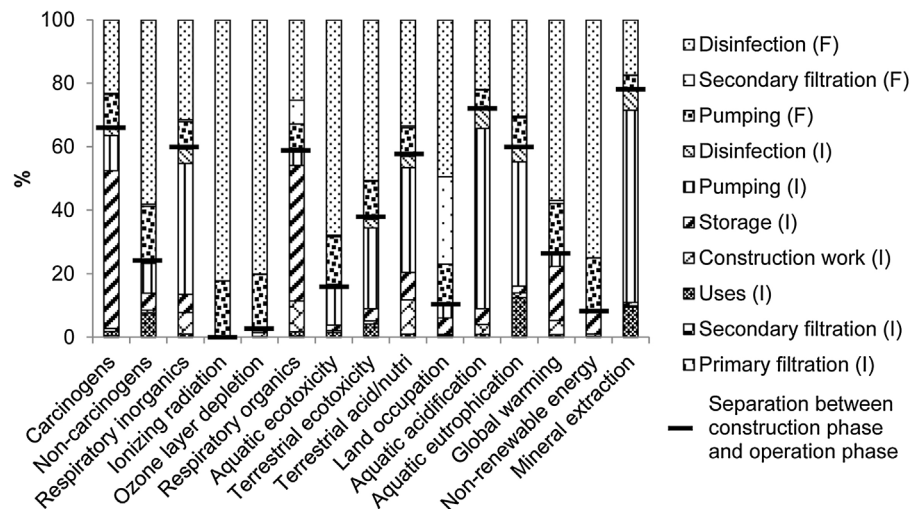


Fig. 7. Impact 2002+ – midpoint categories – contribution of sub-processes. RWH/I/D, rainwater harvesting with infrastructures and disinfection included; I, infrastructure sub-process; F, functioning sub-process.

be used at the same time. As a result, the installed pumps are more powerful in the building than in the household. This result is consistent with the one of Morales-Pinzón who demonstrated that the potential for energy consumption is higher for apartment building than for house (Morales-Pinzón et al., 2012).

3.2.3. Parameter 3: disinfection step included (RWH/D)

Within the RWH system, a disinfection step can be added right after the second filtration to ensure water quality. However, results suggest that disinfection is a very high source of impact, due to the high energy consumption required for the UV lamps.

3.3. Analysis of RWH system sub processes

The relative contributions of sub-processes are evaluated with midpoint categories for an individual household. The results corresponding to the RWH system with infrastructures (RWH/I) and disinfection (RWH/D) included are presented in Fig. 7.

The results show that for some midpoint categories, the construction phase (below dashes in Fig. 7) has major impacts in comparison with the operation phase (above dashes in Fig. 7). Sub-processes linked to the construction of the system contribute to more than 60% of the impact for carcinogens, aquatic acidification, and mineral extraction categories. In particular, the sub-process “storage” corresponding to the installation of the HDPE tank is the most polluting operation in terms of carcinogens and respiratory organics. In terms of function, the most polluting sub-process is disinfection and the second most polluting is pumping. Secondary filtration plays a key role in respiratory organics and land occupation because of the use of active carbon.

These results mirror those presented in Section 3.2: infrastructures and disinfection seriously increase the environmental impacts. Moreover, these results are consistent with the life cycle

assessment results from Crettaz et al. (1999), who showed that energy consumption appears to be the most sensitive factor in the environmental evaluation.

4. Conclusion

In this study, an attributional life cycle assessment was conducted. This methodology takes into account sub-processes implied in the life cycle and evaluates environmental impacts within the current conditions of production and consumption. A water footprint analysis was also conducted. Pilot systems in France were the subjects of case studies designed to collect the necessary data.

The substitution of a portion of the potable water used by rainwater was compared to the exclusive use of potable water on a private individual household. Environmental impacts of these two systems are very similar, and the RWH system slightly has higher impacts. The sub-process with the greatest impact is pumping due to its electricity consumption. The use of an active carbon filter is also unfavourable to respiratory organics and land occupation. Water footprint analysis has revealed that using RWH systems relieve a stress on water resources where it exists while DW systems do not, which is quite interesting.

Besides, according to the local context, some options have to be included and can significantly change the results. As of today in France, the impact of the construction phase increase environmental impacts and cannot be neglected if the RWH system have to be added to pre-existing houses or buildings, while it can be neglected if the DW system already exists. In particular, the installation of the HDPE tank used for storage in the RWH system largely contributes to environmental problems such as the release of carcinogens and respiratory organics. The use of a disinfection stage ensures that there is no sanitary risk; however, it is highly unfavourable

regarding environmental performance because of the high electricity consumption. Setting up the rainwater system on a building scale has also been studied and entails higher environmental impacts because of the more powerful pumps required.

Before implementing RWH systems, research should address issues related to sub-processes with high environmental impacts, such as pumping and infrastructures. Assuming that RWH practice becomes standard in the future, it is likely that it can affect the market in terms of its capacity and its implications for technical change.

5. Recommendation and perspective

The following paragraph points out the different areas of improvement on which future research should focus to make RWH systems even more sustainable.

5.1. Design choices

As mentioned previously, pumping is the sub-process with the greatest impact. A solution to suppress this pump would be to change the position of the tank and put it above the level of toilet. Angrill studied different position of tanks and highlighted the fact that distributed-over-roof tank would be the best solution (Angrill et al., 2011). Ghimire also proposed a minimal RWH scenario where the tank is located above the level of toilet (Ghimire et al., 2014). However, such a lift requires reinforcement steel to withstand the weight of the tank.

In the minimal RWH scenario that Ghimire suggested, pipe length has also been reduced by locating the storage tank and the toilet in the same side of the house. This change combined with the raised storage tank leads the minimal RWH system to outperform DW system for most of the impact categories.

The significant environmental impact caused by the HDPE tank used for storage can be decreased optimising its size. Morales-Pinzón demonstrated that a storage tank volume above 5 m³ is not beneficial from an environmental standpoint (Morales-Pinzón et al., 2014).

Practisers should also pay attention to the scale. Having tested several RWH scales, Morales-Pinzón demonstrated that the optimal scale appears to be the neighbourhood in high density development (Morales-Pinzón et al., 2012).

These design choices are many parameters that practisers have to examine in order to set up the most sustainable RWH system.

5.2. Design tool

Our case study is specific to the Garonne watershed in France. However, some researchers regretted that RWH studies were case specific and could not be extrapolated directly to other types of buildings in other regions (Devkota et al., 2013; Morales-Pinzón et al., 2012). Thus, design tool such as EEAST (Devkota et al., 2013) and Plugrisoft (Morales-Pinzón et al., 2014) have been developed and can be used ahead of setting up a RWH system, to optimise its design and environmental impacts.

At last, other directions combining rainwater and high efficiency toilets (Anand and Apul, 2011) or low flow toilets (Crettaz et al., 1999) may be envisaged and could potentially be a better environmental solution.

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