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Environmental assessment of a drinking water transport and distribution network in small to medium cities and application to a case study network

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Abstract

Until now, few studies have focused on the construction phase of a drinking water transport and distribution network (DWTDN). This article compares the environmental impact of the constructive solutions with pipes made of different materials using the life cycle assessment (LCA) methodology. Two pipe diameters (90 and 200 mm) that are common in small to medium-sized cities are analysed. The results show that the polyvinyl chloride (PVC) pipe constructive solution is the best option for both diameters, being up to 25% less impactful for 90 mm diameters and up to 90% for 200 mm diameters. Installation represents a higher percentage of the environmental impact for small pipe diameters (e.g., 40 to 68% for a high density polyethylene (HDPE) 90 mm diameter) than for greater pipe diameters (e.g., 24 to 57% for an HDPE 200 mm diameter) because of the difference in the amount of material required for the pipe. The methodology of the assessment is applied to calculate the environmental burdens derived from a preliminary case study. The impact of the different elements of the network has been aggregated to obtain the global impact. The results show a potential reduction of between 6 and 16% of the impact, although the results might be greater in networks with more impacting pipe materials such as DI. This methodology has the potential to improve the network and design a more eco-efficient DWTDN.

Keywords: pipe; LCA; urban; infrastructure; eco efficiency; construction

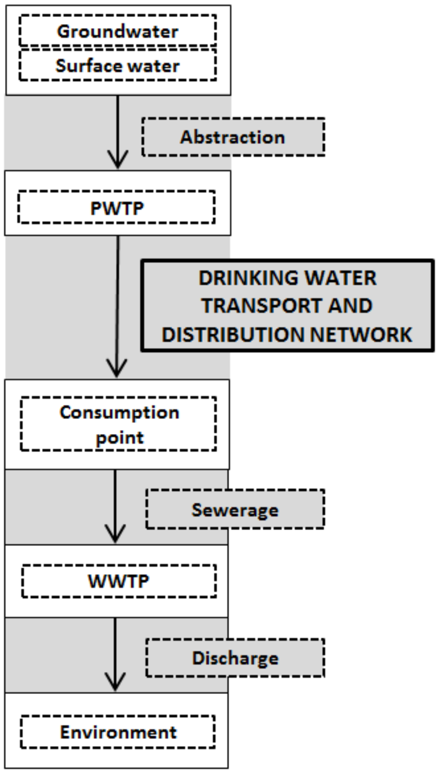
1. Introduction

1.1 Cities and Urban Water Cycle

Water is a major priority all over the world because of its importance for life. Because water needs are dependent on an area's population and activities, the urban water cycle (UWC) is a crucial flow in urban areas (UNESCO, 2012). Almost every village and town in the developed world manages its own UWC, generating very different impacts depending on factors such as the demand, water availability, the location of the net elements and topography, etc. These factors must be considered when assessing the UWC to reduce its environmental impacts and to preserve the environment. This is an important issue because some global patterns show that to supply water to cities, new and different infrastructures as well as the renewal of obsolete infrastructures might be necessary.

The urban population of the world is forecasted to grow from 3.4 billion in 2009 to 6.3 billion people in 2050. Urban growth will be equal to all of the world population growth over this period plus some net moves from the current rural population. New urban areas with water needs will appear, and the global water demand will increase. These new areas will generate an increase in the water demand and infrastructures. Furthermore, because of the effects of climate change, new uncertainties are arising with regard to freshwater supplies and the main water use sectors, such as agriculture and energy, exacerbating uncertainties regarding future demands for water (UNEP, 2012). These facts will make it necessary to optimise water cycle infrastructures and the better use of water resources, for example, reducing the loss of water due to leakages in the network or using alternative water sources such as rainwater harvesting (Farreny et al., 2011).

Water scarcity is already a major problem in the world. There are several examples of overexploitation of groundwater and rivers, which depletes water resources (UNESCO, 2012). This is relevant considering the social, economic and ecological importance of the UWC. *Figure 1* shows the basic stages of the UWC, water as a natural resource in the environment, water treatment, consumption and the interphases between each of the previous stages, including the DWTDN.



PWTP: Potable Water Treatment Plant
WWTP: Waste Water Treatment Plant

Figure 1. Position of the DWTDN within the UWC

1.2 Environmental studies in the water network

Growing challenges are increasing the complexity of the UWC. Globally, the most important pressures on the water cycle are raising populations, climate uncertainty, drought and floods. To make well-informed choices facing these challenges, policy, design and management options must be considered in future studies (Fagan et al., 2010). Therefore, the sustainability of the life cycle of UWC infrastructures must be assessed to determine possible improvements in the present infrastructure as well as in future construction projects.

Few previous studies have analysed the environmental impact of the whole UWC from a life cycle assessment (LCA) perspective. One of these, described in Venkatesh and Brattebø (2011), focused on the operation and maintenance phases of the UWC, and its results show that wastewater treatment is the most impactful element (88% of the aggregated impact). Other studies show that water heating in households is the main energy consumer and an important contributor to the environmental impact (Arpke and Hutzler, 2006).

The weight that each phase has on the global environmental impact depends on the specific case considered. The results from Stokes and Horvath (2006), which implemented a life cycle energy assessment, show that operation (including water pumping) is the phase that contributes the most (60 to 91% of the global impact), followed by maintenance (5 to 36%), whereas construction has the least impact (4 to 5%). Similar results are found in other studies (Stokes and Horvath, 2009; 2011). This shows that the critical phase can change depending on factors that should be analysed.

Different functional units (FUs) have been considered in previous studies to assess the UWC. The environmental impact per cubic meter of the water supplied has been studied by several authors (Lassaux et al., 2007; Muñoz et al., 2010; Amores et al., 2013). Other FUs used are one-year operations of the network (Venkatesh and Brattebø, 2011) and the provision of water and sanitation infrastructure to a given number of new households (Friedrich et al., 2009).

Because of the growing concern of climate change and the priority to act on this issue, some articles have focused on the Global Warming Potential (GWP) impact category. For example, Sharma et al. (2009) calculated the GHG emissions of providing water services for 86,000 residents. Their results show that between 16 and 25 t of CO_2 eq. per year were generated. In a similar study, Friedrich et al. (2009) show that for 200,000 residents, between 5.8 and 10 t of CO_2 eq. per year were generated. Muñoz et al. (2010) calculated the GHG emission from the whole infrastructure and obtained values between 1.5 and 2.5 kg of CO_2 eq./m^3 supplied.

1.3 Environmental studies in drinking water transport and distribution infrastructures

Within the UWC, this article is focused on the DWTDN. The results from Amores et al. (2013), which analyse the whole UWC, show that the DWTDN (including energy for pumping water) represented between 20 and 40% of the impact in 7 out of 9 categories. These results should encourage further study on the distribution network; however, as stated in the previous section, these results vary depending on the specific case.

The DWTDN consists of a series of stages the water covers until the consumption point. As shown in *Figure 1*, after being treated at the DWTP, water is transported through the DWTDN to the consumption points around the urban area. The DWTDN is formed of a network of pipes and other individual components (e.g., valves and hydrants) that transfer the potable water from the PWTP to the consumption point.

Pipes are the most characteristic feature of the DWTDN. The use of pipes made of one or another material might generate variations on the environmental impacts derived from the constructive solution. Data from water pipes (for the whole UWC) show that in France, UK, Germany, Sweden and Switzerland, cast iron is the most common material, used in more than 50% of the grid. Plastic is the most common material in the Netherlands (more than 50%), and steel is the most common in Italy (approximately 35%) (Graty, 2007). For Spain, the main materials being installed at the moment are reinforced concrete, ductile iron (DI), polyethylene (PE), polyvinyl chloride (unplasticised) (PVC-U), steel, PVC with molecular orientation (PVC-O) and glass fibre reinforced polyester (GFRP) (CEDEX, 2009).

Focusing on the GWP, the GHG emissions derived from pipes made of different materials has been compared. Dennison et al. (1999) analysed the production of DI and medium density PE, concluding that the main contributor to the GHG emissions was the manufacturing of the pipe. Piratla et al. (2012) calculated the GHG emissions considering the embodied energy in the materials and concluding that PVC-O had lower emissions than PVC, high density PE (HDPE) and DI. This article compares the environmental impact of pipes made of different materials and considers the installation of the pipe and the transport. Similarly, the present study aims to conduct an assessment of the DWTDN considering the whole constructive solution but for different pipe materials and diameters. The materials and energy required for the production, transport and installation of the network will be included within the study (*Figure 2*). The results will allow networks to be designed or redesigned by taking into account environmental criteria.

