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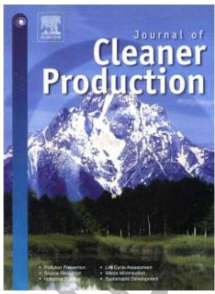

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Water footprint assessment in Wastewater Treatment Plants

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Abstract

Wastewater treatment plants (WWTPs) play an important role within the urban water cycle in protecting receiving waters from untreated discharges. However, WWTPs processes also affect the environment. Life cycle assessment has traditionally been used to assess the impact of direct discharges from WWTPs and indirect emissions related to energy or chemical production. The water footprint (WF) can provide complementary information to evaluate the impact of a WWTP regarding the use of freshwater. This paper presents the adoption of the Water Footprint Assessment methodology to assess the consumption of water resources in WWTPs by considering both blue and grey WFs. The usefulness of the proposed methodology in assessing the environmental impact and the benefits from WWTP discharge to a river is illustrated with an actual WWTP, which treats 4,000 $m^3 \cdot d^{-1}$, using three scenarios: no treatment, secondary treatment and phosphorous removal. A reduction of the water footprint by 51.5 % and 72.4 % was achieved using secondary treatment and phosphorous removal, respectively, to fulfill the legal limits. These results indicate that when treating wastewater, there is a large decrease in the grey water footprint compared with the no-treatment scenario; however, there is a small blue water footprint.

Keywords

Water footprint assessment; Wastewater treatment plants; wastewater; grey water footprint

1. Introduction

Currently, the concern regarding the environmental sustainability of urban development, specifically the use of freshwater resources, has significantly increased due to population growth, which has increased water demand; this problem is exacerbated when combined with water scarcity (which implies limited water availability) (UNEP and UN-Habitat, 2010). The urban water cycle includes water withdrawal from natural resources, water treatment to satisfy the required quality standards for different uses, water distribution, water consumption (drinking water, water for recreational activities, water for cleaning and irrigation of urban areas, water for agriculture and process water for industries), collection and transport of wastewater via sewer systems, and wastewater treatment. Wastewater is treated in wastewater treatment plants (WWTPs), which has the important role within the urban water cycle to improve the water quality before being returned into the natural ecosystems. Traditional wastewater treatment is considered an industrial activity where wastewater is transformed by means of different processes, which consume chemicals and energy, into treated water (of higher quality), which generates by-products (primarily solid wastes and gaseous emissions). Hence, the impact of water emissions into the natural ecosystems is reduced; however, there are increased costs and other environmental impacts (Godin et al., 2012).

One of the most popular methodologies used to evaluate the potential environmental impacts caused by WWTPs is the life cycle assessment (LCA). LCA is a standardized method (ISO 14040-14044:2006), which is used to estimate the impact over a wide range of environmental impact categories (global warming, acidification, eutrophication, human toxicity, etc.) from the construction to the operation of WWTPs (Corominas et al., 2013). Recently, LCA studies have demonstrated the importance of assessing freshwater use by quantifying water consumption from wastewater treatment after current life cycle impact assessment methods were expanded (Kounina et al., 2012). Risch et al., (2014) evaluated the direct water consumption from operating three different wastewater treatment technologies located in three different regions and considered regional factors to account for the water scarcity of the different geographical regions.

The water footprint (WF) of a product/process was introduced for the first time in 2003 and is defined as the volume of freshwater consumed and polluted to produce a product (Hoekstra, 2003). The WF accounts not only for the direct water use of a consumer or producer but also for indirect water use, which depends on the water footprint of the activities related to the studied product/process that goes beyond the boundary of the process (Hoekstra et al., 2011). The WF is divided into three components: blue, green and grey WFs. The blue WF is an indicator of the surface water or groundwater consumption, which includes the evaporated water, water incorporated into the product, and lost return flow, i.e., water that was taken from a catchment and returned to another catchment or the sea or the water that was withdrawn during a period of time and returned in another period of time. The green WF is defined as the consumption of water from precipitation that is stored in the soil and does not run off or recharge the groundwater and thus, is available for evapotranspiration of plants. Finally, the grey WF of a process step indicates the degree of freshwater pollution that can be associated with the process step. The grey WF is defined as the volume of freshwater that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011).

Since its formulation, the WF methodology has been applied in many different fields related to human uses of water. For example, applications in agricultural products and the food industry are extremely popular, where several studies have considered different products and countries. For example, Chapagain and Hoekstra (2007) assessed the water footprint of coffee and tea consumption in The Netherlands, which considered the production in the countries of origin. The WF has also been applied to other products consumed or used by people in the consumption of cotton for clothes production (Chapagain et al., 2006; Chico et al., 2014), rice (Chapagain and Hoekstra, 2011) and several industrial products derived from agriculture (Ercin et al., 2012). Finally, the WF methodology has also been applied to account for the water footprint of different diets (Aldaya and Hoekstra, 2010; Vanham et al., 2013). The WFs of different regions, countries and even all of humanity have also been evaluated (Aldaya et al., 2009; Hoekstra and Mekonnen, 2011). WFs have also been used to assess the production of hydropower energy (Mekonnen and Hoekstra, 2012) and biofuels (Gerbens-Leenes et al., 2012), amongst other applications.

