Determination of capital costs for conventional sewerage systems (collection, transportation and treatment) in a developing country

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ABSTRACT

Unit construction costs expressed as ranges of values are useful in most preliminary studies, in which detailed designs are not available in order to support specific cost estimates. This paper presents ranges of values for capital costs related to conventional sewerage systems in Brazil. The data were based on published references or information from consulting firms and sanitation companies and comprised budgets made at the design stage or after completion of the works. All cost data were converted to the common date of April 2010. The unit costs were expressed as: collection system (US$/m and US$/inhabitant), transportation system (US$/m and US$/inhabitant) and treatment system (US$/inhabitant). Total costs for the implementation of the overall sewerage system (collection, transportation and treatment) ranged from around US$170 to US$770/inhabitant, depending on pipe diameter and on pipe-laying conditions (percentage of rocks and pavement), as well as on the treatment process employed. In all cases, approximately 60% of the total capital costs were represented by the collection system. The influence of the transportation (interceptor) costs was also investigated and found to indicate that, for small populations, the construction costs associated with the interceptors may be larger than those linked to the treatment plants.

Key words | capital costs, construction, sewerage system, wastewater treatment

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INTRODUCTION

Conceptual studies associated with the implementation of the sewerage system to be adopted in a community are usually based on construction costs reported simply as cost functions or ranges of values, and not on detailed and disaggregated cost estimates. Cost estimates based on accurate budgeting are usually done at the basic or executive design stage, in which, for instance, soil and concrete volumes have been calculated and equipment and ancillary works have been specified. This information is, of course, not available during preliminary or feasibility studies, and for this reason, simple cost estimates based on unit values, such as per capita or per metre length of pipes, are very useful.

The international literature presents many reports that aimed to obtain simple functions or cost models, such as Smith (1968), Fraas & Munley (1984) and Reilly & Gottlieb (1993). The United States Environmental Protection Agency has a series of publications on wastewater treatment costs (e.g. USEPA 1983). Maurer *et al.* (2006) presented a survey of cost data from European countries and the USA. The cost data are for the year 2002, and are separated for large countries (which are likely to have larger cities and the possibility of economy of scale) and smaller countries. The typical capital cost figures obtained were: (i) large countries: sewers US$2100/inhabitant; wastewater treatment plant U$500/inhabitant; total U$2600/inhabitant; (ii) small countries: sewers US$3800/inhabitant; wastewater treatment plant U$1000/inhabitant; total U$4800/inhabitant. From these values, it is seen that the costs associated with sewers represent around 80% and the treatment

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plants account for only 20% of the total capital costs involved in the overall sewerage system.

However, most of the published data come from developed nations, in which more sophisticated treatment processes, such as activated sludge, prevail. For developing countries, cost ranges for wastewater treatment are published in reports from the World Bank, such as Davis & Hirji (2003), which presented ranges of values for low income (US$20–80/inhabitant), middle income (US$30–50/ inhabitant) and industrialized countries (US$150–300/ inhabitant). Arthur (1983) presented a widely quoted World Bank report that investigated treatment costs of trickling filters, aerated lagoons, oxidation ditches and waste stabilization ponds, which are treatment processes potentially applicable in developing countries. Von Sperling & Chernicharo (2005) presented a different synthesis based on literature values, with capital cost ranges for 27 different combinations of wastewater treatment processes applied in warm climate regions, with overall values ranging from US $15 to US$70/inhabitant (year 2003) – see Figure 1 – or US$25 to US$105/inhabitant corrected for 2010. Although these values may, of course, vary from country to country, their relative position will probably be somewhat similar.

The present work aims to contribute to this international database on the overall construction costs of wastewater systems (sewage collection, transportation by

