Assessing the energetic and environmental impacts of the operation and maintenance of Spanish sewer networks from a life-cycle perspective

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Abstract

The environmental impacts resulting from sewer networks are best analysed from a life-cycle perspective to integrate the energy requirements of the entire lifetime in the infrastructure design. The energy requirements for pumping wastewater depend on the configuration of the city (e.g., climate, population, length of the sewer, topography, etc.). This study analyses and models the effect of such site-specific features on energy consumption and related effects in a sample of Spanish cities. The results show that the average annual energy used by sewers (6.4 kWh/capita and 0.014 kWh/m^3 of water flow) must not be underestimated because they may require up to 50% of the electricity needs of a typical treatment plant in terms of consumption per capita. In terms of Global Warming Potential, pumping results in an average of 2.3 kg CO_2/capita. A significant positive relationship was demonstrated between the kWh consumed and the length of the sewer and between other factors such as the population and wastewater production. In addition, Atlantic cities can consume 5 times as much energy as Mediterranean or Subtropical regions. A similar trend was shown in coastal cities. Finally, a simple predictive model of the electricity consumption was presented that considers the analysed parameters.

Keywords: Energy, sewer, LCA, operation, city

Highlights

The electricity consumption in sewers varies depending on the city.

Spanish sewers consume, in average, 6.4 kWh per capita.

Atlantic cities require more energy to pump wastewater than Mediterranean regions.

The electricity needs depend on the length of the sewer and the wastewater production

Introduction

1.1 The urban water cycle

Urban regions are high-populated areas in which more than 50% of the world's population lives (The World Bank 2012), and the urban exodus is expected to increase in the coming years (Pacione 2009). Cities can be envisioned as an urban ecosystem with certain metabolic requirements, namely "the materials and commodities needed to sustain the city's inhabitants at home, at work and at play" (Wolman 1965). One of these material flows is the supply and treatment of water. Considering that urban regions are expected to host a greater share of inhabitants in the future, coping with more efficient water infrastructure is essential to sustainably satisfy these demands. Hence, the different stages of the urban water cycle must be analysed (**Figure 1**).

<Figure 1>

In the current situation of climate change and urban growth, water and energy challenges are closely related. For instance, Drinking Water (DWTP) and Wastewater Treatment Plants (WWTP) are more energy intensive in large cities because of greater water and wastewater production (EUREAU 2009); moreover, water is pumped longer distances through a network of pipes. As a result, if urban sprawl increases because of the construction of new settlements, the structural configuration of the cities and pipe networks may vary, and the intensity of this effect depends on geography. In addition, urban expansion may cause certain networks to be obsolete and inefficient; hence, urban planning is essential to optimise these systems. As a consequence, the water-energy relationship should be thoroughly analysed to discover environmentally friendly solutions in the design of these networks (in this case the sewer system) to minimise the environmental burdens caused by urban areas.

1.2 Energy impacts of the sanitation infrastructure

Among the stages of the urban water cycle, the analysis of sanitation infrastructure is important because of the effects wastewater can potentially cause to the environment and human health. Sanitation infrastructure consists of (1) the sewer and stormwater network, which collect and transport wastewater and stormwater runoff, and (2) the WWTPs, in which wastewater is treated.

The energy consumed in the operation and maintenance (O&M) of sanitation infrastructure has been addressed in the past, notably for WWTPs, which are generally thought to be energy-intensive consumers. A study conducted on Japanese water networks revealed that the wastewater treatment process requires nearly 40% of the energy consumed in sanitation (Shimizu et al. 2012), whereas only 9% of the energy is consumed by the pumping of the wastewater. Similarly, Roberts et al. (2008) considered the O&M of PWTPs and WWTPs relevant because it accounted for 35% of the energy used by the municipality; as a result, energy optimisation strategies were presented (e.g., energy audits, monitoring and process optimisation) to reduce energy and economic costs (Biehl and Inman 2010).

The energy and environmental impacts can be analysed using Life Cycle Assessment (LCA) (ISO 2006) to determine the stage with the greatest impacts. From a life-cycle point of view, the contribution of sanitation infrastructure to the burden of the entire urban water cycle varies depending on the city. WWTPs in Oslo (Norway) require 82% of the electricity used in the entire water cycle (Venkatesh and Brattebø 2011). In Alexandria (Egypt), 18% of the impacts of the urban water cycle derived from WWTPs with high energy consumption (Mahgoub et al. 2010). In the case study of Aveiro (Portugal), the electricity consumption exceeded 80% of the impact for most indicators for water extraction and treatment, but not in the case of the WWTP, where the role of wastewater discharge is much more relevant (Lemos et al. 2013). This variability could be because of the water consumption, the population density, the climate and the wastewater composition.

Additionally, the different components in sanitation infrastructure are not always accounted for in the most appropriate manner. Several studies aggregate the effects of the sewer and the WWTP (Cohen 2004; EA 2008; Griffiths-Sattenspiel and Wilson 2009). Further, a single entity is usually responsible for managing the sewer and WWTPs as a whole. As a result, the identification of their respective contributions becomes difficult. Several publications focus exclusively on WWTPs; the aim of this paper is to study the sewerage network separately.

