The environmental impact of household's water use: A case study in Flanders assessing various water sources, production methods and consumption patterns

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Abstract

Responsible water use and sustainable consumption and production are high on the agenda of multiple stakeholders. Different water supply sources are available, including tap water, bottled water, domestically harvested rainwater and domestically abstracted groundwater. The extent to which each of these water supply sources is used, differs over consumption patterns in various housing types, being detached houses, semi-detached houses, terraced houses and apartments. To identify the environmental impact of a household's water use and potential environmental impact reduction strategies, a holistic assessment is required. In this paper, the environmental impact of a household's water use in Flanders (Belgium) was assessed including four different water supply sources and four different consumption patterns by means of a life cycle assessment. The outcomes of this study reveal a large difference between the environmental impact of bottled water use, having a global warming impact of 259 kg CO_2-eq.$\cdot$m^{-3}, compared to the other three supply sources. Tap water supply had the lowest global warming impact (0.17 kg CO_2-eq.$\cdot$m^{-3}) and resource footprint (6.51 $MJ_{ex}\cdot$m^{-3}) of all water supply sources. The most efficient strategy to reduce the environmental impact of household's water use is to shift the water consumption from bottled to tap water consumption. This would induce a reduction in global warming impact of the water use of an inhabitant in Flanders by on average 80 %, saving 0.1 kg CO_2-eq.$\cdot$day^{-1} in case of groundwater-based tap water. These results provide insights into sustainable water use for multiple consumption patterns and can be used to better frame the environmental benefits of tap water use.

Keywords

Water production; Life cycle assessment; Tap water; Resource footprint; Global Warming; Consumption patterns.

1. Introduction

Access to clean water and sustainable water management have been prioritized on a global scale as one of the seventeen Sustainable Development Goals for 2030 (UN General Assembly, 2015). On this global scale, tap water and bottled water are major drinking water supply sources. Tosun et al. (2020) found that improved access to tap water and better communication of the benefits of tap water could shift consumption away from bottled water to tap water. While it is clear that a shift from bottled water to tap water would currently reduce the cost of water consumption, it remains unclear whether shifting water consumption away from bottled water is the most efficient strategy to reduce the environmental impact of a household's water use, as bottled water represents only a small fraction of the total water use. To quantify this environmental impact, the life cycle assessment (LCA) methodology is commonly used. LCA is a standardized method to evaluate the environmental impact of a product or service throughout its lifecycle (ISO, 2006a; ISO, 2006b). Fantin et al. (2014) performed a harmonization study of existing LCA studies, including 24 LCA studies of tap water and 33 LCA studies of bottled water, exclusively covering polyethylene terephthalate (PET) bottles. The mean global warming (GW) impact was 0.9 kg CO_2-eq.$\cdot$m^{-3} for tap water, while it amounted to 162.4 kg CO_2-eq.$\cdot$m^{-3} for bottled water. However, none of the studies took the consumption pattern of household's water use into account, which is required to calculate the benefit of the water consumption shift from bottled to tap water. For a good estimation of this benefit, a detailed assessment of the environmental impact of household's water use is required. Although the difference in environmental impact between tap water and bottled water seems to be evident, a large difference in the estimates for tap water was found by Fantin et al. (2014). These differences are mainly due to different tap water withdrawal sources (e.g. groundwater or seawater) leading to different treatment systems. In addition, different assumptions regarding the distribution network led to varying environmental impact results.

Tap water and bottled water are the main studied water supply sources. However, also domestically harvested rainwater and domestically harvested groundwater can provide water to a household. Ghimire et al. (2014) compared the environmental impact of tap water, domestically harvested rainwater, agriculturally harvested rainwater and abstracted groundwater (well water). The GW impact of these four water supply sources ranged from 0.084 kg CO_2-eq.·m^{-3} in case of agriculturally harvested rainwater to 0.85 kg CO_2-eq.·m^{-3} in case of tap water. However, no study was found which assessed the environmental impact of all four water supply sources, which is required to assess the environmental impact of the total water use of a household. Moreover, the extent to which these four water supply sources are used also differs, as not all water supply sources can be used for the same applications and consumption patterns vary for different housing types (Vlaamse Milieumaatschappij, 2018).

People in Flanders have a relatively low preference for tap water consumption as only 32 % indicated that they mostly prefer drinking tap water over bottled water (Vlaamse Milieumaatschappij, 2018). Based on a European survey, Ecorys (2015) found very different results for neighboring countries. The share of respondents that indicated to prefer mostly tap water over bottled water in the Netherlands, France and Germany was 98, 73 and 85 %, respectively, while in the whole of Belgium, this was 59 %. Geerts et al. (2020) investigated the reasons for Flanders' high bottled water consumption and concluded that this could mainly be explained by social norms and negative perceptions about tap water quality. However, the water quality is strictly regulated in Flanders by the drinking water directive (Vlaamse Regering, 2002). A study in 2019 by the Flanders Environmental Agency summarized tap water quality controls and concluded that the tap water quality in Flanders was to a very high extent in line with the high quality requirements (Vlaamse Milieumaatschappij, 2019b). Tap water is already very accessible in Flanders, which was also indicated by the respondents in the survey of Ecorys (2015). This leaves a better communication of the benefits of tap water as a major strategy to enhance a shift in consumption from bottled water to tap water.

In Flanders, tap water can originate from groundwater or surface water, accounting for 47.3 and 52.7 % of Flanders' tap water supply in 2018, respectively (Vlaamse Milieumaatschappij, 2019a). As the withdrawal source, treatment technologies and distribution network are regionally dependent, a specific environmental impact assessment on tap water supply in Flanders is required to assess the environmental impact of household's water use (Meron et al., 2016). Besides being dependent on the region, the environmental impact of household's water use also depends on technology development over time. Water treatment technologies and auxiliary equipment are constantly evolving, which should also be taken into account (Chen et al., 2019).

The objective of this paper is to assess the environmental impact of household's water use in Flanders. This study contributes to the current state of the art by performing a holistic assessment, which covers both different consumption patterns and different supply sources, and therefore forms a harmonized assessment of the various aspects influencing a household's water use.

2. Material and methods

The environmental impact of household's water use was assessed by means of an attributional LCA, following the ISO guidelines 14040/44 and the four methodological steps being 1) goal and scope definition; 2) life cycle inventory; 3) life cycle impact assessment and; 4) interpretation (ISO, 2006a; ISO, 2006b).

2.1 Goal and scope definition

As the main contributor to the water supply, tap water production was assessed in more detail in a first analysis. Here, the environmental impact of three different sources of tap water was compared; treated by an existing groundwater treatment facility, a newly built groundwater treatment facility with technological differences compared to the first, and an existing surface water treatment facility. The function of these systems was to produce purified water that can be distributed and consumed. The functional unit of the first analysis was therefore 1 m³ water produced at the facility. The scope of this first analysis did not include the distribution of the water to the household. To enable comparison with the surface water treatment, the results of the newly built groundwater treatment facility were provided with and without the infrastructure.

In a second analysis, the environmental impact from the supply of tap water, originating from the newly built groundwater treatment facility, was compared with the environmental impact of the other three water supply sources in Flanders, being (PET) bottled water, domestically harvested rainwater and domestically abstracted groundwater. The function of these water supply sources was to supply water to a household. The functional unit of the second analysis was therefore 1 m³ water supplied to an average Flemish household. The tap water in this analysis was supplied by the newly built groundwater treatment facility including the current distribution network. The newly built groundwater treatment facility was selected to be the tap water supply source as this is the most up-to-date tap water production and no specific information was available on the infrastructure and distribution of the surface water treatment facility.

In the third analysis, the environmental impact of the water consumption of an average inhabitant in Flanders was assessed. This environmental impact was then compared to the environmental impact of the water consumption for inhabitants of different housing types, being terraced houses, semi-detached houses, detached houses and apartments. The function of these consumption patterns was to consume enough water to cover the daily needs of one person in a household. The functional unit of the third analysis was therefore the daily water consumption per capita for a specific household. In this way, also the difference in total water consumption was included in the comparison of the consumption patterns.

The system boundaries started from the groundwater abstraction or rainwater harvesting and end when the water left the tap in the households. Infrastructure, including piping, buildings and tanks, were included in the system boundaries, except for the surface water treatment facility, where this information was not available. Also the distribution inside the household's building was included. The tap itself was not included. The amount of bottled water consumption was assumed to be similar for the different consumption patterns.

