Blue and grey urban water footprints through citizens' perception and time series analysis of Brazilian dynamics

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Predicting future water demands of societies is a major challenge because it involves a holistic understanding of possible changes within socio-hydrological systems. Although recent research has made efforts to translate social dimensions into the analysis of hydrological systems, few studies have involved citizens' participation in the water footprint analysis. This paper integrates time series with citizens' perceptions, knowledge and beliefs concerning sanitation elements to account for municipal blue and grey water footprints in São Carlos, Brazil from 2009 to 2016, and potential water footprints in 2030 and 2050. In this case study, grey footprint potentially exceeds up to 35 times the blue water footprint and volunteered information suggested reduction in water consumption, larger garbage production and more investments in sanitation infrastructure from authorities. We conclude that public knowledge can be used to delineate possible water footprint scenarios and reveal paradoxes in the coevolution of socio-hydrological systems on an urban scale.

Keywords: Urban water footprint, citizen science, citizens' perception, socio-hydrology.

INTRODUCTION

The concept of a Water Footprint (WF) is used to call attention to the direct and indirect uses of water for human consumption. Water is consumed directly in agricultural production, industrial activity, and domestic use, but it is also consumed indirectly through the trade in goods and services across countries and regions. The WF draws attention to the importance of the consumption patterns and lifestyles embedded in indirect use for overall water use. The WF has been compared across cities, regions, and countries to illustrate wide differences in overall consumption (Kumar; Pavithra, 2019, s(Chapagain; Hoekstra, 2008; Ercin; Hoekstra, 2014; Hoekstra; Mekonnen, 2012; Liu et al., 2012; Zhao et al., 2019), and at municipal scales (Paterson et al., 2015), Water footprints are often compared across cities and countries (Jenerette et al., 2006) and incorporated into and included into discuss io virtual water trade components (Vanham; Bidoglio, 2014), analysed the evolution of domestic demands (Cai; Liu; Zhang, 2019) and addressed a socio-hydrological approach at global scale (Hossain; Mertig, 2020).

Water footprints are often produced from the top down using data from international, national, and regional agencies to calculate internal and external consumption or from the bottom up using information provided by citizens to infer direct and indirect consumption patterns. The formal definition of citizen engagement for scientific purposes (Burgess et al. 2017, Catlin-Groves 2012), has been used for decades to address a number of scientific gaps, including the water research agenda (Assumpção et al. 2017, Buytaert et al. 2014), where volunteers usually play the role of sensors in monitoring hydrological variables. Recent studies (McKnee et al, 2020; Mondino et al., 2020) have started to engage citizens not only to monitor the environment, but also to understand the feedbacks of hydrological processes on human behaviour and in turn, the impacts of human behaviours on the hydrological system.

There is growing interest in the scientific community about how to incorporate human social systems on hydrological processes, this field has emerged as socio-hydrology (Sivapalan et al. 2012), which seeks to integrate social and hydrological systems to highlight interconnections, feedbacks and unintended consequences. In the context of this integrative approach of human aspects in hydrology, it has been proposed that new mathematical models should adopt a holistic perspective that views social drivers as endogenous to the system with outcomes reflecting the interplay between humans and hydrology (Blair and Buytaert, 2016; Elshafei et al. 2014; Pande, and Sivapalan, 2017; Sivapalan and Blöschl, 2015). Thus, many studies were conducted under this modelling approaches and have led to an understanding of the most varied hydrological processes, such as the evolution of household demands (Garcia et al. 2016; Gonzales and Ajami, 2017), urban floods (Buarque et al. 2020; Di Baldassarre et al. 2015), development in rural catchments (Sanderson et al. 2017; Van Emmerik et al. 2014) and the collapse of ancient civilizations (Kuil et al. 2016). Although these socio-hydrological studies accomplished their goals of identifying and describing emerging phenomena (Di Baldassarre et al. 2019), Srinivasan et al. (2017) raise attention to the need to engage stakeholders in future socio-hydrological studies to elicit issues that users see as important to systemic dynamic and credible storylines of the future (Gober and Wheater, 2015; Brelsford et al. 2020; Xu et al. 2018).

The objective of this study is to integrate open datasets with citizens' knowledge to better understand the interactions between humans and the hydrological system, as expressed in the water footprint of sanitation processes on a municipal scale. The working hypothesis is that quantitative outputs from citizens' knowledge, based on their personal experiences, consumption patterns and beliefs, might outline alternative water demand scenarios. For this purpose, we used the Water Footprint Assessment method to quantify direct and indirect demands of water from 2009 to 2016. We also built possible scenarios for blue and grey water footprints in sanitation processes through statistical analyses of those time series, and we conducted a survey performed by local citizens from São Carlos, Brazil. Thus, we begin with a description of the case study, which highlights the essential aspects of the case study, such as the demographic aspects, sanitation system facilities and climatic characterisation that might influence the outputs. Next, we depict the methodology of WF accounting and citizens' participation followed by the presentation and discussion of results. Finally, we summarise the main conclusions and lessons learned that could contribute to the existing literature.

CASE STUDY

This work examined the demands of the São Carlos municipality, located in São Paulo state, in the Southeast region of Brazil (Figure 1). Two river basins split the municipality surface area. Although most of this area is situated in the Mogi Guaçu River Basin (MGRB), the urban area is established in the Tietê-Jacaré River Basin (TJRB), and therefore the municipality is under the surveillance of the Tietê-Jacaré River Basin Committee (TJ-RBC).

The municipality of São Carlos, whose surface area corresponds to 1.136,907km², registered 234,002 inhabitants in 2016, 96% of whom lived in the urban area. According to SEADE (2018), it is expected that the population will increase up to 2035, then it starts to decrease, see the supplementary material in Souza (2020). In the context of sanitation systems, the local company provides the water supply and sewage collection service. According to the Brazilian Sanitation Information System (SNIS), during 2016, the whole population of São Carlos was served by the water supply service (SNIS, 2018), which has several pumping wells spread around the city and relies on two surface water abstraction points, one in the Feijão Creek and another in the Espraiado Stream. Conversely, only the urban region of the municipality is attended by sewage system services. The sewage is collected and taken to one of the three treatment plants; two of them are located close to the city and the other one is more distant. One private company responsible for collecting domestic waste, has provided a solid waste management service since 2013. It also operates the current sanitary landfill, which started functioning in 2013. Based on 2015 data, the economic scenario is represented by the services sector, which has the largest share of value added with 60%, followed by industry with 30% and finally the agricultural sector, representing less than 2% (SEADE, 2018).

In terms of climatic characterisation, the local climate is Cwa, according to the Köppen climatic classification, with an annual precipitation average of 1361mm and annual temperature average of 21.5ºC (EMBRAPA, 2019). Cavalcanti et al. (2015) indicate that the region presented an average annual temperature growth of 2ºC from 1960 to 2009, while the annual precipitation average observed increased 1mm/day. On the other hand, Cavalcanti et al. (2015) indicate that the average temperature for some seasons will probably increase up to 4.5ºC, while precipitation records may experience a reduction of up to 10%.

In terms of water resource demands for consumptive purposes, two databases were used in this study. The first one is the Situation Report (SR) published annually by the Tietê-Jacaré River Basin Committee (TJ-RBC). Among various pieces of information, the report describes all demands according to their purpose that can be classified as urban demand, industrial demand and rural demand. Furthermore, these demands are also classified according to their origin, such as surface or groundwater. According to the latest SR, based on 2016 (CBHTJ, 2017), the urban water demand was eight times higher than the industrial demand, while the rural demand was twenty times lower than the urban demand. Regarding the origin of water, the groundwater sources provide about 80% of total demands (CBHTJ, 2017). According to the second database used (SNIS, 2018), the water consumption per capita rose from 174 litres per day in 2009 to 223 litres per day in 2016, see the supplementary material in Souza (2020). Moreover, the SNIS points out that the losses in water supply due to leakages at this time were around 50%.