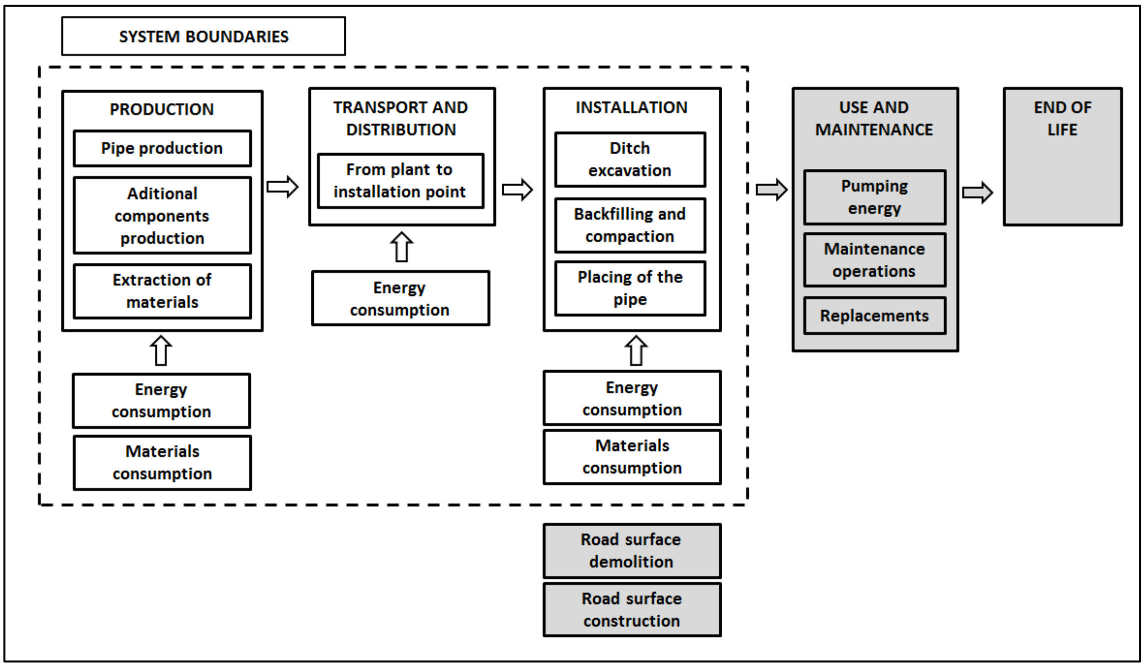


Figure 2 Diagram of the DWTDN life cycle and boundaries of the system

The DWTDN is usually buried in cities. For the installation, a ditch is excavated to place the pipe, and the ditch is refilled once the pipe is placed to finish the installation.

The use phase is characterised by the electricity consumption to pump the water through the network. A study in PWTP in Toronto showed that pumping the water in and out the plant accounted for 73% of the GHG emissions (Racoviceanu et al., 2007), although results from other studies in the same topic show a much lower impact (5%) (Vince et al., 2008). Piratla et al. estimated that the water pumping generated up to 98% of the GHG emissions, and thus, the global environmental impact of the life cycle for pipes made of different materials did not present relevant differences (Piratla et al, 2012). In the case of Venkatesh and Brattebø (2011), the energy for pumping accounted for 17.2% of the global energy consumption for supplying water. These great variations occur because energy consumption is influenced by factors such as the difference of the height between the city and the PWTPs, the pressure of the grid and the efficiency of the pumps. Thus, it is necessary to assess the infrastructure of the DWTDN by focusing on the construction to clearly visualise the variations on the environmental impacts from the use of different solutions. This is the approach adopted in the study (*Figure 2*).

The lifetime and failure of the pipes (due to aging) is an important issue to consider, especially in stagnating grids, where most of the environmental impact comes from the maintenance and replacement of pipes (Venkatesh and Brattebø, 2011; 2012). A possible approach for calculating this phase is the use of the standard values of pipe breakage (Piralta et al., 2012). Once the life of the pipe has lapsed, the network is rarely dismantled for the DWTDN, and the grid is usually left hibernating (Adequa, 2012). For this reason, the end of life phase can be excluded it does not generate environmental impacts. As a consequence of this practice for pipes and other infrastructures, valuable materials are left underground in cities (Krook et al., 2010).

Case study: Betanzos

The municipality of Betanzos has been selected as a case study to apply the methodology proposed in the present study. Betanzos is a small inland city located in the northeast of Spain; *Table 1* shows its basic data.

Table 1. Basic data about Betanzos (Spain)

Data field	Betanzos
Inhabitants	13,565
Surface (km^2)	24.19
Density of population (inhab./km^2)	561
Climate	Atlantic
Precipitation (mm/year)	1,058
Water consumption (m^3/inhab·year)	110
Electricity consumption to supply the drinking water (kWh/ inhabitant)	2.79
Length of the DWTDN (km)	123.5

Source: INE, 2012; Agbar ©

This city has been selected because it is small (the methodology is for small to medium cities) and its DWTDN has been renewed lately, so the pipe materials of the network are commonly used.

Table 2 shows the length of each type of pipe in the DWTDN of Betanzos and the percentage they represent.

The table shows that the pipe material with a longer distance of network is HDPE, accounting for 50% of the network, followed by low density PE (LDPE) (19%) and PVC (17%). There is a lot of heterogeneity in the diameters. Most of the network has pipes with diameters between 40 and 125 mm (approximately 90%). The most common diameters of the network are 63 mm (22%), 110 mm (17%) and 90 mm (15%). Small to medium diameters usually account for a higher percentage of the network because the grid tends to be divided into several smaller pipes (Venkatesh and Brattebø, 2012).

The percentage of the pipe materials and diameters in the DWTDN varies depending on the specific case. For example, the pipe materials are very different depending on the country (Graty, 2007) and how recently the network has been renewed.

Table 2. Length of each type of pipe and percentage of the total length (per material and diameter)

	Diameter[1] (mm)	Length (m)	%
HDPE	63	25,527	21.3
	75	6,668	5.55
	90	14,105	11.8
	110	12,388	10.3
	160	2,278	1.90
LDPE	32	1,723	1.44
	40	7,769	6.47
	50	13,375	11.1
PVC	90	3,649	3.04
	110	7,870	6.56
	125	5,397	4.50
	160	3,822	3.18
DI	100	1,585	1.32
FC	50	2,192	1.83
	80	2,027	1.69
	150	1,624	1.35

[1] Diameters that represent less than 1% of the network are not shown because they are not included in the assessment.

Source: Agbar

2. Materials and methods

2.1 Objectives

This article determines the best environmental alternatives for the DWTDN of small to medium cities or neighbourhoods and creates a methodology to evaluate the environmental impact of the DWTDN. The specific objectives are:

- To elaborate an inventory of the materials, machinery and energy consumption in the production, transport and installation phases of the life cycle of the DWTDN.
- To assess the environmental impact of individual components of the network (valves, hydrants, etc.) to apply the results to medium cities' networks.
- To develop a methodology to estimate the environmental impact of generic networks composed of the individual components analysed.
- To compare the environmental impact of networks considering different pipe materials to determine what the less impactful constructive alternatives are.
- To implement the assessment methodology proposed to assess the environmental impact of the DWTDN in a case study and to estimate the potential environmental improvements.

2.2 Reference flow and functional unit

Pipes with larger diameters or/and made for higher pressures can transport greater flows of water. Because the FU must be related to the quantity of water transported (which is the function fulfilled), the diameters and pressures the pipes are made for must be equal to fulfil the same FU. Pipes from the same material can hold different maximum pressures (depending on their thicknesses). Thus, a maximum pressure for which all the pipes compared are manufactured for must be selected. Two diameters commonly used in small to medium cities have been selected. Similar diameters have been used in previous studies (Dennison et al., 1999; Piratla et al., 2012).

The reference flow considered to compare the environmental impact of the constructive solutions is the production, transport and installation of a lineal meter of network with a pipe 90 mm in diameter and a maximum pressure of 6 bar or a pipe 200 mm in diameter and a maximum pressure of 10 bar, including the accessories of the pipe and the backfilling and bedding materials, required to transport drinking water over the course of 50 years.

The functional unit considered for the assessment is the cubic meter of water supplied per year of service (m3·year) in a small to medium city or neighbourhood.

The reference flow will be converted to FU after being applied to a specific case study using the quantity of water supplied by the DWTDN.

2.3 Data sources

The database from the Institute of Technology of Catalonia (*Metabase Itec*, 2010) was used. This database includes data about construction processes, indicating the materials and the energy consumption. The quantity of materials and energy used in each type of pipe and component as well as the machinery used and its consumption were obtained from this source.

All the environmental information used is from the Ecoinvent 2.2 database (Ecoinvent, 2009) (materials, energy and transport).

Regarding the ditch dimensions and the installation procedure, handbooks from constructor enterprises were consulted (Adequa, 2010; Prefabricados Delta, 2012). Furthermore, the Spanish normative was consulted (CEDEX, 2009), and experts on the subject were interviewed using personal correspondence (Agbar ©).