Finally, a sensitivity analysis was performed to identify the parameters which influence the environmental impact of different water supply sources the most.

2.2 Description of cases

2.2.1 Tap water production analysis

In the first analysis, the current groundwater treatment facility was compared to a new groundwater treatment facility and a surface water production facility. In the new facility, which will replace the existing one, less chemicals were used in the treatment process. However, this came at the cost of a higher energy consumption. The three processes are illustrated in Figure 1.

The **current groundwater treatment facility** produced 2.5 million m³ drinking water per year. The system boundaries and the different processes are illustrated in Figure 1a. The first process step was the abstraction of water from two water abstraction areas situated in Wuustwezel and Essen. The abstracted water was pumped through a piping network to the top of the aerator and flowed through the following treatment steps by gravitational force. After the aerator, the water passes a static decantor, which removes oxidized iron (Fe^{3+}) in the form of $Fe(OH)_3$. Coagulation and flocculation were aided by dosing hydrated lime ($Ca(OH)_2$) to increase the pH, NaClO as an additional oxidizer for iron and the polyelectrolyte FL 4440 SEP as a coagulant. Next, the overflowing water entered a sand filter where the remaining iron was filtered and ammonia and manganese were removed. Then, the water was disinfected with NaClO and stored in reservoirs.

The sludge, sedimented in the decanter and formed after the backwash of the sand filter, entered a buffer reservoir. Next, the sludge was thickened and centrifuged by adding a polyelectrolyte whereby an iron-rich dewatered sludge was obtained. The remaining water with a low sludge content was disposed into a settling basin. The overflow clear water flowed to an infiltration basin, while the settled sludge was pumped to a natural sludge drying basin. Here, water evaporated resulting in an iron-rich dried sludge. The iron-rich dried sludge and iron-rich dewatered sludge were mainly used for desulphurization in biogas production as this is a cheaper way to add iron to the anaerobic digester compared to dosing iron salts. The most regularly dosed Fe is in the form of $FeCl_2$ and therefore, the use of iron-sludge for desulphurization was assumed to replace the use of $FeCl_2$ (Awe et al., 2017).

The **new groundwater treatment facility**, currently under construction, abstracted groundwater from the same two water abstraction areas as the current groundwater treatment facility. However, other purification processes were applied (Figure 1b). First, the raw water flowed through a static mixer to obtain a uniform quality and was then pumped to the top of the spray aerator. Subsequently, the water passed through a first sand filter where iron removal took place. Next, the water was pumped to a second sand filter. A polyelectrolyte was added to improve the coagulation and flocculation of colloid particles present after the first filtration stage. In this sand filter medium, oxidation of ammonia nitrogen and manganese was established by nitrifying and manganese-oxidizing bacteria, respectively. Next, the water was again pumped to the top of an aeration tower to lower the water aggressiveness by reducing the CO_2 concentration. Finally, the water flowed to four reservoirs, where six UV reactors were located downstream for disinfection. The polluted wash water used in both sand filters was expected to undergo the same treatment as the sludge in the current groundwater treatment facility. No hydrated lime was added in the process of the new treatment facility, so a lower total amount of sludge was produced with a higher iron content (380 g $Fe^{3+}\cdot kg^{-1}$ dry solids instead of 260 g $Fe^{3+}\cdot kg^{-1}$ dry solids). Therefore, the same amount of iron ended up in the sludge, which was used for desulphurization.

The **surface water treatment facility** in Harelbeke (Figure 1c) purified water abstracted from the canal Bossuit-Kortrijk and was managed by the water chain company De Watergroep. De Watergroep is the largest tap water supplier in Flanders, delivering tap water to 3.2 million customers. After pumping and sieving, the surface water flowed from the bottom through a granulated bed to the top of one of the five nitrification reactors where NH_4^+ is oxidized to NO_3^- by bacteria. Second, the water flowed over the reactor where it fell by gravity into two flocculators placed in series. In the waterfall, the flocculant $FeCl_3$ and a polyelectrolyte were dosed and microflocs were immediately formed. Then, the water flowed through one of the three filter beds to retain the suspended solids. Next, the water flowed to the pond of the provincial recreation area De Gavers. The water was then pumped to undergo a post-treatment where the water was split into two fractions. A big water fraction was treated by a floc filtration process to remove suspended solids and to reduce the turbidity. This fraction was then stored in a reservoir. Since 2009, 7500 $m^3 \cdot day^{-1}$ extra water was pumped from the pond. This second fraction of water was sieved and then treated by ultrafiltration. Then, both water fractions flowed together through active carbon filters. The water was then stored in reservoirs. Before pumping the water up for distribution, both NaClO and NaOH were added to disinfect and to maintain the desired pH in the pipes, respectively. Occasionally, all types of filtration were backwashed with air and water. The latter was collected in a buffer tank and was then treated. First, the water was pumped to a sludge thickener where a polymer was added to improve floc formation. The overflowing water was filtered with a dynasand filter where $FeCl_3$ was added and then pumped into the pond in De Gavers, while the thickened sludge was mixed with $Ca(OH)_2$, pumped and sent through a filter press. The remaining water returned to the buffer tank and the filter cake was discarded from the plant and further processed in biodigesters. The filter cake was assumed to substitute for $FeCl_2$ in the same quantity as for the groundwater treatment.

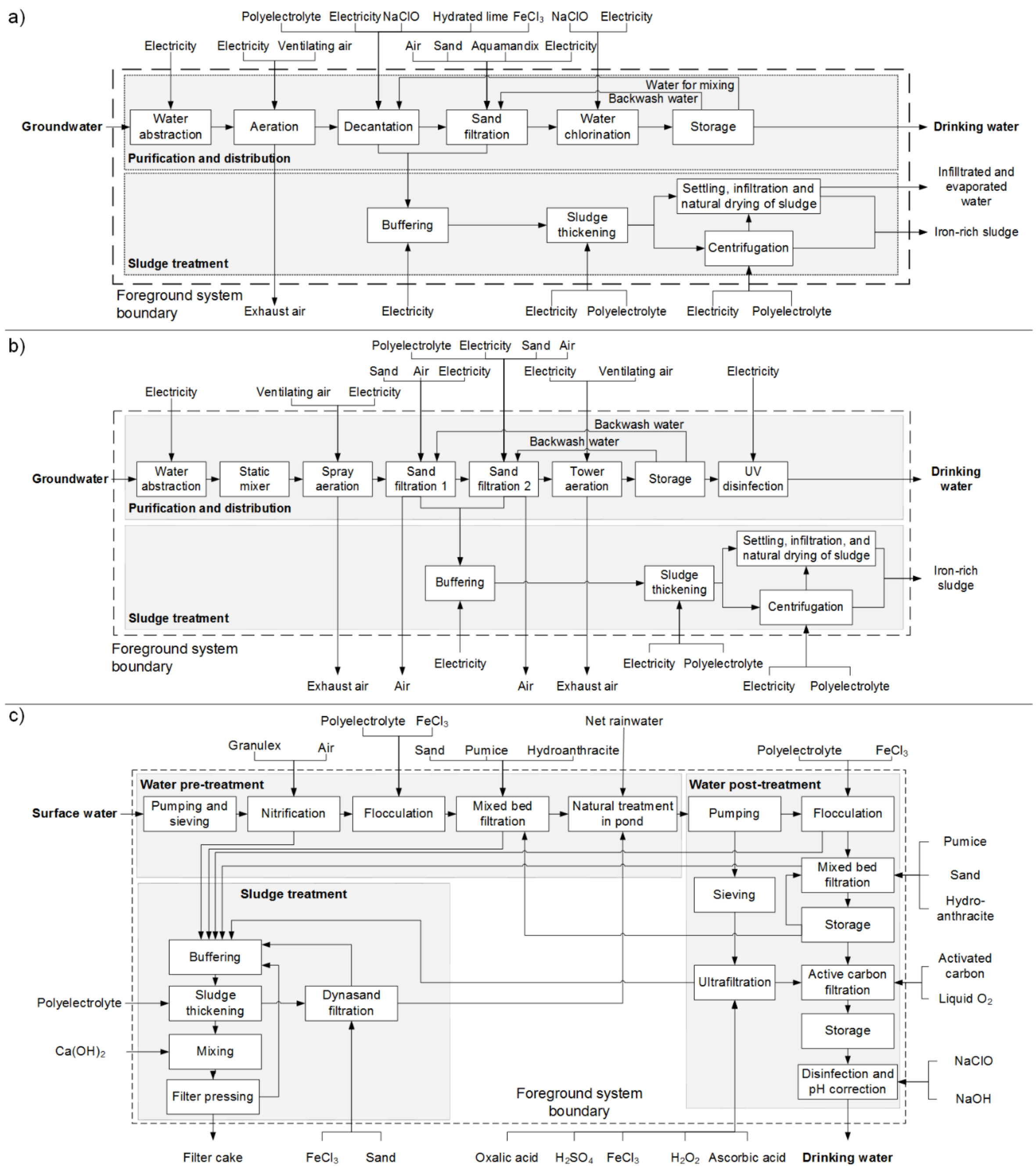

Figure 1. a) Groundwater treatment in current facility (infrastructure was included in the foreground system, but not shown on the figure); b) Groundwater treatment in new facility (infrastructure was included in the foreground system, but not shown on the figure); c) Surface water treatment (electricity was included on the total level and not on a process level)

