Environmental Assessment of Sewer Construction in Small to Medium Sized Cities Using Life Cycle Assessment

Anna Petit-Boix[a]*, David Sanjuan-Delmás[a] , Carles M. Gasol[a,b], Gara Villalba[a,c], María Eugenia Suárez-Ojeda[c], Xavier Gabarrell[a,c], Alejandro Josa[d,e], Joan Rieradevall[a,c]

[a]Sostenipra (ICTA-IRTA-Inèdit), Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain.

[b]Inèdit Innovació SL, Research Park of the Universitat Autònoma de Barcelona, Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain

[c]Department of Chemical Engineering, Biotechnology Reference Network (XRB), School of Engineering (ETSE), Universitat Autònoma de Barcelona (UAB), Campus of the UAB, Bellaterra (Cerdanyola del Vallès), 08193 Barcelona, Catalonia, Spain

[d]Department of Geotechnical Engineering and Geosciences, School of Civil Engineering, Universitat Politècnica de Catalunya-Barcelona Tech (UPC), Barcelona, Spain

[e]Institute of Sustainability, Universitat Politècnica de Catalunya-Barcelona Tech (UPC), Barcelona, Spain

*Corresponding author: Anna Petit Boix (anna.petit@uab.cat). Sostenipra (ICTA-IRTA-Inèdit), Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain. Telephone number: (+34) 935813760

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Abstract

In a world with an increasing urban population, analysing the construction impacts of sanitation infrastructures through Life Cycle Assessment (LCA) is necessary for defining the best environmental management strategies. In this study, the environmental impacts of one linear meter of sewer constructive solution were analysed for different pipe materials and diameters used in Southern Europe; a unit of different sewer appurtenances (pump, manhole and inspection chamber) was also considered. The impacts of the pipe materials were compared considering different lifespan periods and high-density polyethylene (HDPE) turned out to be the worst option, being polyvinyl chloride (PVC) and concrete the most favourable ones. Few data are available on the material and energy flows in the installation stage; therefore, a comparative analysis of trenches with sand and concrete bedding was conducted. The results show that the installation stage represents up to 80% of the total life-cycle impact of the constructive solutions. Concrete pipes with half-concrete/half-sand bedding are the best option and produce 20-30% of the impact of HDPE pipes with concrete bedding. Hence, designers should focus not only on the pipe but also on the trench model. A methodology was presented to enable the impact aggregation of the different sewer elements, and Betanzos (Spain) was selected to conduct a pilot study in small cities. In the future, studies will need to incorporate the use and maintenance stage, as it is not standard and varies according to the physical features of the cities. Finally, this study provides basic concepts for developing eco-efficiency indicators.

Keywords: pipe, appurtenance, LCI, urban, construction, smart cities

Highlights

Different pipe materials and diameters were compared using LCA.

A sensitivity analysis for trenches with concrete and sand beddings was conducted.

Plastic pipes have the greatest impact due to their composition and durability.

The installation stage accounts for 80% of the impacts in most designs.

The methodology helps to aggregate the sewer elements in any city configuration.

1. Introduction

1.1 The urban water cycle and LCA

Water is considered a basic need for humans and is used for activities such as drinking, the production of goods and services and growing food (Gleick 1996). This primary service must be delivered to as many users as possible in proper sanitary conditions; as a result, population centres play an important role in transporting water, especially in urban areas. According to the World Bank, 52% of the world's population and 74% of the population of the European Union lived in urban areas in 2011 (The World Bank 2012), and these percentages are expected to increase in the coming years. The management of the urban water cycle in cities must be taken into account to meet the sanitary requirements of an ever-growing population, to provide good water quality 'status' (EU Water Framework Directive 2000) and to tackle sustainability. Moreover, urban water systems must adapt to climate change conditions and a suitable management approach is required (Short et al. 2012). Important economic and environmental impacts derive from the urban water cycle and the network design of the system can be improved to reduce the burdens of the system.

The urban water cycle consists of different stages (**Figure 1**). Each stage can have important impacts on the overall system due to the depletion of resources, emissions, energy consumption, etc. The Life Cycle Assessment (LCA) can be used to analyse the environmental impacts of the provision of a certain amount of water to the population of a city. The environmental burdens taking place in the different life-cycle stages of this service, i.e., raw materials extraction, construction, transportation, use and maintenance and end-of-life according to the ISO Standard 14040 (ISO 2006) can be estimated, analysed and discussed with the LCA.