System	Construction costs (US$/inhab)
Primary treatment (septic tanks)	12 – 20
Conventional primary treatment	12 – 20
Advanced prim. treatment (chemic. enhanced)	15 – 25
Facultative pond	15 – 30
Anaerobic pond + facultative pond	12 - 30
Facultative aerated lagoon	20 – 35
Complete-mix aerated lagoon + sedimentation pond	20 – 35
Anaerobic pond + facultative pond + maturation pond	20 – 40
Anaerobic pond + facultative pond + high rate pond	20 – 35
Anaerobic pond – facultative pond + algae removal	20 – 35
Slow rate treatment	8 – 25
Rapid infiltration	12 – 30
Overland flow	15 – 30
Constructed wetlands	20 – 30
Septic tank + anaerobic filter	30 – 50
Septic tank + infiltration	25 – 40
UASB reactor	12 – 20
UASB + activated sludge	30 – 45
UASB + submerged aerated biofilter	25 – 40
UASB + anaerobic filter	20 – 30
UASB + high rate trickling filter	25 – 35
UASB + dissolved-air flotation	25 – 35
UASB + maturation ponds	15 – 30
UASB + facultative aerated pond	15 – 35
UASB + compl.mix aerated lagoon + sediment. Pond	15 – 35
UASB + overland flow	20 – 35
Conventional activated sludge	40 – 65
Activated sludge – extended aeration	35 – 50
Sequencing batch reactor (extended aeration)	35 – 50
Conventional activated sludge with biological N removal	45 – 70
Convent. activated sludge with biological N/P removal	50 – 75
Conventional activated sludge + tertiary filtration	50 – 75
Low rate trickling filter	50 – 60
High rate trickling filter	50 – 60
Submerged aerated biofilter with nitrification	30 – 50
Submerged aerated biofilter with biological N removal	30 – 50
Rotating biological contactor	50 – 60

Figure 1 | Typical per capita construction cost ranges for various wastewater treatment systems operating in developing countries (base year: 2003). Source: von Sperling & Chernicharo (2005). Data from 2003. To change to 2010, multiply all values by 1.5 (conversion factor of the exchange rate between US$ and the Brazilian currency, R$, upon which the construction costs in this figure have been based). UASB: Upflow anaerobic sludge blanket.

interceptors and treatment), with ranges of capital costs (or capital expenditure – capex) derived from actual figures from a developing country (Brazil), encompassing a wide range of conditions and processes.

METHODS

Construction costs for the collection network and interceptors were obtained from cost estimates undertaken by a Brazilian consulting company at the detailed design stage. For wastewater treatment costs, the sources were published data (Brostel *et al.* 2001; Jordão & Pessoa 2005) and information from consulting companies in Brazil, as well as the Water and Sanitation Company of Minas Gerais (COPASA). The sewerage systems are of the conventional separate reticulated type, comprised of interceptors and treatment plants.

All costs were converted to the same base of April 2010, using the National Construction Cost Index from Getúlio Vargas Foundation (www.escgaspar.com.br/incc.htm, site in Portuguese), since most of the infrastructure was not imported. The conversion from the Brazilian currency (R$) to US$ was made using the following exchange rate: R$1.00 = US$0.59). Figure 2 illustrates the monthly percentages of cost increases throughout the past 10-year period (2000–2010), together with the cumulative increase. It can be seen that construction costs have increased around 80% in Brazil, even during a period of controlled inflation. This is an important point to highlight for other studies that compare costs from different time periods, because of the potential strong influence of cost increases, especially in developing countries.

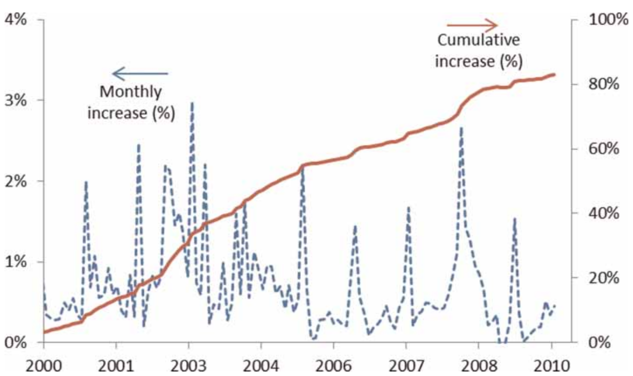

Figure 2 | Absolute and cumulative monthly increases in the construction costs in Brazil from 2000 to 2010.

The cost figures presented in this paper cover all construction costs involved in the implementation of the systems, including material, equipment, personnel, incidental values and other costs. Different cost functions were explored, which indicated that economies of scale and pipe depth on their own were not enough to explain cost variations. Therefore, given the complexity and variety of implementation conditions, cost ranges have been explored instead. These cost ranges were structured in such a way as to comprise the 25 and 75 percentiles of cost values. In other words, 50% (=75 – 25) of the towns are likely to have construction costs that fall within this percentile range, which could be considered as the typical costs. Of course lower and higher values are encountered, reflecting the diversity in the implementation conditions for the units comprising the sewerage system.

