

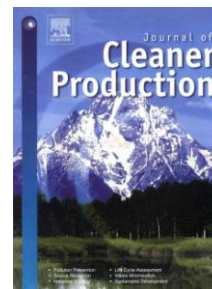
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ACCEPTED MANUSCRIPT



1 Water footprint assessment in Wastewater Treatment Plants

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15

16 Abstract

17 Wastewater treatment plants (WWTPs) play an important role within the urban water
18 cycle in protecting receiving waters from untreated discharges. However, WWTPs
19 processes also affect the environment. Life cycle assessment has traditionally been
20 used to assess the impact of direct discharges from WWTPs and indirect emissions

21 related to energy or chemical production. The water footprint (WF) can provide
22 complementary information to evaluate the impact of a WWTP regarding the use of
23 freshwater. This paper presents the adoption of the Water Footprint Assessment
24 methodology to assess the consumption of water resources in WWTPs by considering
25 both blue and grey WFs. The usefulness of the proposed methodology in assessing the
26 environmental impact and the benefits from WWTP discharge to a river is illustrated
27 with an actual WWTP, which treats $4,000 \text{ m}^3 \cdot \text{d}^{-1}$, using three scenarios: no treatment,
28 secondary treatment and phosphorous removal. A reduction of the water footprint by
29 51.5 % and 72.4 % was achieved using secondary treatment and phosphorous
30 removal, respectively, to fulfill the legal limits. These results indicate that when
31 treating wastewater, there is a large decrease in the grey water footprint compared
32 with the no-treatment scenario; however, there is a small blue water footprint.

33 **Keywords**

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

37 **1. Introduction**

38 Currently, the concern regarding the environmental sustainability of urban development,
39 specifically the use of freshwater resources, has significantly increased due to population
40 growth, which has increased water demand; this problem is exacerbated when combined with
41 water scarcity (which implies limited water availability) (UNEP and UN-Habitat, 2010). The
42 urban water cycle includes water withdrawal from natural resources, water treatment to
43 satisfy the required quality standards for different uses, water distribution, water consumption

44 (drinking water, water for recreational activities, water for cleaning and irrigation of urban
45 areas, water for agriculture and process water for industries), collection and transport of
46 wastewater via sewer systems, and wastewater treatment. Wastewater is treated in wastewater
47 treatment plants (WWTPs), which has the important role within the urban water cycle to
48 improve the water quality before being returned into the natural ecosystems. Traditional
49 wastewater treatment is considered an industrial activity where wastewater is transformed by
50 means of different processes, which consume chemicals and energy, into treated water (of
51 higher quality), which generates by-products (primarily solid wastes and gaseous emissions).
52 Hence, the impact of water emissions into the natural ecosystems is reduced; however, there
53 are increased costs and other environmental impacts (Godin et al., 2012).

54 One of the most popular methodologies used to evaluate the potential environmental impacts
55 caused by WWTPs is the life cycle assessment (LCA). LCA is a standardized method (ISO
56 14040-14044:2006), which is used to estimate the impact over a wide range of environmental
57 impact categories (global warming, acidification, eutrophication, human toxicity, etc.) from
58 the construction to the operation of WWTPs (Corominas et al., 2013). Recently, LCA studies
59 have demonstrated the importance of assessing freshwater use by quantifying water
60 consumption from wastewater treatment after current life cycle impact assessment methods
61 were expanded (Kounina et al., 2012). Risch et al., (2014) evaluated the direct water
62 consumption from operating three different wastewater treatment technologies located in
63 three different regions and considered regional factors to account for the water scarcity of the
64 different geographical regions.