For the transport, a distance of 100 km was considered for all materials except for concrete, graded-aggregate and gravel, for which 30 km was selected. Concrete cannot cover long distances because it sets and hardens. Graded-aggregate and gravel are quite abundant, and long distances are not common. These distances have already been considered previously (Blengini and Di Carlo, 2010; Kellenberger and Althaus, 2009; Stazi et al., 2012).

The data for the case study (Betanzos, Spain) were provided by Agbar (Agbar ©, 2012) from its databases CONTEC (CONTEC ©, 2012) and GISAgua (GISAgua ©, 2012).

2.4 Environmental impacts

The LCA methodology will be applied to determine the environmental impacts. The software Simapro 7.3 (PRé Consultants, 2010) will be used.

According to the European standard of construction works (European Committee for standardization, 2011), the following 7 midpoint impact categories from the CML 2 baseline 2000 were included in the assessment: ADP, AP, EP, GWP, ozone layer depletion (OLDP) and photochemical oxidation (PCOP). Additionally, the Cumulative Energy Demand (CED) was included.

2.5 Methodology

2.5.1 Environmental impact assessment of constructive solutions

The following commonly used pipe materials in small to medium cities have been selected for the study: PVC, HDPE, LDPE and DI. GFRP was also considered because it is being increasingly introduced in piping systems (Faria and Guedes, 2010), and its environmental performance is of interest. The accessories (additional pieces of the pipes) and the pipes are made from the same material in all cases and are considered together in the inventory (*Table 5*). The unions are all made from synthetic rubber.

The potential life expectancy of the pipe for each material is being studied, but few reliable data can be found. Experts argue that PVC, HDPE, LDPE and DI could reach 100 years of life expectancy. However, a life expectancy of more than 50 years would imply high needs of maintenance and preservation of the pipe, including anticorrosion treatments, among other measures (AWWA, 2010; 2011). Moreover, the life expectancy of the pipes might be shortened by fluctuations in the grid pressure (Personal communication: Agbar). Thus, life expectancy also depends on the management of the DWTDN. For this reason, the assumption that all the pipes have the same life span (50 years) has been adopted for the assessment.

For the installation phase, the DWTDN can be placed on the surface or buried. In accordance with the common practice in small to medium cities (Adequa, 2009), only buried networks installed through the excavation of a ditch will be considered. *Figure 3* shows the main steps of the installation.

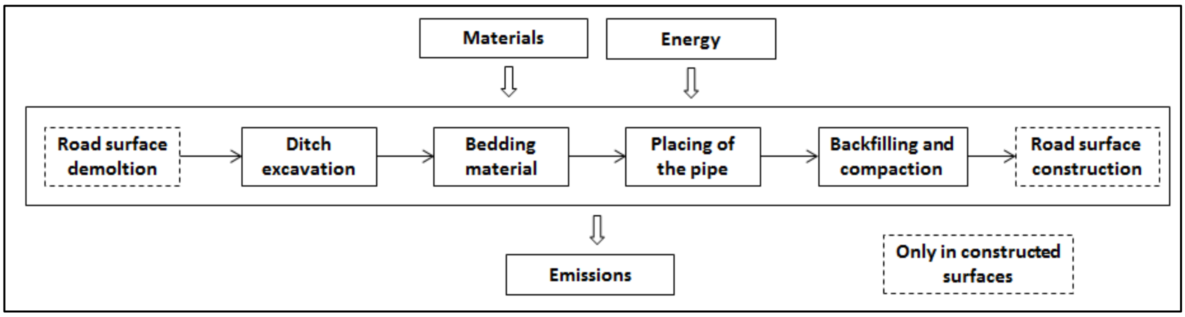


Figure 3. Main steps of the installation of the DWTDN

Within this phase, the materials and energy for the excavation and backfilling of the ditch as well as for the placing of the pipe were considered (*Figure 2*). The road surface construction and demolition were excluded from the analysis because they are the same for all cases and can be very different in each situation. *Table 3* summarises the data on the ditch found in construction enterprises handbooks.

*Table 3***.** Review of the characteristics of the ditch for the installation of the DWTDN.

	Source	**Min. width of the ditch (m)**	**Min. depth of the ditch (m)**	**Backfilling**		**Supporting bed**	
				Max. Ø (mm)	**Backfilling material**	**Min. thickness (cm)**	**Bedding material**
90 mm pipes	Adequa Uralita, 2010	0.8[1]	PD+SBT+ (1[2]/0.6[3])	15	Sand, coarse aggregate	10+0.1Ø	Gravel, sand or crushed stone.
200 mm pipes	Adequa Uralita, 2010	0.8[1]	PD+SBT+ (1[2]/0.6[3])	30	Sand, coarse aggregate	10+0.1Ø	Gravel, sand or crushed stone.

[1]CEDEX, 2009; [2]with traffic; [3]without traffic (sidewalk); [4]angle of the wall >60°
PD= Pipe diameter, SBT= Supporting bed thickness

In all cases, the wall of the ditch was considered to be completely vertical. The depth and width of the ditch and the thickness of the bed from *Table 3* were maintained. A depth of 1 m to the upper point of the pipe was considered, and it was assumed that the pipes are placed under traffic because this is the most impactful option. Gravel was chosen as bedding material and sand as backfilling material in all the cases. *Figure 4* shows the dimensions of the ditches for the two diameters of pipes considered (section 2.3).

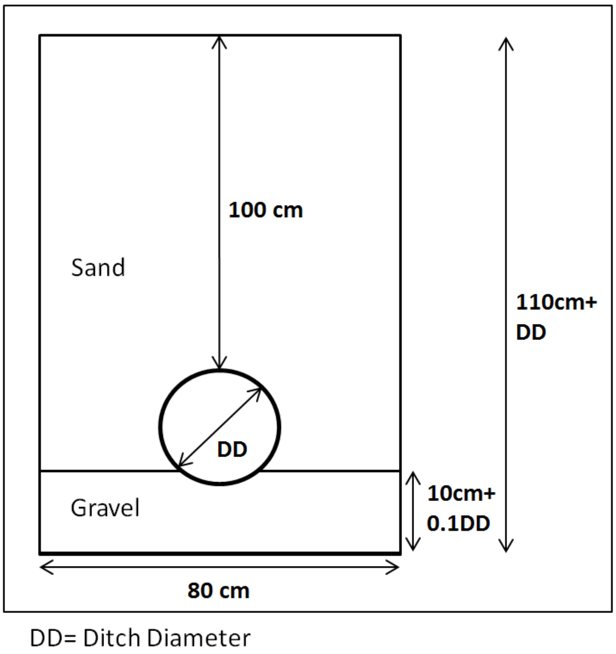


Figure 4. Dimensions of the ditch for 90 and 200 mm pipes.

Regarding the machinery used in the installation phase, *Table 4* shows the different machines considered and their consumptions. *Table 5* shows the inventory for the constructive solutions compared.

Table 4. Machinery used in the installation phase and their energy consumption.

Machine	**Consumption (MJ/hour)**	**Energy source**
Backhoe excavator	432.12	Diesel
Double drum vibrator road roller	60.86	Diesel
Vibrating tamper	60.86	Diesel

Source: Metabase Itec, 2010

As stated in section 1.3, the phases of use and end of use were excluded from the assessment (*Figure 2*).

Table 5. Inventory of the materials and energy per m of network considered for the comparison of the pipes.

	Ecoinvent 2.2 process		**Unit per lineal m**						
	Material	**Processing**	**HDPE (90 mm)**	**LDPE (90 mm)**	**PVC (90 mm)**	**HDPE (200 mm)**	**PVC (200 mm)**	**DI (200 mm)**	**GFRP (200 mm)**
Pressure (bar)	-	-	6	6	6	10	10	10	10
Connections	-	-	W	BP	ER	W	ER	BU-ER	PS
Weight (kg)	-	-	1.0	2.1	1.0	4.7	4.0	36.0	11.4
Life expectancy (years)	-	-	50	50	50	50	50	50	50
HDPE[1] (kg)	Polyethylene, HDPE, granulate, at plant/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	1.52	0	0	5.50	0	0	0
LDPE[1] (kg)	Polyethylene, LDPE, granulate, at plant/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	0	2.63	0	0	0	0	0
PVC[1] (kg)	Polyvinylchloride, at regional storage/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	0	0	1.34	0	4.76	0	0
DI[1] (kg)	Cast iron, at plant/RER S	Metal product manufacturing, average metal working/RER S	0	0	0	0	0	38.8	0
GFRP (kg)	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER S	Injection moulding/RER S	0	0	0	0	0	0	4.96
Synthetic rubber (kg)	Synthetic rubber, at plant/RER S		0.0147	0.0072	0.121	0.0696	0.101	0.245	0.0105
Sand (kg)	Sand, at mine/CH S		1,530	1,530	1,530	1,590	1,590	1,590	1,590
Gravel (kg)	Gravel, round, at mine/CH S		148	148	148	163	163	163	163
Diesel, machinery (MJ)	Diesel, burned in building machine/GLO S		92.0	92.0	92.0	99.2	99.2	99.2	99.2
Transport van (tkm)	Transport, van <3.5t/RER S		0.152	0.263	0.135	0.550	0.487	3.91	0.497
Transport lorry (tkm)	Transport, lorry 16-32t, EURO5/RER S		50.5	50.5	50.5	52.5	52.5	52.5	52.5

[1]Includes the pipe and its accessories made of the same material, [2]pipe, [3]accessories

W= Welded, BP=By pressure, ER= Elastomeric ring, BU=Bell union, PS= Polyester sleeve

Source: Metabase Itec, 2010

2.5.2 Environmental impact of the individual elements of the network

Some individual components of the network are analysed (hydrants, pumps and valves). *Table 6* includes the inventory for the individual elements of the grid.