2.2.2 Comparison supply of tap water, bottled water, domestically harvested rainwater and domestically abstracted groundwater

In the second analysis, four water supply sources were compared, being tap water, produced by the newly built groundwater treatment facility, bottled water, domestically harvested rainwater and domestically harvested groundwater. Figure 2 provides the life cycle of these supply sources. For **tap water**, the distribution network was included in the foreground system (Figure 2a). Drinking water leaving the groundwater treatment facility was pumped into different distribution networks, using high pressure pumps. One water tower was located along the distribution network. Firewater and wash water used for the pipes and leakages accounted for 7.1 % of the total produced drinking water. The fuel consumption of the vehicles, including AdBlue as an additive, was used for the maintenance of the distribution network.

The life cycle of **bottled water** was illustrated in Figure 2b. The bottled water was assumed to originate from natural sourced water, which was treated by a carbon filter, water softener, UV system and ozone system (Dettore, 2009). A reverse osmosis system was excluded due to its irrelevance for European markets, following the assumptions of Vanderheyden and Aerts (2014). In the bottling facility, the bottles were rinsed, filled, labelled, capped and packed. Afterwards, the bottles were transported to retail, where they were bought by the consumers. After the water consumption, the bottles were collected, sorted and recycled to secondary PET granules (87 %) (Fost Plus, 2017). The remaining part was incinerated where the energy was recovered.

Figure 2c illustrated the life cycle of **domestically harvested rainwater**. According to the regulation in Flanders, the provision of a rainwater harvesting system that can store at least 5 m^3 was in most cases obligated for newly built or rebuilt houses (Vlaamse Regering, 2014). A two-story house was considered with a surface area of 100 m^2 and a height of 6.4 m (Ghimire et al., 2014; Winters et al., 2013). The gutter, where the rainwater was collected, was assumed to consist of a half-open PVC pipe and has a length equal to the perimeter of the roof (Ghimire et al., 2014). The water passed through the downpipe, was stored in a storage tank of 5 m^3 (Alim et al., 2020) and distributed through the household.

The process system for **domestically abstracted groundwater** was illustrated in Figure 2d and Figure 2e. The well was made out of a polyvinyl chloride (PVC) casing with a diameter of 20 cm. Inside the PVC casing, a PVC pipe was placed. Around the PVC casing, a clay seal was applied around the first two meters and the last two meters of the pipe (VLAREM II, 2019). At the beginning of the PVC casing, a gravel filter was positioned to filter the abstracted water. Besides the PVC pipe to abstract the water, a PVC pipe to monitor the well was placed. In addition, a PVC well screen was included to close both the abstraction pipe and PVC casing. After abstraction, the water was distributed in the household. Before entering the household, a chamber was constructed where the different control devices can be placed. This chamber had a 1 meter length, a 2 meter width and a 1.2 meter depth as are the minimal requirements (VLAREM II, 2019).

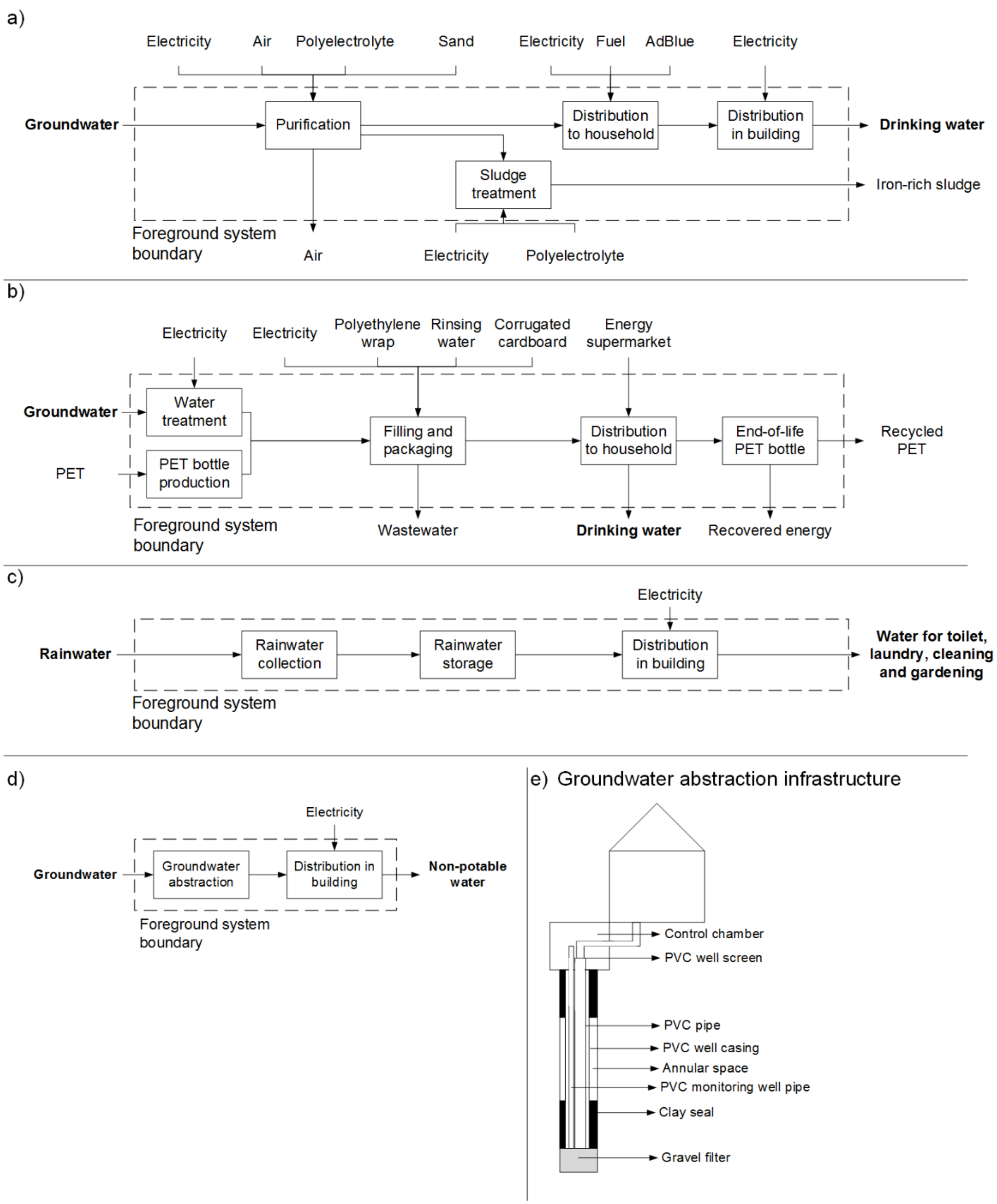

Figure 2 a) Tap water production (Infrastructure was included in the foreground system, but not shown on the figure); b) Bottled water production (Transport and infrastructure were also included in the foreground system, but not shown on the figure; For PET bottle production, the blow molding process was included in the foreground system); c) Domestically harvested rainwater

(Infrastructure was included in the foreground system, but not shown on the figure); d) System boundaries domestically abstracted groundwater (The infrastructure for the distribution in the building was also included, but not shown on the figure); e) Groundwater abstraction infrastructure.