METHODOLOGY

The flowchart in Figure 2 illustrates the process we followed to meet the objectives of this work: accounting for blue and grey water footprints at an urban scale in sanitation processes. Sanitation systems, according to the recent federal enactment (Brazil, 2020), comprises water supply, wastewater treatment, garbage collection and stormwater drainage. First, we selected the temporal and spatial scales to understand the processes that occur within the study area (Blöschl and Sivapalan, 1995). Since our focus is to account for water demands at a municipal scale, our spatial scale is the municipality limits of São Carlos, which comprise both urban and rural areas. Although climatic, hydrological and resources consumption present monthly variations, this work estimates the yearly water footprints to capture these variations along the year between 2009 and 2016, but addressing seasonality is strongly recommended when data is available. For the future, we performed a statistical analysis from the historical data, and we engaged citizen participation to help in building scenarios for 2030 and 2050.

Therefore, we followed the guidelines proposed by Hoekstra et al. (2011) to quantify the direct and indirect municipal water demands, defined as water footprint accounting for a municipality. According to the authors, the water footprint can be split into three components to better quantify them. The Blue Water Footprint (BWF) refers to direct abstraction from water bodies to meet human and economic demands. Differently, the Grey Water Footprint (GWF) indicates the indirect water demand needed to dilute pollution loads to meet regulated standards of potability. Finally, the Green Water Footprint quantifies the amount of water retained in the soil by plants' roots or the fraction that returns to the atmosphere as evapotranspiration. In this paper, we account for Blue and Grey Water Footprints (BWF and GWF) because they are directly included in sanitation processes from domestic activities in urban environments, water delivery, wastewater treatment and garbage production.

The next step is checking data availability for the study area (Table 1). Some databases are publicly available but have no connection among them. Thus, we put all this information together in our database to define which data could be useful for water footprint accounting and which information was missing. For example, we did not find information regarding the volume of leachate production, so we developed a new approach to quantify the WF involved in this process. Afterwards, we selected the variables that could be quantified, observed and reported by citizens who live within the study area, based on their personal living experiences. Thus, we proposed questions based on these observations that enabled us to understand and account for personal consumption patterns from locals and how they imagine the indirect variables involved in water demands could change in the future.

Volunteers' participation

To investigate the humanistic perspective, volunteer's participation approach was deemed appropriate for this research. A set of questions with quantitative and qualitative purposes were designed and presented in Table 2. Face-to-face interviews were conducted by the authors in three different public spaces within the study area to reach a diverse sample. On December 2018, we visited shopping malls, the city centre and the municipal bus station to gather information. Fifty citizens volunteered to participate in the research and the sample selection process followed a non-probability convenience (Bornstein et al. 2013, Lavrakas, 2008). To meet the purpose of the research an exclusion criterion was advocated to engage a representative target population. The exclusion criteria for volunteers included:

i) who lived in São Carlos for less than 10 years or;

ii) who did not know the answers for the questions on personal consumption.

Once the volunteer agreed to participate, the interviewer introduced the project description and the consent form, which was submitted and approved by the University Ethics Committee (USP) because of human participation, see the supplementary material in Souza (2020). The selection of such approach was necessary due to the restrictions with time and resources, however to minimise limitations of convenience sampling (Bornstein et al. 2013) and allow the data to fit to the purpose of the study (Lavrakas, 2008) the exclusion criteria was rigidly applied. Fifty participants were adequate sample size to perform T-student statistics. We acknowledge the limitation that extrapolating the results for the whole city based on this sample set may incur some bias in the result, therefore no such claims have been made. The quantitative questions illustrated in Table 2 aims to identify the behavioural aspects of local residents in terms of water consumption, garbage production and individual's beliefs. The importance of the convenience sampling strategy is further justified by three main reasons: a) every quantitative question, has a particular standard deviation that implies in different population's representativeness (Edgar and Manz, 2017); b) the statistical parameters from the population is unknown and, therefore, a probabilistic sampling method might lead to ill-suited samples (Jager et al. 2015); c) this work neither provides a prediction about the future in São Carlos, nor generalizable outcomes for similar case studies, it is a starting point to address how citizen's perspectives differ from traditional scenario-building on water demands.

Questions' formulation

The questions identified by numbers 1 to 4 have quantitative purposes. They were asked to understand personal consumption patterns and to translate their beliefs about investment in sanitation structures at different periods of time: ten years ago; the moment when the questions were asked; and about future scenarios from 2030 and 2050. Since the reference unit is the residence, the aim of questions 1 (Table 2) is to find out how many people live in the same house as the interviewee. The number of residents may vary over time, as well as the collective consumption. Next, questions 2 were proposed to indirectly verify the volume of water that was/is/will be consumed by the number of people indicated in questions 1. We can quantify this volume through the average annual water price, in BRL/m³, which is available at SNIS (2018). Then, questions 3 aim at understanding how household waste production has been changing over the last ten years and how citizens think it will change in the future. To quantify this variation, we asked the volunteers how many plastic garbage bags their residences usually produce for the same period of previous questions (10 years ago, present, 2030 and 2050). This question was formulated based on a common habit in Brazilian cities, whereby people throw their household waste away in supermarket plastic bags while waiting for the garbage truck to come and pick them up (Moura et al. 2018). Therefore, we used the plastic bags as a reference unit to make it easier for citizens to quantify the variance of their waste production over time. The last quantitative question focuses on translating the importance given to sanitation infrastructure by local authorities in order to enhance water quality

(Dadson et al. 2017). For this purpose, we designed questions 4, which ask what fraction of municipal financial resources is allocated to sanitation systems, on a percentage scale. We intended to capture the variation of the investments made by local authorities over the years to enable us to quantify the grey water footprint. This information will be explained in detail later on in this section. Finally, we propose the qualitative questions from numbers 5 to 9. They were designed to check if citizens recognise the most fundamental elements of sanitation elements in the city and if they are concerned about not having sufficient water for future generations by the end of the century.

All information regarding detailed processes, assumptions and hypothesis involved in the procedure to calculate each WF are described below.

Blue Water Footprint accounting methodology

In this study, the BWF fraction represents the household demands, which comprise domestic water consumption and the percentage of losses caused in water transportation pipes (Varriale, 2018), whose time series between 2009 and 2016 are available at SNIS (2018). Thus, we can find the annual volume of losses during water distribution through Equation 1 (PMSC, 2012) and the total household demand can be obtained by Equation 2, where Q_l is the annual volume of water losses due to leakages in the water network (m³/year); Q_{hh} is the annual volume of water consumed by residences (m³/year), L is the index of losses in water networks (%);D_{hh} is the annual household demand (m³/year).

$$Q_l = \frac{Q_{hh}}{1-L} - Q_{hh} \quad (1)$$

$$D_{hh} = Q_l + Q_{hh} \quad (2)$$

We built possible scenarios of blue water footprint using the demography projections from SEADE (2018), the historical leakage rate average (SNIS, 2018) and three calculation procedures to estimate the annual consumption per capita: a) the confidence interval based on the statistical inference of the average water consumption per capita between 2009 and 2016 (SNIS, 2018) through the Student's T-distribution at a 95% confidence level; b) the individual daily consumption adopted in the Municipal Master Plan of São Carlos (MMPSC), which corresponds to 200 daily litres per person – also suggested by several national handbooks (Von Sperling, 1995; Tsutiya, 2006; Tomaz, 2000) and; c) responses for questions 2, which were based on how volunteers believe their water bills will change according to the number of residents, changes in individual water consumption patterns and growth in water tariffs. Thus, the annual volume of water consumed by residences in São Carlos was obtained from the product of population projections for the city and the individual water consumption average.