Hydrants include their register well, and a standard connection diameter of 100 mm was selected to estimate the environmental impact. For shut-off valves, 2 standard connection diameters of 50 and 100 mm were selected.

For the components, no reliable data about their lifespans were found, and the same data as those of the pipe were considered (50 years). A different life expectancy of the elements of the network would significantly vary the environmental impact of the network.

2.5.3 Environmental impact of a DWTDN

The assessment of the DWTDN of a municipality requires data about the materials and diameters of the pipes and the length of each type of pipe, as well as data about the individual elements. The use of geographical information system (GIS) technologies is needed to obtain these data.

The first stage of the assessment consists of calculating the environmental impact per lineal meter of network for each type of pipe of the DWTDN following the methodology used in the assessment of the constructive solutions (section 2.5.1). The total environmental impact of the network can then be calculated using the length of the pipe.

For the case study (Betanzos, Spain), the sorts of pipes that represent less than 1% of the network have been excluded from the analysis because they do not represent a significant part of the impact. Additionally, the potential of the improvement of the DWTDN of Betanzos has been calculated. The potential has been assessed assuming that the entire network is made of the best constructive solutions found in the comparison.

Table 6. Inventory of the materials and energy considered for hydrants, pumps and shut-off valves.

	Ecoinvent 2.2 process		kg per unit				
	Material	**Processing**	**Hydrant, 100 mm**	**Pump, 35 m^3/h**	**Pump, 60 m^3/h**	**Shut-off valve, 50 mm**	**Shut-off valve, 100 mm**
Steel	Steel, low-alloyed, at plant/RER S	Metal product manufacturing, average metal working/RER S	-	3.5	16.5	1.9	4.5
Cast Iron	Cast iron, at plant/RER S	Metal product manufacturing, average metal working/RER S	168	31.5	148.5	10.5	25.2
Galvanised steel	Steel, low-alloyed, at plant/RER S	Metal product manufacturing, average metal working/RER S	0.2	-	-	-	-
Epoxy resin	Epoxy resin, liquid, at plant/RER S	-	0.3	-	-	-	-
Synthetic rubber	Synthetic rubber, at plant/RER S	-	-	-	-	0.13	0.3

Source: Metabase Itec, 2010

3. Results and discussion

3.1 Comparison of the environmental impact of the different pipes

A comparison of the constructive solutions reveals differences between the environmental impacts derived from each solution. *Figure 5* shows the comparison of the environmental impact for constructive solutions with 90 mm diameter pipes. The figure shows that PVC has the lowest environmental impact for all the impact categories (5-25% lower), whereas LDPE has the highest (up to 20% higher).

The same ditch dimensions are considered for the 3 cases; for this reason, the phases of transport and installation have similar environmental impacts. The differences in the impact are derived from the production phase. LDPE has higher environmental burdens (per kg) than HDPE and PVC in 4 out of the 7 impact categories. Furthermore, the LDPE option requires a higher amount of material to manufacture the pipe than the other options (up to 90% more than PVC).

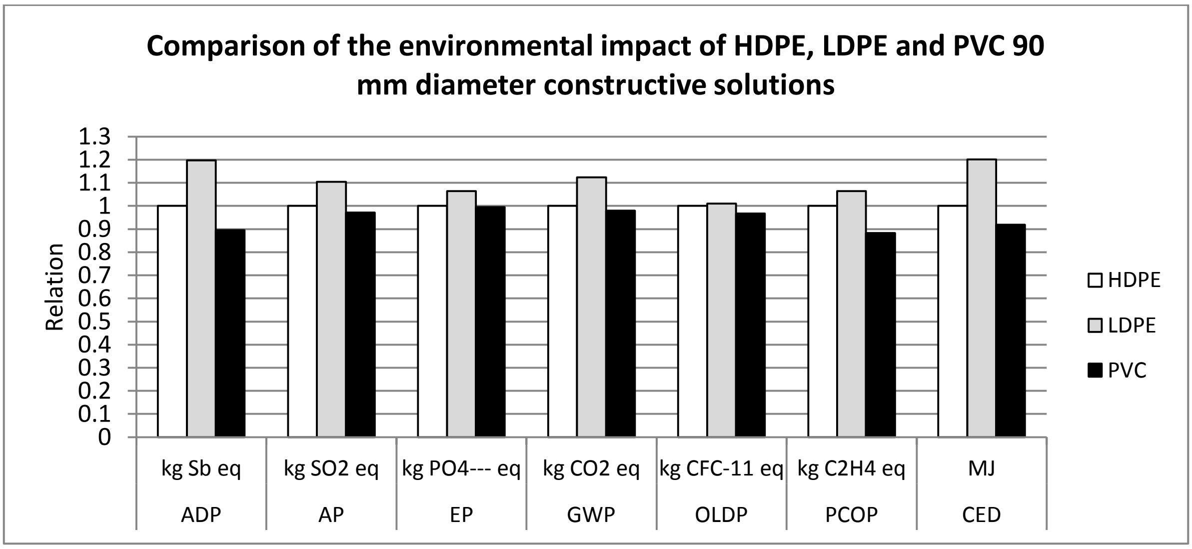


Figure 5. Comparison of the environmental impact of 90 mm diameter constructive solutions

These results are different from those for 200 mm diameter pipes (*Figure 6*). In this case, HDPE and PVC present the lowest environmental impacts, between a 40 and 90% lower impact than DI and GFRP. This is because DI and GFRP pipes are made with higher amounts of material (4.76 kg/m of PVC vs. 36.3 kg/m of DI). Similar to what was observed in the 90 mm diameter pipes, PVC presents a lower environmental impact than HDPE (up to 25% lower) in 5 out of 7 impact categories. Again, this is because of the higher amount of material required (5.5 kg/m of HDPE vs. 4.76 kg/m of PVC; section 3).

Considering these results, DI and GFRP are not recommended from an environmental perspective. DI presents the highest environmental impacts in all impact categories and an impact up to 12 times greater than that of HDPE. The environmental impact of GFRP is between 45 and 75% lower than that of DI in 6 out of 7 impact categories. Nevertheless, if further research proves that the lifespan of DI and GFRP pipes is greater than that of PVC and HDPE, the results would be much favourable for DI and GFRP. To have lower impacts, the life span of DI should be from 3 to 11 times that of PVC, whereas GFRP should have 2 to 2.5 times the PVC life expectancy.

The results of the CED contrasted with those from Piratla et al. (2012), which show that the embodied energy of PVC was higher than that of DI and HDPE.

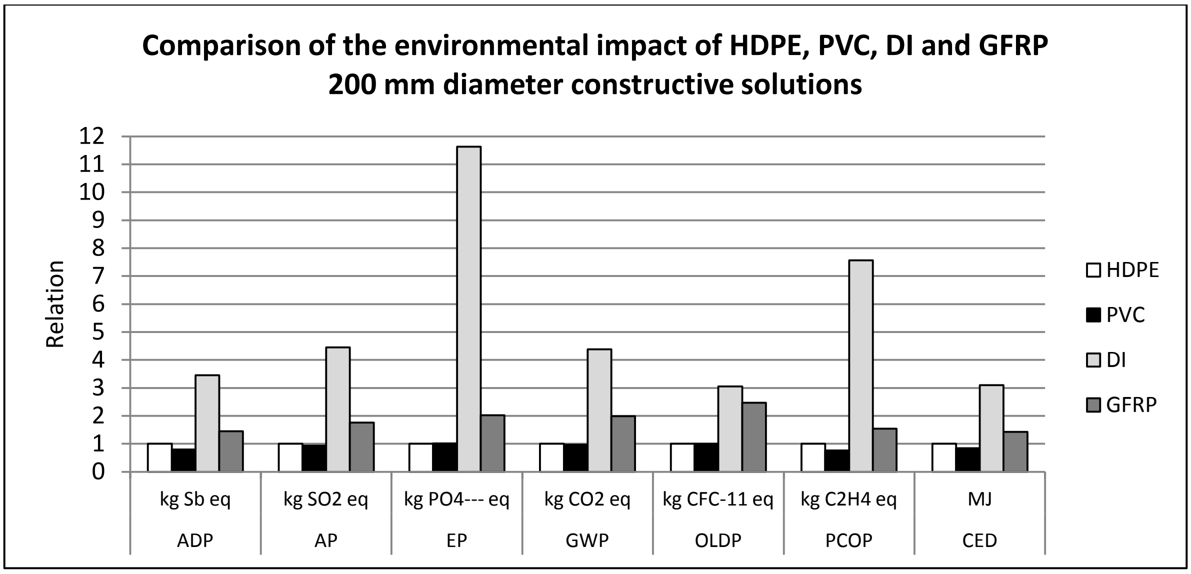


Figure 6. Comparison of the environmental impact of 200 mm diameter constructive solutions

It must be considered that the pipe might not reach its end of life. In cities, it is common to rebuild some streets to refurbish them and modify urban planning, among other reasons. Thus, the constructive solution could be changed in a shorter period than expected. This factor would favour the use of less impactful pipes even if they have a shorter lifespan because they may not reach their end of life.

