Wastewater infrastructure costs and urban sprawl: the case of Douro region

Introduction

Sustainable water and wastewater infrastructure systems are more difficult to implement in regions that are characterized by complex morphology and susceptibility to extreme weather events. These natural features hinder the development of mobility networks and the accessibility to services, resulting in land occupation patterns composed of many small and scattered urban clusters. Therefore, comprehensive infrastructure systems are faced with obvious technical challenges in terms of design, construction, operation and maintenance. Such is the case in Northeastern Portugal, more specifically in the Douro Region, despite significant improvements to water and wastewater infrastructure through substantial World Bank funding in the 1980s. These effective improvements have allowed different land occupation dynamics such as urban sprawl, a phenomenon that has increased in the past 10 years despite declining population trends.

The relationship between infrastructure cost and urban sprawl is explored in this paper. Rigorous procedures for estimating infrastructure cost are fundamental for planning, programming and selecting investment options and supporting medium and long-term decisions regarding location and extension of service networks. Research activities devoted to developing tools for parametric cost estimation for wastewater infrastructure are presented. For each area and system under study, data were collected regarding specific social and demographic parameters, technical characteristics of each infrastructure component and cost. Independent variables and cost drivers were selected for identifying and analysing the correlation between system cost and urban sprawl, providing a starting point for a discussion on how costs correlate to dispersion processes within the service area.

Northeastern Portugal: the Douro region

The Douro region has been, for the past decades, the focus of several projects and territorial development programmes that shared common purposes. Specifically, these include World Bank funding in the beginning of the 1980s and additional support from the European Union in the 1990s. The relative improvement of the quality of life of the populations in terms of the reinforcement and extension of water supply infrastructure coverage, social equipment network and partial modernization of the economical and social fabric are visible results and evidence of the positive impact brought by the incentives and associated investments (Danko and Lourenço, 2008a).

The heterogeneous topography of the region is responsible for the rather severe variations in climate conditions across the region and throughout the year. Spatial climate variations can be quite extreme (severe droughts and frequent flooding) and microclimate areas can be identified, attending to the differences in sun exposure and wind direction derived by the distinct morphological features of the terrain (Danko and Lourenço, 2008b).

The region's natural heritage is intimately linked to the agro-forestry uses of the land. Three main trends have been observed for rural development: (1) the complementarity and interchangeability between agricultural, forestry and tourism uses; (2) the global regression of the agro-forestry uses, and (3) the expansion of barren land. In regional terms though not in a homogeneous manner, agricultural uses have decreased while forested and barren land areas have increased. Between 1990 and 2000, there was an increase in the areas devoted to urban uses, vineyards, eucalyptus forests and areas lost to forest fires (Lourenço et al, 2008).

This is considered a sparsely populated area, yielding a mere 43 inhabitants per km^2, which is a value well below the national average of 115 inhabitants per km^2. The region of the country has long suffered with population decline in favour of the more developed coastal areas, a migration dynamics that is driven by a number of different factors. Historically, population numbers have been gradually declining for the entire Northeastern region. This population decline is related to several local factors, particularly migration in search of better employment opportunities towards the more developed coastal areas or even abroad (Danko and Lourenço, 2008a). See Figure 1.