2.2.3 Comparison water use by detached, semi-detached, terraced and apartment households

In the third analysis, the water consumption was compared for four consumption patterns as provided in Table 1. On average, in Flanders, 0.4 liter bottled water·person^{-1}·day^{-1} was used for consumption, whereas tap water, mainly used for household applications, such as cooking, showers, toilets and laundry added up to 100 liter water·person^{-1}·day^{-1} (Vlaamse Milieumaatschappij, 2018). Besides consuming tap water bottled water, households in Flanders consumed on average 11.9 liter domestically harvested rainwater·person^{-1}·day^{-1} and 1.7 liter domestically abstracted groundwater·person^{-1}·day^{-1} (Vlaamse Milieumaatschappij, 2018).

Table 1. Composition of the water supply for multiple consumption patterns in Flanders in 2016 (Vlaamse Milieumaatschappij, 2018)

	Average consumer	Detached house	Semi-detached house	Terraced house	Apartment
Tap water	87.7 %	79.7 %	85.0 %	91.6 %	96.1 %
Bottled water	0.4 %	0.3 %	0.4 %	0.4 %	0.4 %
Harvested rainwater	10.4 %	17.9 %	11.3 %	8.0 %	3.5 %
Abstracted groundwater	1.5 %	2.0 %	3.3 %	0.0 %	0.0 %
Total water consumption per person	114 l·day^{-1}	115 l·day^{-1}	108 l·day^{-1}	94 l·day^{-1}	101 l·day^{-1}

2.3 Life cycle inventory

For the life cycle inventory of the current groundwater production facility, primary data from an existing plant in Essen were used, managed by the water chain company Pidpa. Pidpa is the main water supplier in the province of Antwerp, delivering tap water to 1.2 million customers. The data covered average operating conditions in 2017. For the chemical consumption, average quantities bought by the company in the time period 2012-2017 were included. Data from the infrastructure were based on the demolition inventory of the facility. However, only half of the installation was considered as the other half is not in use anymore. Of the operational facility, only 40 % of the capacity is currently used as the facility is located in the outskirts of Flanders. Data for background processes were retrieved from the ecoinvent database, version 3.5 (Wernet et al., 2016), using the software Simapro, version 9.0.0.33. The input data for the current groundwater production facility and the corresponding life cycle inventory can be found in Table A1 and Table B1 in the Supplementary Information, respectively.

Primary predicted design data from Pidpa were used for the life cycle inventory of the new groundwater treatment facility. The facility operated at an expected occupation rate of 63 %, which is the average operation rate of Pidpa's 11 groundwater treatment facilities. Consequently, the newly built groundwater treatment facility produced 4.3 million $m^3 \cdot year^{-1}$ of drinking water. Table A2 and B2 in the Supplementary Information can be consulted for an overview of all the input parameters and the full life cycle inventory, respectively, of the new groundwater treatment facility.

For the life cycle inventory of the operational surface water treatment facility, primary data from the water chain company 'De Watergroep' were obtained. Chemical consumption data for this facility were based on average consumption in the period 2013-2017. The quantities for the filter media were approximated values. The total annual energy consumption was provided and was not further allocated to the different process steps. No data on the infrastructure were available. Full information on the input data and the life cycle inventory of the surface water treatment facility is provided in Table A3 and B3 of the Supplementary Information, respectively.

To assess the tap water supply, the distribution network of Essen was included, which is approximately 281 km long and is currently serving 21,000 people and 130 companies. Inside the household's building, a piping system of 23.7 m of PVC pipes with a diameter of 19 mm was assumed, in accordance with the assumption of Ghimire et al. (2014) for the in-house distribution of domestically abstracted groundwater. Table A4 and B4 can be consulted for the full input data and the corresponding life cycle inventory of the tap water distribution, respectively.

The data from the bottled water production originated mainly from Vanderheyden and Aerts (2014). The bottles were assumed to be 1.5 liter PET bottles (Vanderheyden and Aerts, 2014). Labels, ink and glue were excluded, following the assumption of Dettore (2009) that their environmental impact is less than 1 % of the impact of the total system. Transportation between the bottle producing company, bottling facility (250 km), retail (500 km) and household (16 km round-trip) was included (Vanderheyden and Aerts, 2014). One passenger car was assumed to carry 30 items of retail goods. Therefore, one thirtieth of the environmental impact of the round trip was allocated to the 1.5 liter bottle (Vanderheyden and Aerts, 2014). The input parameters and the life cycle inventory of bottled water can be found in Table A5 and B5 in the Supplementary Information, respectively.

The data for the domestically harvested rainwater were mainly based on the LCA from Ghimire et al. (2014). The harvested rainwater was assumed to be only suitable for toilet flushing, laundry, cleaning and gardening. On average, 50 liter water·day^{-1}·person^{-1} was used for these four purposes (Vlaamse Milieumaatschappij, 2018). An average household consisted of 2.32 persons, which led to a total amount of 116 liter·day^{-1}·household^{-1} of rainwater used (Statistiek Vlaanderen, 2018). Table A6 and B6 in the Supplementary Information provide the input data and life cycle inventory of the domestically harvested rainwater, respectively.

For the domestically abstracted groundwater, the life cycle inventory was calculated based on the Flemish regulations for ground water wells in soft soil layers (VLAREM II, 2019). The well was assumed to be 7.5 m deep, based on an average Flemish domestic groundwater well (Vlaamse Milieumaatschappij, 2020). Domestically abstracted groundwater can be used for all water applications in the household; however, the quality of the water can be questionable. On average, 1.7 liter·person^{-1}·day^{-1} domestically abstracted groundwater was consumed. However, as only 8.7 % of the Flemish households used this water supply, this means that per household abstracting its own groundwater, 45 liter·day^{-1} of water was abstracted (Vlaamse Milieumaatschappij, 2018). The assumption was made that this water was used additionally to the rainwater as other applications are possible for rainwater. Domestically abstracted groundwater would therefore substitute for tap water and not for rainwater. All input data and the full life cycle inventory of the domestically abstracted groundwater can be found in Table A7 and B7 in the Supplementary Information, respectively.

2.4 Life cycle impact assessment

For the environmental impact assessment, two different methods were used. To quantify the environmental impact related to the emissions, the fourteen emission-related midpoint indicators of the ReCiPe 2016 method were used (Huijbregts et al., 2016). To quantify the resource-related environmental impacts, the Cumulative Exergy Extracted from the Natural Environment (CEENE) method was used (Alvarenga et al., 2013; Dewulf et al., 2007). The CEENE method accounts for the cumulative amount of exergy which is extracted from nature during the entire lifecycle of a product and was recommended as the most appropriate method to quantify resource use based on thermodynamics (Berger et al., 2020; Liao et al., 2012). The exergy of a resource is the upper limit of the useful work that can be obtained from this resource, given the prevailing environmental conditions. Exergy is expressed in one common unit (joules of exergy) and includes both the quantity as well as the quality of the resource. The CEENE method includes multiple natural resource categories being abiotic renewable energy; fossil fuels; nuclear energy;

metal ores; minerals (and mineral aggregates); water resources; and land and biotic resources (Dewulf et al., 2007).

2.5 Sensitivity analysis

An LCA study is sensitive to the quality of the used variables (Reap et al., 2008). Therefore, it is important to assess the sensitivity of the outcome to variations in the different variables. The extent to which each of the included parameters influenced the indicators, was assessed in a sensitivity analysis, which was based on a Monte Carlo analysis. In this way, the most important parameters could be identified and further discussed in more detail. All input parameters in the model, which can be consulted in Supplementary information A, were varied (10,000 iterations) within a triangular distribution (-10 %;+10 %) to identify the crucial parameters that influence the results the most (Thomassen et al., 2019). To perform this sensitivity analysis, Oracle's Crystal Ball software was used.

3. Results

The main impact categories of interest for this study were the GW impact and the resource footprint. The GW impact was selected because this was found to be the most used environmental impact indicator and this choice enabled the comparison of the results with other studies. The resource footprint was selected as this environmental impact indicator focusses on resource use instead of emissions and provides therefore additional insights compared to the GW impact. The results of the other impact indicators are provided in Supplementary information C.