To the best of our knowledge, the application of the WF assessment methodology to WWTPs is limited to the work of Liu et al., (2012) and Shao and Chen (2013). The first study only estimated the grey water footprint of anthropogenic emissions to major rivers, not specifically from WWTPs, and the second study only accounted for the blue water footprint (the study also did not account for sludge treatment, which is extremely important in LCA). The objective of this paper is to adopt the general WF methodology that considers both the blue and grey WFs to assess the water resource consumption of WWTPs. The usefulness of the proposed methodology in assessing the environmental impact and benefits of a WWTP discharging to a river is illustrated with an actual case study.

2. Methodology for water footprint assessment in WWTPs

To evaluate the water footprint of products and consumers, the Water Footprint Network (WFN) developed a methodology for water footprint assessment (WFA) to evaluate the impacts on water consumption caused by an activity (Hoekstra et al., 2011). The WFA methodology addresses freshwater resources appropriation using a four-step approach: (i) set the goals and scope; (ii) account for the water footprint of a process, product, producer or consumer as a spatiotemporally explicit indicator of freshwater appropriation; (iii) evaluate the sustainability of this water footprint and focus on a multi-faceted analysis of the environmental, economic and social aspects; and (iv) formulate strategies to improve the water footprint.

This section introduces the adoption of the WFN methodology for WWTP application and expands the WF accounting phase using a framework for the grey water footprint calculation. As shown in Figure 1, the methodology consists of four phases, which is similar to those in an LCA analysis.

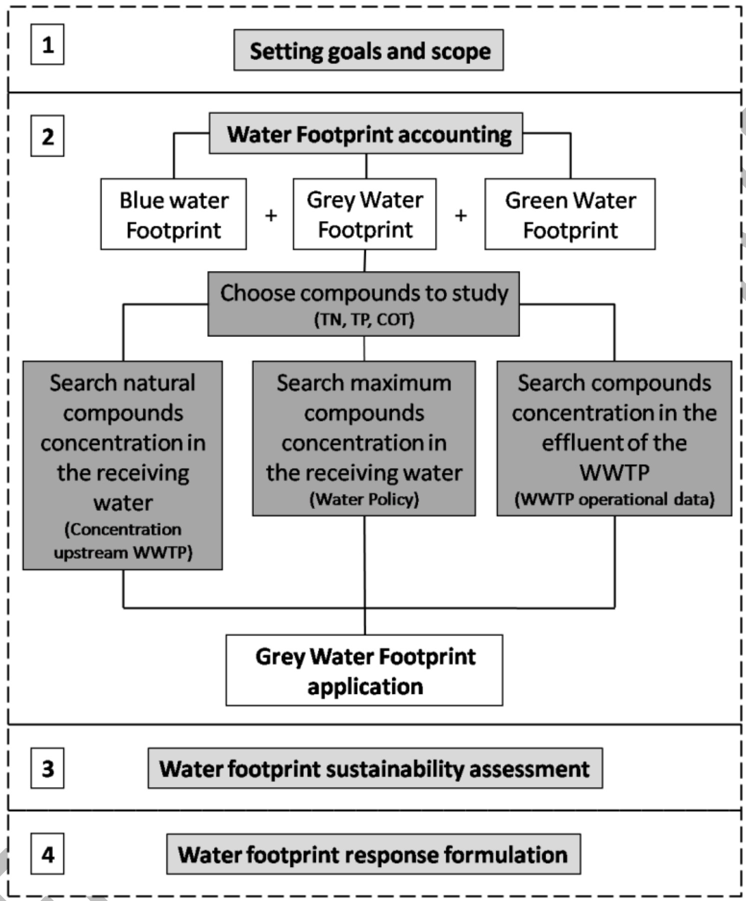

Fig. 1. General framework to assess the water footprint in WWTPs. The dark grey boxes explain the proposed development to calculate the grey water footprint of WWTPs.

The first phase consists of defining the goal and scope of the assessment and includes the functional unit, the types of WF to be considered and the data sample. In the second phase, data are collected, and the water footprint is calculated. In the third phase, the water footprint is evaluated from a sustainability point of view, which considers the water availability in the analyzed region or period, and finally in the fourth phase, several recommendations are drawn to reduce the water footprint of the product or system analyzed.