65 The water footprint (WF) of a product/process was introduced for the first time in 2003 and is
66 defined as the volume of freshwater consumed and polluted to produce a product (Hoekstra,
67 2003). The WF accounts not only for the direct water use of a consumer or producer but also

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

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

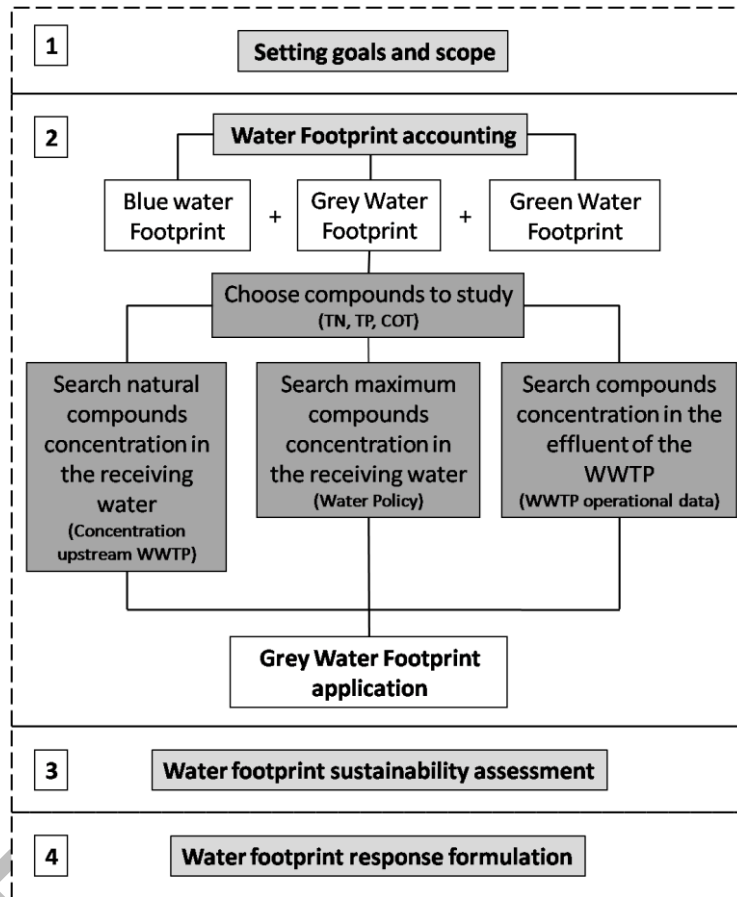
92 al., 2009; Hoekstra and Mekonnen, 2011). WFs have also been used to assess the production
93 of hydropower energy (Mekonnen and Hoekstra, 2012) and biofuels (Gerbens-Leenes et al.,
94 2012), amongst other applications.

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

104 **2. Methodology for water footprint assessment in WWTPs**

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

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



118

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

121 The first phase consists of defining the goal and scope of the assessment and includes the
 122 functional unit, the types of WF to be considered and the data sample. In the second phase,
 123 data are collected, and the water footprint is calculated. In the third phase, the water footprint
 124 is evaluated from a sustainability point of view, which considers the water availability in the

125 analyzed region or period, and finally in the fourth phase, several recommendations are
126 drawn to reduce the water footprint of the product or system analyzed.

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

$$130 \quad WF = WF_{blue} + WF_{green} + WF_{grey}$$

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

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

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

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

$$154 \quad Q_e \cdot c_{e(p)} + WF_{grey} \cdot c_{nat(p)} = (Q_e + WF_{grey(p)}) \cdot c_{max(p)}$$

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

$$156 \quad WF_{grey} = \max[WF_{grey(p)} = (Q_e \cdot (c_{e(p)} - c_{max(p)})) / (c_{max(p)} - c_{nat(p)})] \text{ (volume/time)} \text{ (for } p=1 \text{ to } p)$$

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

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

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

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

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

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

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

193 Accounting for the different WF components was calculated using monthly averaged data for
 194 the WWTP effluent flow rates and pollutant concentrations during the period from January
 195 2007 to November 2010. Table 1 summarizes the inventory data used for the WF assessment.

196 **Table 1.**
 197 Input data for the WF assessment.