<Figure 1>

1.2 Environmental Background

1.2.1 Environmental assessment of the urban water cycle

Different studies of the environmental burdens of the entire urban water cycle have been conducted. There is debate as to whether the largest impacts derive from the water discharge due to eutrophication and acidification (Lassaux et al. 2007) or from home use due to electricity use for water heating (60-90% of the total impact) (Klein et al. 2005; Arpke and Hutzler 2006; EA 2008; Griffiths-Sattenspiel and Wilson 2009).

The environmental burdens of the use and maintenance phase, which are discussed in most papers, can also be addressed by examining the quality and quantity of water supplied and treated outside of the home. Venkatesh and Brattebø (2011) identified that, in Oslo, the energy consumed per capita during the wastewater treatment process (0.8 kWh/m^3) was 2-fold higher than the energy consumed during the supplying of water (0.4 kWh/m^3). When focusing only on infrastructure, Friedrich et al. (2009) concluded that, in South Africa, the collection of wastewater consumed 0.14 kWh/m^3 while the distribution of potable water consumed 0.10 kWh/m^3. However, when considering the contribution of both materials and energy, the CO_2 emissions of the two systems were found to be similar ($1.5\cdot10^{-1}$ and $1.39\cdot10^{-1}$ kg/m^3, respectively).

While these data are generally reliable, energy consumption depends on different factors. First of all, the energy requirements in wastewater treatment plants (WWTP) vary according to the applied treatments (primary, secondary and tertiary) and the design of the plant depends on the water and pollutant flows in the city. In the case of the supply and sewer networks, water leakages and the location of the potable water treatment plant (PWTP) and WWTP imply different levels of pumping requirements.

On the other hand, studies sometimes tend to aggregate the components of the wastewater system, i.e., the sewer system and the WWTP (Cohen 2004; EA 2008; Griffiths-Sattenspiel and Wilson 2009). This can be problematic, as it precludes the identification of the contributions of each stage. It would be more useful to study these stages separately so that the relevance and the effects derived from their life cycle can be analysed more thoroughly.

1.2.2 Impact assessment of a sewer system

The importance of the sewer system was made evident when the sewers and WWTPs of diffuse and small municipalities were compared (Roux et al. 2011). The sewer system had greater contributions than WWTPs in 10 of 15 mid-point impact categories, representing more than 75% of the impact in most indicators (Roux et al. 2011). Because the studied cities were small, these results might be due to the low energy use in small WWTPs, where only a basic primary treatment is required. Moreover, the territorial structure in these cities was diffuse and the sewer system was much longer than in compact cities; for these reasons, the sewers had larger contributions than the WWTP.

The installation stage of a sewer system is of great importance, as it involves material removal, excavation and use of energy (Anders and Anders 1997; Nielsen et al. 1998). If the pumping energy is excluded from the life cycle, the CO_2eq emissions of the construction and installation stage account for 98% of the total impact (Strutt et al. 2008). However, if the sewer pumping energy is considered, the use phase can account for 92% of the CO_2eq emissions (Strutt et al. 2008). When the growth rate of the network diminishes, the greenhouse gas (GHG) emissions of the operation, maintenance and rehabilitation stages can be almost 3 times higher than the production and installation stages (Venkatesh et al. 2009). The variation on emissions is expected to depend on the time during which the network is used, the energy, rehabilitation and maintenance requirements and the materials and designs used in the construction of the network.

For the use phase, a comparison of the energy use and the urban pattern can be useful. A compact city, which has fewer pipes, has the lowest energy use (depending on the pumping needs) and thus has the lowest contributions at all mid-points (Roux et al. 2011). Topography can also be of paramount importance for pumping requirements. However, Roux et al. (2011) found no significant effects of topography in their models and stated that further research was required to model the indirect effects of topographic on the installation stage due to parameters such as the presence of rocks.

There are therefore many important factors that affect the use stage in a sewer, including the length of the system, the topography and the location of the urban elements. The use phase does not always account for the majority of emissions. For instance, in a network where water is transported from high to low locations, gravity does most of the work; as a result, a small amount of energy may be required and the contribution of the use phase is therefore low or almost inexistent and the infrastructure accounts for the main impacts.

1.2.3 Impact assessment of construction materials

Different construction materials for pipe production can be compared. A wide variety of materials are used to construct pipes, including polyvinylchloride (PVC), clay, concrete, high-density polyethylene (HDPE), iron, fibrocement, steel, bricks and polymer concrete (CEDEX 2009; Venkatesh et al. 2009; Bueno 2010). The type of material used varies according to the local sewage requirements, traditions and economic costs.