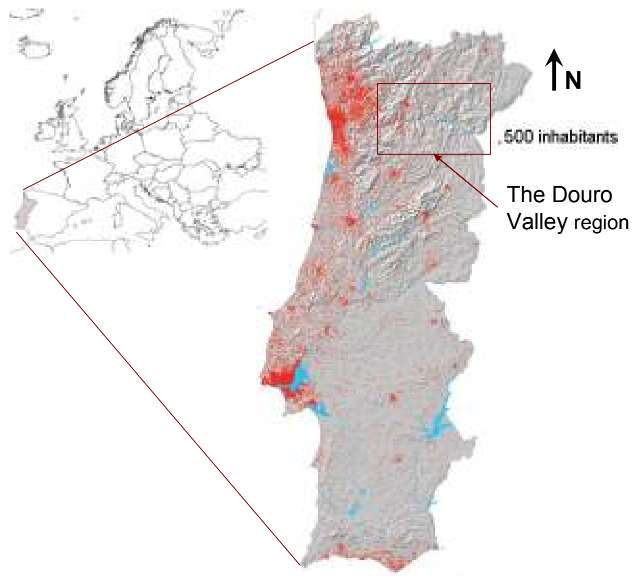

Figure 1 – Case study area in relation to Europe and Portugal

Cities and towns within coastal areas, particularly the metropolitan areas of Porto (North) and Lisbon (Centre), offer more job opportunities and consequently, a better chance for improved life conditions. The uneven distribution of people among the coastal and interior areas of the country has carried standing effects on urban growth and development. Urban clusters are small and dispersed. Having struggled with this phenomenon over the last five centuries Portugal has nowadays called on extensive strategic programmes aimed at protecting and assisting the more deprived interior, offering the possibility of a more equitable territorial model for development and well-being. The strategy focuses on steering the country's development processes according to sustainability guidelines, while vying for the participation of citizens and a variety of economic and social agents (Danko and Lourenço, 2008a).

Infrastructure costs and urban sprawl

Cost estimation is an educated approximation that provides valuable knowledge for political and entrepreneurial decisions (Carr apud Otero, 2000). Infrastructure cost estimation is a fundamental step in the process of planning and selecting investments, and also for supporting medium and long-term strategic decisions (Earle, 1997). In terms of sanitation infrastructure, the preliminary information derived from such estimations is used as an initial estimate of the probable final cost of a system's components and has proven to be extremely useful for managing services, consulting agents, designers and local authorities, who seldom have access to detailed cost data when strategic decisions are warranted.

In a context of urban sprawl, the need for accurate infrastructure cost estimation becomes more important since disperse urban types imply increased design, implementation, managing and operation and maintenance costs as opposed to more compact urban clusters, where these costs are kept lower.

Aciolly and Davidson (1998) refer population density as an important decision factor in the context of technical and financial evaluations of infrastructure and public services in residential areas. In principle, the greater the density, the better and more efficient will be the utilisation of urban infrastructure. Accordingly, lower densities may imply longer networks for fewer consumers and higher per capita investment, operation and maintenance costs (Mancini, 2008). Where higher densities might lead to network overload and inefficiency of service, disperse urban settlements typically drive higher urbanisation costs, particularly because of the longer distances and areas to cover (Figure 2).

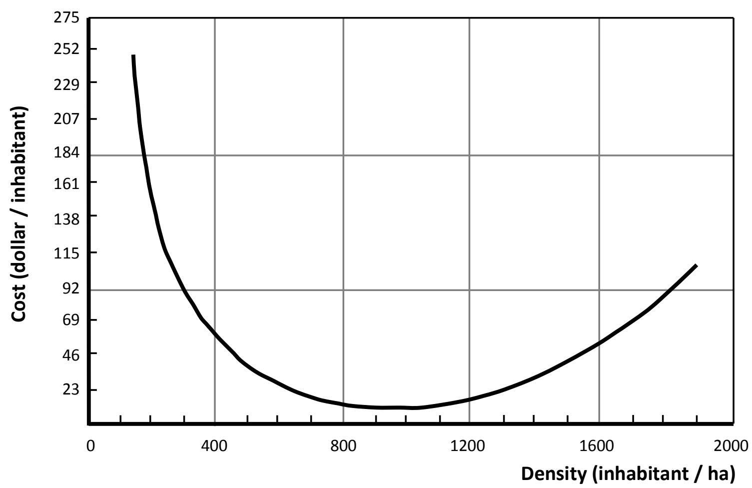

Figure 2 – Infrastructure per capita cost and population density in Venezuela (Source: Neumann, 2003)

As seen above, the minimum infrastructure per capita cost corresponds to an optimal value of approximately 1000 inhabitants per hectare (Neumann, 2003). Note how the rate of cost increase is significantly higher for lower than for higher densities. These findings are supported by Burchell et al. (2002), pointing out to savings of 227 billion of dollars (US) for a 25-year period of controlled urban development and growth.