The general equation to calculate the water footprint of a WWTP, which is the volume of water consumed during a period of time and includes the blue (WF_{blue}), green (WF_{green}) and grey (WF_{grey}) water footprints, is defined as the following:

$$WF = WF_{blue} + WF_{green} + WF_{grey}$$

Eq. 1. General equation for the water footprint calculation of a WWTP.

Blue water footprint (WF_{blue}). In WWTPs, the blue water footprint accounts for the water that evaporates during wastewater treatment and the water used for all processes related to the different WWTP unit operations (chemicals, energy consumption, residue management, transportation and sludge treatment) that is incorporated into the final product. For example, the consumption of chemicals and energy has an associated blue water footprint due to the water incorporated during the production of chemicals and energy. However, the lost return flow, which is considered in the blue water footprint, of other processes or products will be zero when the treated WWTP water is discharged into the same catchment. In certain cases, it can be interesting to consider the route of blue water, particularly in processes or products from agriculture (distinction of the water based on if it comes from the surface, groundwater or another source). Water recycled back to the process or used for other applications (e.g., WWTPs that have tertiary treatment and produce reclaimed water) should also be accounted (as avoided water) because it reduces the blue water footprint.

Green water footprint (WF_{green}). In conventional WWTPs, the green WF is not considered because it does not promote the evaporation of water from the soil or from vegetables and does not promote the incorporation of soil water with treated water.

Grey water footprint (WF_{grey}). The proposed calculation for the grey water footprint in the WFA manual (Hoekstra et al., 2011) has been adapted to the specific domain of WWTPs. The new equation is based on a mass balance at the WWTP discharge point (see Equations 2 and 3 and Figure 2). This mass balance-based approach considers that the grey WF is the minimum volume of water required to dilute the pollutant concentration from the WWTP effluent concentration to the maximum poll utant concentration allowed in the river.

$$Q_e \cdot c_{e(p)} + WF_{grey} \cdot c_{nat(p)} = (Q_e + WF_{grey(p)}) \cdot c_{max(p)}$$

Eq. 2. Mass balance of pollutants at the WWTP discharge point.

$$WF_{grey} = max[WF_{grey(p)} = (Q_e \cdot (c_{e(p)} - c_{max(p)}))/(c_{max(p)} - c_{nat(p)})) \ (volume/time)] \ \text{(for p=1 to p)}$$

Eq. 3. Grey WF equation based on the mass balance of pollutants.

where Q_e is the effluent flow rate (volume/time), $C_{e(p)}$ is the concentration of a pollutant *p* in the WWTP effluent (mass/volume), $C_{max(p)}$ is the maximum concentration of a pollutant *p* permitted in the receiving water body, and $C_{nat(p)}$ is the natural concentration of a pollutant *p* in the receiving water body.

Because many pollutants exist in WWTP discharge, a $WF_{grey(p)}$ is calculated separately for each of the compounds. Then, the resulting WF_{grey} is the WF that ensures an adequate dilution capacity for all compounds, and hence, the maximum of the $WF_{grey(p)}$ values is obtained. The compounds included in the assessment depend on the goal of the study.

The sustainability of the blue WF is assessed by comparing the blue WF with the water availability (water ready to be used) in the studied region. However, if the grey WF is less than the river flow rate to assimilate the pollution, then the calculated grey WF is sustainable. It is important to consider the yearly fluctuations in water availability.

3. Description of the case study (full-scale La Garriga WWTP and the Congost river)

The WF was calculated for the La Garriga WWTP, which treats 4,000 $m^3 \cdot d^{-1}$ and discharges into the Congost river in the Besòs river catchment (NE of Spain). The WWTP, was designed for 29,000 population equivalents with a Modified Ludzak-Etinger (MLE) configuration and treats organic matter and nitrogen. The treated water is discharged to the Congost river, where its average flow of 0.048 $m^3 \cdot s^{-1}$ represents approximately 16% of the flow; however, this flow can represent up to 25% or 30% in the summer. The inventory data for the WWTP was provided by the *Consorci per la Defensa de la Conca del riu Besòs* (CDCRB), whereas the data from the river were obtained from the Catalan Water Agency (ACA). The WWTP effluent flow and the selected pollutant concentrations (total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC)) were used to calculate the $WF_{grey(p)}$. The energy consumption, transportation of chemicals and sludge, sludge treatment and consumption of chemicals were used to calculate the WF_{blue} after applying the water consumption factors for these processes obtained from the Ecoinvent 3.0 database (Swiss Centre for Life Cycle Inventories). The evaporated water was calculated from solar radiation data in the area, which was 14.5 $MJ \cdot (m^2 \cdot day)^{-1}$ (Generalitat de Catalunya, 2000); the surface area of the WWTP reactors is 1,413 m^2.