Concrete was found to score better than PVC and vitrified clay in all impact categories (INTRON 1995); all of these materials had a functional unit of 1 metre of pipe with a diameter of 300 mm (Ø300) and a lifespan of 40 years; the better scores of concrete are mainly associated with the raw materials required (PVC uses petroleum) and emissions produced in their fabrication (1.5-4.2 times lower). Concrete pipes have also been shown to have a longer lifespan (more than 50 years); in addition, because the raw materials for concrete are abundant (e.g., limestone), concrete has better environmental results in terms of resource scarcity (Anders and Anders 1997) than other materials.

With concrete pipes, the process that creates the greatest CO_2 emissions (40%) is the production of cement (Lundström et al. 1996; van Drunen et al. 2000; Knoeri et al. 2013), followed by transport and landfill (30%) of the leftover materials; for other impact categories, the combustion of fossil fuel, which also derives from the cement production process (Lundström et al. 1996), is predominant. The impact of cement could be reduced by changing the type of fuel or raw materials (additives) used in its production (Valderrama et al. 2013) and implementing more efficient processes with lower fuel requirements (Valderrama et al. 2012).

In contrast, iron pipes had environmental impacts that were 10-15 times higher than those of any other alternatives, e.g., PVC, polypropylene (PP), HDPE and concrete (AG 1998; Venkatesh et al. 2009). The zinc coating of iron pipes is the main contributor to the total energy required in the manufacturing of iron pipes (Dennison et al. 1999).

The smallest pipelines (Ø<249 mm) are usually made of PVC or HDPE, which are the most suitable materials for these diameters from a technical point of view (Personal communication: CLABSA 2013) given their ductility and price. However, the GHG emissions associated with plastics are 10 (Venkatesh et al. 2009) to 26 times greater than those associated with concrete (Ø>500 mm) (Viñolas 2011). Therefore, while plastic is technically better, its environmental impacts are more important.

1.3 Justification

The main focus of previous studies in the field of the urban water cycle was generally the WWTP, while little attention was paid to transport infrastructures such as the sewer system. Moreover, the environmental burdens of the latter are not clear at all, as the energetic impacts taking place in the use phase, which depend on site-specific features, were often treated somewhat generally (Section 1.2.2).

Furthermore, studies have paid little attention to the materials used in the construction of trenches and the impacts of the system are often aggregated. Insufficient data were found on the contribution of the materials used to construct trenches despite the fact that they can be of great relevance and may affect the decision of designers to focus their attention on the pipe or the trench design. In this line, Beale et al. (2013) concluded that trenchless techniques can save 80% of the CO_2 emissions per metre of pipe when rehabilitation activities take place. Additionally, the LCA of sewer appurtenances such as pumps, manholes or inspection chambers is generally excluded from the system boundaries in most analyses. Besides, in growing cities, choosing the best sewer design is crucial to avoiding environmental impacts that can take place worldwide.

In the present study, pipes were analysed according to materials (fibrocement, concrete, HDPE and PVC). The most common diameters used in medium-to-small cities for the transport of wastewater inside buildings and home connections (Ø110 mm) and for the transport through subsidiary and main sewers (Ø300, 800, 1200 mm) were chosen; the distribution of materials was also taken into account, as plastic (PVC/HDPE) is more common in smaller pipes and concrete is usually found in bigger pipes due to its resistance and the abundance of its raw material (CPSA 2010; MetaBase ITeC 2010; Viñolas 2011; Personal Communications: CLABSA 2013, Aquagest 2013). The main sewer appurtenances (pumps, manholes and inspection chambers) were also considered.

2. Goal and Scope

2.1 Objectives

The main goal of this study was to quantify the environmental impacts of a sewer system and to determine the most environmentally friendly design strategy for small to medium sized cities. To achieve this goal, the specific objectives were:

- To compose an inventory of the material and energy inputs in the life cycle of a sewer system;
- To identify the impacts of the production, transport, installation and demolition stages of standard constructive solutions by pipe material, diameter and trench design and sewer appurtenances using LCA;
- To determine the effects of different lifespan of pipes on the environmental impacts of the infrastructure;
- To propose a methodology for the estimation of the network's global impact based on the aggregation of the individual elements (constructive solutions and appurtenances) and to facilitate the corresponding decision-making process;
- To apply the methodology to the infrastructure of a small city;
- To analyse and discuss possible eco-efficiency indicators (impact per capita, per m^2 or m^3) to propose the best constructive solutions.