		Input data	TN	TP	TOC
WF_{grey}		C_e (g·m⁻³)	9.66	3.55	11.18
		C_{nat} (g·m⁻³)	1.03	0.04	2.07
		C_{max} (g·m⁻³)	2.65	0.17	5.05
		WWTP effluent flow (m³·month⁻¹)	123,894		
WF_{blue}		Energy consumption (kwh·m⁻³)	0.484		
		Chemicals (kg·m⁻³)	0.026		
		Sludge to treatment (kg·m⁻³)	0.917		
		Other residues (kg·m⁻³)	0.029		
		Evaporation (m³·month⁻¹)	237.200		
		Transport (tkm·m⁻³)	0.040		

198
 199 WF can also be referred to as the water consumption for 1 kg of pollutant removed (TOC, N
 200 and P) and the cost of treating 1 m³ of wastewater in the WWTP of La Garriga (0.2 €·m⁻³).

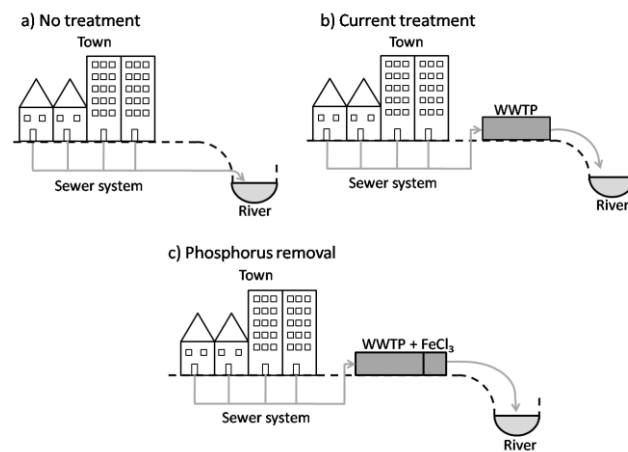
201 4. Results and discussion

202 4.1. Water footprint assessment for La Garriga WWTP and the Congost river

203 4.1.1. Goal and scope

204 The goals of this WF assessment are to identify the relative importance of the blue and grey
 205 WFs in WWTPs, to illustrate the positive roles of these installations in reducing the
 206 environmental impact and to propose measures for reducing the WF of a WWTP. To achieve
 207 these goals, three different scenarios regarding wastewater treatment were studied: no-
 208 treatment scenario (direct discharge of untreated wastewater into the river), conventional

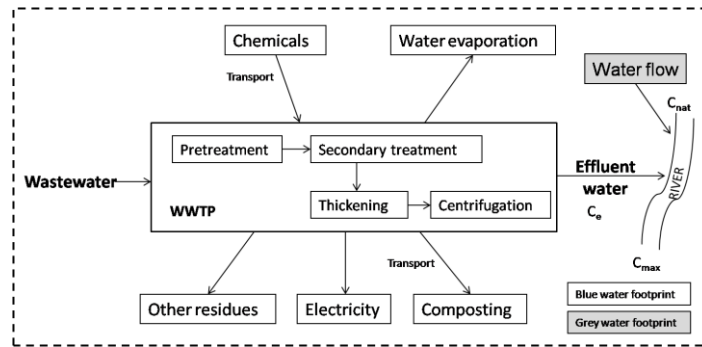
209 wastewater treatment (current operation, i.e., organic matter and nitrogen removal) and
 210 wastewater treatment with phosphorous removal (Figure 2). The no-treatment option implies
 211 only calculating the WF_{grey} assuming that the influent WWTP concentration is C_e from
 212 equation 2. In this case, the influent concentrations ($50.41 \text{ mg}\cdot\text{l}^{-1}$ of TN, $6.45 \text{ mg}\cdot\text{l}^{-1}$ of TP
 213 and $181.73 \text{ mg}\cdot\text{l}^{-1}$ of TOC) were applied. For the phosphorous removal scenario, the water
 214 consumed to produce 1 kg of FeCl_3 was obtained from the Ecoinvent 3.0 database and
 215 multiplied by the mass of FeCl_3 in kg that is consumed to reduce the amount of phosphorous
 216 to the legislation limit ($2 \text{ mg}\cdot\text{l}^{-1}$).