According to Mascaró and Yoshinga (2005), infrastructure services are split between two groups. While the first one comprises all services that are essential to any city or neighbourhood, including water and wastewater systems, the second group corresponds to the larger metropolitan transportation networks that are typically found in larger cities and metropolitan areas and hence, are not the focus of this work.

Water and wastewater infrastructure costs

Infrastructure systems can also be classified according to function. Water and wastewater systems are considered symmetrical branched systems: while final water distribution branches stem out of one or more main distributor lines, wastewater collection starts out from branches that converge to form one or more collection lines, leading to the final treatment and disposal facilities. Also, water systems are pressurised, closed systems – in order to help preserve the sanitary integrity of the water being supplied – while wastewater typically flows by gravity, with the occasional use of intermediate pumping stations where necessary to circumvent terrain limitations.

This is often the best engineering practice to adopt where the alternative would generally involve costly earth removal and changes to the site's topography (Mascaró and Yoshinga, 2005). Burchell et al. (2002) refers a potential 15-20% reduction in urban infrastructure costs in terms of water and wastewater systems.

Overall, water and wastewater systems correspond to 20% (6% and 14%, respectively) of the total infrastructure cost of an urban system that also includes transportation, energy and communication systems (Mascaró and Yoshinga, 2005). The contribution of each system component to the overall cost is presented in Table 1.

Infrastructure system	**Network (%)**	**Residential connections (%)**	**Ancillary equipment (%)**	**Total (%)**
Water	15.5	25.5	59.0	100
Wastewater	39.0	3.0	58.0	100

Table 1 – Contribution of each component to the total infrastructure cost (Source: Mascaró, 1987)

Abiko et al (2003a and 2003b) list a number of factors that influence the cost of sanitation infrastructure: (1) network type and configuration; (2) size of serviced area; (3) shape of serviced area; (4) density of serviced area, and (4) slope in serviced area. Depending on the system, these factors become more or less important. However, both water and wastewater system costs highly depend on type and configuration of the network – hierarchical or mesh – and less so on the size and shape of the area to be serviced.

In the case of the Douro region, the cost of equipping dispersed urban clusters is compounded by the complex natural topography and morphology of the terrain. For instance, broader wastewater collection systems – because they are gravity based – are not only bound to the number and size of urban clusters but also to the limitations of the terrain.

Cost quantification methodology

Sixty wastewater infrastructure projects within the Douro region were analysed from the standpoint of cost of their different components. The social and economic features of the project sites were also taken into account. Given the on-going nature of this project, the results presented herein are preliminary and not all-encompassing as of yet. The project includes two main goals: the development of mathematic models that can streamline the cost estimation procedure; and establishing a correlation between cost and population dispersion. For the purposes of the analysis presented below, the cost is to be understood as the final cost that includes consulting fees, project implementation, man-hours, taxes and insurance, amongst other elements. The obtained data were used to generate statistical models using regression analysis techniques. A number of parametric cost correlations were derived accordingly.

Cost parametric models imply the definition of the estimated cost as a function of one or more independent and relevant variables (Colossi, 2002), namely those that can express population dispersion. Note that not all relationships between independent variables can be converted into parametric correlations. In order to achieve that, there must be a logical connection between the fundamental variable and the cost estimate. Additionally, it must display a strong statistical adjustment and high level of confidence. Data collection is typically the most critical step towards establishing parametric cost correlations (PCC). Cost data sources are diverse: project databases from other companies, public archives and others. Tough amply used, they might not be uniform in terms of criteria, specifications, materials and implemented technologies and thus, are inconvenient in that cost data will require some form of normalisation and adjustment, particularly in terms of inflation/deflation for different time spans. Another problem is the occurrence of outliers that must be identified and excluded from the analysis (USDOD, 1995).