Furthermore, the management of the network at its end of life is an important point. Studies about “urban mining” are already taking place (Krook et al., 2010), and in the future, the pipe materials might be recovered instead of left hibernating.

In stagnating grids, the maintenance and replacement of pipes is important (Venkatesh and Brattebø, 2011; 2012). This makes the lifetime relevant because pipes with a longer lifetime will be less demanding with regard to replacement.

3.2 Environmental impact of the life cycle phases

Figure 7 shows the contribution of each life cycle stage to the environmental impact of the 90 mm diameter pipes. The figure shows that the 3 pipes show similar percentages in most of the impact categories.

The phase of installation, including the materials for the backfilling of the trench, is the main contributor, with more than 40% of the impact in 5 out of 7 impact categories for the 3 options. This highlights the importance of analysing the whole constructive solution instead of only the pipe, especially for small pipe diameters. Otherwise, a great part of the environmental impact is omitted. Transport contributes between 20 and 40% of the impact and production between 10 and 20% in all the impact categories. Thus, transport and production are also relevant phases of the global environmental impact.

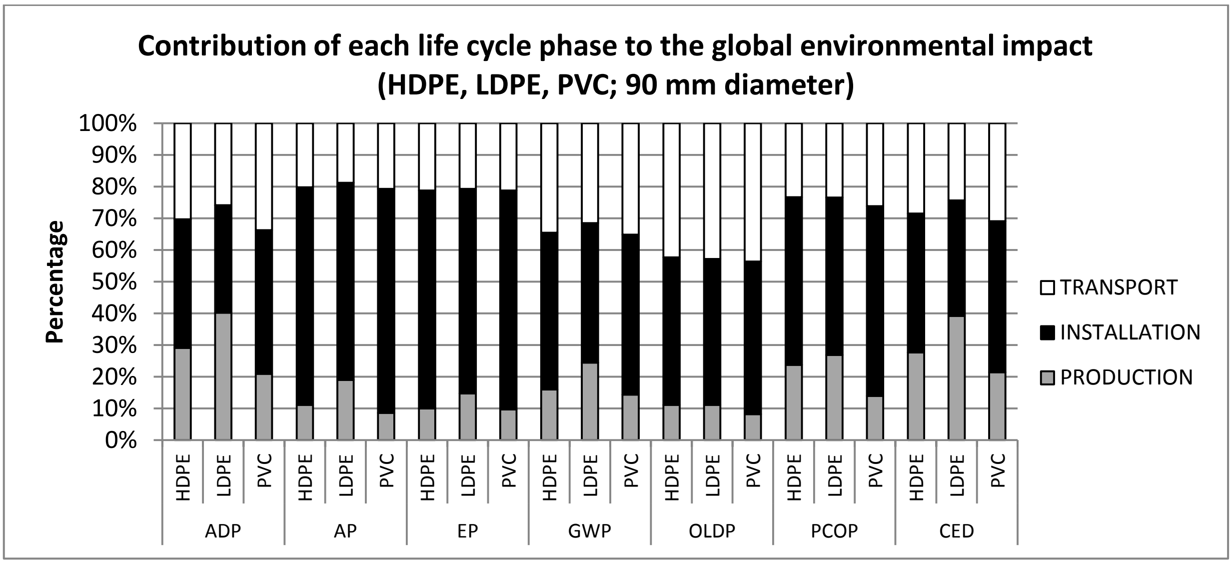


Figure 7. Contribution of each life cycle stage to the global environmental impact of 90 mm diameter pipes.

Figure 8 shows the contribution of each life cycle phase for 200 mm –diameter pipes. In contrast with the previous comparison, production is the main contributor to the global environmental impact.

For DI and GFRP, production represents more than 60% of the impact in all impact categories because of the high environmental burdens of these materials in comparison with other impacts of the life cycle, such as the energy consumption in installation.

For HDPE and PVC, production represents more than 35% of the impact in 4 out of 7 impact categories. This is a significantly higher percentage than in the case of 90 mm diameters for the same material. Because the considered ditch is very similar (only 11 cm deeper), the increase in the amount of material of the pipe (approximately 3.5 times greater) results in an increase of the percentage that the production phase represents. This shows that the percentage of contribution of each life cycle phase is related to the diameter of the pipe because higher diameters require more materials, which increases the percentage of the impact due to production.

The installation phase is also relevant for HDPE and PVC, representing 20-55% of the impact in all impact categories. Transport has minor relevance, representing between 5-40% of the environmental impact.

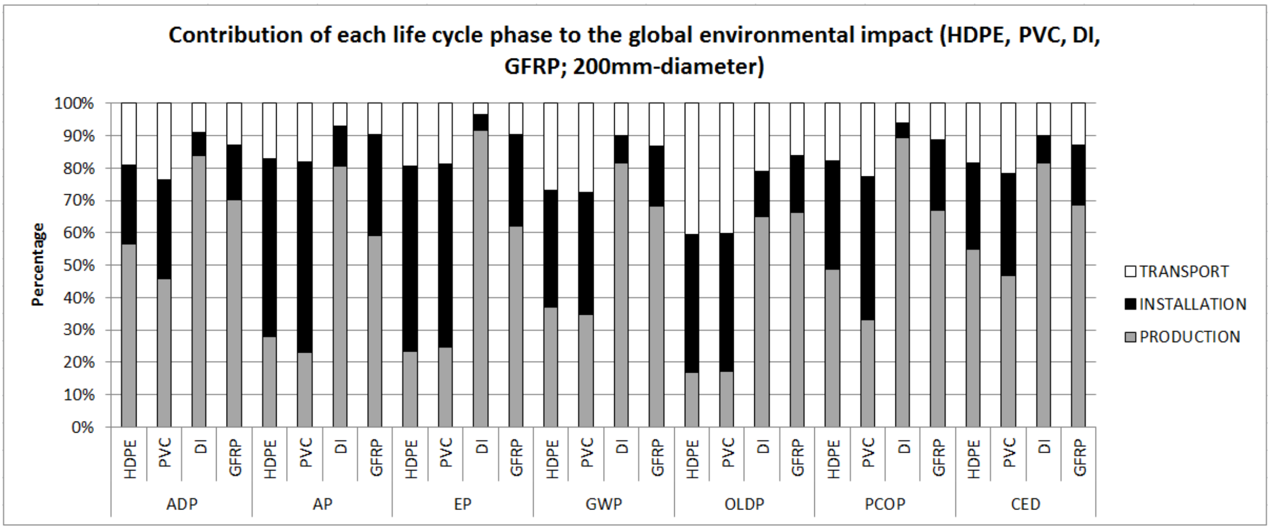


Figure 8. Contribution of each life cycle stage to the global environmental impact of 200 mm diameter pipes

3.3 Environmental impact of the materials and processes

Table 7 shows the contribution of each element of the life cycle to the whole environmental impact. The table shows that for the 90 mm diameter HDPE pipe, the most relevant contributors to the global impact are the diesel consumption for the installation (24-66%) and the transport of the backfilling material (19-40%). Thus, the optimisation of the dimensions of the ditch and the process of installation should be assessed by detecting possible improvements to reduce the environmental impact. The percentages for the constructive solutions with LDPE and PVC 90 mm diameter pipes have not been included in *Table 7* because they show similar percentages to the ones presented for HDPE.

In the case of the 200 mm diameter HDPE pipes, in contrast with the results for the 90 mm diameter pipes, the material of the pipe (HDPE) doubles the percentage of contribution to the global environmental impact of the whole life cycle (up to 50%). Diesel and the transport by lorries of sand and gravel for backfilling are still significant contributors, with 15 to 40% of the impact. In this case, although the installation phase also has great relevance, it is also important to consider the pipe itself to reduce the environmental impact. The percentages of the 200 mm diameter PVC-pipe constructive solution are very similar to the ones presented for HDPE and are not included in *Table 7*.