Grey Water Footprint accounting methodology

Regarding the GWF, we split it into two categories because of different sources of pollution within sanitation processes. The first one is related to the emissions from the treated domestic wastewater in the water bodies. In this study, all these effluents come through sewage pipelines; they are properly treated in one of the local sewage treatment plants and then they are ultimately discharged into the closest river. The annual volume of collected sewage was obtained from SNIS (2018), while the remaining polluting load is available from the SR published by the TJ-RBC. Thus, we used Equation 3 (Tucci, 2017) to calculate the dilution volume Q_{dw} due to treated wastewater, where: Q_{pw} is the annual volume of wastewater (m³/year) production in São Carlos, c_{pw} is the concentration of Biochemical Oxygen Demand (BOD) (mg/m³) of treated waste water discharged in São Carlos' water bodies, Q_d is volume of water (m³/year) needed to dilute the polluting loads Q_{pw} and reach the target BOD concentration c_t, c_d is the concentration of BOD for dilution volume (1mg/l), and c_e is the accepted concentration of BOD (mg/m³) of the nearest water body, according to the classification established by Resolution 357 of the Environmental National Council (CONAMA).

$$Q_{pw} * c_{pw} + Q_{dw} * c_d = \left(Q_p + Q_{ds}\right) * c_e \quad (1)$$

To calculate the volume needed to dilute the household effluents in the future, it is necessary to have at hand the volume of sewage produced by the population and the respective polluting load. We used two methods to determine the annual volume of sewage production *per capita* in 2030 and 2050: a) the confidence interval based on the time series from 2009 to 2016 and; b) the average daily volume of sewage produced per person based on the individual water consumption from the MMPSC and the return rate recommendation from Von Sperling (1995), which is equal to 160 litres of wastewater/day per person.

Regarding the polluting load, we performed a linear regression to establish the polluting load (c_{pw}) as a function of annual investments in sewage infrastructures (in local currency, BRL). For this purpose, we transformed the value of investments made in previous years into the Net Present Value (NPV) by using the time series of the Brazilian annual Consumer Price Index (CPI), which measures the inflation in Brazilian cities. Since we do not know how much will be invested in the future, we normalized these investments into a fraction of municipal GDP and we created two conditions. In the first one, we considered that the future investments would be the average of precedent percentages, while in the second one we considered this fraction would change at the same ratio of the answers to questions 4, shown in Table 2. Finally, we obtained the value of investment for future scenarios considering that the municipal's GDP would follow the same national GDP's growth rate. For example, if 1% of São Carlos' GDP is invested in sewage infrastructure today and the average of responses indicates that it will increase by 50%, we multiply the future GDP by 1% and then by 1.5 in order to find the value that will be invested. Next, this amount is the input data in our equation obtained by the linear regression for c_{pw} as a function of investments in sewage infrastructures.

The second component of the grey water footprint is the volume needed to dilute the polluting load due to the leachate from the municipal sanitary landfill. As we did not find any existing model that translated the processes of the leachate production, we developed our own model to calculate the GWF according to the steps described from letters a) to d). To perform this accounting, we consulted the State Inventories of Domestic Waste, which have been released yearly since 2003 by the Environmental Company of São Paulo State (CETESB). In these reports, the company has published the daily average production of household waste over the last years (tons/day). Considering that the current sanitary landfill started to be operated in 2013, its capacity corresponds to 2,2 mega tons and its surface area is equal to 0,2 km², we calculated:

(1) How many years would be necessary to reach its full capacity based on Equation 4, where T is the time required to reach maximum capacity of sanitary landfill (years); C_{sl} is the capacity of sanitary landfill (tons); Pop_i is the population of São Carlos municipality in year i (inhabitants) and; g_i is the production of household waste per person (tons/person*year) in year i. The future projections were obtained based on the upper and lower limits of the confidence interval from the CETESB time series (2003 to 2017) and were compared to the responses that volunteers provided in questions 3 (Table 2);

$$C_{sl} \geq \sum_{i=1}^{T} Pop_i * g_i \quad (4)$$

(2) how much leachate volume from the sanitary landfill will there be over the T years based on the water balance of Equation 5, which considers that: i) the surface area set for the sanitary landfill does not receive any external surface runoff and; ii) waterproofed inner walls. Therefore, L_i is the volume of leachate in year i (mm); P_i is the precipitation incident on the sanitary landfill's surface area in year i (mm) and; ETp is the potential evapotranspiration in year i (mm). We obtained the last two items from a meteorological station operated by EMBRAPA (EMBRAPA, 2019) and the outcomes of the climate change projection model HADGEM-2S for the municipality of São Carlos, concerning the Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5 (Chou et al. 2014a, 2014b; Lyra et al. 2018).

$$L_i = P_i - ETp_i \quad (5)$$

(3) the equivalent leachate volume for each year from Equation 6, where Q_{g_i} is the equivalent leachate volume for year i (m³/year); G_i is the total waste expected for year i (tons); C_{sl} is the capacity of sanitary landfill (tons) and; L_T is the sum of leachate from the beginning of the sanitary landfill operation to the end of its useful life.

$$Q_{g_i} = \frac{G_i}{C_{sl}} * \sum_{j=1}^{j=T} L_j \quad (6)$$

(4) The dilution volume Q_{dl} (m³/year), which is the GWF for every year i due to the yearly leachate volume Q_{g_i} (m³/year) from the sanitary landfill. (2 is an adaptation of (1, where Q_{g_i} assumes the meaning of Q_{pw} as the polluting load, c_l is the yearly average of BOD concentration in leachate from Sao Carlos' sanitary landfill, measured by Justo (2018), c_d is the concentration of BOD for dilution volume

(1mg/l), and c_e is the accepted concentration of BOD (mg/m³) of the nearest water body.

$$Q_{g_i} * c_l + Q_{dl} * c_d = \left(Q_{g_i} + Q_{dl}\right) * c_e \qquad (2)$$

Equations 4 to 7 were created to estimate not only the future GWF of sanitary landfill, but also the past GWF since they rely on the garbage production intensity and consequent landfill's life cycle. We expect that the different methods to estimate garbage production will imply in different GWF for every year considered. In addition, the method implies that the optimum GWF happens for a smaller surface area, less time of exposure to rain regimes (Equation 5) and less domestic waste production (Equation 6).

RESULTS AND DISCUSSION

While the water footprints for previous years were accounted based on historical data, possible scenarios for 2030 and 2050 ranged accordingly to the different calculation methods used. We begin with a discussion on the quantitative results regarding the Water Footprint Assessment method. The results are presented in separate graphics to differ the water footprint of each sanitation component (water consumption, treated wastewater and landfill's leachate) and highlight the contribution of citizens' participation in the scenario building process.

Table 3 presents the statistics of each answer to the questionnaire in Table 2, the average, standard deviation, upper and lower limit of t-student for 95% confidence interval. The responses presented large standard deviation for all quantitative questions. Regarding the answers on water bills and garbage production, such high deviation might be resulted from the experiment design, which opted for public places visited by an heterogenous audience, so we would be able to capture several consumption patterns.

Similarly, the responses for changes in sanitation investments also presented a high variation. This can be either a consequence of different beliefs or the lack of knowledge on that aspect. Since the historical data reveals that investments in the sanitation sector did not exceed 1% of municipal GDP over the last ten years, we assumed that the actual values do not represent the real fraction of investments. However, we considered the rate of change pointed out by the volunteers in our computation. For example, if one affirms that current investment is equal to 2% of municipal GDP and it will be 3% in the future, we calculated the increase of 50% of this fraction for the possible scenario. Surveying data in places where citizens, with heterogeneous conditions of preferences and behaviours, was an attempt to capture the variability of the population in this experiment. However, a relatively small sample size was selected for this study and therefore more sophisticated probability sampling methods and a larger sample size would be key factors in addressing the reduction of sampling bias in future experiments.

Blue Water Footprint Results

Figure 3A presents the historical domestic BWF from 2009 to 2016, represented by the black straight line, and the possible scenarios for 2030 and 2050, following the three methods detailed in the methodology. The first method, represented by the red line and square markers, follows the Municipal Master Plan of São Carlos' (MMPSC) recommendations on a daily average of individual water consumption, which is equal to daily 200 litres per person. We reinforce that the differences for each year, for this method, is a consequence of demography projections from SEADE (2018) because the individual consumption remains the same. The demography is expected to grow up to 2035, see the supplementary material in Souza (2020). The second method, represented by the green lines and the star markers, is the historical consumption per capita based on the time series analysis, which ranges between 182 and 208 daily litres per person at a

95% confidence level. Lastly, the third method, represented by the purple lines and round markers, was based on the responses from volunteers, which indicated that, in comparison to the present, their consumption, in terms of water bills (BRL/person in Present Net Value) used to be 3% higher ten years ago and they expect it will be 12% lower in 2030 and 64% lower in 2050.