For this project, wastewater infrastructure cost data were collected for December 2000-2008, and adjusted to December 2008 values. Cost components included: pumping stations, collection networks, transmission and gravity lines and wastewater treatment facilities (WWTF). Table 2 presents the variables defined for each of them.

Component	Sub-component	Dependent variables	Independent variables
Pumping station	Construction, equipment and testing	Total cost (€)	Power (W)
Network	Construction, equipment and residential connections	Total cost (€) unit cost (€/m) per capita cost (€/inhabitant)	Population (inhabitants) length of network (m) inhabitants/m
Transmission and gravity lines	Construction, equipment and testing	Total cost (€)	Length of line (m) line diameter (m)
WWTF	Construction, equipment and testing	Total cost (€) per capita cost (€/inhabitant)	Population (inhabitants)

Table 2 – Wastewater infrastructure components: dependent and independent variables

Data were subjected to regression analysis using the least square method, to obtain simple linear, multiple or non-linear models. Each correlation was then tested with regards to its significance, by analysing the quality of the data, the logical connection between parameters, using the F-test and calculating the standard deviation, the correlation and determination coefficients. In order to determine each model's ability for forecasting, it became necessary to analyse the number of observations, outliers and data range. The following sections present a series of charts depicting the relationship between dependent and independent variables for each of the components listed above. The statistical analysis parameters are presented in Appendix.

Pumping stations

Figure 3 displays the variation of total pumping station cost with power installed.

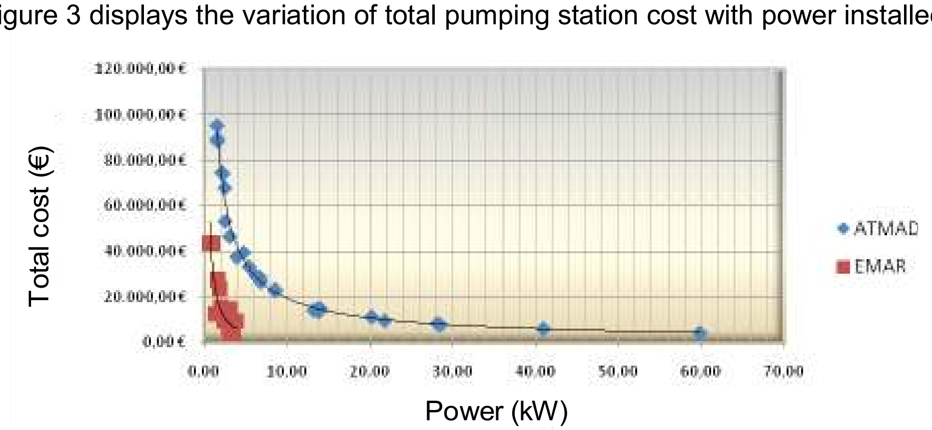

Figure 3 – Pumping station: total cost versus power

The data refer to several systems managed by two separate managing agencies, ATMAD and EMAR. As seen, total cost is significantly higher for lower power installations. Though the correlation coefficient for the EMAR regression is not as good as the one for ATMAD, both significance values are less than 5%, denoting a significant correlation between the selected variables.

The same trends can be observed in Figure 4. Lower flowrates to pump imply significantly higher pumping costs. As for the previous case, a significance correlation was found between cost and flowrate.