3.1 Tap water production analysis

In the first analysis, the difference in environmental impact of 1 m^3 tap water produced by the current groundwater treatment facility, the new groundwater treatment facility and the current surface water treatment facility was assessed. Figure 3 provides the difference in GW and resource footprint for the different components. The new groundwater treatment facility had a 25 % lower GW impact but a 6 %

higher resource footprint than the current groundwater treatment facility. The lower GW impact can be explained by the lower chemical consumption of the new groundwater treatment facility. While the chemical consumption contributed 37 % to the GW impact of the current water treatment facility, it contributed only 3 % to the GW impact in the new water treatment facility. The chemicals with the highest GW impact in the current groundwater treatment facility were the hydrated lime and NaClO used in the decantation stage, contributing 18 and 8 % to the GW impact, respectively. The new groundwater treatment facility had a 45 % higher energy consumption for the water treatment process compared to the current treatment facility. In the new groundwater treatment facility, this energy consumption contributed 65 % to the GW impact instead of 33 % in the current groundwater treatment facility.

The 6 % higher resource footprint of the water produced by the new water treatment facility was mainly caused by its higher energy consumption. The resource footprint of the chemicals in the new groundwater treatment facility was 10 times lower than in the current groundwater treatment facility. The resource footprint of the infrastructure was 28 % higher for the current groundwater treatment facility than for the new groundwater treatment facility. This can be explained by the higher operational rate of the new groundwater facility, 63 %, compared to the 40 % operational rate of the current groundwater facility. Fossil and nuclear resources were the most extracted resources for both facilities. Regarding the fossil resources, 40 % were used for chemical production for the current groundwater treatment facility, whereas 72 % were used for the energy production in the new groundwater treatment facility. Regarding the nuclear resources, energy consumption was responsible for 94 and 99.7 % of the nuclear resource use in the current and new groundwater treatment facility, respectively.

Not taking into account the infrastructure, surface water treatment had a seven times higher GW impact and a five times higher resource footprint than the new groundwater treatment facility. This can be explained by the more extended purification process which required both more energy and chemicals. In the surface water treatment, the energy consumption contributed 49 % to the total GW impact. Active carbon which was required for filtration, contributed 57 % to the GW impact of all chemicals and 30 % to the total GW impact of surface water treatment. NaClO used in the disinfection process was responsible for 8 % of the GW impact of surface water treatment. In the groundwater treatment process without infrastructure, 92 % of the total GW impact was attributed to the energy consumption, where the energy requirement for groundwater abstraction contributed 65 % to the total GW impact.

Regarding the resource footprint, fossil and nuclear resources had the highest contribution to the resource footprint of both treatment processes. In the groundwater treatment, fossil and nuclear resources were mainly consumed for the groundwater abstraction energy, which contributed 70 % and 71 % to these resource categories. During the surface water treatment, fossil and nuclear resources were mainly consumed for the overall energy use (46 and 93 %, respectively). The main chemicals contributing to the resource footprint were active carbon and NaClO responsible for 33 and 8 % of the total fossil resource use.

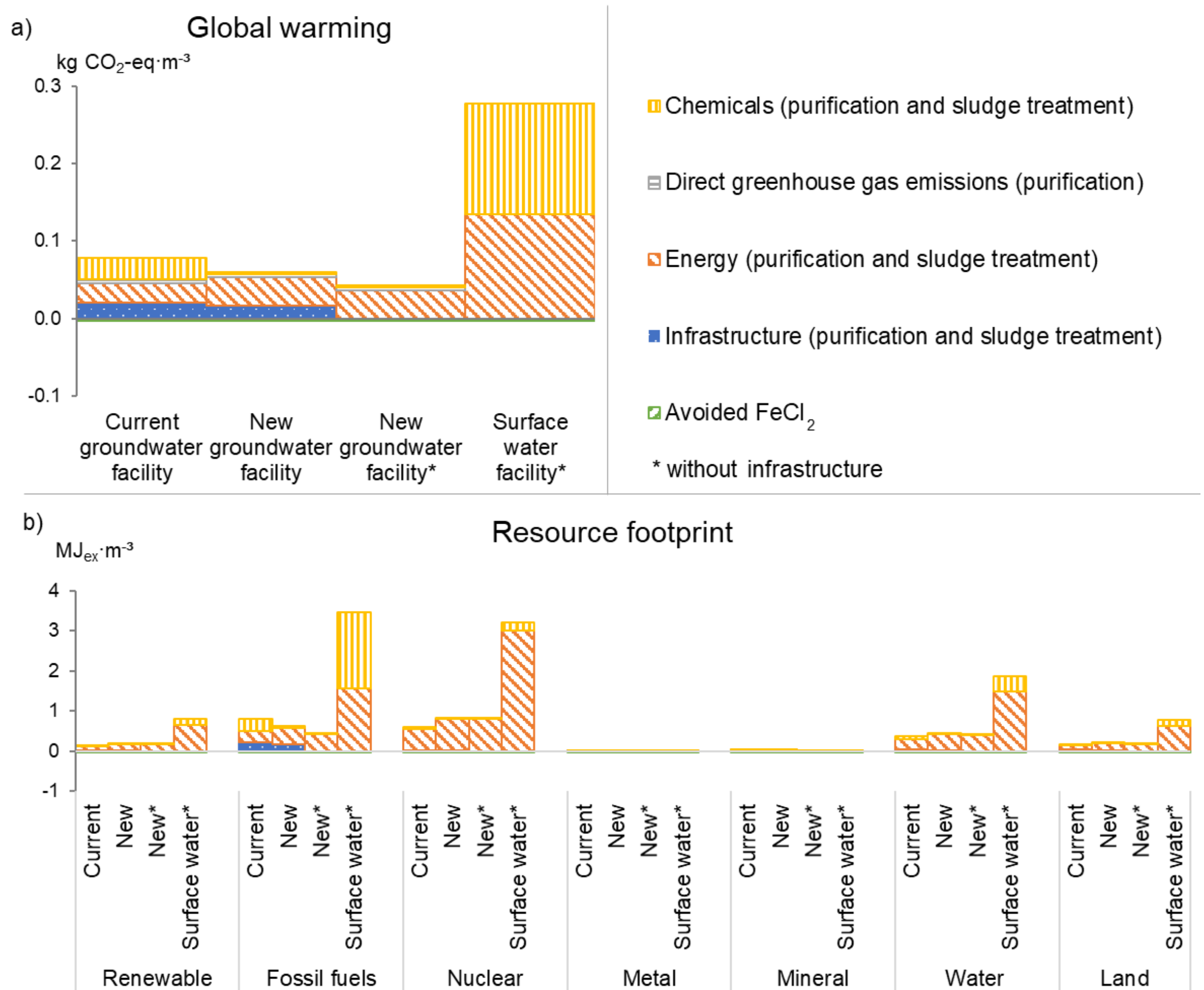

Figure 3. Global warming (a) and resource footprint (b) of the current groundwater treatment facility, new groundwater treatment facility, new groundwater treatment facility without infrastructure and current surface water treatment facility without infrastructure per m³ drinking water produced

3.2 Comparison supply of tap water, bottled water, domestically harvested rainwater and domestically abstracted groundwater

Table 2 provides the GW impact and resource footprint of the four water supply sources as compared in the second analysis. A particularly large difference in global warming and resource footprint existed between bottled water and the other three water sources. Tap water, originating from the new groundwater treatment facility, had the lowest GW impact and resource footprint. Fossil fuel had a large contribution to the resource footprint for all four water supply sources, contributing 34 % for tap water, 71 % for bottled water, 43 % for domestically harvested rainwater, and 28 % for domestically abstracted groundwater. Nuclear resources were also important for the resource footprint of tap water, domestically harvested rainwater and domestically abstracted groundwater (i.e. 32 %, 30 % and 36 %).

Table 2. Global warming (GW) impact and resource footprint of the four water supply sources

	GW (kg CO_2-eq·m^{-3})	Resource footprint (MJ_{ex}·m^{-3})
Tap water	0.17	6.51
Bottled water	259	5236
Domestically harvested rainwater	0.67	31.6
Domestically abstracted groundwater	0.90	39.8

Figure 4 presents the contribution of the different components to the GW impact and resource footprint of the water supply sources. For tap water supply, the energy consumption to pump the drinking water through the distribution network was responsible for 31 and 43 % of the GW impact and resource footprint, respectively. Important components for the fossil resource use in the infrastructure and maintenance of the distribution network were the pipes (22 % of the total fossil resource use) and the fuel consumption during transport for maintenance (15 % of the total fossil resource use). The majority of the nuclear resources, 55 %, were used for the energy consumption in the distribution network.