Information on the C_{max} concentrations in the Besòs river Basin was obtained from the River Basin Management Plans from Catalonia (ACA, 2007), which were developed for the implementation of the Water Framework Directive (EU., 2000). Data from a water quality monitoring station located upstream of the WWTP were used to establish the C_{nat} concentrations.

Accounting for the different WF components was calculated using monthly averaged data for the WWTP effluent flow rates and pollutant concentrations during the period from January 2007 to November 2010. Table 1 summarizes the inventory data used for the WF assessment.

Table 1.
Input data for the WF assessment.

	Input data	**TN**	**TP**	**TOC**
WF_{grey}	C_e ($g \cdot m^{-3}$)	9.66	3.55	11.18
	C_{nat} ($g \cdot m^{-3}$)	1.03	0.04	2.07
	C_{max} ($g \cdot m^{-3}$)	2.65	0.17	5.05
	WWTP effluent flow ($m^3 \cdot month^{-1}$)	123,894		
WF_{blue}	**Energy consumption** ($kwh \cdot m^{-3}$)	0.484		
	Chemicals ($kg \cdot m^{-3}$)	0.026		
	Sludge to treatment ($kg \cdot m^{-3}$)	0.917		
	Other residues ($kg \cdot m^{-3}$)	0.029		
	Evaporation ($m^3 \cdot month^{-1}$)	237.200		
	Transport ($tkm \cdot m^{-3}$)	0.040		

WF can also be referred to as the water consumption for 1 kg of pollutant removed (TOC, N and P) and the cost of treating 1 m^3 of wastewater in the WWTP of La Garriga (0.2 €$\cdot m^{-3}$).

4. Results and discussion

4.1. Water footprint assessment for La Garriga WWTP and the Congost river

4.1.1. Goal and scope

The goals of this WF assessment are to identify the relative importance of the blue and grey WFs in WWTPs, to illustrate the positive roles of these installations in reducing the environmental impact and to propose measures for reducing the WF of a WWTP. To achieve these goals, three different scenarios regarding wastewater treatment were studied: no-treatment scenario (direct discharge of untreated wastewater into the river), conventional wastewater treatment (current operation, i.e., organic matter and nitrogen removal) and wastewater treatment with phosphorous removal (Figure 2). The no-treatment option implies only calculating the WF_{grey} assuming that the influent WWTP concentration is C_e from equation 2. In this case, the influent concentrations (50.41 $mg \cdot l^{-1}$ of TN, 6.45 $mg \cdot l^{-1}$ of TP and 181.73 $mg \cdot l^{-1}$ of TOC) were applied. For the phosphorous removal scenario, the water consumed to produce 1 kg of $FeCl_3$ was obtained from the Ecoinvent 3.0 database and multiplied by the mass of $FeCl_3$ in kg that is consumed to reduce the amount of phosphorous to the legislation limit (2 $mg \cdot l^{-1}$).

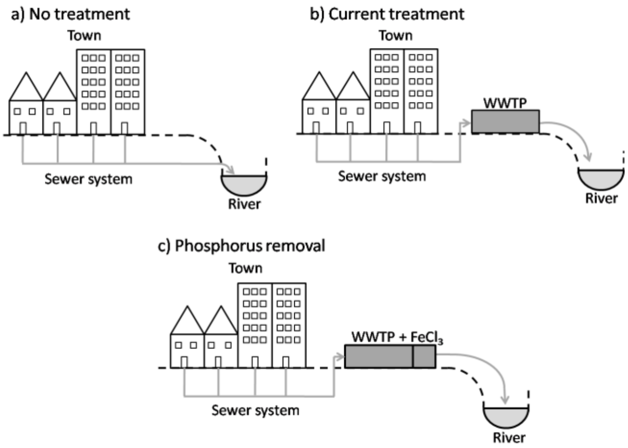

Fig. 2. Scenarios considered for the analysis.

As is shown in Figure 3, the system boundaries for the studied system include the different steps of the WWTP (pretreatment, secondary treatment, sludge thickening and sludge centrifugation), chemical and energy consumption, sludge treatment outside the plant, water evaporation from the plant and pollutants concentration in the effluent water. The functional unit of this case study is the volume of treated wastewater during one month of operation, i.e., 123,894 $m^3 \cdot month^{-1}$.

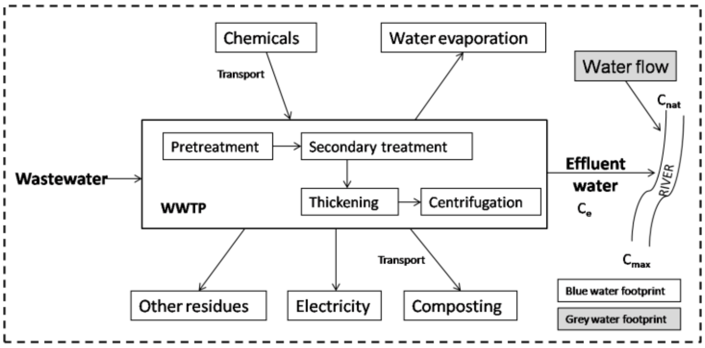

Fig. 3. System boundaries for the WWTP under study.