For the 200 mm diameter GFRP pipe, the main contributors are the consumption of GFRP (30 to 60% of the global environmental impact) and its manufacturing (8 to 33%). In this case, the installation and transport phases have minor importance because most of the impact in all impact categories is focused in the production phase. The 200 mm diameter DI pipe constructive solution presents similar results, with between 65 and 90% of the whole environmental impact from the consumption of DI and the manufacturing of the pipe. These two cases accentuate the importance of the pipe material for greater diameters because the pipe represents a higher percentage of the environmental impact of the constructive solution, whereas the impact of the installation is smaller.

Table 7. Contribution to the environmental impact of each material and process for 1 m of network of 90 mm and 200 mm diameter HDPE and 200 mm diameter GFRP pipes.

	Impact category	**Percentage of the total impact**						
		PRODUCTION		**INSTALLATION**			**TRANSPORT**	
		Materials	**Manufacturing**	**Gravel**	**Sand**	**Diesel**	**Transport, lorry**	**Transport, van**
HDPE, 90 mm	**ADP**	25.0	4.1	1.2	12.2	27.3	29.3	1.0
	AP	7.7	3.4	1.7	17.7	49.3	19.3	0.8
	EP	2.6	7.4	2.1	21.7	45.0	20.1	1.1
	GWP	11.7	4.3	1.4	14.6	33.5	33.4	1.1
	OLDP	0.3	10.8	1.3	13.1	32.2	41.1	1.3
	PCOP	19.5	4.3	1.7	17.2	34.0	21.1	2.2
	CED	23.2	4.5	1.7	17.3	24.8	27.5	1.0
HDPE, 200 mm	**ADP**	50.9	5.9	0.7	7.1	16.5	17.0	2.0
	AP	20.8	7.3	1.4	13.7	39.6	15.0	2.3
	EP	7.6	15.9	1.8	17.5	37.8	16.3	3.1
	GWP	29.3	7.7	1.1	10.4	24.8	23.9	2.9
	OLDP	1.3	15.7	1.2	11.6	29.8	36.6	3.9
	PCOP	41.9	7.0	1.1	10.6	21.7	13.0	4.7
	CED	48.2	6.8	1.1	10.3	15.3	16.4	2.0
GFRP, 200 mm	**ADP**	60.0	10.2	0.5	4.9	11.4	11.8	1.2
	AP	51.2	8.0	0.8	7.8	22.6	8.5	1.2
	EP	45.7	16.5	0.9	8.7	18.7	8.1	1.4
	GWP	59.4	9.0	0.5	5.2	12.5	12.0	1.3
	OLDP	33.5	32.9	0.5	4.7	12.1	14.8	1.4
	PCOP	57.5	9.6	0.7	6.9	14.1	8.4	2.8
	CED	57.4	11.1	0.7	7.2	10.7	11.5	1.3

3.4 Analysis of a case study DWTDN

The environmental impact per lineal meter has been calculated for each type of pipe, and the results obtained have been used together with data from Table 2 to calculate the global environmental impact of the Betanzos DWTDN (*Table 8*). The table shows that the material of pipe that contributes the most to the global environmental impact is HDPE (more than 40% for all impact categories), followed by LDPE and PVC (10 to 40%). This is because these materials are the most common along the DWTDN (51% of the network HDPE and 19% LDPE and PVC). Remarkably, the individual elements (hydrants, pumps and valves) that were considered generate between 16 and 17% of the environmental impact for EP and PCOP.

Table 8. Total environmental impact of the Betanzos network

		Environmental impact						
Impact category	**Unit**	**HDPE**	**LDPE**	**PVC**	**DI**	**Fibre cement**	**Individual elements**	**TOTAL**
ADP	kg Sb eq	1.3E+04	3.9E+03	4.2E+03	1.0E+03	1.2E+03	1.62E+03	2.5E+04
AP	kg SO2 eq	8.0E+03	2.8E+03	2.7E+03	6.7E+02	9.4E+02	9.63E+02	1.6E+04
EP	kg PO4--- eq	2.0E+03	7.2E+02	7.2E+02	4.0E+02	2.4E+02	6.91E+02	4.8E+03
GWP	kg CO2 eq	1.6E+06	5.3E+05	5.5E+05	1.3E+05	1.9E+05	2.01E+05	3.2E+06
OLDP	kg CFC-11 eq	2.0E-01	6.8E-02	6.7E-02	1.0E-02	2.1E-02	1.14E-02	3.8E-01
PCOP	kg C2H4 eq	3.0E+02	9.3E+01	9.6E+01	4.8E+01	3.6E+01	8.48E+01	6.6E+02
CED	MJ	3.2E+07	9.9E+06	1.1E+07	2.3E+06	3.0E+06	3.45E+06	6.1E+07

>40% of the global impact	10-40% of the global impact	<10% of the global impact

Table 9 shows the environmental impact of the DWTDN converted to FU (m^3·year) and to other units. Further research on this field or the application of this methodology to other case studies might provide new data that could be compared with the results.

The estimated scenario shows that a potential reduction of between 6 and 16% of the total environmental impact can be achieved. This is significant considering that the only action applied was changing the pipe material for the renewal of the network. However, it must be stated that the actual network of Betanzos is mainly built using HDPE, LDPE and PVC pipes (90% of the network). Thus, the difference of impact between these pipes and PVC pipes is small. The application to other case studies with a DWTDN with more impacting pipes such as DI (section 3.1) might present higher percentages of reduction.

The methodology proposed can be applied to any grid as far as the length of each type of pipe and the individual elements are known. This methodology allows the designers of the DWTDN to calculate the environmental impact derived from the network, which is useful for decision making during the design of the network.

Table 9. Actual environmental impact of the Betanzos DWTDN and estimation of the potential impact reduction.

		Actual environmental impact				**Estimated environmental impact**				**% reduction**
Impact category	**Unit**	**per m^3·year**	**per municipality·year**	**per inhabitant·year**	**per m of DWTDN·year**	**per m^3·year**	**per municipality·year**	**per inhabitant·year**	**per m of DWTDN·year**	
ADP	kg Sb eq	4.4E-04	4.9E+02	3.6E-02	4.1E-03	3.8E-04	4.3E+02	3.2E-02	3.6E-03	**-13**
AP	kg SO2 eq	2.9E-04	3.2E+02	2.4E-02	2.7E-03	2.6E-04	3.0E+02	2.2E-02	2.5E-03	**-8**
EP	kg PO4--- eq	8.5E-05	9.6E+01	7.1E-03	8.0E-04	7.7E-05	8.6E+01	6.4E-03	7.2E-04	**-10**
GWP	kg CO2 eq	5.6E-02	6.3E+04	4.7E+00	5.3E-01	5.1E-02	5.8E+04	4.3E+00	4.8E-01	**-9**
OLDP	kg CFC-11eq	6.7E-09	7.5E-03	5.6E-07	6.3E-08	6.3E-09	7.1E-03	5.2E-07	5.9E-08	**-6**
PCOP	kg C2H4 eq	1.2E-05	1.3E+01	9.7E-04	1.1E-04	9.8E-06	1.1E+01	8.2E-04	9.2E-05	**-16**
CED	MJ	1.1E+00	1.2E+06	9.0E+01	1.0E+01	9.6E-01	1.1E+06	8.0E+01	9.0E+00	**-11**

4. Conclusions

It is important to consider the whole constructive solution instead of only the pipe; otherwise, up to 90% of the environmental impacts from the installation and transport phases may be omitted. To reduce the environmental impacts, the constructive solutions of the network must not be treated homogeneously. The installation phase is especially relevant for constructive solutions with smaller pipe diameters (more than 40% of the impact for 90 mm diameter HDPE), whereas the production of the pipe becomes more relevant with greater pipe diameters (35% of the impact in 4 out of 7 impact categories for 200 mm diameter HDPE). Thus, the reduction of environmental impacts involves the optimisation of the trench dimensions and the process of installation as well as the selection of pipe materials with lower environmental impacts in the production phase.

Constructive solutions with PVC pipes are preferable because they have shown to be environmentally less impactful (25% lower than HDPE and LDPE for 90 mm diameter pipe constructive solutions; 40 to 90% lower than DI and GFRP for a 200 mm diameter pipe). These differences are due to the lower quantity of material and the lower environmental impacts per kg of the PVC pipe in the production phase. For 200 mm pipe constructive solutions, the production of the pipe material is the most impactful element, especially for DI and GFRP pipes (more than 60% in all the impact categories).

Future studies should provide global data about the lifetime of the pipes because the lifetime can significantly influence the environmental impact of each constructive solution. Furthermore, future changes in the management of the network at its end of life (recovering the pipe materials or sending it to landfill) might influence the environmental impact of the constructive solutions.