1.3 Environmental assessment of sewer networks

Applying the LCA methodology to sewers, the impacts resulting from the raw material extraction, pipe and appurtenance production, transport, installation, O&M, demolition and end-of-life can be estimated (**Figure 2**) as reported in previous literature (Venkatesh et al. 2009; Roux et al. 2011; Petit-Boix et al. 2014). Among all life-cycle stages, the focus of the present analysis is on the O&M. Energy consumption patterns might vary depending on different variables such as the geography and sewer design. Therefore, a standard electricity value cannot be assumed in the entire LCA of sewers.

<Figure 2>

In particular, the O&M consists of different activities, namely the energy used to pump wastewater and clean the infrastructure by specialised maintenance vehicles, and the material and energy requirements for rehabilitating and repairing damaged sections of the network.

Barjoveanu et al. (2014) reported that pumping energy accounted for 77% of the environmental effects experienced during the O&M of a sewer network in Romania, whereas 23% derived from maintenance activities. Considering the entire life cycle of a sewerage network, Roux et al. (2011) reported low electricity consumption during the O&M in France. The effect was only notable in the radiation indicator due to nuclear power generation in this country. By contrast, a comparative analysis of the entire cycle with and without O&M showed that the pumping energy can account for 92% of the Greenhouse Gas emissions. However, if O&M is excluded from the analysis, then 98% of the emissions originate from construction and installation (Strutt et al. 2008).

In addition, if the construction of new sewerage pipelines ceases, then the effects of the O&M stage are 3 times higher than the pipe production and installation stages on an annual basis as forecasted in the city of Oslo (Venkatesh et al. 2009). However, this increase might depend on the lifespan of the network and the structural design. With regard to other parameters such as density, the annual energy consumption per capita can be reduced by 10% if the population density is increased from 10 to 275 inhabitants/ha (i.e., the energy used to manufacture, repair and dispose of pipes and to pump water) (Filion 2008). In the case of water supply systems, it was also observed that cost-efficiency varied among scenarios considering different urban configurations (Farmani and Butler 2014).

Although most studies show the contribution of the O&M to the total impact of the sewer system, the environmental burdens of this stage are not homogeneous and vary by city. Following the hypothesis presented by Petit-Boix et al. (2014) in a previous study on sewer infrastructure, 3 parameters potentially affect the pumping requirements in a city: the length of the system, the topography and the location of the WWTP. In general, if a municipality is located at a high elevation and the WWTP is at the bottom of a valley or at sea level, then wastewater gravitationally flows; as a result, little energy is required, except in the occasional changes of slope, in which a certain amount of electricity is likely needed. No significant effects were found in cities in France by Roux et al. (2011); however, flat areas displayed radiation indicators 50% lower than uneven regions, which is because of lower nuclear-power consumption. Other aspects, such as decentralisation, water consumption or the population size, also affect the performance of the system (Sitzenfrei et al. 2013) and could explain the electricity requirements in different cities.

Therefore, the O&M stage of sewer networks should be addressed independently of WWTPs. Each life-cycle stage is conditioned by different factors, which may vary depending on the area under study. The electricity consumed during wastewater pumping can be heterogeneous depending on the city whereas the effects of sewer construction are less diffuse (Petit-Boix et al. 2014). Consequently, this paper aimed to describe the energy consumption patterns in sewers of different cities, the implications of local features on pumping requirements and the consequent environmental effects from a life-cycle perspective.

1. Objectives

The main goal of this study was to analyse and model the effect of regional and physical features on the energy consumption in and the environmental impacts of the O&M stage of urban wastewater- and stormwater-transport networks in Spanish cities from a life-cycle perspective. To achieve this goal, the specific objectives were as follows:

- To collect and analyse data on the electricity consumption in a representative sample of Spanish municipalities;
- To identify the physical (e.g., location of the WWTP, length of the sewer and wastewater flow) and regional features of the network (e.g., climate, seasonality, distance to the coast, population density and income) that affect the energy consumption and environmental impacts through a statistical analysis;
- To model the energy consumption of urban sewer systems depending on physical and regional parameters and analyse optimisation strategies;
- To compare the contribution of the electricity consumption to the construction phase of a specific case study.

2. Material and Methods

2.1 Sample selection

To analyse the effects of different physical and regional parameters, a representative sample of municipalities was selected. Spain was chosen to develop the study because the country displays important climatic variability and because data covering 2011 were easily obtained. The data were supplied and retrieved by CETaqua (Water Technology Centre) from the CONTEC© and GISAgua© (2012) databases in the framework of the LIFE+ AQUAENVEC Project that supports this study.

To be included in the sample, the cities had to meet the following requirements:

1. Reside in Spain (including the islands);
2. Be exclusively supplied by a sewer network not serving other cities to clearly define the burdens of one network in one city.
3. Provide data for at least the following parameters: population, electricity consumption for pumping wastewater and length of the network.

As a result, 68 cities were selected for analysis. The total population and population density of these cities are in a medium range with respect to all cities (395) with records in the databases (**Table 1**). Other parameters needed to perform the analysis are also presented in **Supplementary Material 1**. The required parameters were occasionally reported as zero, but it could not be determined whether this was a true zero or an unavailable result. Therefore, cases containing this exception were maintained in the sample but zeros were not accounted for in the statistical analysis. As a result, 48 cities were studied in terms of electricity consumption (36 depending on the data availability of other variables), whereas all 68 cities were considered in the analysis of other parameters such as population or wastewater production.