2.2 Declared units and Functional Unit

Different declared units (DU) were used as specified in EN 15804:2011 on the environmental product declarations for construction materials. In the case of constructive solutions, the DU is one linear metre of pipe with diameters of 110, 300, 800 and 1200 mm over a time period of 100 years. Pipes made of 4 different materials (fibrocement, concrete, HDPE and PVC) were considered for their common use in cities. At the same time, a DU of one sewer appurtenance unit was also studied for pumps, manholes and inspection chambers. With these DU and using a specific methodology, the results of the assessment can be applied to any city configuration. The functional unit (FU) is defined as the infrastructure necessary for the collection and transportation of 1 m^3 of wastewater in small to medium sized cities in a year.

3. Materials and Methods

The environmental impacts of the sewer system infrastructure were calculated using LCA. In the following sections, the methodology for constructive solutions (Section 3.1) and sewer appurtenances (Section 3.2) is presented.

3.1 Environmental impact of constructive solutions

The environmental impact of standard pipes was assessed for the life-cycle stages of materials extraction, pipe production, transport, installation and demolition (**Figure 2**). The use and maintenance stages were excluded, as pumping energy varies by site (Section 1.2.2) and its impact is therefore not standardised. Furthermore, it was assumed that, after demolition, the pipes were left at the construction site.

<Figure 2>

Pipes with diameters of 110, 300, 800 and 1200 mm made with different materials (e.g., concrete, fibrocement, HDPE and PVC) were compared. Although concrete pipes with diameters of 110 mm are not common outside buildings, they were considered to analyse their environmental feasibility. This study considers that concrete and fibrocement pipes have a lifespan of 100 years and that HDPE and PVC last 50 years (CPSA 2010; Personal Communication: CLABSA 2013).

In the first life-cycle stage of the sewer, the materials and processes associated with pipe production, including the selected pipe materials and their respective sealing compounds, are considered. In fibrocement pipes, asbestos was replaced with sulphate pulp, as the use of asbestos was forbidden in recent years. In the case of concrete, the concrete block process was considered to be the most similar to the concrete pipe production, but more details are required. The inventory data for the pipe production process are presented in **Table 1**.

<Table 1>

The next life-cycle stage is the transportation of the material (both the pipes and trench materials) from the producer to the construction site. An average distance of 30 km was estimated for the transport of concrete, cement mortar, fibrocement, gravel, sand and wood; an average distance of 100 km was used for plastics (HDPE and PVC) and synthetic rubber.

For the installation phase, the materials used for trench construction (concrete, sand and compacted soil (i.e., gravel)), the diesel consumed (for digging, compacting and filling), the support elements (i.e., wood beams (3 uses) and other wood supports (10 uses)) were considered (**Online Resource 1**). The pipe laying process using a truck was not included due to lack of data reported; however, its exclusion was not expected to underestimate the impacts of the system. Trench designs differ depending on the standards, the local tradition and various parameters such as the pipe material and the depth of the trench. Thus, a sensitivity analysis was carried out to address the impacts of 2 different solutions for concrete and fibrocement pipes (CP1 and CP2) and of 2 plastic pipes (PP1 and PP2) (**Figure 3**) using adapted versions of the models of Clavegueram de Barcelona (CLABSA) (2013), the Catalonia Institute of Construction Technology (ITeC) (2010) and the Centre for Hydrographic Studies (CEDEX 2009). All configurations enabled the pipe to support the same amount of weight, i.e., soil and road traffic. For instance, plastic pipes embedded in a sand base need a thicker upper soil layer to be protected from road traffic. The different solutions in current use carry out the same function: embedding the pipe and protecting it from the presence of other subterranean infrastructures and traffic.

The surface pavement (asphalt, concrete, cement-treated and granular layers) was excluded from the analysis, as it was considered constant in all cases. Its impact for different sections has been analysed in other previous studies (for instance, Mendoza et al. 2012). Finally, the diesel consumption for dismantling the infrastructure was considered in the demolition stage.

<Figure 3>

3.2 Environmental impact of sewer appurtenances

Three relevant sewer appurtenances were analysed in this study: submersible pumps, manholes and inspection chambers (**Online Resource 2**). A submersible pump with 60 m^3/h of wastewater was considered as an example and it was assumed that each one was installed at the bottom of a manhole (MetaBase ITeC 2010). A standard 100-cm diameter manhole was considered; in the case of inspection chambers, three different dimensions were analysed for their application in the pipe diameters selected in Section 3.1.