For bottled water, the distribution from the retail to the household was responsible for 45 % of the GW impact. Other important GW impacts were originating from the PET production (27 %) and the bottled water transport to the retail (25 %). The transport from the retail to the household consumed 47 % of the fossil resources. Another major contributor to the fossil resource footprint was the PET production (42 %), however, 71 % of this fossil resource use was compensated by the recycling of PET.

The main responsible for the GW impact and resource footprint of domestically harvested rainwater was the energy consumption of the pump (59 and 68 %, respectively). The material requirement for the 5 m³ HDPE storage tank had a contribution of 60 %, whereas the pump energy consumption consumed 34 % of the fossil resources. For the mineral resource category, the collection system through the gutter (25 %) had a large contribution.

For the domestically abstracted groundwater, the pumping energy had the largest contribution to both the GW impact (69 %) and the resource footprint (83 %). Also, fossil and nuclear resources were mostly consumed by the pumping energy (64 and 96 %). In the mineral resource category, the concrete for the control chamber had a contribution of 81 %.

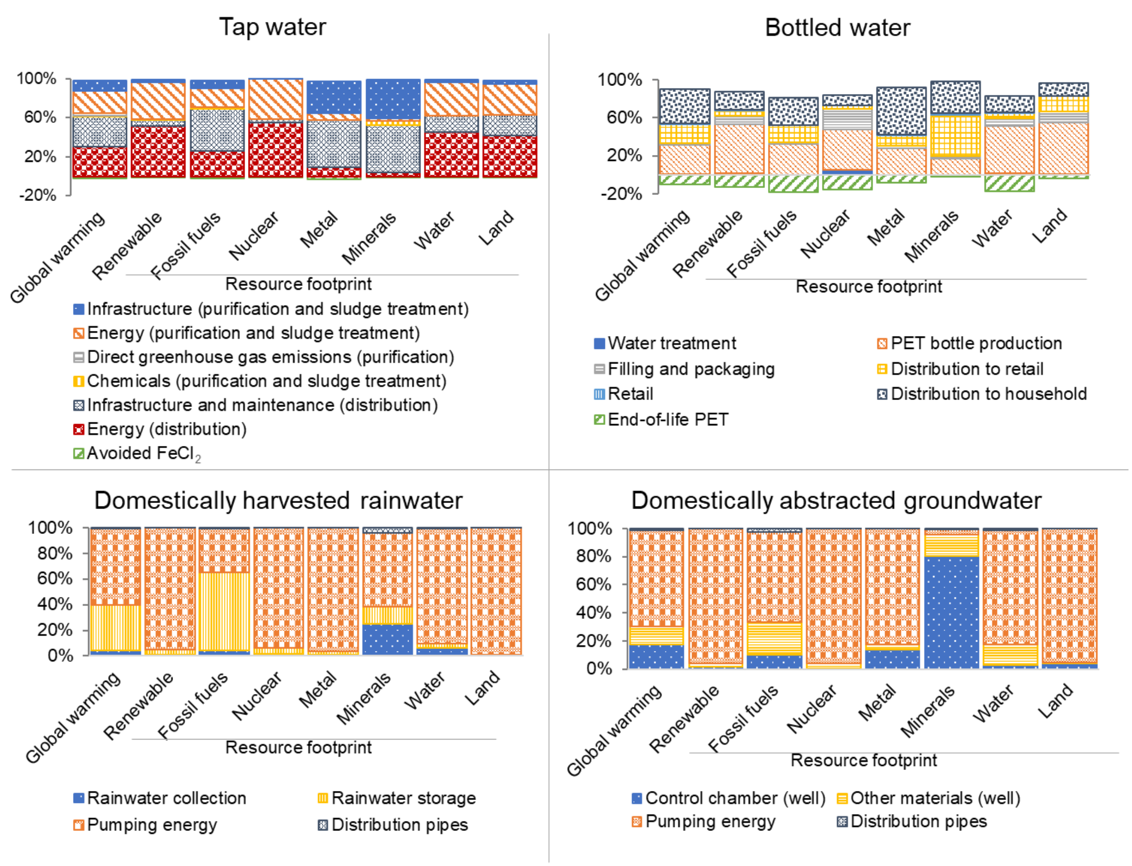

Figure 4. Contribution of the different components of the water supply sources to global warming and resource footprint impact categories based on a functional unit of 1 m³ water supplied to a household

3.3 Comparison water use by detached, semi-detached, terraced and apartment households

Figure 5 provides the comparison between the water consumption, the related GW impact and resource footprint for an average inhabitant in Flanders and for the different consumption patterns. For an average inhabitant, tap water took up 88 % of its daily water use. However, tap water was only responsible for 13 and 20 % of the GW impact and resource footprint of this daily water use, respectively. Bottled water, on the contrary, contributed only 0.4 % to the daily water use, but was responsible for 80 and 66 % of the GW impact and resource footprint of the daily water use of an average person in Flanders, respectively.

Detached house inhabitants had the highest environmental impact due to their largest water consumption. Moreover, detached house inhabitants used more rainwater and domestically abstracted groundwater, which both had a larger environmental impact per m³ than tap water. Terraced house inhabitants had the lowest water consumption. However, they used more domestically harvested rainwater, which led to a higher GW impact and resource footprint compared to apartment inhabitants.

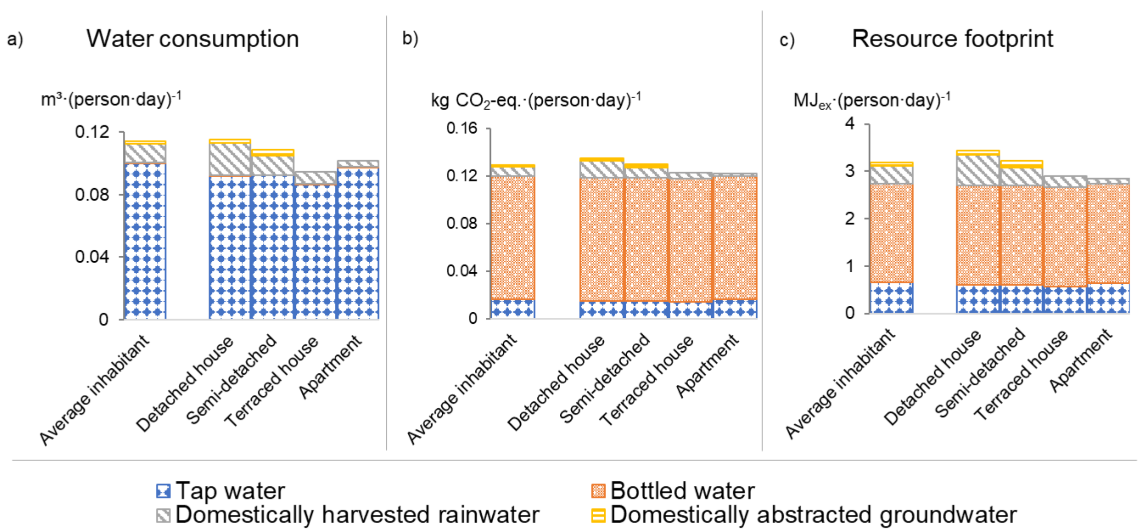

Figure 5. Comparison in (a) water consumption (b) global warming impact and (c) resource footprint for an average inhabitant and inhabitants of different housing types in Flanders.

3.4 Sensitivity analysis

In Figure 6, the parameters that influence the environmental impact the most for the four water supply sources are provided. For the new groundwater treatment facility, the energy consumption in the distribution network, the energy during water abstraction and the upstream GW impact and nuclear resource use of the electricity mix used for the distribution were the most important parameters. The environmental impact of tap water in Flanders was therefore highly dependent on the electricity mix in Flanders. The energy consumption in the distribution network of Essen is relatively low compared to the energy consumption in Pidpa's other water treatment facilities, where it can be up to 56 % higher. This can be explained by the location of the water treatment facility and the relatively low required pressure for water entering for the distribution network. If this higher distribution energy consumption would be assumed, the GW impact and resource footprint of the tap water supply would increase with 18 % (to 0.19 kg CO_2-eq.·m^{-3}) and 24 % (to 8.07 MJ_{ex}·m^{-3}), respectively.