4.1.2. Water footprint accounting

Figure 4a and Table 3 shows the total WF for the three scenarios. The highest WF corresponds to the no-treatment scenario (7,479,507 $m^3 \cdot month^{-1}$), the second highest WF corresponds to the current wastewater treatment (3,628,295 $m^3 \cdot month^{-1}$) with a WF_{grey} contribution of 95 % and a WF_{blue} contribution of 5 %, and the smallest WF corresponds to the wastewater treatment with phosphorous removal (2,062,718 $m^3 \cdot month^{-1}$). It can be observed that there is a high reduction of the water footprint when wastewater treatment is applied with (72.4 %) and without phosphorous removal (51.5 %).

The grey WF values, i.e., the volume of water required to dilute the WWTP effluent until natural concentrations in the river are reached, were 539,317 $m^3 \cdot month^{-1}$; 3,448,115 $m^3 \cdot month^{-1}$ and 261,779 $m^3 \cdot month^{-1}$ for TN, TP and TOC, respectively, for the current wastewater treatment (Figure 4c and Table 2). The WF_{grey} for TP is much greater compared with the other pollutants because the WWTP is not designed to remove TP, and hence, the WWTP effluent concentrations are high. With respect to the no-treatment scenario, the WF_{grey} is reduced by 51.5 % (from 7,479,507 $m^3 \cdot month^{-1}$ to 3,448,115 $m^3 \cdot month^{-1}$) at the expense of a slight increase in the WF_{blue} (180,180 $m^3 \cdot month^{-1}$). TP is the limiting factor for the WF_{grey} calculation for the treated wastewater, whereas TOC is the limiting factor for the no treatment option. For the wastewater treatment with the phosphorous removal scenario, a dosage of 1 mol of $FeCl_3$ per mol of phosphorous (according to the Minnesota Pollution Control Agency) achieves a 72.4 % reduction of the grey WF for total phosphorous while maintaining the same reductions for nitrogen and organic matter (Table 2 and Figure 5).

The blue WF for the current wastewater treatment scenario was 180,180 $m^3 \cdot month^{-1}$ (Figure 4b and Table 2), where the major contributors are the energy consumption (95.85 %) and residues treatment. The residues treatment consist of the treatment of oils and grease and sludge compost and deposition in a landfill of solid residues (3.53 %), both of which account for more than 99 % of the WF_{blue}. Evaporation in the reactors accounted for only 0.13 % of the WF_{blue}. With respect to the wastewater treatment in the phosphorous removal scenario, similar values were obtained for the blue WF, even though there was an increase of 12,337 $m^3 \cdot month^{-1}$ due to the consumption of more chemicals ($FeCl_3$), which increased the phosphorus removal efficiency, and also due to the increase in sludge mass sent to composting. The addition of the $FeCl_3$ increased the WF_{blue} by 6.8 % compared with the current wastewater treatment scenario; however, overall, the results showed a reduction of 72.4 % in the total WF. In agreement with previous studies (Ercin et al., 2010; Jefferies et al., 2012), the freshwater use associated with supporting activities and materials used in the business (e.g., chemicals, transports), which is not completely associated with the production of the specific product considered, i.e., the overhead water footprint, constitutes a minor fraction of the supply-chain water footprint (0.2–0.3 %).

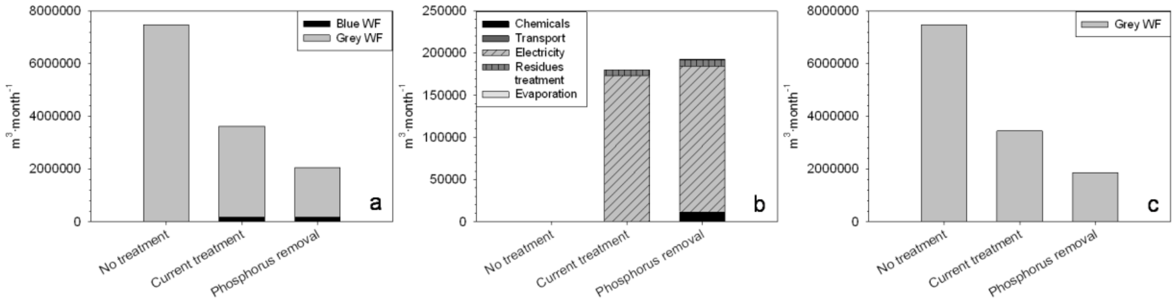

Fig. 4. WF results for the three scenarios; a) Total WF, where WF_{blue} and WF_{grey} are distinguished b) WF_{blue} and its contributors, and c) WF_{grey}.