Most of the network of the case study is formed by pipes made of HDPE (50%), LDPE (19%) and PVC (19%). Regarding the diameters of the pipes, there is a lot of heterogeneity, but 90% of the network has diameters between 40 and 125 mm. Substituting all the constructive solutions of the DWTDN for PVC constructive solutions in the pilot case study can reduce the environmental impact from the construction of the network (between 6 and 16% of the impact). This potential of improvement with the renewal of the network can be greater in DWTDN with more impactful pipe materials such as DI. The materials used are very different depending on the country.

The assessment of the environmental impact of the Betanzos DWTDN consisted of calculating the unitary impacts for each type of pipe and individual element (hydrants, valves and pumps) and multiplying it by the length and number of units of the DWTDN to obtain the global environmental impact. This methodology can be applied to other small to medium cities or neighbourhoods if the length of each type of pipe (diameter and material) and the number of each sort of individual element is known.

The development of a tool based on this methodology would be useful for the environmental design of DWTDN. Constructors and municipal managers could easily estimate the environmental impact of the construction of the network and thus design cleaner networks.

5. Acknowledgements

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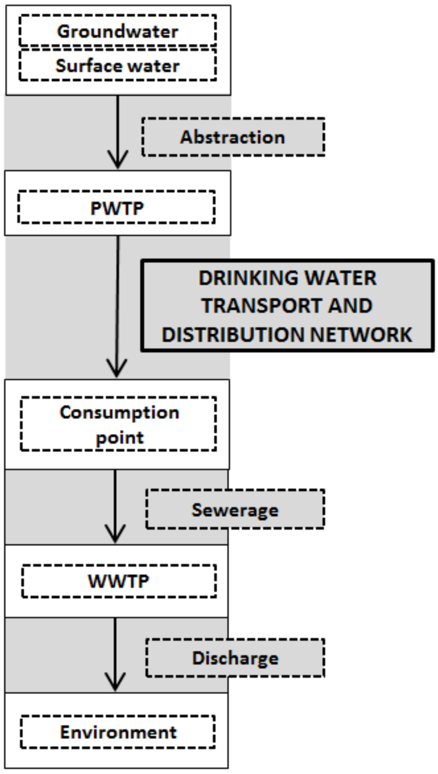
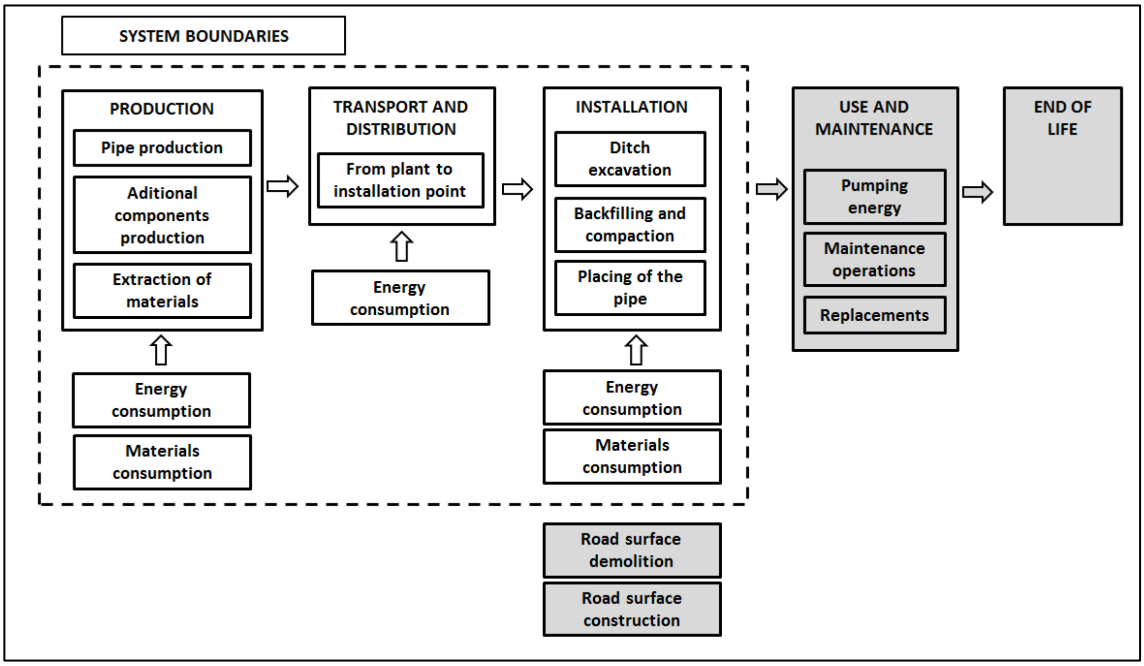
Figure

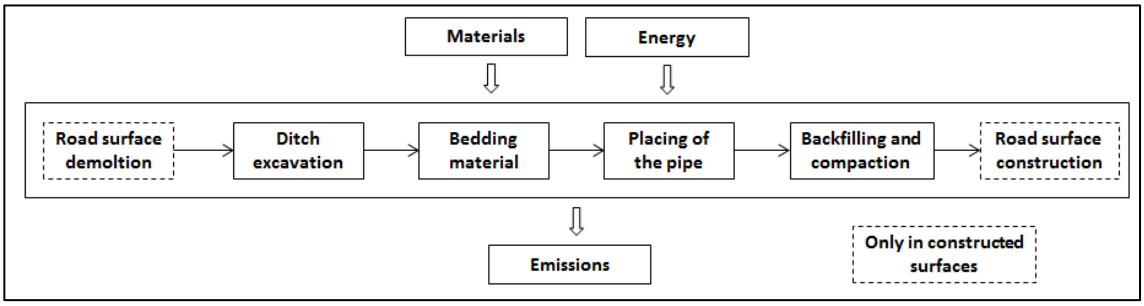


PWTP: Potable Water Treatment Plant
WWTP: Waste Water Treatment Plant

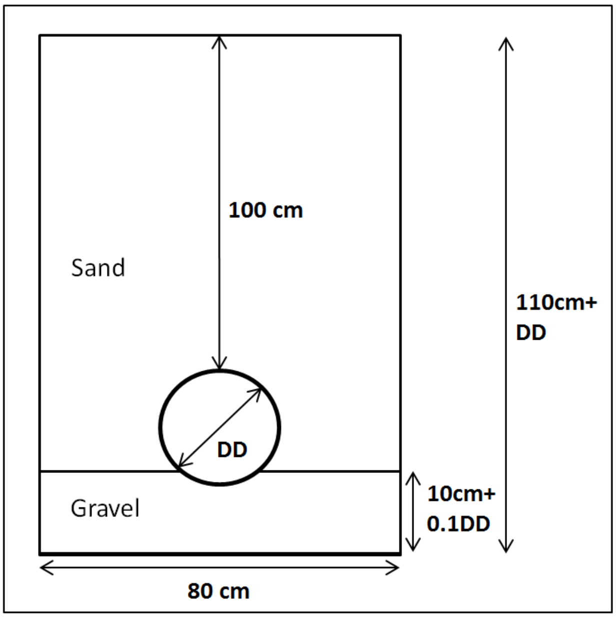
Figure


SYSTEM BOUNDARIES
PRODUCTION
Pipe production
Aditional components production
Extraction of materials
Energy consumption
Materials consumption
TRANSPORT AND DISTRIBUTION
From plant to installation point
Energy consumption
INSTALLATION
Ditch excavation
Backfilling and compaction
Placing of the pipe
Energy consumption
Materials consumption
Road surface demolition
Road surface construction
USE AND MAINTENANCE
Pumping energy
Maintenance operations
Replacements
END OF LIFE

Figure

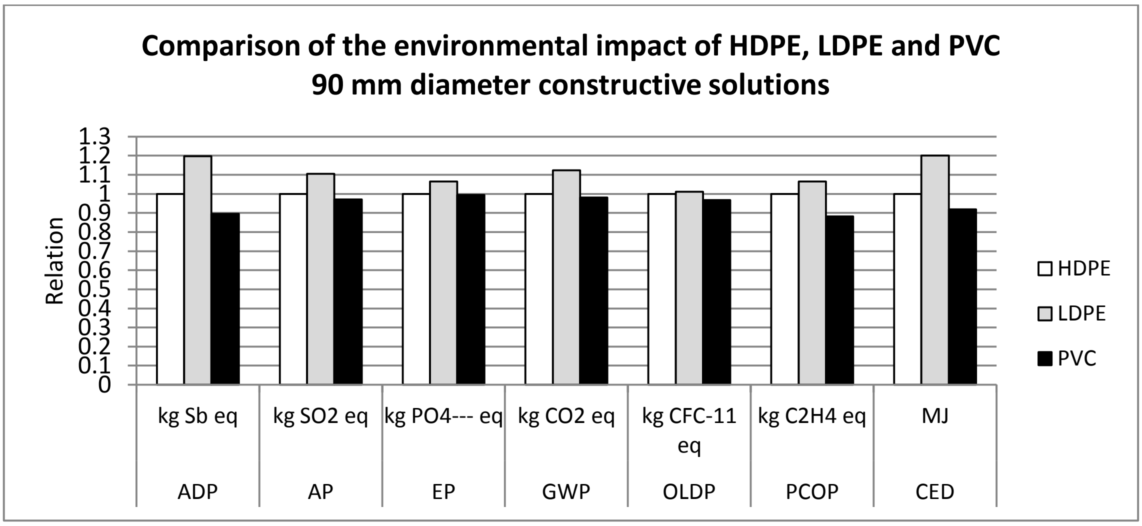

Materials
Energy
Road surface demoltion
Ditch excavation
Bedding material
Placing of the pipe
Backfilling and compaction
Road surface construction
Emissions
Only in constructed surfaces