217

218 **Fig. 2.** Scenarios considered for the analysis.

219 As is shown in Figure 3, the system boundaries for the studied system include the different
 220 steps of the WWTP (pretreatment, secondary treatment, sludge thickening and sludge
 221 centrifugation), chemical and energy consumption, sludge treatment outside the plant, water
 222 evaporation from the plant and pollutants concentration in the effluent water. The functional
 223 unit of this case study is the volume of treated wastewater during one month of operation, i.e.,
 224 $123,894 \text{ m}^3\cdot\text{month}^{-1}$.



225

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

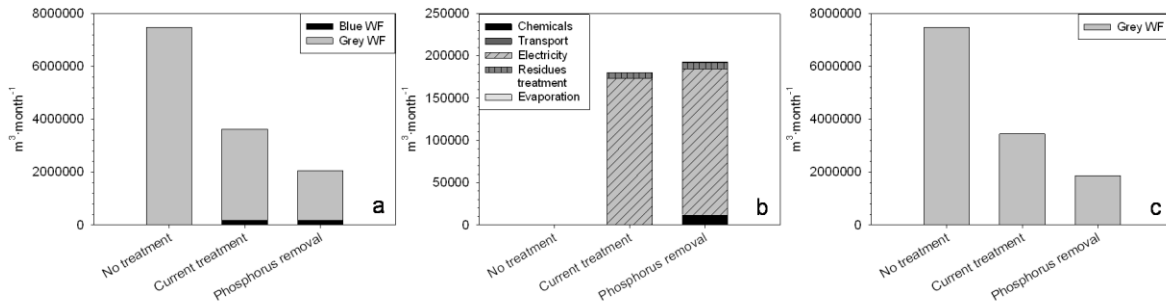
227 *4.1.2. Water footprint accounting*

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

235 The grey WF values, i.e., the volume of water required to dilute the WWTP effluent until
 236 natural concentrations in the river are reached, were $539,317 \text{ m}^3 \cdot \text{month}^{-1}$; $3,448,115$
 237 $\text{m}^3 \cdot \text{month}^{-1}$ and $261,779 \text{ m}^3 \cdot \text{month}^{-1}$ for TN, TP and TOC, respectively, for the current
 238 wastewater treatment (Figure 4c and Table 2). The WF_{grey} for TP is much greater compared
 239 with the other pollutants because the WWTP is not designed to remove TP, and hence, the
 240 WWTP effluent concentrations are high. With respect to the no-treatment scenario, the
 241 WF_{grey} is reduced by 51.5 % (from $7,479,507 \text{ m}^3 \cdot \text{month}^{-1}$ to $3,448,115 \text{ m}^3 \cdot \text{month}^{-1}$) at the
 242 expense of a slight increase in the WF_{blue} ($180,180 \text{ m}^3 \cdot \text{month}^{-1}$). TP is the limiting factor for
 243 the WF_{grey} calculation for the treated wastewater, whereas TOC is the limiting factor for the

244 no treatment option. For the wastewater treatment with the phosphorous removal scenario, a
245 dosage of 1 mol of FeCl_3 per mol of phosphorous (according to the Minnesota Pollution
246 Control Agency) achieves a 72.4 % reduction of the grey WF for total phosphorous while
247 maintaining the same reductions for nitrogen and organic matter (Table 2 and Figure 5).