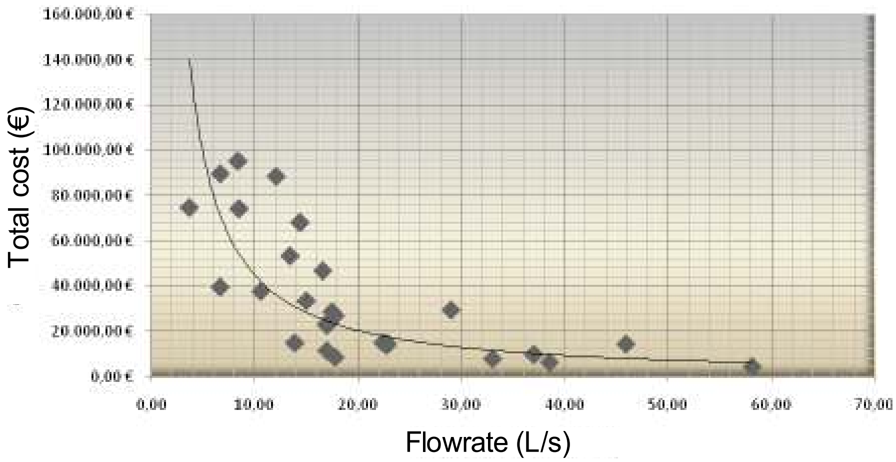

Figure 4 – Pumping station: Total cost versus flowrate

Since the flowrate to pump is directly proportional to the size of population served, it is logical to infer that the total pumping station costs will also be higher for smaller populations.

Networks

As presented in figure 5 and 6, the total network cost increases with growing populations and network size. In both cases, the correlation between was found to be significant.

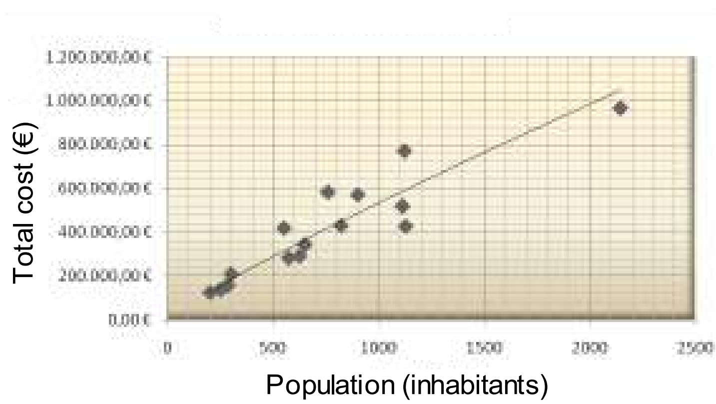

Figure 5 – Network: total cost versus population

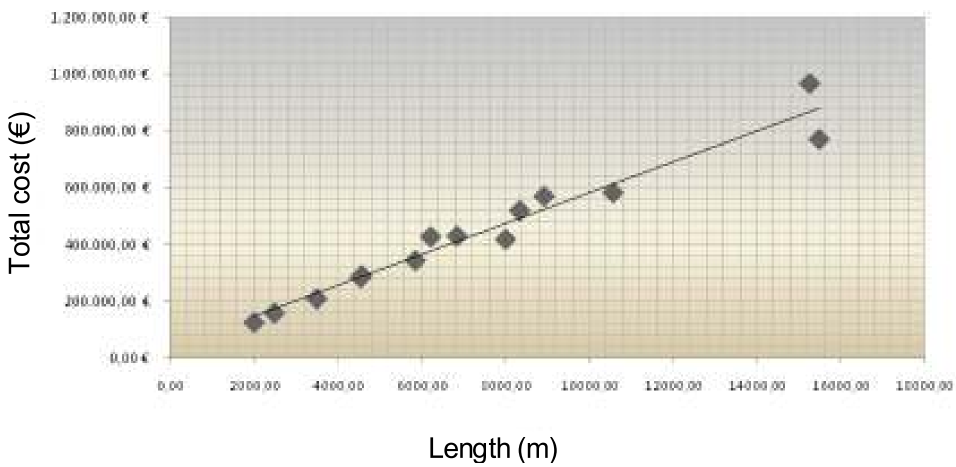

Figure 6 – Network: total cost versus length

In order to analyse the behaviour of network costs in terms of type of population dispersion, the following charts (Figures 7 and 8) establish the relationship between unit cost and inhabitant per meter of network.