<Table 1>

3.2 Modelling the electricity consumption

3.2.1 Statistical analysis

The electricity consumption was studied under different physical and regional conditions that may potentially affect the pumping requirements in the sewer network of a municipality (**Table 2**). Data for the year 2011 was considered.

First, energy issues were analysed considering the regional features of the sample to qualitatively identify trends. Therefore, cities were classified according to their population, population density, income per capita, climate, seasonality and location, and the results are presented using a box plot displaying the minimum, mean and maximum. Second, the electricity consumption was correlated to all quantitative parameters to identify the strongest Pearson's coefficient (R; a measure of the linear correlation between two variables). Finally, linear and multiple regression models were run for those factors that presented stronger correlations with the electricity consumption. A p-value <0.01 or <0.05 indicated a significant relationship. The entire statistical analysis was performed in PASW Statistics 18 (2009) from the Statistical Package for the Social Science (SPSS).

<Table 2>

3.2.2 Assumptions

Some variables were estimated considering different assumptions. The height difference was calculated considering the altitudes of the WWTP and the middle of the city because other topographic variations in the network could not be incorporated; thus, this assumption deviates from reality. Regarding wastewater, no flow metres were installed in the municipalities, therefore the wastewater production was assumed to be equal to the water supplied to the households. Further, the stormwater runoff was estimated considering the stormwater catchment area, a runoff coefficient equal to 0.9 (CEDEX 2009) and the annual mean rainfall in the region (retrieved from the Spanish National Meteorological Agency) (AEMET 2013). Economically, the income per capita was obtained from the Statistical Institutes of Catalonia (Idescat 2013), Extremadura (ieex 2011), Murcia (CREM 2011), Andalusia (IECA 2010) and Galicia (IGE 2009).

The results of the analysis are presented in absolute (i.e., total electricity consumption) and relative terms, namely the consumption per capita and per m^3 of water flow per year. To account for the tourist population, the consumption per capita was expressed in terms of total equivalent population (TEP). TEP consists of the registered population plus the seasonal population linked to second residences. The latter was estimated considering the number of second residences in the city, an average occupancy of 2.6 people per household (INE 2013) and an average occupancy of these second residences of 30 and 120 days in inland and coastal cities, respectively, based on the assumptions made in a report by the Galician Water Agency (Augas de Galicia 2011).

3.2.3 Environmental impacts

To account for the environmental effects deriving from the electricity consumption, the impact category Global Warming Potential (GWP) was used to estimate the CO_2eq emissions from a life-cycle perspective. Considering the CML IA method (Guinée et al. 2002) and the ecoinvent 2.2 (ecoinvent 2009) database, the Spanish electricity mix adapted to 2011 (IEA 2014) had an emission factor of 366 g of CO_2eq per kWh of electricity.

3.3 Maintenance activities

When studying the O&M stage of a sewer network, different elements must be accounted for in the overall impacts: (1) the electricity consumption, (2) the rehabilitation rate, i.e., the length of the system that must be replaced because of failures, and (3) the cleaning tasks.

Similar to the pumping requirements, the rehabilitation rate varies by site. Siltation problems, protruding connections, infiltration, fat deposition, encrustation, root infestation and the slope may affect the performance of small pipelines (Fenner 2000; Ugarelli et al. 2010), and thus, a consideration of these factors assists in determining the best time to rehabilitate the network. As a result, the pipe rehabilitation and cleaning of sediment-related blockages requirements of every city will be different and might vary over time (Rodríguez et al. 2012). Because of insufficient data, neither the rehabilitation nor the cleaning activities were analysed using a statistical approach, but these parameters should be monitored in the future.

A city with potentially large maintenance needs (i.e., coastal, seasonal, flat and with a WWTP located further inland) was selected to determine the relevance of the maintenance activities with respect to pumping (ID = 15, see **Supplementary Material 1**). Field work in the city showed that 400 L of diesel were required to clean the network every 3 months. Given that approximately 1,400,000 kWh of electricity were consumed in 2011 in the pumping of wastewater, the maintenance accounts for 1.2% of the total impacts of the O&M stage. The contribution of the diesel is also expected to be negligible in other cities, and this contribution was therefore not analysed through a statistical approach. However, further analyses should consider possible variations depending on the city.

4. Results and Discussion

4.1 General descriptive analysis of the electricity consumption

To establish a general view of the electricity consumption in the case study cities, a description of the annual energy use in the sewer systems is presented in **Table 3**. According to the results, 50% of the sample municipalities consume between 0.5 and 8.1 kWh per TEP and between $1.7 \cdot 10^{-3}$ and $2.6 \cdot 10^{-2}$ kWh per m^3 of water flow. In terms of environmental impacts, the average electricity consumption per TEP and m^3 of water flow are 2.3 kg and $5.1 \cdot 10^{-3}$ kg of CO_2eq., respectively. The deviations suggest that not all cities have identical configurations or other aspects affect the pumping requirements; as a result, the sample must be analysed in small groups that share similar characteristics (Section 4.2) to determine the factors that may have a significant effect on the electricity consumption.

<Table 3>

However, these values also represent other findings for sanitation infrastructure. The selected Spanish sewers consume an average of 6.4 kWh/TEP and 0.014 kWh/m^3 of water flow; these values could be compared to the consumption patterns of WWTPs. For instance, Hospido et al. (2008) found that Galician WWTPs that serve 72,000-125,000 inhabitants required 13.2-36.6

kWh per capita. This means that a sewer network might require between 18 and 50% of the electricity used by a treatment plant.