The most important parameter influencing the environmental impact of bottled water was the amount of items purchased per round trip to the retail, which was assumed to be 30 (Vanderheyden and Aerts, 2014). This amount of items was used to allocate the passenger car transport to one bottle of 1.5 liter water. Following this allocation method, 356 km of passenger car transport was allocated to 1 m^3 purchased bottled water, as a round trip equaled 16 km. An alternative allocation method of the passenger car transport can be based on the economic value of a bottle of water relative to the total purchased retail goods by an average household. Following this alternative method, 224 km of passenger transport would be allocated to 1 m^3 bottled water, resulting in a GW impact of 215 kg CO_2-eq.·m^{-3} and a resource footprint of 4,477 MJ_{ex}·m^{-3}. The calculation for both allocation methods is provided in Supplementary information D.

As the amount of purchased items was identified as a crucial parameter, maximizing the amount of purchased items at each round trip reduces the environmental impact of bottled water. On the other hand, purchasing only one item at a round trip increases the GW impact with 1,418 % to 3,670 kg CO_2-eq.·m^{-3} and the resource footprint with 1,233 % to 64,554 MJ_{ex}·m^{-3}. A second important parameter for the environmental impact of bottled water was the environmental impact of the transport mode per km. If the consumer would simply walk to the retail instead of using a car, the GW impact of the bottled water would equal 141 kg CO_2-eq.·m^{-3} water, which is a reduction of 45 % compared to the trip by car. In this case, the resource footprint would be reduced by 39 % compared to the car trip (3,191 MJ_{ex}·m^{-3}). Other important parameters influencing the environmental impact of bottled water were the PET consumption and the upstream fossil resource use for the PET production.

The environmental impact of the domestically harvested rainwater was highly influenced by the amount of rainwater used per day and the pump electricity consumption. The electricity consumption used in this study was based on a median empirical value of 1.4 kWh·m^{-3}, found by a review study of Vieira et al. (2014). This value was considerably higher than the median theoretical value, being 0.2 kWh·m^{-3}. If this theoretical value would have been used in the current study, the GW impact and resource footprint of domestically harvested rainwater would have been reduced with 51 and 58 %. Similar important parameters were also identified for the domestically abstracted groundwater. If the median theoretical pump energy consumption was used as well to calculate the energy consumption, the GW impact and resource footprint would have been reduced with 62 and 76 %, respectively. Accordingly, an optimal design of the pumping system and an optimal use of groundwater and rainwater in the household are strategies to reduce the environmental impact of these two water supply sources.

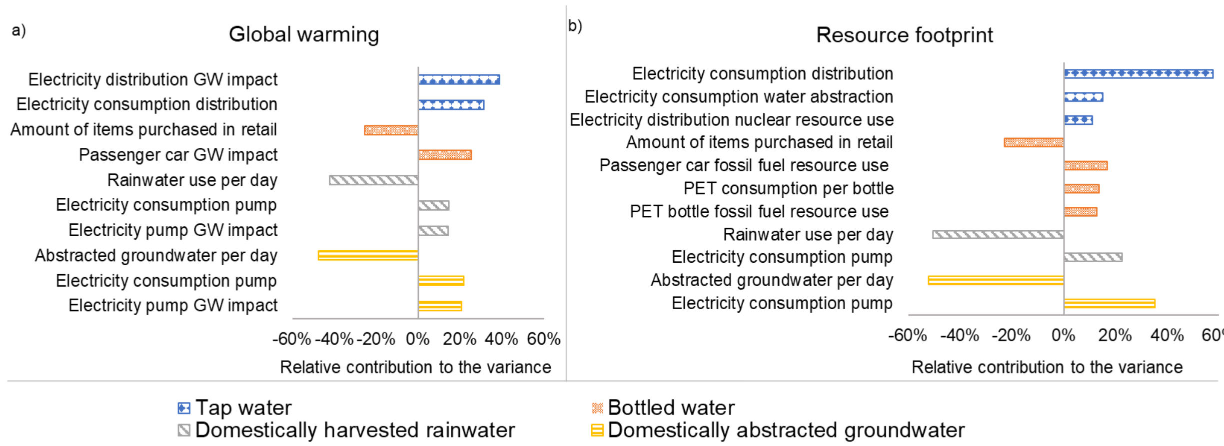

Figure 6. Relative contribution of the critical parameters to the variance in (a) global warming and (b) resource footprint. Only the parameters that have an impact of more than 10 % on the variance of the indicators are provided.

4. Discussion

In the first analysis, a currently operational groundwater treatment facility was compared with a newly built groundwater treatment facility with technological differences compared to the first. However, the current facility only operated at 40 % of its design capacity, while the new groundwater treatment facility will operate at 63 % of its design capacity. If both facilities would have been assumed to produce the same amount of drinking water, i.e. 2.5 million m³, the new groundwater treatment facility would have had an operational rate of 37 %. As a consequence of this lower operational rate, the impact of the infrastructure would have a higher share. In addition, the electricity consumption per liter produced water would be 9 % higher, as the electricity use does not always scale in a linear way when increasing the water production. Under these assumptions, the GW impact and resource footprint of the new groundwater treatment facility would have been 16 % smaller and 1.7 % larger, respectively, compared to the current groundwater treatment facility. The resource footprint of the infrastructure would have been 33 % higher in the new groundwater treatment facility compared to the current groundwater treatment facility despite the same drinking water production volume. This higher resource consumption of the infrastructure is due to the more stringent building requirements of contemporary building codes. The increase in operating capacity has a relatively large effect on the results. It is therefore important to consider the difference between operating and design capacity in LCA studies of water treatment plants, which was also recommended in the critical review on the application of LCA in wastewater treatment plants by Corominas et al. (2020).

In the second and third analysis, tap water was assumed to be fully based on groundwater. According to the Flanders Environmental Agency, only 47.3 % of the tap water originates from groundwater, whereas the other 52.7 % originates from surface water. As no infrastructure and distribution data were available for surface water, surface water was not further included in the tap water supply. As the GW impact and resource footprint of surface water was found to be higher compared to groundwater, the GW impact and resource footprint of tap water as quantified in this study will be lower than the average tap water in Flanders. According to the first analysis, the GW impact and resource footprint of the surface water production without infrastructure and distribution were 7 and 5 times larger than the groundwater production without infrastructure and distribution. If the infrastructure and distribution phase of the surface water would be assumed to have the same GW impact and resource footprint as for the newly built groundwater production facility, the GW impact and resource footprint of surface water would change to 0.4 kg CO_2-eq.$\cdot m^{-3}$ water and 14.5 $MJ_{ex}\cdot m^{-3}$, respectively.

The calculated GW impact for tap water, produced by the newly built groundwater production facility, equaled 0.17 kg CO_2-eq. per m^3 in this study. Compared to the range of 0.2-2.2 kg CO_2-eq. per m^3 tap water, which was found in the review study of Fantin et al. (2014), the value in this study is relatively low. This can be explained by the limited distance of the distribution network in Flanders and the lower GW impact of the considered groundwater treatment compared to other more energy intensive processes, such as reverse osmosis. A meta-analysis on LCA studies of tap water supply systems by Meron et al. (2016) found a range in GW impact between 0.16-3.40 kg CO_2-eq. per m^3 tap water. The water production stage was often identified as the most important. However, in regions where water is sourced from groundwater or spring water, the distribution system had a high contribution to the environmental impact, which was also affirmed in the current study (Amores et al., 2013; Barjoveanu et al., 2013).

For bottled water, the GW impact equaled 259 kg CO_2-eq. per m³ in this study. This value was in the range of 71-318 kg CO_2-eq. per m³ bottled water, which was found in the review study of Fantin et al. (2014). In the study of Horowitz et al. (2018), a GW impact of 673 kg CO_2-eq. per m³ bottled water was found. This higher value can be explained by the large total transportation distance (3292 km) and the assumption that the PET bottle would be landfilled instead of recycled. Horowitz et al. (2018) also assessed the environmental impact of bottled water with bottles made out of recycled PET, polylactic acid (PLA) and a biodegradable plastic (ENSO), which led to a GW impact compared to the regular PET of 93, 92 and 166 %, respectively. In the study of Garfí et al. (2016), tap water and bottled water were compared in various scenarios, leading to a GW impact of 0.5 kg CO_2-eq. per m³ tap water and 75.1 kg CO_2-eq. per m³ bottled water. Transport and distribution were excluded from the system boundaries.