An LCA was carried out for one unit of each appurtenance and the material extraction, production, transport to the construction site, trench excavation and demolition were considered. In the case of the submersible pump, excavation and demolition were excluded from the system boundaries, as it was assumed that this type of pump is installed at the bottom of a manhole. The transport assumptions were the same as those used for the constructive solutions (Section 3.1), but it was assumed that pumps were transported for a distance of 300 km. A lifespan of 50 years was assumed for manholes and inspection chambers, whereas pumps were assigned an average lifespan of 10 years. It was assumed that a manhole and an inspection chamber could be found every 50 m. Inventory data are presented in **Online Resource 3**.

3.3 Environmental impact of the sewer system in a small city (Betanzos)

Given that the complexity level of the sewer system at the rural scale is relatively low, the impact estimation is much simpler for small cities than it would be for large and complex cities. However, because high precipitation levels require bigger pipes, the model could be applied to bigger cities in the future. The city of Betanzos (Galicia, Spain) was the case study selected to analyse the impact of the entire sewer system. Betanzos, a small city (13,537 inhabitants in 2011; 24.2 km^2) with a wastewater production of 95,475 m^3/year (2011), is characterised by an Atlantic climate where the precipitation is above 1,000 mm/year.

The impacts obtained using the methodology described in Sections 3.1 and 3.2 were applied to the sewage system of Betanzos; this system consists of an 80-km-long pipeline; the materials and diameter distributions of the system are presented in **Table 2.** Cast iron and clay pipes were excluded (<1% of the pipeline). From this distribution, PVC, HDPE and concrete pipes with diameters of 110, 300 and 1200 mm were selected for the analysis; these types of pipe account for 74% of the network. In the case of PVC, the actual size of the pipes was 315 mm; however, in this estimation, diameters of 300 mm were used. In the case of sewer appurtenances, no data regarding the total number of manholes and inspection chambers were available; as a result, the proportions presented in 3.2 were used. Overall, the impacts of 1600 manholes, 1600 inspection chambers and 13 pumps (GISAgua© 2012) were estimated. Eco-efficiency indicators were calculated per capita, per m^2 of city area, per metre of sewer and per m^3 of wastewater transported.

<Table 2>

3.4 Environmental calculation tools

Of all of the stages included in the LCA methodology (ISO 2006), only the classification and characterisation were considered. The CML 2 baseline 2000 method V2.05 (Guinée et al. 2001) was used; as a result, the results could be compared with those of other studies using the same methodology. The impact categories selected were Abiotic Depletion Potential (ADP; kilogram Sb equivalents), Acidification Potential (AP; kilogram SO_2 equivalents), Eutrophication Potential (EP; kilogram PO_4^{3-}equivalents), Global Warming Potential (GWP; kilogram CO_2 equivalents), Ozone Depletion Potential (ODP; kilogram CFC-11 equivalents), Human Toxicity Potential (HTP, kilogram 1.4-DB equivalents) and Photochemical Ozone Creation Potential (POCP; kilogram C_2H_4 equivalents). The Cumulative Energy Demand V1.08 (CED) was also selected to evaluate energy issues.

The Ecoinvent 2.2 (Ecoinvent 2009) database, linked to the software SimaPro 7.2.0 (PRé Consultants 2010), was used for the evaluation of emissions related to the materials and energy. All processes were adapted to the Spanish electricity mix of the year 2011.

Data regarding materials and pipes sizing were supplied by CLABSA (2013) and retrieved from the MetaBase ITeC (MetaBase ITeC 2010). For Betanzos, the total length of the sewer and the number of pumps was supplied by Agbar and their private databases CONTEC© and GISAgua© (2012).

4. Results and Discussion

4.1 Impact assessment of constructive solutions

The environmental impacts are disaggregated into two main life-cycle stages: the pipe production (**Figure 4**) and the installation processes and materials (**Figure 5**). The total impacts are presented in **Online Resource 4**. The use and maintenance and end-of-life stages were excluded.

4.1.1 Impacts in the pipe production

In general, concrete pipes scored better than the other types of pipe in the pipe production stage (**Figure 4**). This finding is consistent with the results of previous studies on this topic (INTRON 1995; Anders and Anders 1997). In contrast, HDPE-made pipes seem to be the least environmentally friendly; moreover, their impact varies by pipe diameter.