Additionally, a Catalan WWTP that serves a large city consumed an average of 0.382 kWh/m^3 (Abril and Argemí, 2009). According to data retrieved from CONTEC© (2012), Galician and Catalan WWTPs consume an average of 0.53 and 0.86 kWh/m^3, respectively. By contrast, the average value calculated in terms of m^3 of water flow is much lower than that of WWTP because of the estimates of the water flow. Nevertheless, two case studies were thoroughly analysed in the framework of the LIFE project, and the real water flow entering the WWTP was obtained. A Catalan city (ID =15) consumed 0.46 kWh/m^3 in the sewer and 0.35 kWh/m^3 in the WWTP in 2011, whereas a Galician city (ID = 12) consumed 0.11 kWh/m^3 in the sewer and 0.46 kWh/m^3 in the WWTP in 2011. Therefore, energy issues in wastewater transport infrastructures should not be underestimated.

Even so, the relevance of the sewer with respect to the WWTP is variable and it might depend on the features of the system, such as the length of the sewer, and the type of treatment technologies required. Moreover, when cities are analysed individually, apparent differences can be detected, but there tend to be different management practices that influence the sewer performance. So far, authorities have generally given preference to ensuring the transport of wastewater instead of optimising the system. At the end, this decision can lead to increasing environmental and economic costs and the maintenance of inefficient networks. The identification of these aspects was not possible in the sample of cities; however, it is a matter to consider when assessing the electricity consumption in different scenarios.

In line with the LCA for sewer construction developed by Petit-Boix et al. (2014), the environmental impact of the operation of the sewer in a city was compared to its construction. The study considered a representative stretch of the network made of plastic (60%) and concrete (40%) and an estimated number of appurtenances (i.e., pumps, manholes and inspection chambers). When comparing the annual impacts of the system in this city, the pumping energy represents 18-25% of the total environmental impact on an annual basis. This value deviates substantially from previous literature (Strutt et al. 2008). However, variations among cities and design parameters are responsible for these changes in the contributions of the use phase to the total impact of the system (Section 4.2 and 4.3).

4.2 Electricity required by city clusters

The cities were classified into clusters according to regional features shown in **Table 2**, and the electricity consumption was studied. No significant differences were found between clusters when the analysis was conducted in absolute terms (**Supplementary Material 2**) and electricity per m^3 of water flow (**Supplementary Material 3**). However, regional differences were noted in the electricity per capita. A correlation analysis might provide an explanation to this finding (Section 4.3). The extreme values were not excluded from the analysis because few cases would remain in the dataset and the outcome would worsen.

In terms of electricity per capita (**Figure 3**), differences were detected for climatic conditions and city locations. In the former, Atlantic cities displayed greater pumping requirements (19.8 kWh/TEP) than Mediterranean and Subtropical regions (~4 kWh/TEP). This higher pumping requirement is because of intense precipitation in the North and North-West of the country with unitary sewer networks that cannot separate stormwater runoff from wastewater. In line with the results of Hospido et al. (2008), the consumption patterns in sewers and WWTPs are in the same order of magnitude (13.2-36.6 kWh/capita).

Similarly, coastal municipalities consume more electricity (9.4 kWh/TEP) than inland cities (2.8 kWh/TEP). The lack of slope in sea level cities can cause sediment blockages. Therefore, water must be pumped more often to maintain the flow. In addition, coastal cities tend to pump wastewater upwards to WWTPs located further inland to preserve the landscape and prevent odour issues.

The remaining variables did not show significant differences and presented a p value greater than 0.2 in most cases. However, several trends could be identified. For instance, more pumping takes place in high-income cities, likely because of higher water consumption patterns (Section 4.3) and, as a result, more wastewater production. This could also be related to the population density, given that cities with high-income are usually organised in low-density neighbourhoods. However, differences were hardly seen in this case.

<Figure 3>

4.3 Identifying the main variables

A correlation analysis was performed to identify strong and weak relationships between the electricity consumption and the factors described in Section 3.2. All significant results are presented in **Table 4**.

<Table 4>

Three factors displayed a significant ($p<0.05$) positive relationship with the electricity consumed in the pumping of wastewater: the total length of the sewer network, the number of inhabitants and the total wastewater production. As expected, the length of the sewer plays an important role in terms of energy. Longer networks may require more pumping stations along the pipeline to prevent stagnation in and blockages of the main water flow. Additionally, the length of the system shows a strong correlation with the wastewater production ($R=0.92$) and the population ($R=0.91$) (data not shown). This finding is not surprising because these 2 parameters are key in the design of sewer networks (CEDEX 2009). Furthermore, wastewater production is highly correlated with the number of inhabitants ($R=0.97$), whereas the wastewater production per capita is significantly ($p<0.01$) affected by socioeconomic parameters such as the income per capita ($R=0.51$) and the population density ($R=0.29$). Higher-income inhabitants tend to consume more water for various activities such as filling swimming pools or watering gardens (Domene and Saurí 2003). The electricity use per unit of volume has a positive correlation with income. These findings are also consistent with the results shown in Section 4.2.