248 The blue WF for the current wastewater treatment scenario was $180,180 \text{ m}^3 \cdot \text{month}^{-1}$ (Figure
249 4b and Table 2), where the major contributors are the energy consumption (95.85 %) and
250 residues treatment. The residues treatment consist of the treatment of oils and grease and
251 sludge compost and deposition in a landfill of solid residues (3.53 %), both of which account
252 for more than 99 % of the WF_{blue} . Evaporation in the reactors accounted for only 0.13 % of
253 the WF_{blue} . With respect to the wastewater treatment in the phosphorous removal scenario,
254 similar values were obtained for the blue WF, even though there was an increase of $12,337$
255 $\text{m}^3 \cdot \text{month}^{-1}$ due to the consumption of more chemicals (FeCl_3), which increased the
256 phosphorus removal efficiency, and also due to the increase in sludge mass sent to
257 composting. The addition of the FeCl_3 increased the WF_{blue} by 6.8 % compared with the
258 current wastewater treatment scenario; however, overall, the results showed a reduction of
259 72.4 % in the total WF. In agreement with previous studies (Ercin et al., 2010; Jefferies et al.,
260 2012), the freshwater use associated with supporting activities and materials used in the
261 business (e.g., chemicals, transports), which is not completely associated with the production
262 of the specific product considered, i.e., the overhead water footprint, constitutes a minor
263 fraction of the supply-chain water footprint (0.2–0.3 %).



264

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

267 **Table 2.**

268 Comparison between the water footprint for the three scenarios studied.

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

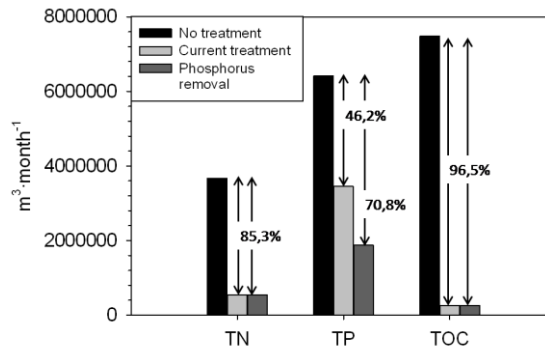
269

270 The WF obtained in this study for the current wastewater treatment ($3,628,295 \text{ m}^3 \cdot \text{month}^{-1}$) is
 271 much larger than the WF obtained in the study by Shao and Chen (2013), which only
 272 included the WF_{blue} . Still, comparing the WF_{blue} values from both studies shows that a much
 273 larger value was obtained in our study ($180,180 \text{ m}^3 \cdot \text{month}^{-1}$, 1.45 m^3 freshwater as $\text{WF}_{\text{blue}} \cdot \text{m}^{-3}$
 274 3 treated wastewater). The difference is due to the freshwater resource consumption related to
 275 electricity generation. In this case, the calculation used the water consumption from the
 276 Ecoinvent 3.0 processes for electricity, chemicals, residues and transport and data from the
 277 plant. Differently, in the study by Shao and Chen (2013), the calculation used a hybrid

278 method that considered the operational expenses from the WWTP and the national freshwater
279 consumption for every productive sector in China in 2007, which relates freshwater
280 consumption with the economy. Considering their approach in our case study, the freshwater
281 consumption would be $4.78 \cdot 10^{-3} \text{ m}^3 \cdot \text{kWh}^{-1}$, whereas when considering the Ecoinvent 3.0
282 processes for the medium voltage electricity in Spain, the freshwater consumption is
283 approximately $2.88 \text{ m}^3 \cdot \text{kWh}^{-1}$. It should also be mentioned that the freshwater used to produce
284 the electricity greatly depends on the country and the technologies used to produce it.

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

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



297

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

299 Considering the total water footprint for the current wastewater treatment, the intensities for
 300 this case study are $171.7 \text{ m}^3 \text{ water} \cdot \text{kg}^{-1}$ of TOC removed, $718.7 \text{ m}^3 \text{ water} \cdot \text{kg}^{-1}$ of N removed,
 301 $10,068.9 \text{ m}^3 \text{ required} \cdot \text{kg}^{-1}$ of P removed and $146.4 \text{ m}^3 \text{ water} \cdot \text{€}^{-1}$. The blue water footprint of 1
 302 kg of organic matter removed is $8.53 \text{ m}^3 \text{ water}$ (96.5 % removal) in the present study versus
 303 $0.01 \text{ m}^3 \text{ water} \cdot \text{kg}^{-1}$ COD (86% removal) in the study by Shao and Chen (2013) because, as it
 304 is mentioned above, the volume of water consumption for electricity production differs a lot
 305 due to the approach used to calculate the water consumption. Despite in both cases, Shao and
 306 Chen (2013) and this work, water withdrawal is considered, in our case, using a process-
 307 based approach and data from Ecoinvent, we considered not only the water used directly
 308 during the electricity production process but also all the indirect water consumption (for
 309 example for coal production).