More attention should be given to the third method, because it outlines possible demands for the uncertain future. The responses from volunteers indicated larger variation for 2030 than for 2050, but presents substantial, and convergent, decrease for the later. The purpose of this discussion is not to agree or not with the results but understand what led citizens to indicate that their consumption will change, and to what direction those changes will point to. For both scenarios, the average (see Table 3) indicated a reduction on individual consumption. We raise two possibilities for such behaviour, an experiment design issue or an environmental awareness manifestation.

When we designed the experiment, we opted for the water bill variable to infer the changes on water consumption for the sake of measurability and familiarity by the lay citizens. Although water consumers know how much they pay and how much they used to pay for the water service, they might not be aware of the factors that led tariffs change over time. In spite of water consumption has a causal effect on water bills, there are also other elements that affects how much people pay for water services and the way it changes over time, i.e. inflation and conservation policies. For this reason, we added an extra question at the beginning of the interview to make them think about those additional elements that impact on the price they pay in the present in comparison to the price they used to pay in the past. However, when we asked them about the price they will pay in the future, we expected they would consider changes in the number of consumers who will live in their homes, changes (or not) in their consumption patterns and those additional elements that yearly affect the water tariffs. This later “elements” open the room for uncertainty and, therefore, might has biased the responses, especially for the far-future, which is surrounded by uncertainties.

The other possible explanation for the decrease in expected water consumption might be a purposeful manifestation of an environmental concern that can be illustrated using psychological theories. Fransson and Gärling (1999) identified that there a number of reasons that make a group of people be more or less aware about ecological issues. Furthermore, Larson et al (2009) review the three elements, from the attitude theory, that impacts on environmental perspectives: the affective component, which is the personal feeling we have about a subject; the cognitive component, representing the personal beliefs on the reasons and consequences about a topic and; the conative component, which is the way we act or behave. Illustratively, the alternative reasons that explains the expected decrease in water consumption is the fear of water scarcity (effective), the belief that water might not meet the demands in the future (cognitive) and conservation behaviour to avoid water shortages (conative). We emphasize that these reasons are possible explanations and must be properly addressed by specific psychological experiments and clinical assays.

Grey Water Footprint Results

The GWF was split into two parts. The first one accounted for the volume needed to dilute domestic effluent discharges into water bodies; and the second one regarding the production of sanitary landfill leachate, which contains high loads of BOD.

Regarding the wastewater GWF, we determined the volume of domestic sewage production per person for 2030 and 2050 using the methods described in the Methodology section: i) the combination of individual daily water consumption (from the MMPSC) with the return rate of 0.80 (recommended by Von Sperling, 1995), which is equal to 160 daily litres per person and; iii) the confidence interval based on the time series, which range from 55.16 to 70.30 cubic meter per year per person.

Next, we performed a linear regression in order to find out the relation between polluting load concentration in domestic effluent after treatment (BOD kg/m3) as a function of investments made in sewage infrastructure (BRL/year in Net Present Value). The trend line presented R^2 equal to 0.67 based on the time series for São Carlos (SNIS, 2018) between 2009 and 2016. The regression line is presented in the supplementary material (Souza, 2020), where independent variable is ammount of investments made in the sewage infrastructure in São Carlos (10^6 BRL) and the dependent variable is the polluting load of domestic effluents after treatment (BOD kg/m^3). Afterwards, we transformed these investments into a fraction of São Carlos' GDP. This fraction was estimated from total investments for the period between 2009 and 2016, while for 2030 and 2050 we created two scenarios. The first one was based on the responses to questions 4 (Table 2), asked to local citizens. The volunteers affirmed that those investments would be 40% and 73% higher in 2030 and 2050, respectively, compared to the present (0,01% in 2016). The second scenario assumed the historical average fraction, based on the time series from 2009 to 2016 – that represent almost 0.04% of the municipal GDP (SEADE, 2018; SNIS, 2018) – and GDP projections for 2030 and 2050 (EPE, 2015). Thus, to determine the grey water footprint, correspondent to the dilution volume for treated domestic effluents, we used Equation 3. The outcomes for these two methods – time series' analysis and volunteers' perception – are presented in Figure 3B and Figure 3C, respectively. The graph in Figure 3C presents higher values than Figure 3B not only because of the difference between historical (0.04%) and volunteers' averages (0.014% and 0.017% for 2030 and 2050) in investments that lead to higher BOD concentrations in treated wastewater, but also because of the larger confidence interval analysis in volunteers' responses, represented by the darker area in Figure 3C, which increases the uncertainty. In other words, the lower the investments, the higher the pollutant load and, consequently, the water for dilution.

On the other hand, Figure 3D presents the annual volumes of water needed to dilute the leachate from São Carlos' sanitary landfill. As the company responsible for operating the sanitary landfill began operating in 2013, and the amount of daily domestic solid waste collection has increased since 2013, we decided to establish the confidence interval as of 2013, which presented values ranging from 0.89 to 0.90 daily kg/person. The immediate consequence of this fact is that the dilution factor presented very few variations within the confidence interval of garbage production per person. The only significant changes regarding the time series analyses are consequences of possible scenarios in climatic variables (rain and evapotranspiration) that are resulted from the scenarios RCP 4.5 and 8.5. Alternatively, as the time series may properly reflect possible changes in solid waste generation, we used the volunteers' responses to perform this projection. According to the volunteers, individual household waste production will probably increase to 3% and 12% when comparing 2030 and 2050 to the present, respectively.

The high production of domestic waste leads to the reduction of the sanitary landfill's useful life. Nevertheless, at some point there will be an inflection: although the shortening time of the sanitary landfill operation leads to less volume of leachate, the weighing factor in Equation 6 ($\frac{G_i}{C_{sl}}$) may be large enough to overcome the benefit of having a landfill exposed for a short period of time. This is what happened with the outcomes from volunteers' perceptions, in Figure 3D. Although the growth in waste production leads to a reduction in the sanitary landfill's useful life, the corresponding leachate for each year i Q_{g_i} is higher than the analysis based on the time series. It is also interesting to note that scenarios RCP 4.5 for both methods – volunteers' perception and statistical analysis - presented higher volumes of leachate than scenarios RCP 8.5. This is because the volume of precipitation exceeded the volume of evapotranspiration.

The three curves in Figure 3D represent different outcomes for two methods of analyses. The green one with star markers presents how the outcomes range from scenarios RCP 4.5 to RCP 8.5 based on the time series analysis of solid waste production. Since the upper and lower values of the confidence interval for the time series is not high, the variance is caused by the difference of precipitation and potential evapotranspiration of those climate change scenarios, which is equal to the volume of leachate produced over time. The results presented higher values for RCP 4.5 and lower for RCP 8.5. Meanwhile, the orange curve with round markers and purple curve with square markers indicate the variance in the grey water footprint based on historical data of solid waste production from 2009 to 2016 plus the upper and lower limit intervals of volunteers' responses, respectively, for possible changes of solid waste production in 2030 and 2050 considering the aforementioned RCP scenarios. Similarly to the green curve, the orange and purple ones have higher volumes of GWF for RCP 4.5 than RCP 8.5. In this graph, the highest and lowest values for each method are highlighted for 2016, 2030 and 2050.

For all three curves in graphic 3D there are two noteworthy points, the high increase for all cases in the period between 2012 and 2013 and the changing behaviours from 2016 to the possible scenarios. The first one happens because of the records in solid waste production that matches with the same period when the current company responsible for operating the solid waste management in São Carlos started the operations. The latter one occurs because of the pace of waste production that can increase or decrease the sanitary landfill useful life and, consequently, the volume of leachate.