However, the water flow (i.e., wastewater plus stormwater runoff) is not correlated with total energy. The transport of stormwater was not significantly related; therefore, climatic differences in terms of rainfall could not be modelled. In this case, both the precipitation intensity and the catchment area are considered. Hence, an Atlantic city with a relatively small catchment area and a high annual mean rainfall could transport an amount of water similar to that collected in a drier Mediterranean city with a greater rainwater catchment area. In terms of energy per capita, the stormwater and total water flow transported per capita are correlated (R=0.35 and R=0.44, respectively) because population is a more site-specific feature.

As predicted, the slope did not display a significant relationship with the electricity used because this parameter only considered the height difference between the middle of the city and the WWTP. Internal slope variations along the network need to be considered; however, given the size of the sample and limited data availability, they could not be easily calculated. Therefore, the slope will most likely present a strong effect on the pumping requirements if it is analysed more thoroughly.

4.4 Approach to running energy use models

After identifying the most relevant parameters using correlation analyses, simple and multiple regression models were run (**Table 5**). Models 1-4 represent the factors and equations potentially affecting the total electricity consumption of a sewer network, whereas models 5-7 assess the electricity per capita and per m^3 according to the findings presented in Section 4.3.

<Table 5>

In terms of total energy, the length of the network (model 1) is the variable with the highest effects on electricity consumption (R^2=0.62). The total population (model 2) and the wastewater production (model 3) explain 38 and 35% of the electricity consumption of a city, respectively. Additionally, important data dispersion is noted.

However, given that all these factors interact, as presented in Section 4.3, a multiple regression model was considered. The effects of population, length of the sewer and wastewater production were addressed together. The R^2 increased to 0.66, higher than the other models. Additionally, the standard error of the estimate slightly reduced. Despite these improvements, the population coefficient was not significant ($p=0.84$) and, therefore, not included in Model 4, which only contains the significant variables. Nevertheless, the effect of population is implicitly represented in wastewater production (Section 4.3).

Given that the models did not display stronger correlations between the factors and the consumption per TEP or per m^3 of water flow, equation (1) represents the total electricity used in sewers with an $R^2=0.67$:

$$TEC = 3{,}394\ L - 0.07\ WW - 113{,}395 \qquad (1)$$

where TEC is the total electricity consumption in kWh, L is the total length of sewer in km and WW is the wastewater production in m^3.

4.5 Model validation

To estimate the error of Equation (1), the model was validated using data from 35 cities from the sample for the length of the network, the wastewater production and the real electricity consumption in 2011. Two different alternatives were compared to obtain the best approach (Equations 2 and 3).

Equation (2): if $3{,}394\ L > -0.07\ WW - 113{,}395 \rightarrow TEC = 3{,}394\ L - 0.07\ WW - 113{,}395$

if $3{,}394\ L < -0.07\ WW - 113{,}395 \rightarrow TEC = (-1)\ (3{,}394\ L - 0.07\ WW - 113{,}395)$

Equation (3): if Climate = Atlantic $\rightarrow$ TEC = Equation (2) $\cdot$ 5

if Coastal = Yes $\rightarrow$ TEC= Equation (2) $\cdot$ 1.5

if Coastal = No $\rightarrow$ TEC = Equation (2) / 1.5

The factors included in Equation (3) are related to the differences among clusters in terms of climate and coastal conditions (Section 4.2). When comparing the estimated electricity from these equations to real values, the error of the prediction is reduced by 22% on average when Equation (3) is applied. However, only 34 and 29% of the cases presented less than 50% deviation from reality in the predictions of Equations (2) and (3), respectively. Hence, a degree of error remains in the models.

To determine the reliability of Equation (3), the confidence interval of the mean was calculated using Student's t-test with 70% confidence (i.e., a 70% chance that the mean is included in $8.5 \cdot 10^5 \pm 2.7 \cdot 10^5$ kWh). Further analyses are needed to improve this model and to include other key parameters such as the height difference between the WWTP and the cities that were not accounted for in the present study because of a lack of data. Nevertheless, additional effort should be invested to standardise and improve the data collection process and prevent the use of biased or unknown values.

5. Conclusions

The present paper focuses on the O&M of sewer networks in the framework of the urban water cycle. On average, Spanish sewers consume 6.4 kWh/TEP of electricity (2.3 kg CO_2eq.) in the pumping of wastewater from households to the WWTP. In some cases, this system is not irrelevant when compared to the WWTPs in terms of energy consumption; sewer networks can require up to 50% of the electricity used in the wastewater treatment.

Given that the electricity consumption in sewers was thought to be dependent on different regional (population, population density, income per capita, climate, seasonality and distance to the coast) and physical length of the sewer, slope, stormwater runoff and water flow) parameters, a statistical analysis was performed on a sample of Spanish cities. The total electricity consumption was positively and significantly correlated with the length of the network (adjusted $R^2=0.62$) and was weakly correlated with the population ($R^2=0.38$) and wastewater production ($R^2=0.35$). Regional features, such as the stormwater runoff, were identified considering the electricity per capita. The simple model that best predicted the total electricity consumption in a city ($R^2=0.67$) includes the length of the sewer and the wastewater production. The wastewater production depends on other parameters, such as the population and the income per capita, given that social factors also affect the water consumption among collectives.

Further, significant differences were noted in the electricity consumption per capita when the cities are compared according to their features. In general, Atlantic cities require almost 5 times more pumping energy than Mediterranean and Subtropical cities because of more rainfall throughout the year. Coastal cities also require more energy than those located further inland because of blockage problems and the location of the WWTP.