Table 2.
Comparison between the water footprint for the three scenarios studied.

No treatment option		Current wastewater treatment		Wastewater treatment with phosphorous removal	
Grey WF ($m^3 \cdot month^{-1}$)	Blue WF ($m^3 \cdot month^{-1}$)	Grey WF ($m^3 \cdot month^{-1}$)	Blue WF ($m^3 \cdot month^{-1}$)	Grey WF ($m^3 \cdot month^{-1}$)	Blue WF ($m^3 \cdot month^{-1}$)
TN 3,672,231 TP 6,415,114 TOC 7,479,507	0	TN 539,317 TP 3,448,115 TOC 261,779	180,180	TN 539,317 TP 1,870,201 TOC 261,779	192,517
Total WF ($m^3 \cdot month^{-1}$)	7,479,507	Total WF ($m^3 \cdot month^{-1}$) (% reduction)	3,628,295 (51.5 %)	Total WF ($m^3 \cdot month^{-1}$) (% reduction)	2,062,718 (72.4%)

The WF obtained in this study for the current wastewater treatment (3,628,295 $m^3 \cdot month^{-1}$) is much larger than the WF obtained in the study by Shao and Chen (2013), which only included the WF_{blue}. Still, comparing the WF_{blue} values from both studies shows that a much larger value was obtained in our study (180,180 $m^3 \cdot month^{-1}$, 1.45 m^3 freshwater as $WF_{blue} \cdot m^{-3}$ treated wastewater). The difference is due to the freshwater resource consumption related to electricity generation. In this case, the calculation used the water consumption from the Ecoinvent 3.0 processes for electricity, chemicals, residues and transport and data from the plant. Differently, in the study by Shao and Chen (2013), the calculation used a hybrid method that considered the operational expenses from the WWTP and the national freshwater consumption for every productive sector in China in 2007, which relates freshwater consumption with the economy. Considering their approach in our case study, the freshwater consumption would be $4.78 \cdot 10^{-3}$ $m^3 \cdot kwh^{-1}$, whereas when considering the Ecoinvent 3.0 processes for the medium voltage electricity in Spain, the freshwater consumption is approximately 2.88 $m^3 \cdot kwh^{-1}$. It should also be mentioned that the freshwater used to produce the electricity greatly depends on the country and the technologies used to produce it.

The different methods used in this study and Shao and Chen (2013), explains the difference in water consumption. A process-based inventory allows obtaining very specific and detailed inventories but has some limitations such as it is very time-consuming and requires large amount of data (Zhang et al., 2014). On the other hand, Input-Output analysis, is based on economic input-output tables, with information of industrial flows of transactions of goods and services, but the information is not as accurate and specific as in process-based inventories. Finally, an extended method combining both approaches, an hybrid LCA, which is the one used in Shao and Chen, 2013, allows to overcome these limitations, to increase the completeness of the system boundary and reduce uncertainty (Zhang et al., 2013). However, in this study a process-based inventory is considered to be the most adequate due to the availability of data.

Additionally, the study of Shao and Chen (2013) did not consider residue treatment.

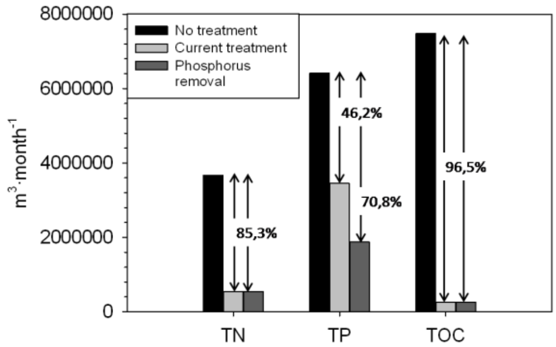

Fig. 5. Grey water footprint reduction with wastewater treatment.

Considering the total water footprint for the current wastewater treatment, the intensities for this case study are 171.7 m^3 water·kg^{-1} of TOC removed, 718.7 m^3 water·kg^{-1} of N removed, 10,068.9 m^3 required·kg^{-1} of P removed and 146.4 m^3 water·€$^{-1}$. The blue water footprint of 1 kg of organic matter removed is 8.53 m^3 water (96.5 % removal) in the present study versus 0.01 m^3 water·kg^{-1} COD (86% removal) in the study by Shao and Chen (2013) because, as it is mentioned above, the volume of water consumption for electricity production differs a lot due to the approach used to calculate the water consumption. Despite in both cases, Shao and Chen (2013) and this work, water withdrawal is considered, in our case, using a process-based approach and data from Ecoinvent, we considered not only the water used directly during the electricity production process but also all the indirect water consumption (for example for coal production).