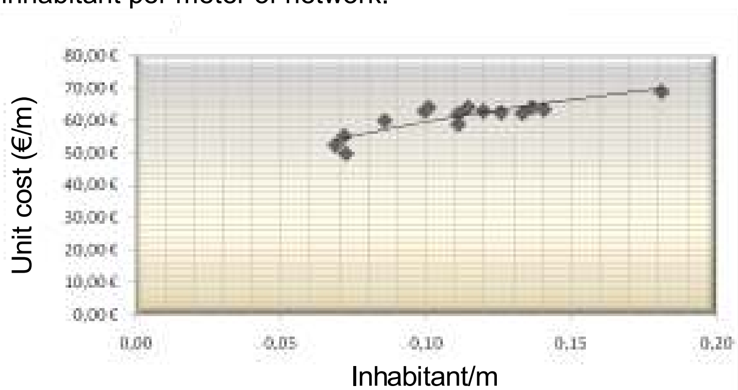

Figure 7 – Network: unit cost versus inhabitant/m

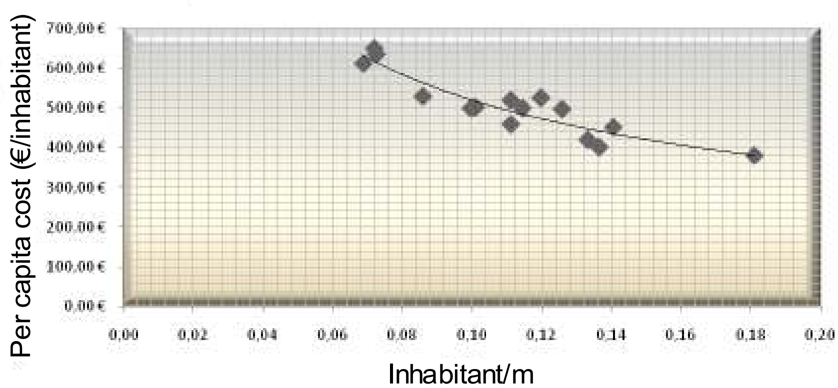

Figure 8 – Network: per capita cost versus inhabitant/m

From Figure 7, unit cost increases with the number of inhabitants per meter of network. This means that for the same network length, its cost increase is directly proportional to population size. This increase is due to the need for larger pipe diameters and greater number of residential connections to the service network.

Conversely, the per capita cost is higher for lower values of inhabitants per meter of network (Figure 8). This is because the increase in unit cost is not sufficient overcome the reduction in per capita cost, suggesting economic advantages to implementing networks for denser population clusters.

Lines

The trend observed in Figure 9 is not surprising, given the results from Figure 6.

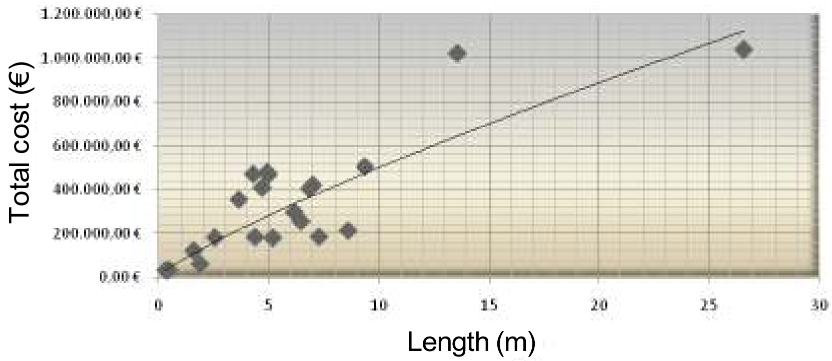

Figure 9 – Lines: total cost versus length

Similar trends are displayed in Figure 10, for any of the diameter ranges, though costs tend to be higher for larger diameter lines.