Combined Blue and Grey Water Footprints

Finally, Figure 4 provides a complete picture of the Water Footprint of sanitation systems in São Carlos from 2009 to 2016 and possible scenarios of such WF in 2030 and 2050. The Blue Water Footprint component combines the historical data of domestic and economic activities for previous years, while it provides favourable and unfavourable scenarios for 2030 and 2050 in terms of water security - the lower WF is the better for society and the environment. Similarly, the Grey Water Footprint component combines two elements; the water required to dilute pollutants from treated wastewater discharge and leachate from the municipal sanitary landfill. However, for the former element we computed the historical data, while the latter computed the average of all outputs presented in Figure 3D for each year between 2009 and 2016. Considering the 2030 and 2050 scenarios, Figure 4 presents possible footprints in terms of water security by combining the two lowest elements of GWF for the favourable scenario and the two highest GWF for the unfavourable scenario.

Although the comparison in Figure 4 reveals that GWF is responsible for most of the total Water Footprint, the sewage collection and wastewater treatment services provided by the local company is essential for presenting good results compared to other Brazilian cities, where most sewage is not collected and not even treated. In addition, the GWF of treated wastewater did not include the advantage of ecosystem services provided by aquatic bodies (Taffarello et al. 2020). Thanks to the natural capacity of BOD depletion in rivers, the total load of BOD pollution diminishes until it reaches a better quality. This means that the pollutant load will decrease and, consequently, the GWF will follow the same ratio.

Additionally, Figure 4 presents the individual water footprints for the sake of comparison across different case studies. One relevant aspect is the ratio GWF/BWF, which represents how many times grey water footprint is larger than the blue water footprint. For the period between 2009 and 2016, this ratio ranged between 17 to 35 that are much higher values than the outputs from studies conducted by Hoekstra and Mekonnen (2012) and Vanham (2014). In addition, our study offers a different approach from Cai and Zhang (2019) in Chinese cities, where Water Footprints per capita decreased over time. We built possible optimistic and pessimist storylines with assistance of volunteers that shows either decrease and increase WF, respectively. These two particularities, the ratio of GWF/BWF and the evolution of municipal WF, reinforce the need to comprehend how different regions consume water and how the consumption might change in the future from the perspective of historical data and from the lens of locals.

Analysis of volunteers' responses about sanitation systems in their city

In addition to the questions regarding the quantitative aspects, we also verified if volunteers recognise key elements of the sanitation processes that have some relation to water quality and quantity in the municipality where they live. Numbers 5 to 9 in Table 2 identify the questions with these goals.

The results to those questions are illustrated in Figure 5 and they reveal that citizen's knowledge is limited. Although most of them know which company is responsible for supplying water to their house, almost one third of this sample does not know where the water comes from. It is even surprising that forty percent do not know that domestic effluents, which leave their houses, go to the treatment plants and then they are discharged into water bodies. A small sample fraction responded they believe it is treated and then goes back to their house for consumption, while others have no idea about what happens to the sewage. This fact reinforces the need to disseminate environmental education to the whole population to raise awareness about environmental conservation. If the population knew where the water comes from and the final destination of sewage, they could develop better attitudes towards water conservation and water use efficiency (Gunda et al. 2019), increase pressure on local authorities in order to protect water bodies and make investments in sewage treatment. These principles meet the recent federal enactment that aims to provide Brazilian citizens the basic sanitation services (Brazil, 2020).

The results presented in Figure 5 also revealed that the residence time of volunteers in the city does not have such a big impact on their knowledge about sanitation elements and environmental awareness. While 21% of citizens who have lived in São Carlos for less than 20 years were able to answer positively and correctly all the questions, no volunteers who have lived in the city between 20 and 30 years responded to the five questions correctly. However, almost 60% of the volunteers who have lived in the city for more than 30 years answered four or five questions positively/correctly out of five questions, while 16% of citizens who have lived in the city between 20 and 30 years and 35% of those who have resided there for less than 20 years had the same performance. The lack of political will to utilize public participation and engagement in water management in the city may constitute such lack of awareness. Further factors such as education, income or age might have a different impact and are valid aspects of the research which could not be captured in depth for this research. Engaging volunteers, to help decision-making processes of water resources however is an important aspect which requires further in-depth investigation.

CONCLUSION AND RECOMMENDATIONS

This study addressed the Water Footprint concept through the engagement of citizens and analysis of existing short time series to build possible scenarios of water demands regarding the sanitation processes. The analysis focused on the water consumption for households– Blue Water Footprint – and the volume of water required to dilute pollutants from domestic sewage and leachate of sanitary landfill – Grey Water Footprint. The outcomes revealed that GWF of sanitation processes was in the range of 17 to 35 times higher than the BWF between 2009 and 2016, in a Brazilian municipality. Additionally, we built alternative scenarios with assistance of citizens, who outlined a substantial decrease in direct water consumption, growing garbage production and an increase in investments on sanitation facilities. Since the grey water footprint was responsible for the highest demands, we recommend to better understand its processes in future studies, such as capturing the variation in the quality and quantity of leachate production throughout the year, as well as the seasonality of hydrological and climatic variables, the effect of BOD depletion from treated wastewater in water bodies and the real impact of investments in sewage treatment. These elements can improve the accuracy of results and provide a better picture of real human demands.

Regarding the volunteered information used to capture possible changes in behaviours, the results revealed that São Carlos' citizens have raised environmental awareness in terms of water security for the region in which they live. This conclusion is a consequence of volunteers' beliefs that they will save more water in long-term scenarios, the investments in sanitation infrastructures will grow over time, compared to the present, and most of the interviewees responded they are concerned about not having enough water by the end of the century.

The approach proposed in this study complements the traditional time series analyses because it addresses unexpected changes in individual behaviours that cannot be predicted. This is the role of public participation and volunteers' engagement in this work, they provided an alternative method to outline potential water demand trajectories. Based on these possibilities, we recommend that policy makers adopt the Water Footprint indicator in official reports to assess the broad water security context at municipal or river basin scales and use it as a strategy to communicate water consumption to the local population. Additionally, although civil society is represented in many river basin committees, lay-citizens' have much to say and contribute to the management and planning of the water resources governance.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at http://dx.doi.org/10.17632/mmsfb8pzdz.1

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FIGURE CAPTION

Figure 1. Mapping the case study. A) Location of São Paulo State on a map of Brazil; B) River basins' threshold in São Paulo state; C) Limits of São Carlos city and the water bodies and sanitation facilities.

Figure 2. General methodology proposed to account for Blue and Grey Water Footprints in sanitation processes on an urban scale including both time series and citizen participation.

Figure 3. Outcomes for Blue Water Footprint and Grey Water Footprint accounting from the sanitation processes in the case study. A) presents the BWF from domestic demands; B) and C) outline the GWF accounting for domestic wastewater processes and D) for leachate production within the municipal sanitary landfill. Scenarios in B) consider that investments in wastewater treatment in 2030 and 2050 will receive the same historical average fraction of municipal GDP in the future, while C) considers this fraction as indicated by volunteers in questions 4 from Table 1. D) provides possible storylines for GWF considering projections based on time series analyses on solid waste production, answers from volunteers for questions 3, in Table 1, and projections of climatic variable for scenarios RCP 4.5 and RCP 8.5.

Figure 4. Water security assessment on possible scenarios – the graph breaks down the two components of water footprint for previous years and provides favourable and unfavourable scenarios for 2030 and 2050. The left-hand y axis refers to the bar plots, which is the municipal water footprint in Mm3/year, while the right-hand y axis refers to the markers, which are the yearly individual WF in m3*capita-1*year-1.

Figure 5. Responses from citizens to qualitative questions, where A) represents the answers from all volunteers and B) evaluates the number of answers according to their residence time in the case study.

TABLE TITLE

Table 1. List of datasets used in this work to account for the Blue Water Footprint (BWF) and the Grey Water Footprint (GWF) at the municipal scale.

Table 2. Questions asked to volunteers who live in the case study. Questions 1 characterise citizens who participated in this study. Questions 2 refer to indirect consumption of drinkable water in their residences. Questions 3 account for the solid waste production by residence. Questions 4 aim at understanding people's beliefs regarding changes in sanitation investments. Questions 5 to 9 provide an overview about volunteers' knowledge and awareness about water processes within the place they live.