When comparing results, the distinction between water consumption and water withdrawal has to be considered. However, in many cases consumptive use data are not available, thus more efforts should be put to obtain better water consumption inventories.

4.1.3. WF sustainability assessment

Due to lack of specific data, the blue water availability in the studied region (249,100 $m^3 \cdot month^{-1}$) was estimated as the average value (data from 1940 to 2008) of the global water balance of the Catalan catchments. The ratio between the blue water footprint of the process (180,180 $m^3 \cdot month^{-1}$) and the blue water availability (249,100 $m^3 \cdot month^{-1}$) is equal to 0.72 (<1), which indicates that the blue water footprint is sustainable. Additionally, in the case for improved phosphorus removal (with a blue WF of 192,517 $m^3 \cdot month^{-1}$), the blue WF is sustainable with a value of 0.77.

The ratio between the grey WF (3,448,115 $m^3 \cdot month^{-1}$) and the river water flow rate (808,877 $m^3 \cdot month^{-1}$) (4.3>1) indicates that the grey WF is not sustainable. Additionally, in the case when phosphorus is removed to fulfill the legal limit (2 $mg \cdot l^{-1}$ P-PO_4^{3-}), the grey WF is not sustainable because the ratio between the grey WF (1,870,201 $m^3 \cdot month^{-1}$) and the river flow rate is equal to 2.3. This result occurs because the Congost river has a small flow rate with respect to the amount of phosphorous that must be assimilated. The grey WF would become sustainable if the WWTP improved its phosphorous removal to reach an effluent concentration of 0.95 $mg \cdot l^{-1}$ (which assumes a removal efficiency of 85.3 %). Additionally, if phosphorous is not considered in the estimation of the grey WF, then it becomes sustainable because the river has enough capacity to assimilate the pollution generated by nitrogen and organic matter.

4.1.4. Water footprint response formulation

The ratio of required freshwater per unit of treated water (1.45 m^3) is extremely small compared with the water footprint of many other agricultural and industrial products (www.waterfootprint.org, Hoekstra et al., 2011).

After analyzing the water footprint sustainability assessment for the WWTP, it is important to formulate modifications for operational conditions to further reduce the water footprint. In this case, the application of $FeCl_3$ to achieve a greater total phosphorus removal efficiency resulted in a greater reduction in the grey water footprint. In addition to the energy savings, the sludge treatment practices should be further improved by optimizing the operational costs and also by reducing the blue water footprint.

4.2. Complements between LCA and WFA.

The WFA methodology and its application in agriculture and several industrial products are well known. However, there are a limited number of studies regarding its application in the urban water cycle, particularly in water and wastewater infrastructures. Therefore, a discussion on the possibilities and unclear aspects of its application for WWTPs is required.

Although the goal of LCA is to assess the environmental impacts of a product or activity (a system of products) over its entire life cycle, where water is just one criteria among others (e.g., carbon footprint, land use), whereas the goal of WFA is management-focused, i.e., is focused on the sustainable allocation and use of water. Both methodologies could take advantage of each other and thus complement each other. For example, during the accounting phase for WFA, LCA inventory databases could allow WFA to be more precise, despite, as noted in section 4.1.3, a significant amount of uncertainty is associated with the water quantities assigned to electricity generation depending on the data sources. However, the quantitative green and blue footprint indicators for agriculture can be used within the LCA inventory analysis (Boulay et al., 2013), which complements other developed methods (Kounina et al., 2012). Additionally, regarding the blue water footprint, information from many LCA databases is typically related to water withdrawal (or water used) and not to water consumption, which thus implies an overestimation of the blue water footprint. One should be aware of this gap between water consumption and withdrawal. Indeed, Risch et al., (2014) underlines the need for better estimates of the water consumption and a greater understanding of its impacts during wastewater treatment. In WWTPs, as shown in our case study, although the blue water footprint represents a low value compared with that of the total water footprint (approximately 5% in our case study), the blue water footprint should not be neglected because it is already estimated thanks to the most recent Ecoinvent 3.0 database, which provides water consumption for industrial processes.

The grey water footprint, which is not used in LCA because it represents a theoretical quantification of water pollution, provides complementary information regarding the effluent water quality and WWTP removal efficiencies. During the impact assessment phase, when assessing the sustainability of a WWTP operation, the LCA analysis provides an environmental impact (eutrophication, global warming, etc.), which can be smaller for activated sludge or larger for a membrane bioreactor; however, in any case, there will always be a certain impact. In contrast, the water footprint concept demonstrates that the environmental impact of wastewater is reduced when using a WWTP because the grey water footprint is reduced. In the interpretation and response formulation phase, LCA and WFA methods could complement each other in assessing the sustainability of freshwater use and its impact in a more comprehensive way (Boulay et al., 2013). When comparing different technologies for wastewater treatment, sometimes having only one value to compare (i.e., the water footprint) can be an advantage with respect to LCA studies, which always provide different categories; a multi-criteria problem is thus created, where the best solution depends on the weights assigned to each criterion/category.