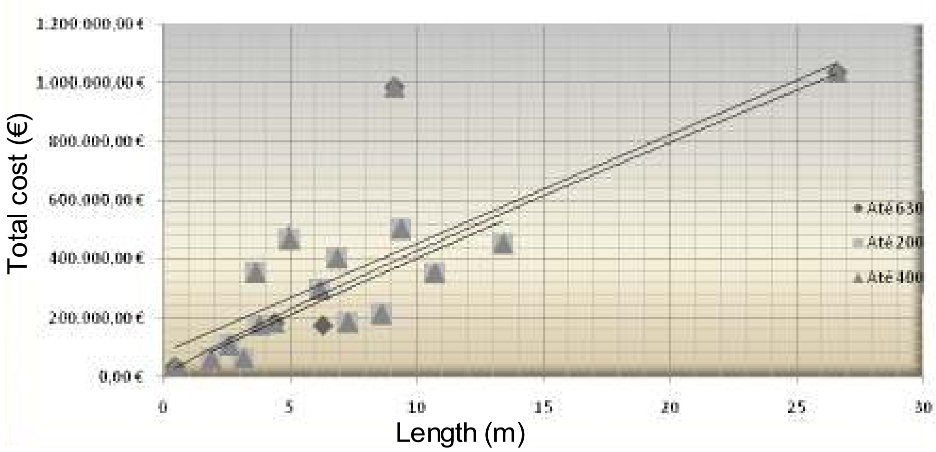

Figure 10 – Lines: total cost versus length, function of diameter

For both sets of data, the variables were found to correlate significantly.

Wastewater treatment facilities

Once again, Figure 11 shows rising cost in increase in population size. However and similarly to Figure 8, per capita costs are significantly lower for larger populations (Figure 12).