The construction costs associated with the network of sewage collection pipes were divided into two categories, representing different degrees of difficulty in the implementation of the system: (i) soil with less than 10% rocks and with less than 40% of paved streets; (ii) soil with more than 10% rocks and with more than 40% of paved streets. The unit costs were expressed as US$ per metre length and US$ per inhabitant served by the system. Data came from 18 different towns, with each town having one sewerage network. The population values were those adopted in the design of the sewerage system.

The costs related to the transportation of the wastewater to the treatment plant (interceptors) were segregated into the following categories: (i) soil with less than 10% rocks; pipe diameters less than or equal to 300 mm; (ii) soil with less than 10% rocks; pipe diameters greater than 300 mm; (iii) soil with more than 10% rocks; pipe diameters less than or equal to 300 mm; (iv) interceptors with special laying conditions, interferences or crossings. In all cases the soil was considered dry or predominantly dry (presence of water in less than 40% of cases). Data were obtained from 47 towns.

Pumping stations are not included in this paper, because they depend essentially on the topography of the area, and in overall terms have been shown to represent only between 2 and 6% of the total capital costs involved with the complete sewerage system.

The treatment plants were separated into eight categories, representing commonly applied systems in Brazil: (i) facultative ponds and anaerobic + facultative ponds; (ii) facultative and anaerobic + facultative ponds followed by maturation ponds; (iii) UASB (upflow anaerobic sludge blanket) reactors; (iv) UASB reactors + one or two maturation ponds in series; (v) UASB reactors + three or more maturation ponds in series; (vi) UASB reactors + anaerobic filters; (vii) UASB reactors + trickling filters; (viii) activated sludge. Data from 84 treatment plants were used.

RESULTS AND DISCUSSION

Sewerage collection systems

Table 1 and Figure 3 present a summary of the cost data related to the implementation of the pipelines for sewage collection. The different pipe-laying conditions (presence of rocks and paving conditions on the streets that receive the pipelines) clearly influence the construction costs. Removal of rocks and pavement, followed by further rebuilding of the pavement, increases the construction costs for the installation of sewers. Expressing the costs in round figures, it can be said that, under favourable conditions, costs for collection systems range from US$100 to US$200 per inhabitant, and under more complex conditions, they can more than double, ranging from US$300 to US$400 per inhabitant. The conversion of costs per metre and costs per inhabitant depends on the population density in the towns. In the present case, average unit lengths of pipelines ranged from 2 to 5 m per inhabitant.

Interceptors

The summary of cost data related to the construction of sewage interceptors is presented in Table 2 and Figure 4. Again, pipe-laying conditions have a large influence on the costs. For the more common case of favourable conditions and pipe diameters less than or equal to 300 mm (which prevail in small towns), round figures for unit costs are US$75 to US$130 per metre length. These values can more than double for interceptors with large diameters or with special conditions, such as interferences and crossings. Expressing costs per inhabitant is not entirely appropriate for interceptors, because these costs will depend largely on the distance

Table 1 | Capital cost information for the sewerage collection network (base year: 2010)

Type	Number of data	Ranges of values in the database: Depth (m) (min–max)	Ranges of values in the database: Population (inhab) (min–max)	Costs per unit length (US$/m) 25–75%iles (median = 50%ile)	Costs per inhabitant (US$/inhab) 25–75%iles (median = 50%ile)
Soil with <10% rocks and <40% of paved streets	6	1.15–1.74	254–7,231	51–58 (55)	108–208 (168)
Soil with >10% rocks and >40% of paved streets	12	0.85–1.76	296–13,998	59–87 (68)	291–414 (329)