Figure



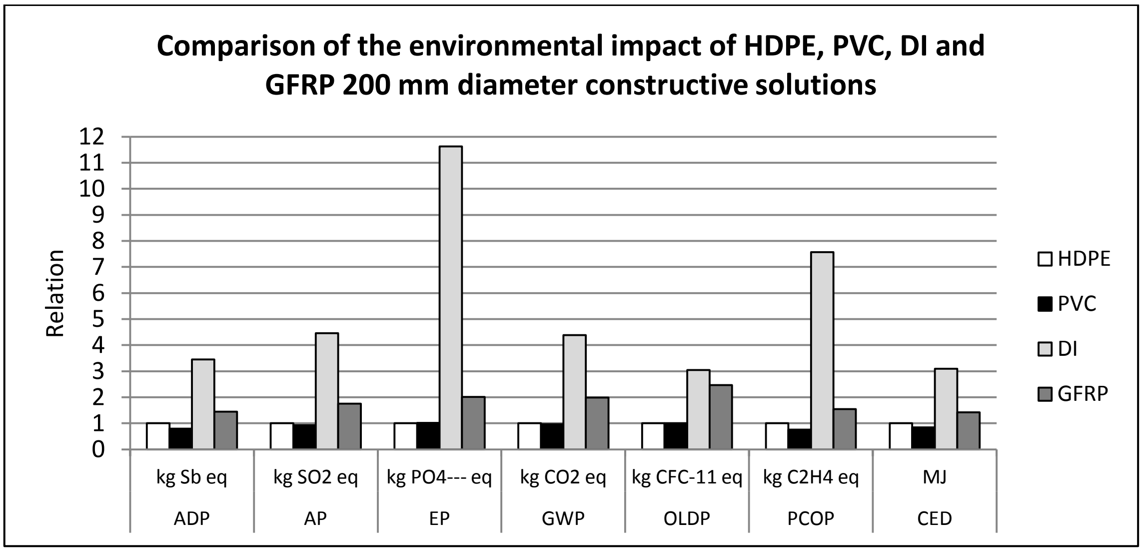
DD= Ditch Diameter

Figure

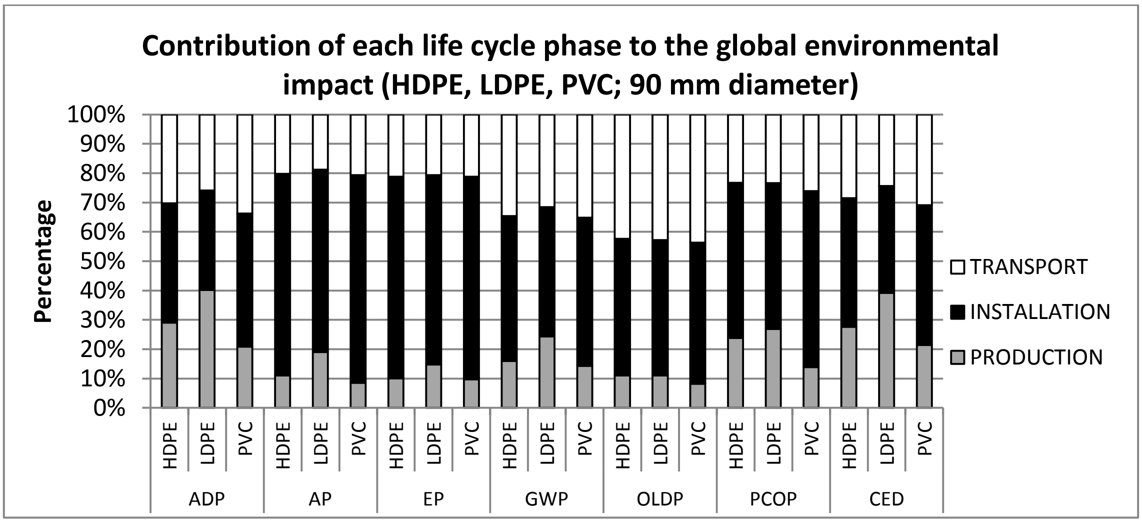


Comparison of the environmental impact of HDPE, LDPE and PVC
90 mm diameter constructive solutions
Relation
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
kg Sb eq
kg SO2 eq
kg PO4--- eq
kg CO2 eq
kg CFC-11 eq
kg C2H4 eq
MJ
ADP
AP
EP
GWP
OLDP
PCOP
CED
HDPE
LDPE
PVC

Figure


Comparison of the environmental impact of HDPE, PVC, DI and GFRP 200 mm diameter constructive solutions
Relation
0
1
2
3
4
5
6
7
8
9
10
11
12
kg Sb eq
ADP
kg SO2 eq
AP
kg PO4--- eq
EP
kg CO2 eq
GWP
kg CFC-11 eq
OLDP
kg C2H4 eq
PCOP
MJ
CED
HDPE
PVC
DI
GFRP

Figure


Contribution of each life cycle phase to the global environmental impact (HDPE, LDPE, PVC; 90 mm diameter)
Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
HDPE
LDPE
PVC
ADP
AP
EP
GWP
OLDP
PCOP
CED
TRANSPORT
INSTALLATION
PRODUCTION

Figure

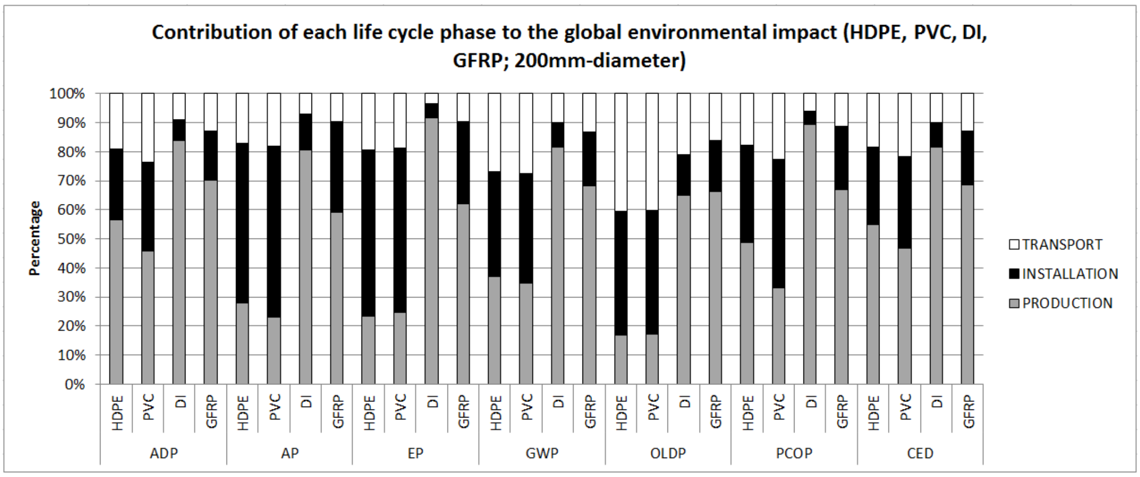

Contribution of each life cycle phase to the global environmental impact (HDPE, PVC, DI, GFRP; 200mm-diameter)
Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
HDPE
PVC
DI
GFRP
ADP
AP
EP
GWP
OLDP
PCOP
CED
☐ TRANSPORT
■ INSTALLATION
▨ PRODUCTION

Figure captions

Figure 1. Position of the DWTDN within the UWC

Figure 2. Diagram of the DWTDN life cycle and boundaries of the system

Figure 3. Main steps of the installation of the DWTDN

Figure 4. Dimensions of the ditch for 90 and 200 mm pipes.

Figure 5. Comparison of the environmental impact of 90 mm diameter constructive solutions

Figure 6. Comparison of the environmental impact of 200 mm diameter constructive solutions

Figure 7. Contribution of each life cycle stage to the global environmental impact of 90 mm diameter pipes.

Figure 8. Contribution of each life cycle stage to the global environmental impact of 200 mm diameter pipes