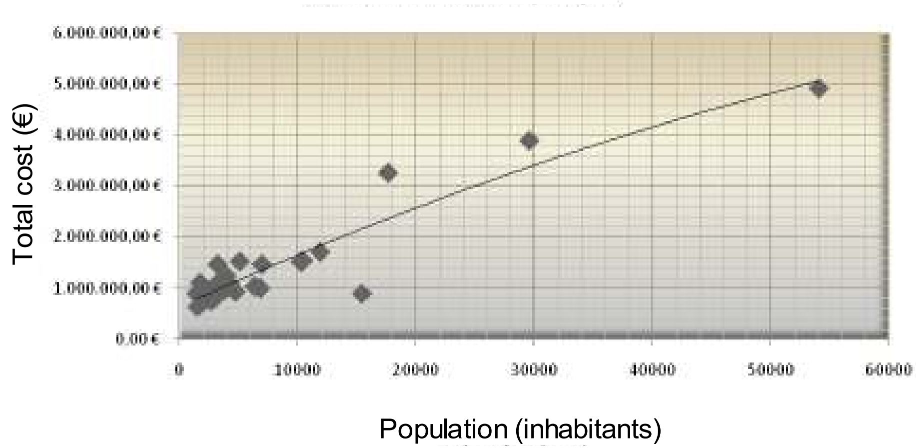

Figure 11 – WWTF: total cost versus population

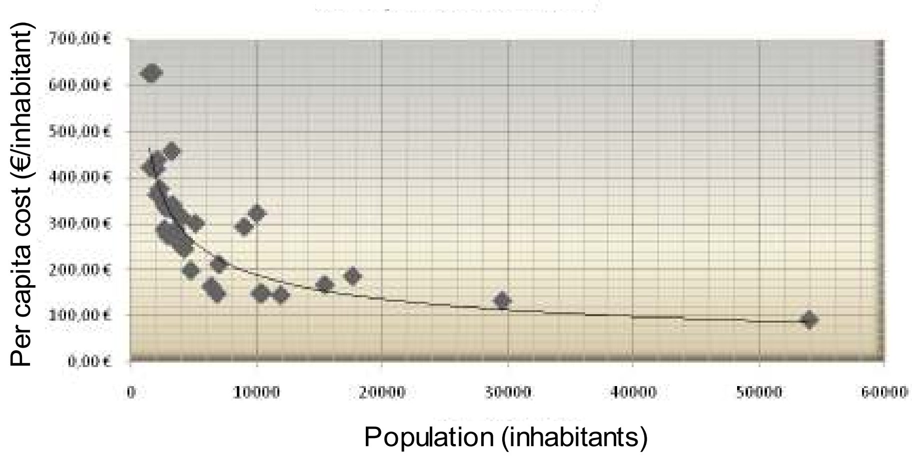

Figure 12 – WWTF: per capita cost versus population

These results suggest the benefit of treating larger volumes of wastewater in one WWTF rather than carrying out treatment of smaller volumes distributed by smaller treatment installations, as possibly required for more disperse urban types.

The statistical analysis results presented in Appendix demonstrate the significant correlation between the variables under study for instances of the analysis. However and in some instances, the correlation coefficient is lower than desirable (< 0.9). This indicates the need to caution if and when using the corresponding parametric model for cost estimation.

Conclusions

The relationship between wastewater infrastructure cost and urban sprawl – using selected infrastructure projects from the Douro region – was explored through a series of parametric models defined for a number of components that best describe the whole of a wastewater infrastructure system.

Though preliminary in nature, the models adequately correlate the cost of each component with population dispersion-related variables, confirming initial assumptions that denser urban clusters provide for economical advantages in terms of implementation of wastewater systems. With regards to the statistical analysis conducted so far, the results suggest the need for caution when using the proposed models. Additional data and further refinement of the regression methodology is recommended.

Additional work is already under way towards conducting a similar methodology for determining parametric cost estimation models for water and other infrastructures. This improved and detailed knowledge on infrastructure layout and costs will further enhance the quality of future planning decisions in critical areas, aiming for more balanced development and investment strategies.

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Appendix

Figure	Model	Sample size	Outliers (exclusions)	Correlation coefficient	Determination coefficient	Adjusted Determination coefficient	F-test	Significance
3 (EMAR)	$y = 18752{,}592 \cdot X^{-0.905}$	11	1	0.746	0.557	0.501	10.045	0.013
3 (ATMAD)	$y = 104113{,}75 \cdot X^{-0.759}$	27	0	0.993	0.987	0.986	1881.819	0.000
4	$y = 483610{,}542 \cdot X^{-1.066}$	27	0	0.796	0.633	0.619	43.205	0.000
5	$y = 800.547 \cdot X^{0.920}$	15	0	0.954	0.911	0.904	132.81	0.000
6	$y = 68.663 \cdot X^{0.967}$	15	0	0.979	0.959	0.956	305.867	0.000
7	$y = 111.692 \cdot X^{0.352}$	15	0	0.747	0.558	0.524	16.433	0.001
8	$y = 933.273 \cdot e^{-6.008}$	15	0	0.920	0.846	0.834	71.215	0.000
9	$y = 74402.338 \cdot X^{-0.827}$	21	0	0.89	0.792	0.781	72.424	0.0002
10 (<200 mm)	$y = 74402.338 \cdot X^{-0.827}$	13	0	0.732	0.536	0.494	12.725	0.004
10 (<400 mm)	$y = -536948.241 + 132990.985 \cdot X$	9	5	0.72	0.518	0.449	7.53	0.029
10 (< 630 mm)	$y = 74402.338 \cdot X^{-0.827}$	4	0	0.901	0.536	0.718	8.625	0.099
11	$y = 14870.116 \cdot X^{0.475}$	36	1	0.927	0.859	0.854	176.216	0.000
12	$y = 14870.116 \cdot X^{0.475}$	36	1	0.876	0.768	0.761	109.392	0.000