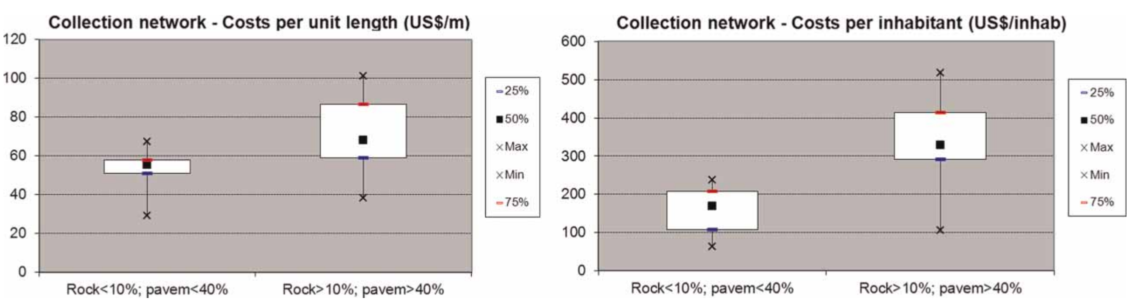

Figure 3 | Construction costs for the sewage collection network, expressed as capital costs per unit length (US$/m) and per inhabitant (US$/inhabitant) (base year: 2010).

Table 2 | Capital cost information for the sewage interceptors (base year: 2010)

Type	Number of data	Ranges of values in the database: Depth (m) (min–max)	Ranges of values in the database: Population (inhab) (min–max)	Costs per unit length (US$/m) 25–75%iles (median = 50%ile)	Costs per inhabitant (US$/inhab) 25–75%iles (median = 50%ile)
Soil with <10% rocks; diameters <300 mm	26	0.75–2.46	49–7,955	73–130 (94)	37–102 (57)
Soil with <10% rocks; pipe diameters >300 mm	6	1.52–2.52	7,976–61,125	145–302 (203)	14–43 (31)
Soil with >10% rocks; diameters <300 mm	7	0.92–2.78	316–6,067	116–157 (134)	51–63 (56)
Special conditions (interferences and crossings)	8	1.08–2.14	1,277–176,637	221–295 (261)	37–73 (57)

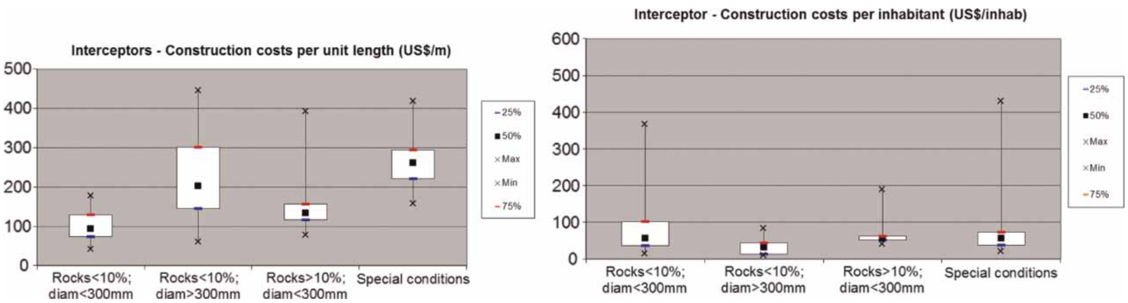

Figure 4 | Construction costs for the sewage interceptors, expressed as capital costs per unit length (US$/m) and per inhabitant (US$/inhabitant) (base year: 2010).

through which the collected sewage must be transported, along the bottom of a valley, until reaching the treatment plant. However, for the sake of completeness, these costs are presented here, allowing an approximate idea of usual per capita values. Still, it can be seen that the median of per capita costs are around US$60 per inhabitant for the more common case of diameters less than or equal to 300 mm (including special conditions).

Wastewater treatment plants

Traditionally it is assumed that there is economy of scale when implementing a wastewater treatment plant. For instance, Maurer (2009) made an analysis of the influence of the population size on the capital costs of wastewater treatment plants and found that, for the same treatment process, the ratio between capital costs for two cities with different populations is equal to the ratio of the populations raised to a scaling factor; based on a literature survey, the value of this scaling factor is typically around 0.7. However, in the present work, as mentioned in the Methods section, economy of scale could be observed for some wastewater treatment processes, while for others its influence was negligible. Figure 5 shows two examples of this situation. Another point that is clear from Figure 5 (and for many other similar graphs, not presented here) is that there was a substantial scatter of the per capita cost values. The inconsistent evidence of the economy of scale and the scatter in the per capita cost values led to the decision to report the treatment plant costs as simple ranges of typical per capita values instead of further exploring the influence of the population size on the per capita costs.