Table 3. Result of questions asked to volunteers regarding Figure 3. The results present the average for each variable obtained from the respective questions. * Indicates that water bills were transformed into Net Present Value.

Figure 1: Mapping the study site. A) Location of São Paulo State on a map of Brazil; B) River basins' threshold in São Paulo state; C) Location of water bodies and sanitation facilities in São Carlos.

Figure 2: General methodology proposed to account for Blue and Grey Water Footprints in sanitation processes on an urban scale including both time series and citizen participation.

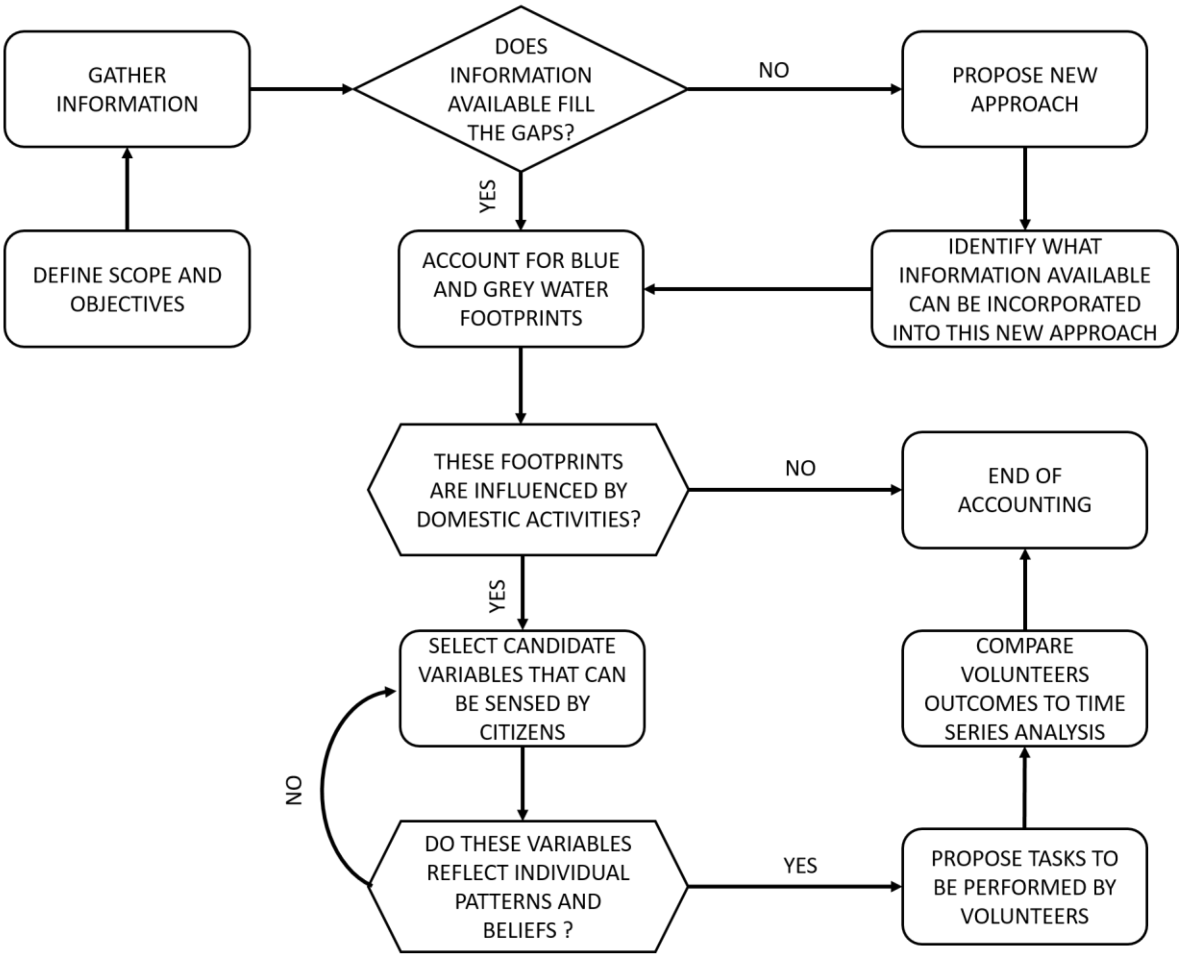

Figure 3: Questions asked to volunteers who live in São Carlos. Questions 1 characterise citizens who participated in this study. Questions 2 refer to indirect consumption of drinkable water in their residences. Questions 3 account for the solid waste production by residence. Questions 4 aim at understanding people's beliefs regarding changes in sanitation investments. Questions 5 to 9 provide an overview about volunteers' knowledge and awareness about water processes within the place they live.

How long have you lived in São Carlos?

In what neighborhood do you live in?

1a) How many people lived in your house ten years ago?

1b) How many people live in your house today?

1c) How many people will live in your house in 2030?

1d) How many people will live in your house in 2050?

2a) How much did you use to pay for water bills ten years ago?

2b) How much do you pay for water bills today?

2c) How much do you think you will pay for water bills in 2030?

2d) How much will you pay for water bills in 2050?

3a) How many bags of waste did your household use to produce on a weekly basis ten years ago?

3b) How many bags of waste does your household produce on a weekly basis today?

3c) How many bags of waste will your house produce on a weekly basis in 2030?

3d) How many bags of waste will your house produce on a weekly basis in 2050?

4a) What percentage of government wealth used to be invested in water supplies and sanitation structures 10 years ago?

4b) What percentage of government wealth is invested in water supplies and sanitation structures today?

4c) What percentage of government wealth will be invested in water supplies and sanitation structures in 2030?

4d) What percentage of government wealth will be invested in water supplies and sanitation structures in 2050?

5) Where does the water you drink come from?

6) Who/Which company is responsible for bringing water into your home?

7) What happens to the sewage produced by your house?

8) Who consumes more water in your city: population, industries or farms?

9) Are you concerned about whether or not the city you live in will have drinkable water in 2100?

Figure 4: Outcomes for Blue Water Footprint from domestic demands (A) and economic activities (B). For both cases, the historical BWF was obtained from official reports, while future scenarios followed the methodology described in Section 3.2.