This study highlights the importance of separately analysing the O&M stage of sewers in the framework of LCA. Moreover, evidence suggested that sewer networks present a great variability because of their configuration in different areas; therefore, a sample of cities presenting different features is important to include in the analysis. The model presented in this paper should assist urban planners in determining the most suitable configuration of the network for a city to reduce the energy requirements and the environmental impacts by using only simple variables. The location of the WWTP and the pumping optimisation should also be considered in new designs. However, some improvements should be included in further analyses. The height difference between the WWTP and the city is apparently a critical parameter in the definition of the pumping requirements. However, the topographic complexity of cities limited the analysis of this parameter.

In addition, during the O&M stage other impacts can occur. Maintenance activities were excluded from this analysis. Even in theoretically extreme situations, maintenance accounted for only 1% of the CO_2 emissions of the O&M. Furthermore, direct greenhouse gas emissions can be generated in the system because of the degradation of wastewater (e.g., the formation of methane, hydrogen sulphide and nitrous oxide). Therefore, future studies must integrate these emissions into the LCA to determine their relative contribution to the impacts and the variability between sewer networks.

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Fig. 1 Stages of the urban water cycle and the system under study

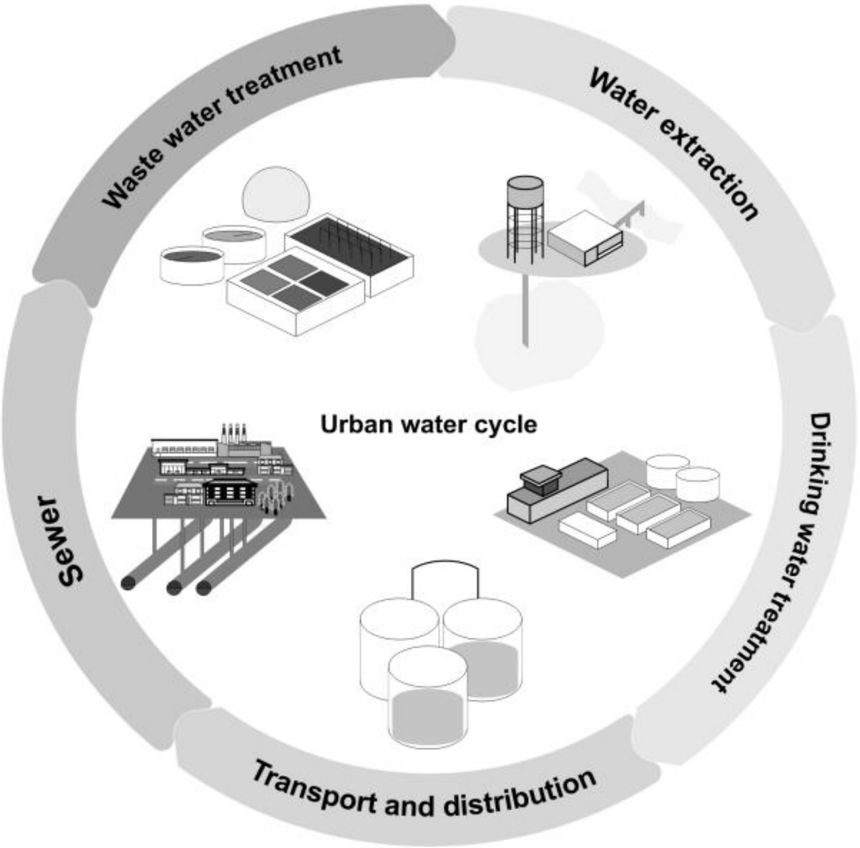

Fig. 2 Life-cycle stages of the sewer system and studied stage

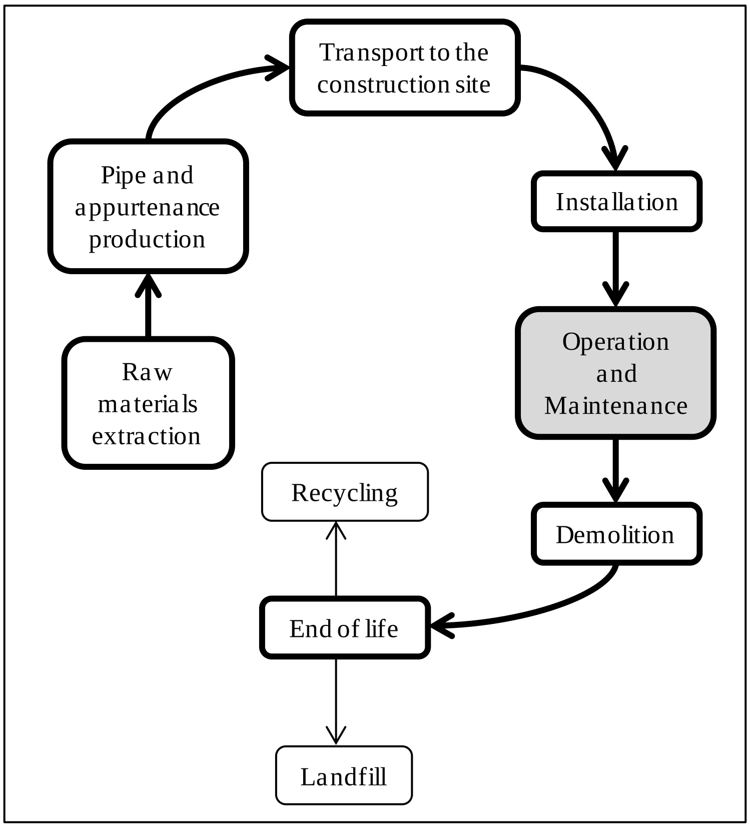

Fig. 3 Comparison of the electricity consumption per TEP in kWh under different regional conditions. The numbers in the box plot refer to the ID number of the city (see **Online Resource 2**).