< Figure 4>

For the smallest pipes (Ø110 mm), HDPE had the largest impacts in 5 of 8 impact categories, while PVC and fibrocement had greater impacts in the remaining impact categories. When the diameter of the pipe increases, the relative dominance of HDPE-made pipes becomes even more pronounced, and, in pipes with diameters of 1200 mm, their impacts are up to 30 times higher than those of the other alternatives. Therefore, PVC, concrete and fibrocement are more competitive materials when the pipe diameter increases. The larger impact of plastic-made pipes is due to their composition, as 90% of the pipe is made of oil derivatives. The Portland cement used in concrete and fibrocement pipes is the main contributor to the impacts (40-75%). Although HDPE and PVC contain oil derivatives, their relative impact is different.

In this study, the quantity of material per linear metre used in the production of the pipe plays an important role in the LCA. Concrete pipes require the largest amount of raw materials (20-960 kg of concrete), while PVC pipes require the smallest amount (2.5-51 kg). Nonetheless, the requirements for HDPE pipes increase much faster with the pipe diameter than those for PVC (**Table 1**), e.g., for diameters of 110 mm, the HDPE requirements per linear metre of pipe are 1.2 times higher than those of PVC; for diameters of 1200 mm, the requirements are 6.3 times higher. This difference is primarily due to the properties of the materials used in pipe construction.

Repositioning was considered in the model in the case of plastic pipes, as these pipes have a lifespan of 50 years and must be replaced at least once in a time span of 100 years. In this case, however, the durability of plastics will most likely be high, as the pipes experience no degradation due to the sun and might last up to 50 years. Accounting for the impacts of 100 years, different scenarios were compared considering different lifespan, which might vary due to the soil and the pipe handling during the installation. The case of pipes with diameters of 300 mm is presented (**Figure 5**). Regarding the CO_2 emissions, HDPE is never the most suitable material and even in the most advantageous scenario its impact is 3 times higher than PVC and concrete.

<Figure 5>

4.1.2 Impacts in the installation process

The trench designs were compared for the installation process (**Online Resource 5**). In general, trench designs CP2 and PP2 had 30-80% higher environmental burdens than their respective counterparts (CP1 and PP1). This is due to a change in the base material, as the pipe is completely embedded in concrete in the CP2 and PP2 designs, and the material accounts for 60-90% of the installation impact (**Figure 6**). The impacts of PP1 and PP2 also increase due to the need for repositioning.

Another important variable which must be highlighted is the diesel consumption. In PP1, the effects of sand and gravel account for slightly more than 30% of the impact, which means that diesel accounts for approximately 70% of the impact. The material contributions were presented only for pipes with diameters of 300 mm, as all diameters presented the same trends.

A distinction was made between concrete and fibrocement pipes because different pipe widths entailed slight differences in the material requirements (**Online Resource 1**). In the case of concrete, the pipes were thicker, resulting in wider trenches and greater impacts.

As in the pipe production stage (Section 4.1.1), there were variations in the impacts of PP1 and PP2 depending on the pipe diameter. The former type requires a thicker soil layer (**Figure 3**) so that the pipe can be properly protected from road traffic and other infrastructure (water supply, gas pipelines, electrical grids, etc.). This characteristic is more relevant in the smallest pipes, where the impact of diesel in PP1 is more similar to the impact of concrete in PP2 in most categories. This means that when the pipe diameter increases, the amount of concrete used in PP2 becomes more important than the digging, filling and compaction of a bigger trench. However, it is possible that concrete bases provide better protection and thus confer a longer lifespan to the infrastructure; in this case, the environmental burdens of PP2/CP2 would be lower.

< Figure 6>

4.1.3 Total impacts of the constructive solutions

The results for the global impacts of constructive solutions are shown in **Online Resource 4**. Generally, concrete and fibrocement pipes appear to be the best options in all cases, producing only 20-30% of the impact of HDPE pipes.

HDPE pipes with trench design PP2 stand out as the least environmentally friendly solution in all mid-points for pipe diameters of 800 and 1200 mm. However, for the same pipe material, the relative importance of PP1 is greatest for pipes with diameters of 110 and 300 mm. In most mid-points, there are slight differences in impact between PP1 and PP2 for the smallest pipes due to the concrete and diesel requirements of each trench design (Section 4.1.2).

Only the life-cycle contributions of pipes with diameters of 300 mm were shown, as all diameters exhibited approximately the same trends. Depending on the model, the overall impact will be more or less determined by a certain stage; however, in all cases, demolition was always negligible (**Figure 7**). In contrast, the contribution of transport should not be underestimated, as it accounts for 10-50% of the impacts; in general, the impact of transport was more important in plastic pipes, as distances were generally longer and the weight transported by the lorry was lower for the same volume unit (low density).