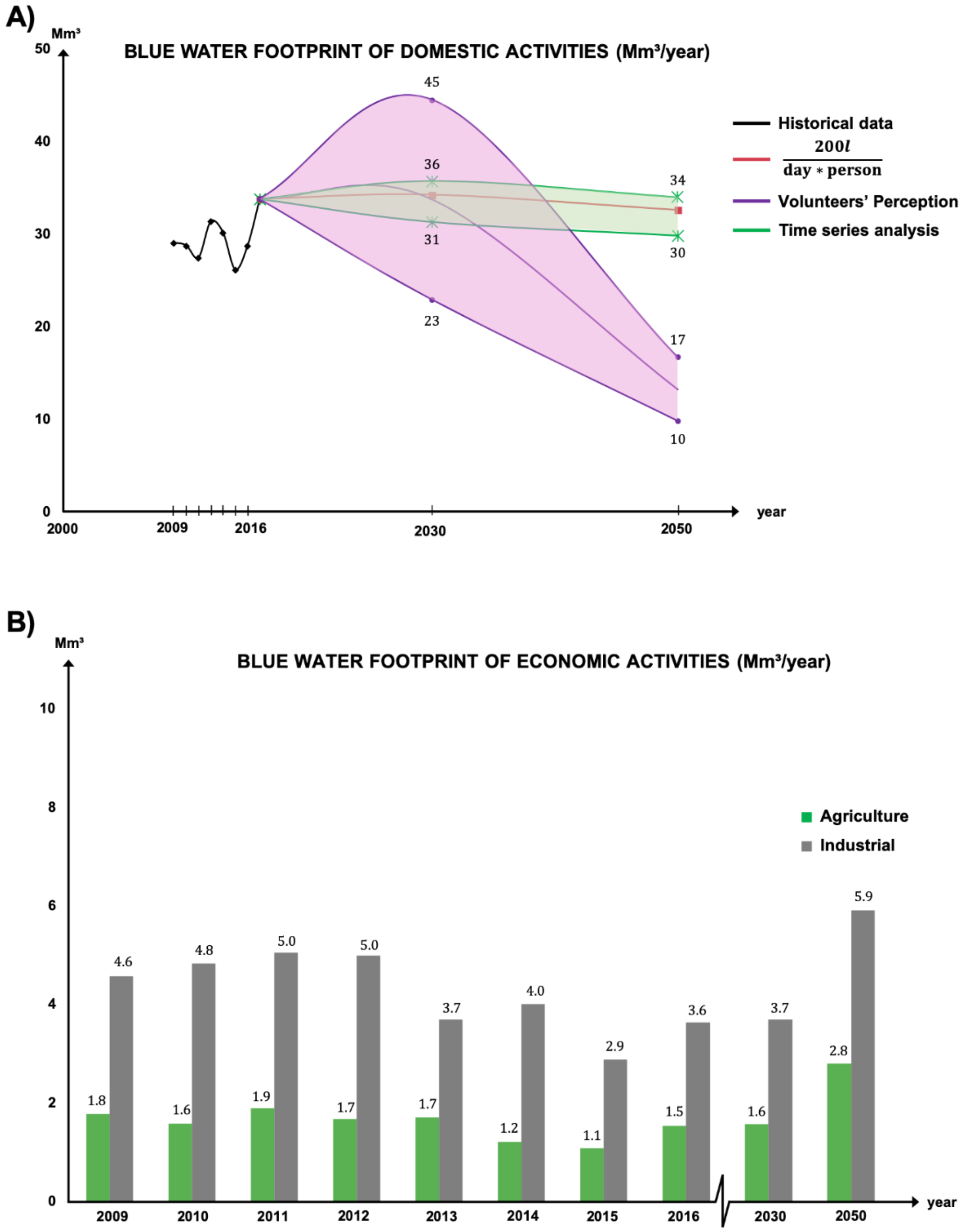

Figure 5: Results for Grey Water Footprint accounting for different processes in São Carlos. A) and B) represent the GWF accounting for domestic wastewater processes and C) for leachate production within the municipal sanitary landfill. Scenarios in A) consider that investments in wastewater treatment in 2030 and 2050 will receive the same fraction of municipal GDP in the future, while B) considers this fraction as indicated by volunteers in questions 4 from Figure 3, which influences the wastewater quality discharged in local water bodies. C) provides the outcomes for GWF considering projections based on time series analyses on solid waste production, answers from volunteers for questions 3, in Figure 3, and projections of climatic variable for scenarios RCP 4.5 and RCP 8.5.

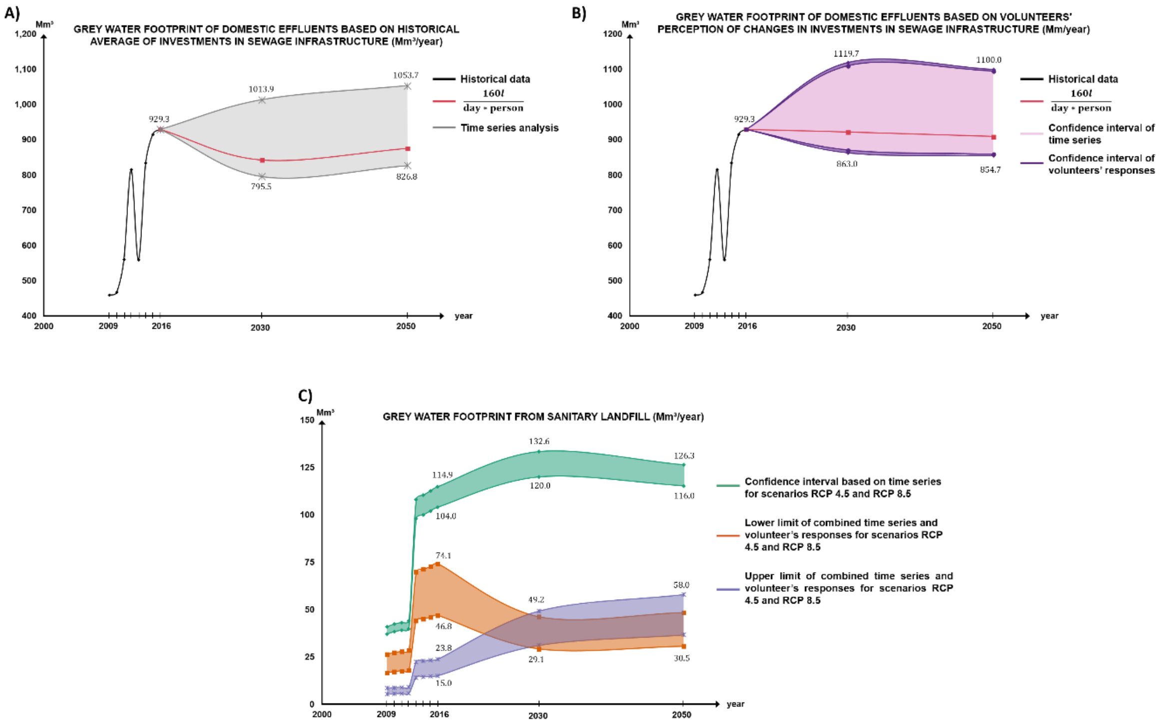

Figure 6: Water security assessment on possible scenarios – the graph breaks down the two components of water footprint for previous years and provides favourable and unfavourable scenarios for 2030 and 2050

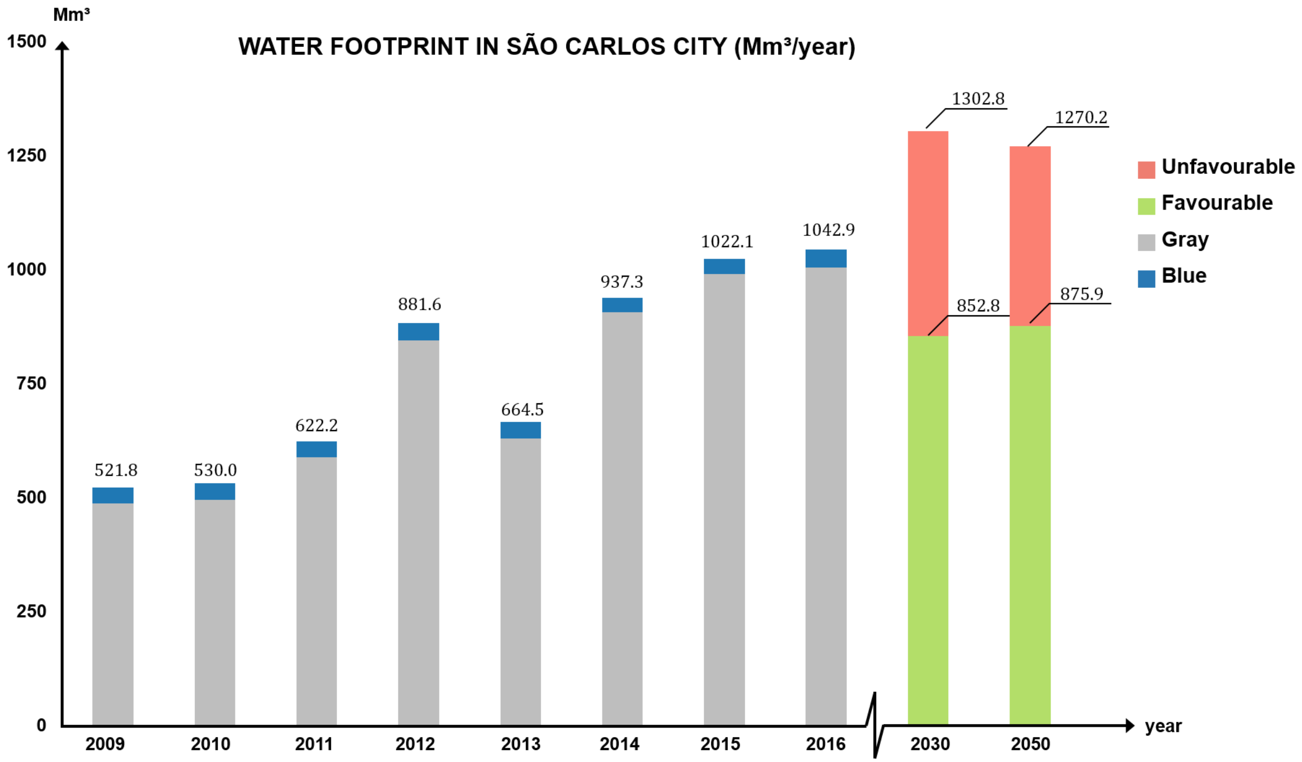

Figure 7: Responses from citizens to qualitative questions, where A) represents the answers from all volunteers and B) evaluates the number of answers according to their residence time in São Carlos city