5. Sensitivity Analysis

A sensitivity analysis was performed to analyze the contribution on the results of the most important factors. The factors considered were the concentration of phosphorus in the WWTP effluent, the natural concentration of phosphorus in the river, the maximum concentration of phosphorus permitted in the river and finally, the electricity consumption of the plant, since they are the major contributors to the water footprint. The analysis was performed by increasing and decreasing a 25% each one of the factors studied.

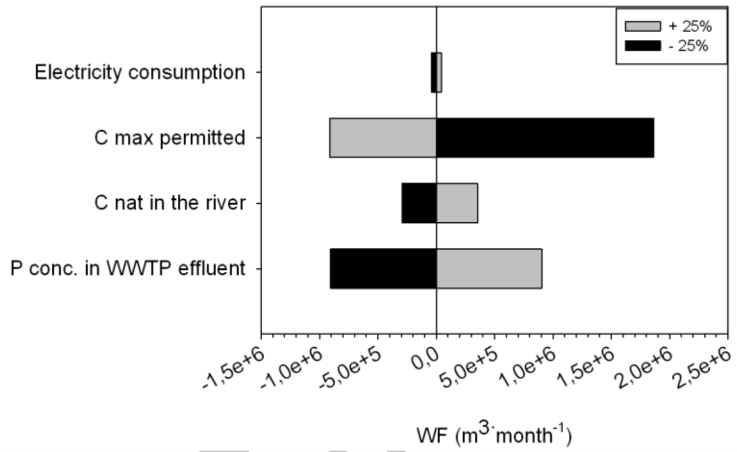

Fig. 6. Sensitivity analysis results. The WF with the current treatment is taken as reference (0 $m^3 \cdot month^{-1}$), negative values means a decrease of the WF, positive values means an increase of the WF.

As is shown in Figure 6, the most sensitive factor is the maximum concentration permitted in the river. If increasing the permitted concentration by a 25%, the water footprint decreases around 912,000 $m^3 \cdot month^{-1}$ (approximately a 25% decrease of the water footprint). On the other hand, if decreasing the maximum concentration permitted in the river by a 25%, the water footprint increases around 1,865,000 $m^3 \cdot month^{-1}$ (approximately a 51% increase of the water footprint). The second most sensitive factor is the concentration of pollutant in the WWTP effluent, with a decrease and increase of the water footprint of 900,000 $m^3 \cdot month^{-1}$

approximately (which represents approximately a 25% increase or decrease, respectively, of the water footprint). The third one is the natural concentration of the pollutant in the river, which increases the water footprint by 10% and decreases about 8%. Finally, the factor with the lowest contribution is the electricity consumption. If increasing and decreasing the electricity consumption in a 25%, the water footprint only increase or decrease about 43,000 $m^3 \cdot month^{-1}$ (+/- 1.2%), respectively. Even though the electricity consumption is the most important contributor to the blue water footprint and considering also that the blue water footprint calculated here is higher than the calculated in Shao and Chen, 2013, the increase or decrease of its consumption has not an important effect on the overall results (an increase or decrease by 1.2%, respectively) because the blue water footprint is very low compared with the grey water footprint. The legislation about the maximum concentration permitted of the pollutant in the river together with the level of treatment are the most important factors determining the water footprint of a WWTP, this highlights the importance to develop good normative and to improve the water treatment in order to achieve a lower and more accurate water footprint.

6. Conclusions

The following conclusions were obtained from the work presented in this paper:

- The applicability of the water footprint methodology in WWTPs was demonstrated.
- The application to a specific WWTP, which currently treats 4,000 $m^3 \cdot d^{-1}$, resulted in a water footprint of $3.6 \cdot 10^6$ $m^3 \cdot month^{-1}$ for the current operation, with an intensity of 1.45 m^3 required for freshwater$\cdot m^{-3}$ treated wastewater and $2.1 \cdot 10^6$ $m^3 \cdot month^{-1}$ for enhanced phosphorous removal.

- The WWTP under study reduced the water footprint by 51.5 % and 72.4 % when using secondary treatment and phosphorous removal, respectively, to fulfill the legal limits, where blue water footprints of 180,180 and 192,517 $m^3 \cdot month^{-1}$, respectively, were obtained.
- Phosphorous removal should be a priority due to its higher impact after treatment and higher reduction of the water footprint.
- The water footprint illustrates the beneficial role of WWTPs within the urban water cycle.

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