The impacts of the pipe production phase are more visible in HDPE pipes with diameters of 800 and 1200 mm, accounting for more than 55% of the total impact in 5 of 7 impact categories; in HDPE pipes with diameters of 110 mm, the production phase accounts for less than 10% of the total impacts. The implications of using plastic materials in large pipes become evident and explain why these materials are less preferable when the pipe diameter increases (Section 4.1.1).

The stage that stands out in all cases is the installation; for all pipes except large HDPE pipes, the installation accounts for nearly 80% of the impacts due to the materials (concrete base) and energy used (diesel consumed by the machinery). As a result, designers must take into account the processes and materials involved in the installation instead of just considering the impact of the pipe. The installation stage must be optimised and the most suitable designs should be selected and applied.

<Figure 7>

4.2 Impact assessment of sewer appurtenances

The impacts derived from a unit of each sewer appurtenance for a period of 100 years are presented in **Table 3**. The manhole is the element with the greatest material requirements (**Online Resource 3**) as it physically consists of different parts, i.e., walls, steps, base, frame and manhole cover. Although the walls require a larger amount of material (concrete), the main impacts (~90%) derive from the frame and manhole cover, which is made of iron. A similar situation occurs for the inspection chamber. In the pump, where steel and cast iron are the only materials used, the manufacturing process is clearly responsible for the greatest contribution (40-65% of the impact).

<Table 3>

Excluding the pumps (as their presence and distribution vary by city), if the entire sewer infrastructure is analysed in terms of 1 linear metre of sewer system (with Ø300 mm+PVC+PP2, for instance), 2% of a manhole and 2% of an inspection chamber can be attributed to each linear metre (Section 3.2; 1 every 50 m). In this case, 48-85% of the impact comes from the pipe, followed by the manhole (13-43% of the impact); the inspection chamber (50x50 cm in this case) accounts for only 2-9% of the impact. Hence, the impact of the manhole should not be underestimated.

4.3 Case study: LCA of the sewer infrastructure in Betanzos

The case of Betanzos shows that the theoretical profiles analysed can be adapted to real studies (**Table 4**). Two different scenarios were considered, given that the specific trench designs used were unknown. In scenario ST1, trench designs consisting of a sand base were included, i.e., CP1 and PP1; in scenario CT1, concrete base trenches were considered. Sewer appurtenances were also included (Section 3.3). The final results are shown in **Table 5**. If sand trenches are used, the impacts can be reduced by 10% in 4 of 8 impact categories and the carbon footprint of the system can be diminished by 50%. The 10% difference between alternatives is due to the presence of 300-mm diameter pipes, where slight differences in impact occur for PP1 and PP2 (Section 4.1.3).

<Table 4>

When the entire infrastructure is considered, the sewer appurtenances should not be underestimated, as they account for 22-64% of the total impacts. If the infrastructure is analysed in terms of 1 linear metre of sewer system, the same trends found in Section 4.2 apply, as the impact of the pumps does not exceed 2%.

Improvements in pipeline design could be made in Betanzos. Currently, 300-mm diameter pipes account for more than 70% of the network and 61% of these pipes are made of PVC. Given that plastic pipes tend to score worse than concrete ones (Section 4.1.3), the substitution of the 61% of PVC pipes for concrete pipes (ST2 and CT2) should be considered (**Table 5**). The results show that a 30-40% reduction in impact takes place in almost all mid-points because the pipeline has a longer lifespan and does not need to be repositioned for 100 years. However, the savings in the overall impact of the sewer infrastructure are smaller because sewer appurtenances also have a relevant share of the burden.

Finally, to estimate the impacts of a certain region over a certain time period, potential eco-efficiency indicators such as the annual impact per capita, per m^2 of city area, per linear metre of sewer or per m^3 of wastewater collected can be presented (**Table 5**). In this city, the annual CO_2eq emissions in CT1 (worst scenario) are $1.5 \cdot 10^1$ kg/capita, $8.4 \cdot 10^{-3}$ kg/m^2, $2.5 \cdot 10^2$ kg/m and 2.1 kg/m^3 of wastewater; in terms of energy, the attributions are $4.4 \cdot 10^1$ kWh/capita, $2.5 \cdot 10^{-2}$ kWh/m^2, $7.5 \cdot 10^2$ kWh/m and 6.3 kWh/m^3. Currently, to the authors' knowledge, no other studies have presented such indicators or analysed energy consumption of stages other than the use stage (Friedrich et al. 2009); as a result, the values obtained in this study cannot be compared with those of other studies. However, other authors developed sets of sustainability indicators to carry out the city blueprints, considering different methodologies such as the water footprint or the ecosystem services, (van Leeuwen et al. 2013) that facilitate the decision-making process (Pearson et al. 2010).