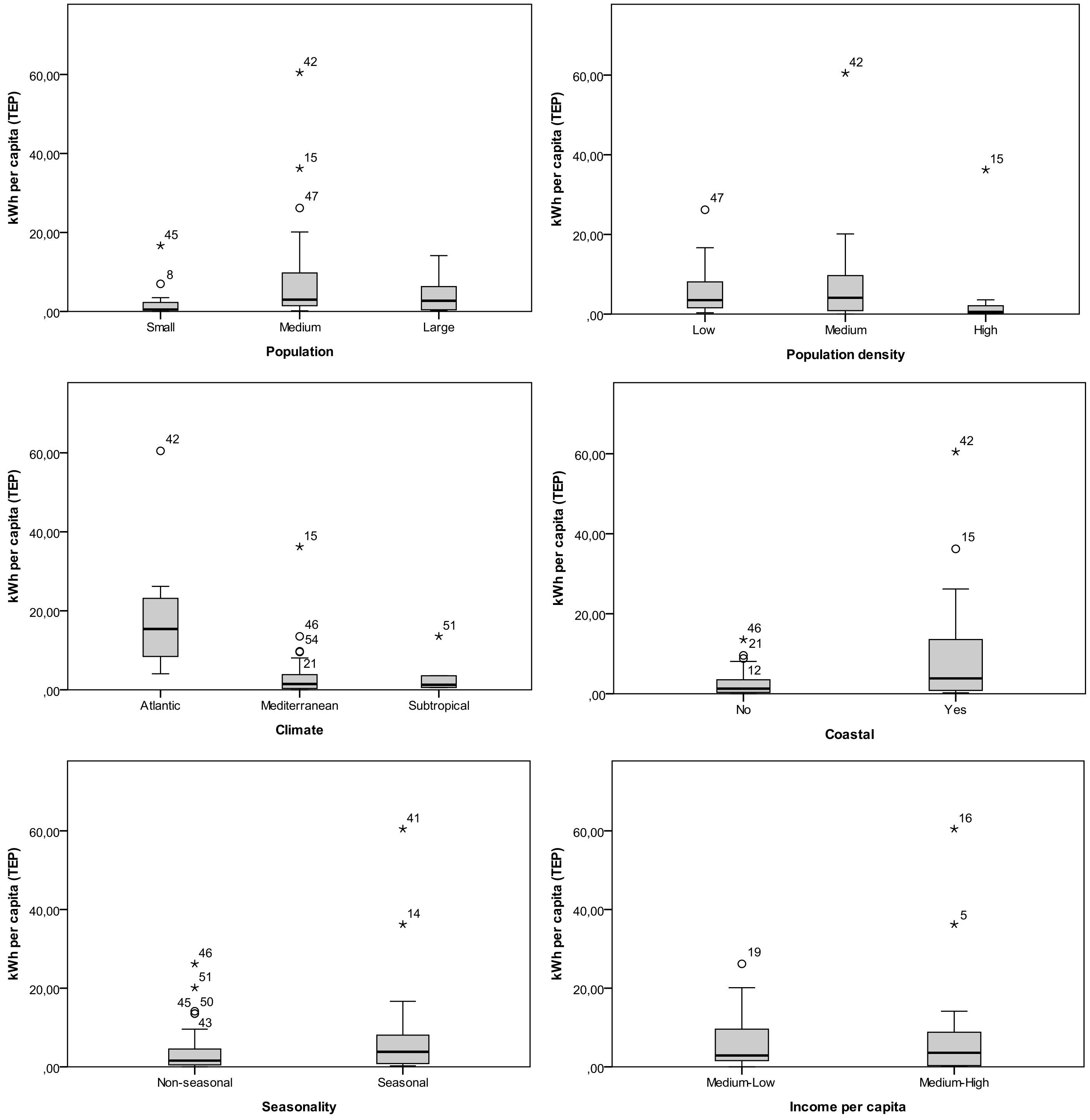

Table 1 Features of the complete set of cities and the sample selected for the analysis

System	Number of cities	Number of inhabitants			Population density (inhabitants/km^2)		
		Mean	Maximum	Minimum	Mean	Maximum	Minimum
All cities	395	23,235	1,615,448	99	601	16,449	1.9
Sample	68	49,448	443,657	632	717	3,426	5.2

Table 2 Factors potentially influencing the electricity consumed during the pumping of wastewater and their classification criteria