The GW impact for domestically harvested rainwater was 0.67 kg CO_2-eq.$\cdot$m^{-3}. In the study of Ghimire et al. (2014), a GW impact of 0.41 kg CO_2-eq.$\cdot$m^{-3} domestically harvested rainwater was found. This lower value can be explained by the lower energy consumption of the pump (49 kWh$\cdot$year^{-1} compared to 59 kWh$\cdot$year^{-1} in the current study). In the study by Angrill et al. (2011), a value of 3.21 kg CO_2-eq.$\cdot$m^{-3} was found. The concrete tank with steel reinforcements (in contrast to the high density polyethene tank in the current study) had the largest contribution to the GW impact. According to Angrill et al. (2011), a rooftop tank had the lowest GW impact, being 0.64 kg CO_2-eq.$\cdot$m^{-3}. In the study of Godskesen et al. (2013), tap water in the city of Copenhagen (Denmark) was compared with centralized harvested rainwater and stormwater. Centralized harvested rainwater and stormwater were found to have a lower GW impact than tap water.

For domestically abstracted groundwater, no studies were found for comparison. Although the environmental impact of well water was assessed in some studies (e.g. Ghimire et al. (2014)), these wells were never domestically owned. This had a large impact on the abstracted water per day, which was identified as the most important parameter influencing the environmental impact. Therefore, these well water estimates could not be used for comparison with the results from the current study.

The environmental impact of bottled water was very sensitive to the assumption made about the consumer’s transportation to the retail. In this study, the retail was assumed to be 8 km away from the household and a passenger car was assumed for transportation. Of the environmental impact of this trip, one thirtieth was allocated to the bottled water. This assumption was retrieved from a similar study for Flanders which compared filtered water with bottled water (Vanderheyden and Aerts, 2014). In the study of Horowitz et al. (2018), a distance of 27 km from retail to consumers was taken into account. Of the environmental impact of this trip, 1 % was allocated to 0.479 liter bottled water and the other 99 % was allocated to other purchases at the same trip. In the study of Nessi et al. (2012), a roundtrip distance of 10 km was assumed to purchase six 1.5 liter bottles of water. To this six-pack, one thirtieth of the overall burden of the roundtrip was allocated. The importance of the amount of items bought per purchase was stressed as they found an increase in impacts of 96 % when only the six-pack of water was purchased. In the review of Fantin et al. (2014) lower values for GW of bottled water were reported, assuming mostly a 5 km distance to the retail. The use of 5 km distance in this study would reduce the GW impact by 17 % (215 kg CO_2-eq.$\cdot m^{-3}$ water) and the resource footprint by 15 % (4,469 $MJ_{ex} \cdot m^{-3}$). The assumption on transport distance and total amount of purchased goods had a large impact on the results, however, no study was found that provided a transparent peer-reviewed value for these parameters. Therefore, more research on the consumer trip to retail is required.

The production of the PET bottles had a large contribution to the environmental impact of bottled water as well. However, a major environmental problem related to plastic bottles is the littering which causes harm to multiple ecosystems, for example the marine environment. This effect is currently not captured by the environmental impact indicators, but progress to include this impact in the future has been made (Woods et al., 2019).

The data used for the tap water production and supply originated from three water treatment facilities in Flanders. They do not represent a full overview of the water supply source in Flanders, but only a fraction based on specific cases. For the housing types and water consumption, average values were used. Consequently, the GW impact and resource footprint of households within the same housing type can also vary. In addition, temporal variation between water consumption exists as well. For example, the water use for gardening will be much larger for households with a large garden during a dry summer. Accordingly, this will also influence the GW impact and resource footprint.

The environmental impact of household's water use is dominated by bottled water. Although the water supply of a household can consist of four sources, they are not all interchangeable. Tap water can be used for all applications if the quality is sufficient. If someone, drinking 1 liter of bottled water per day, switches to drinking groundwater-based tap water instead, then the GW impact of his or her total water use would decrease 11 times, saving 0.26 kg CO_2-eq.$\cdot$day^{-1}. This saving in GW impact would equal 91 % of the original daily GW impact of water use. An average inhabitant in Flanders consumes 0.4 liter bottled water per day. Assuming all inhabitants in Flanders would consume groundwater-based tap water instead of bottled water, the resulting GW impact of the total daily water use would be 20 % of its current GW impact, saving 0.1 kg CO_2-eq.$\cdot$person$^{-1}\cdot$day^{-1}. This saving equals 246 kton $CO_2\cdot$year^{-1} for the whole of Flanders, taking into account 6.5 million inhabitants.

Also domestically harvested rainwater and domestically abstracted groundwater have a lower GW impact than bottled water, however, as their water quality is lower, they are not fitted without further treatment to replace bottled water. Furthermore, their impact is strongly related to the amount used. This amount used is restricted by external conditions, such as the amount of rainfall. Domestically abstracted groundwater could be of better quality, but for this case a deeper well would need to be excavated instead of the average well depth used in this study. Therefore, increasing the use of domestically harvested rainwater and domestically abstracted groundwater will not have a large impact on the environmental impact of household's water use, given the used assumptions in this study. Optimization strategies inside the groundwater or surface water treatment facilities only had a minor impact on the total environmental impact of household's water use due to the large difference with bottled water.

The resource footprint included the resource use of water resources. According to the results, tap water had the lowest water resource use (1.2 $MJ_{ex} \cdot m^{-3}$), being 0.3, 25 and 15 % of the water resource use of bottled water, domestically harvested rainwater and domestically abstracted groundwater, respectively. However, an important impact that was not assessed is the impact of water abstraction on water scarcity. For example, domestically harvested rainwater can increase the amount of available water, which can lower the pressure on groundwater reserves. Domestically abstracted groundwater may have an opposite effect as it can cause a relatively higher pressure on local groundwater reserves than tap water. Specific methods, such as the Available Water Remaining (AWaRe) method, exist to assess the impact on water scarcity (Boulay et al., 2017). However, no method was found which could differentiate between the different water supply sources as assessed in this study.

The current study used specific data for the region of Flanders. To adapt the results to other regions, the treatment processes, travel distances and consumption patterns will vary and will influence the results accordingly. However, the general conclusions are expected to remain valid in a broader scope. The wastewater treatment in the end-of-life phase was excluded from the system boundaries as this was assumed to be similar for the different supply sources and consumption patterns.

In this study the environmental impact of a household's water use was assessed from a holistic perspective, including multiple consumption patterns and water supply sources. However, households are not the only actors in an economy using water. By adding industrial water use to this assessment, the results could be extended to a higher level and the environmental impact of water use by a city, a region or a country could be assessed.

Different strategies to reduce the environmental impact of household's water use have been discussed in this study. The impact of implementing these strategies does not only affect the foreground system, but can also influence background processes. To assess the consequences of the implementation of these strategies, a consequential LCA could be an interesting path for further research.

5. Conclusions

Although bottled water contributed only 0.4 % to the daily water use, bottled water was responsible for 80 and 66 % of the GW impact and resource footprint regarding the daily water use of an average person in Flanders, respectively. The most promising strategy to reduce the environmental impact of household's water use is therefore to shift away from bottled water consumption. Different consumption patterns due to different household types, variations in the tap water supply, improvement in the tap water treatment methods and the increase of domestic water supply through rainwater harvesting and domestic groundwater abstraction only had a minor influence on the environmental impact. The main contributors to the large environmental impact of bottled water were the distribution phase, including both the distribution to the household and the distribution to retail, and the bottle production phase. The most efficient strategy to reduce the environmental impact of bottled water itself, was changing the transport mode of the buyer to the retail. In the region of Flanders, there seems to be no reason from an environmental sustainability perspective to explain the relatively high bottled water consumption based on the investigated impact indicators and the given assumptions. The findings of this study can play a role in communicating the environmental benefits of a shift from bottled water consumption to tap water consumption, which could lead to a five-fold reduction in the environmental impact of a household's water use in Flanders in case of groundwater-based tap water.

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