< Table 5>

5. Conclusions

The constructive solutions for sewer pipelines and the sewer appurtenances analysed in this study were standard for small/medium municipalities. All of the life-cycle stages of the sewer infrastructure except the use stage and the end of life stage were studied.

The LCA showed that different pipe materials do not have the same impacts. On the one hand, plastics (mainly HDPE) present greater environmental burdens ~~(up to 30 times the impact of other materials)~~ because of their composition ~~(e.g., oil derivatives)~~ even though less material is required for their production. On the other hand, plastic-made pipes have a shorter lifespan and must be replaced once in a 100-year time span, which doubles their environmental impact. However, considering different lifespan scenarios, HDPE still has the greatest impacts ~~(up to 3 times the impact of PVC and concrete).~~

In previous studies, little attention was paid to the trench materials in the installation stage; however, this phase was found to be significant, accounting, on average, for 80% of the total impact. Trench models with either sand or concrete bases were analysed. Two distinct variables affect the environmental burdens of the installation stage: the concrete base and the diesel consumption. ~~Compared to concrete-bedded trenches for plastic pipes (PP2), sand-bedded trenches (PP1) had greater impacts in small HDPE-made pipes (Ø110 mm) because the contributions of concrete bedding in bigger pipes are larger than the contribution of diesel consumption in PP1.~~ The most environmentally friendly infrastructure was the concrete pipe with a CP1 trench (half-concrete/half-sand bedding); fibrocement pipes were similarly environmentally beneficial. HDPE-made pipes were the worst option both in terms of the pipe production and installation stages, but their impacts vary by pipe diameter. ~~Transport must also be considered, as it accounts for 10-50% of the impacts and is especially relevant in the case of plastics~~

~~where longer distances are travelled and less material is transported in the lorry due to the low material density. In contrast, the impacts of demolition are negligible.~~

The standard constructive solutions and sewer appurtenances were applied to the specific case study of Betanzos, a small city with an Atlantic climate where the theoretical profiles could be adapted and an annual carbon footprint of 2.1 kg CO_2eq/m^3 of wastewater and an energy impact of 6.3 kWh/m^3 were estimated. A sensitivity analysis showed that these emissions can be reduced by 50% if sand-bedded trenches are used instead of concrete-bedded ones. Moreover, important environmental savings could be achieved if all pipes were made of concrete. Sewer appurtenances are also relevant in this system, accounting for 22-64% of the total impact.

The main recommendation of this study is that future plans focus on the proper selection of sewer eco-designs and should consider not only the production of pipes but also the installation stage, which proved to be of paramount importance. Technical requirements may invalidate the results obtained because of pipe durability and economic costs, etc., but this is a first step that will be coupled with an economic assessment in forthcoming studies.

The methodology presented in this paper enables the aggregation of different individual elements, which facilitates the calculation of the overall impact and enables comparisons. Additionally, eco-efficiency indicators were proposed to facilitate the impact estimation in different regions and over different time periods.

An in-depth analysis of the impacts in the use and maintenance stages, which were found to be dependent on different physical variables, should be attempted in the future. More pipe materials and different sizes should be included in future analyses to enable further comparisons; the results should be applied to diffuse areas and other local treatment solutions such as septic tanks should be considered. The impact of other sewer elements such as rainwater retention tanks should be analysed, and ways of improving sewer appurtenances and their means of transport (e.g., diesel substitution) should be determined.

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Figure Captions

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

Fig. 2 Simplified diagram of the sewer network and system boundaries for constructive solutions

Fig. 3 Trench designs for concrete and fibrocement pipes (CP1 and CP2) and plastic-made pipes (PP1 and PP2). *DN/DO*: exterior nominal diameter; *b* is based on the width requirements of CEDEX (2009)

Fig. 4 Impact assessment of the pipe production stage (100 years) relative to the material with the highest impact in each category (plastics are accounted for twice due to repositioning)

Fig. 5 Scenario analysis considering different pipe lifespan (25, 50, 75 and 100 years) for the Global Warming Potential and pipes with diameters of 300 mm

Fig. 6 Contributions of the trench materials and machinery to the installation impact of concrete/fibrocement and HDPE/PVC pipes with diameters of Ø300mm

Fig. 7 Contributions of the life-cycle stages of pipes with diameters of 300 mm