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

313 *4.1.3. WF sustainability assessment*

314 Due to lack of specific data, the blue water availability in the studied region (249,100
315 $\text{m}^3 \cdot \text{month}^{-1}$) was estimated as the average value (data from 1940 to 2008) of the global water
316 balance of the Catalan catchments. The ratio between the blue water footprint of the process
317 ($180,180 \text{ m}^3 \cdot \text{month}^{-1}$) and the blue water availability ($249,100 \text{ m}^3 \cdot \text{month}^{-1}$) is equal to 0.72
318 (<1), which indicates that the blue water footprint is sustainable. Additionally, in the case for
319 improved phosphorus removal (with a blue WF of $192,517 \text{ m}^3 \cdot \text{month}^{-1}$), the blue WF is
320 sustainable with a value of 0.77.

321 The ratio between the grey WF ($3,448,115 \text{ m}^3 \cdot \text{month}^{-1}$) and the river water flow rate
322 ($808,877 \text{ m}^3 \cdot \text{month}^{-1}$) ($4.3 > 1$) indicates that the grey WF is not sustainable. Additionally, in
323 the case when phosphorus is removed to fulfill the legal limit ($2 \text{ mg} \cdot \text{l}^{-1} \text{ P-PO}_4^{3-}$), the grey WF
324 is not sustainable because the ratio between the grey WF ($1,870,201 \text{ m}^3 \cdot \text{month}^{-1}$) and the
325 river flow rate is equal to 2.3. This result occurs because the Congost river has a small flow
326 rate with respect to the amount of phosphorous that must be assimilated. The grey WF would
327 become sustainable if the WWTP improved its phosphorous removal to reach an effluent
328 concentration of $0.95 \text{ mg} \cdot \text{l}^{-1}$ (which assumes a removal efficiency of 85.3 %). Additionally, if
329 phosphorous is not considered in the estimation of the grey WF, then it becomes sustainable
330 because the river has enough capacity to assimilate the pollution generated by nitrogen and
331 organic matter.

332 4.1.4. *Water footprint response formulation*

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

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

342 4.2. *Complements between LCA and WFA.*

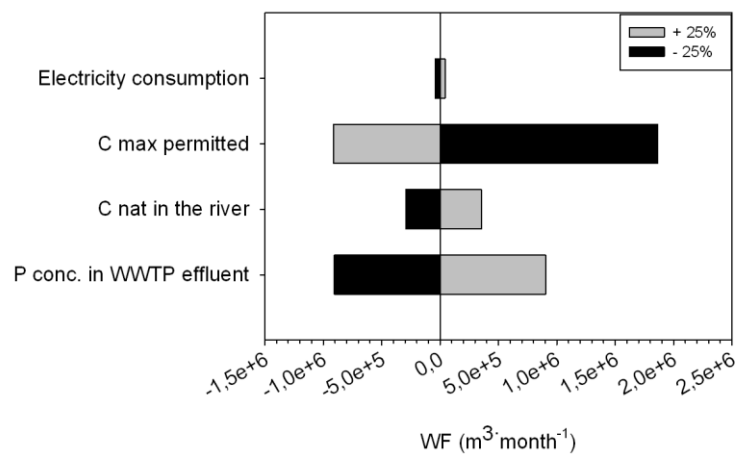
343 The WFA methodology and its application in agriculture and several industrial products are
344 well known. However, there are a limited number of studies regarding its application in the
345 urban water cycle, particularly in water and wastewater infrastructures. Therefore, a
346 discussion on the possibilities and unclear aspects of its application for WWTPs is required.
347 Although the goal of LCA is to assess the environmental impacts of a product or activity (a
348 system of products) over its entire life cycle, where water is just one criteria among others
349 (e.g., carbon footprint, land use), whereas the goal of WFA is management-focused, i.e., is
350 focused on the sustainable allocation and use of water. Both methodologies could take
351 advantage of each other and thus complement each other. For example, during the accounting
352 phase for WFA, LCA inventory databases could allow WFA to be more precise, despite, as
353 noted in section 4.1.3, a significant amount of uncertainty is associated with the water
354 quantities assigned to electricity generation depending on the data sources. However, the
355 quantitative green and blue footprint indicators for agriculture can be used within the LCA
356 inventory analysis (Boulay et al., 2013), which complements other developed methods
357 (Kounina et al., 2012). Additionally, regarding the blue water footprint, information from
358 many LCA databases is typically related to water withdrawal (or water used) and not to water
359 consumption, which thus implies an overestimation of the blue water footprint. One should