		Factors	Description
Quantitative data	Physical configuration of the network	Length of the sewer	• Total km of sewer • Metres of sewer per TEP
		Altitude difference between the middle of the city and the WWTP	• Height (metres)
		Wastewater flow	• Total volume (m^3) of wastewater produced • Volume (m^3) of wastewater produced per TEP
		Stormwater runoff	• Total volume (m^3) of stormwater • Volume (m^3) of stormwater per TEP
		Water flow (wastewater + stormwater)	• Total volume of (m^3) of water transported • Volume (m^3) of water transported per TEP
	Regional features	Population	• Small city: ≤ 10,000 inhabitants • Medium city: 10,000 – 50,000 inhabitants • Large city: > 50,000 inhabitants
		Population density	• Low density: ≤ 300 inhabitants/km^2 • Medium density: 300-1,000 inhabitants/km^2 • High density: >1,000 inhabitants/km^2
		Income per capita	• Medium-Low: <15,000 € per capita • Medium-High: 15,001 – 24,000 € per capita
Qualitative data		Climate	• Atlantic • Mediterranean • Subtropical
		Seasonality	• Seasonal $\left(\frac{\text{maximum population}}{\text{registered population}} \geq 1.25\right)$ • Non-seasonal $\left(\frac{\text{maximum population}}{\text{registered population}} \leq 1.25\right)$
		Location	• Coastal • Inland

Table 3 Descriptive statistics of the electricity consumption and environmental impacts in Spanish sewer networks in 2011

Descriptive variable	Total		Per capita (TEP)		Per m^3 of water flow		Per m^3 of wastewater	
	kWh	kg CO_2eq	kWh	kg CO_2eq	kWh	kg CO_2eq	kWh	kg CO_2eq
N (size of the sample)	48	48	48	48	36	36	43	43
Mean	3.3E+05	1.2E+05	6.4E+00	2.3E+00	1.4E-02	5.1E-03	1.1E-01	3.9E-02
Standard Error of Mean	1.0E+05	3.7E+04	1.6E+00	5.8E-01	2.9E-03	1.1E-03	3.0E-02	1.1E-02
Standard Deviation	7.0E+05	2.6E+05	1.1E+01	4.0E+00	1.8E-02	6.4E-03	2.0E-01	7.3E-02
Variance	5.0E+11	6.6E+10	1.2E+02	1.6E+01	3.1E-04	4.1E-05	3.9E-02	5.3E-03
Range	4.3E+06	1.6E+06	6.0E+01	2.2E+01	7.7E-02	2.8E-02	9.4E-01	3.5E-01
Minimum	4.8E+01	1.8E+01	1.0E-02	1.9E-03	2.5E-04	1.0E-04	7.9E-05	2.9E-05
Percentile 10	1.7E+03	6.1E+02	2.6E-01	9.5E-02	8.8E-04	3.0E-04	3.0E-03	1.1E-03
Percentile 25	2.2E+04	8.2E+03	5.0E-01	1.8E-01	1.7E-03	1.0E-03	7.2E-03	2.6E-03
Percentile 50	6.4E+04	2.3E+04	2.0E+00	7.5E-01	4.7E-03	1.5E-03	3.1E-02	1.1E-02
Percentile 75	3.6E+05	1.3E+05	8.1E+00	3.0E+00	2.6E-02	9.5E-03	1.3E-01	4.7E-02
Percentile 90	9.0E+05	3.3E+05	1.7E+01	6.2E+00	4.0E-02	1.5E-02	2.2E-01	8.0E-02
Maximum	4.3E+06	1.6E+06	6.0E+01	2.2E+01	7.7E-02	2.8E-02	9.4E-01	3.5E-01

Table 4 Pearson’s correlation coefficient between the electricity consumption and other variables related to the energy requirements in sewers (only those variables with $p<0.05$ are shown).

		Total length of sewer	**Population (TEP)**	**Total wastewater production**
Total electricity consumption (kWh)	Pearson Correlation (R)	0.79**	0.62**	0.61**
	Sig. (2-tailed)	0	0	0
	N	47	48	43

		Rainwater per TEP	**Water flow per TEP**
Electricity consumption per TEP (kWh)	Pearson Correlation (R)	0.35*	0.44**
	Sig. (2-tailed)	0.031	0.008
	N	39	36

		Income per capita
Electricity consumption per m^3 of water flow (kWh)	Pearson Correlation (R)	0.51*
	Sig. (2-tailed)	0.037
	N	17

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)

Table 5 Regression models between the electricity consumption (y) and causal variables (x) (y=ax+bz+c)

		Variables	Model			Coefficients		
			Adjusted R square	Standard Error	Sig.*	Value	Standard Error	Sig.*
Total electricity consumption (kWh)	**Model 1**	Length of the sewer (km)	0.62	439,515	0	1,983	230	0
		Constant (c)				-113,841	82,701	0.18
	Model 2	Population (TEP)	0.38	554,992	0	4.43	0.82	0
		Constant (c)				21,016	98,740	0.83
	Model 3	Wastewater production (m^3)	0.35	592,997	0	0.07	0.01	0
		Constant (c)				20,725	114,768	0.86
	Model 4	Length of the sewer (km)	0.67	423,715	0	3,394	535	0
		Wastewater production (m^3)				-0.07	0.02	0.006
		Constant (c)				-113,395	84,686	0.19
kWh per TEP	**Model 5**	Rainwater per TEP (m^3)	0.096	10.4	0.03	0.004	0.002	0.03
		Constant (c)				3.49	2.10	0.11
	Model 6	Water flow per TEP (m^3)	0.17	10.2	0.008	0.007	0.003	0.008
		Constant (c)				1.90	2.31	0.42
kWh per m^3	**Model 7**	Income per capita (€)	0.21	0.86	0.04	0	0	0.04
		Constant (c)				-2.23	1.11	0.06

*The model is significant at the 0.05 level (2-tailed). Constant: Intercept