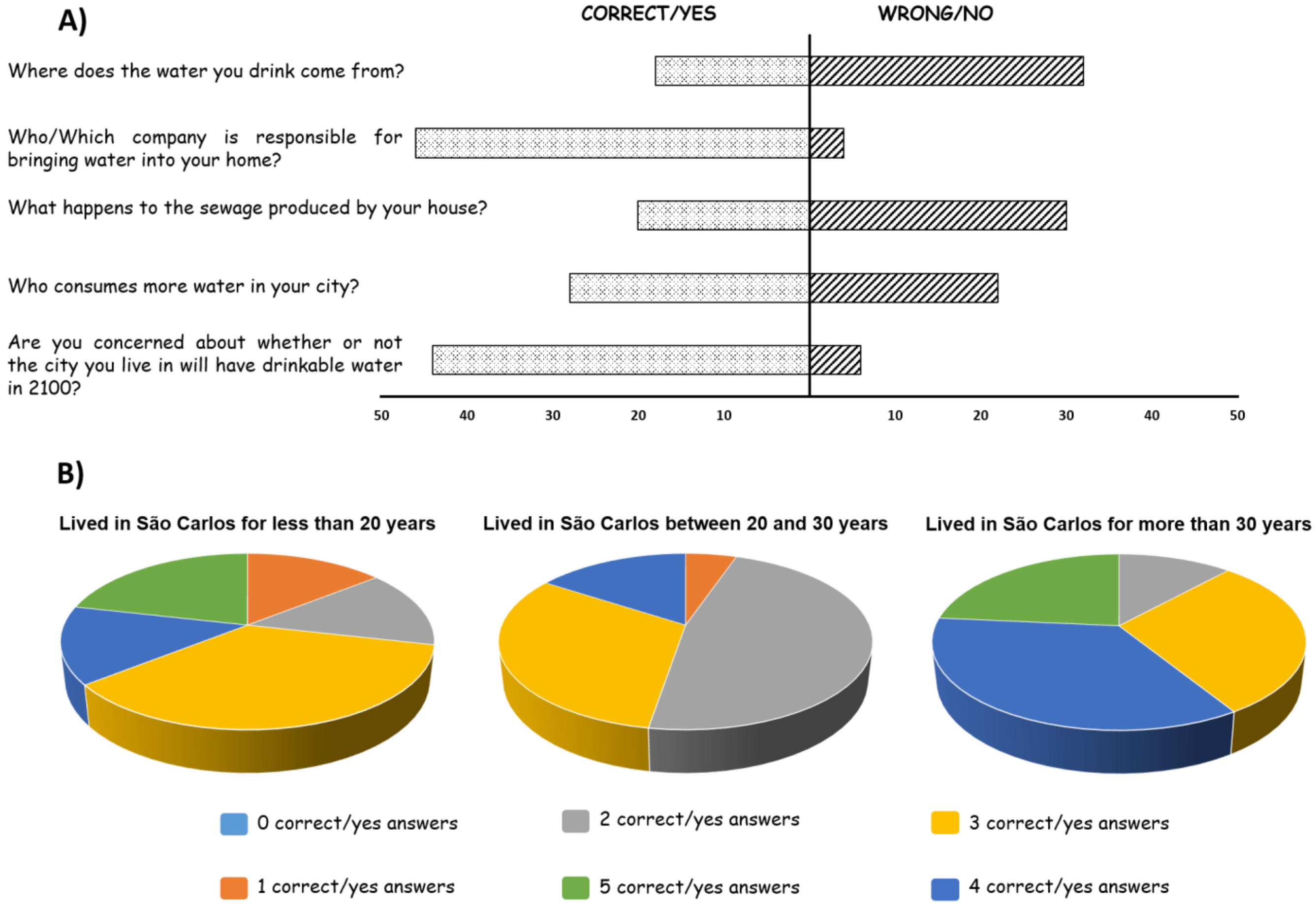

Table 1**:** List of datasets available for São Carlos that were used in this study to account for the Blue Water Footprint (BWF) and the Grey Water Footprint (GWF)

Type of variable	**Unit**	**Source**
Average daily consumption per capita	l/hab./day	
Index of losses in water networks	%	
Average water rate	$R\$/m^3$	(SNIS, 2018)
Volume of sewage collected	m^3/year	
Average sewage rate	$R\$/m^3$	
Investment made in sewage structures	R$/year	
Rural water demand	m^3/s	(CBHTJ, 2019)
Industrial water demand	m^3/s	
Organic load of pollution due to domestic sewage	kg BOD/day	
Projection of index of losses in water networks	%	(PMSC, 2012)
Projections of GDP growth	U$	(PWC, 2017)
Population	inhabitants	(SEADE, 2018)
Consumer Price Index	%	(IBGE, 2018)
Projections of precipitation under climate change scenarios	mm	(PROJETA, 2019)
Projections of evapotranspiration under climate change scenarios	mm	
Participation of Agriculture in Brazilian GDP	%	(ANA, 2017; EPE, 2015)
Participation of Industry in Brazilian GDP	%	
Projection of Brazilian GDP growth	%	
Projection of population growth	inhabitants	(SEADE, 2018)
Agricultural area	ha	
GDP	R$	
Time series of precipitation	mm	(EMBRAPA, 2019)
Time series of evapotranspiration	mm	
Time series of household waste production	tons	(CETESB, 2019)

Table 2: Result of questions asked to volunteers regarding Figure 3. The results present the average for each variable obtained from the respective questions. * Indicates that water bills were transformed into Net Present Value.

Question	Variable	Average	Standard Deviation	Upper Limit (t-Student 95%)	Lower Limit (t-Student 95%)
2a)	Water bill per person ten years ago (R$/person)*	28.75	23.56	35.99	21.50
2b)	Water bill per person today (R$/person)	29.69	23.57	36.54	22.85
2c)	Water bill per person in 2030 (R$/person)*	26.18	28.82	34.54	17.81
2d)	Water bill per person in 2050 (R$/person)*	10.79	9.57	13.60	7.98
3a)	Plastic bags of waste per person ten years ago (unit/person)	2.58	3.10	3.48	1.68
3b)	Plastic bags of waste per person today (unit/person)	3.01	3.32	3.96	2.07
3c)	Plastic bags of waste per person in 2030 (unit/person)	3.10	3.18	4.01	2.20
3d)	Plastic bags of waste per person in 2050 (unit/person)	3.39	3.75	4.47	2.31
4a)	Fraction of investments on sanitation from total resources available ten years ago (%)	23%	23%	30%	16%
4b)	Fraction of investments on sanitation from total resources available today (%)	21%	19%	26%	15%
4c)	Fraction of investments on sanitation from total resources available in 2030 (%)	29%	27%	37%	21%
4d)	Fraction of investments on sanitation from total resources available in 2050 (%)	36%	30%	44%	27%
5)	Number of volunteers that correctly answered the origin of tap water	18			
6)	Number of volunteers that correctly answered the agency responsible for bringing water to their house	46			
7)	Number of volunteers that correctly answered the destination of wastewater	20			

8)	Number of volunteers that recognised citizens demand more water than other sectors	28
9)	Number of volunteers that affirmed they are concerned about water availability in 2100	44