360 be aware of this gap between water consumption and withdrawal. Indeed, Risch et al., (2014)
361 underlines the need for better estimates of the water consumption and a greater understanding
362 of its impacts during wastewater treatment. In WWTPs, as shown in our case study, although
363 the blue water footprint represents a low value compared with that of the total water footprint
364 (approximately 5% in our case study), the blue water footprint should not be neglected
365 because it is already estimated thanks to the most recent Ecoinvent 3.0 database, which
366 provides water consumption for industrial processes.

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

382 **5. Sensitivity Analysis**

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



389
 390 **Fig. 6.** Sensitivity analysis results. The WF with the current treatment is taken as reference (0
 391 $\text{m}^3 \cdot \text{month}^{-1}$), negative values means a decrease of the WF, positive values means an increase
 392 of the WF.

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

400 approximately (which represents approximately a 25% increase or decrease, respectively, of
401 the water footprint). The third one is the natural concentration of the pollutant in the river,
402 which increases the water footprint by 10% and decreases about 8%. Finally, the factor with
403 the lowest contribution is the electricity consumption. If increasing and decreasing the
404 electricity consumption in a 25%, the water footprint only increase or decrease about 43,000
405 $\text{m}^3 \cdot \text{month}^{-1}$ (+/- 1.2%), respectively. Even though the electricity consumption is the most
406 important contributor to the blue water footprint and considering also that the blue water
407 footprint calculated here is higher than the calculated in Shao and Chen, 2013, the increase or
408 decrease of its consumption has not an important effect on the overall results (an increase or
409 decrease by 1.2%, respectively) because the blue water footprint is very low compared with
410 the grey water footprint. The legislation about the maximum concentration permitted of the
411 pollutant in the river together with the level of treatment are the most important factors
412 determining the water footprint of a WWTP, this highlights the importance to develop good
413 normative and to improve the water treatment in order to achieve a lower and more accurate
414 water footprint.

415 **6. Conclusions**

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

- 417 • The applicability of the water footprint methodology in WWTPs was demonstrated.
- 418 • The application to a specific WWTP, which currently treats $4,000 \text{ m}^3 \cdot \text{d}^{-1}$, resulted in a
419 water footprint of $3.6 \cdot 10^6 \text{ m}^3 \cdot \text{month}^{-1}$ for the current operation, with an intensity of
420 1.45 m^3 required for freshwater $\cdot \text{m}^{-3}$ treated wastewater and $2.1 \cdot 10^6 \text{ m}^3 \cdot \text{month}^{-1}$ for
421 enhanced phosphorous removal.

- 422 • The WWTP under study reduced the water footprint by 51.5 % and 72.4 % when
423 using secondary treatment and phosphorous removal, respectively, to fulfill the legal
424 limits, where blue water footprints of 180,180 and 192,517 m³·month⁻¹, respectively,
425 were obtained.
- 426 • Phosphorous removal should be a priority due to its higher impact after treatment and
427 higher reduction of the water footprint.
- 428 • The water footprint illustrates the beneficial role of WWTPs within the urban water
429 cycle.

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441

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443 8. References

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