Costs associated with sewage treatment are summarized in Table 3 and Figure 6, for different treatment processes. Natural treatment by ponds (facultative or anaerobic + facultative) has unit costs between US$50 and US$90/inhabitant (round figures), and the inclusion of a pathogen removal stage by maturation ponds increase

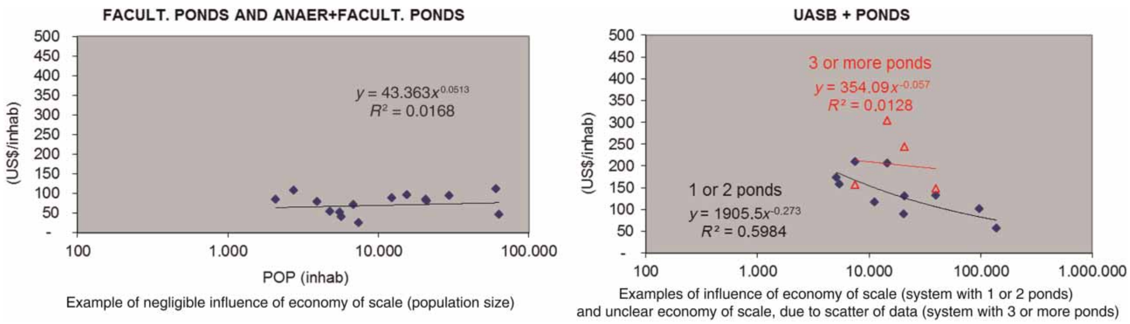

Figure 5 | Examples of wastewater treatment processes, without and with influence of population size on the per capita capital costs (y = per capita costs, in US$/inhabitant; x = population, in inhabitants).

Table 3 | Capital cost information for the wastewater treatment plants (base year: 2010)

Type	Number of data	Population (inhab) (min–max)	Costs per inhabitant (US$/inhab) 25–75%iles (median = 50%ile)
Facultative and anaerobic + facultative ponds	15	2,089–61,000	53–92 (81)
Facultative and anaerobic-facultative ponds + maturation ponds	10	1,000–14,485	119–215 (134)
UASB reactors	5	4,320–15,146	23–72 (31)
UASB + one or two maturation ponds in series	10	5,135–138,000	106–170 (132)
UASB + three or more maturation ponds in series	4	7,292–41,330	154–258 (200)
UASB + anaerobic filters	9	1,381–199,041	85–126 (98)
UASB + trickling filters	22	4,584–300,000	86–145 (109)
Activated sludge	9	40,000–1,500,000	141–174 (165)

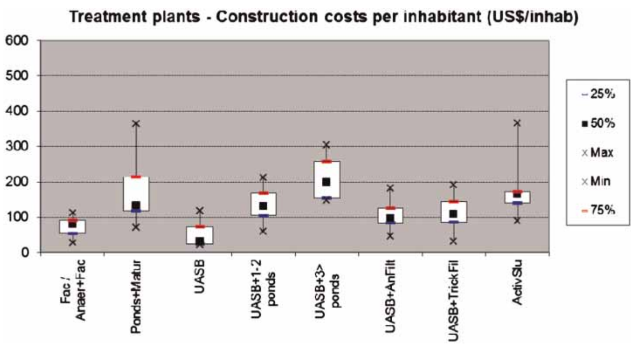

Figure 6 | Construction costs for the wastewater treatment plants as a function of the treatment process, expressed as capital costs per inhabitant (US$/inhabitant) (base year: 2010).

the total costs by a factor around 2.4 (associated with the larger number of ponds and total area required). Treatment by UASB reactors alone represents the cheapest variant, with round unit costs between US$25 and US$70/inhabitant. Several post-treatment options for the UASB effluent are presented here, from natural to compact systems. Post-treatment by ponds raises the total costs to around between US$100 and US$170/inhabitant, in the case of one or two ponds, and between US$150 to US$260/inhabitant, in the case of three or more maturation ponds. Post-treatment by compact systems, such as anaerobic filters and trickling filters, has somewhat similar total costs, in the range of US$85 to US$140/inhabitant. Treatment by activated sludge has the highest costs among the compact systems.

The comparison of processes based purely on per capita costs hides the fact that the processes investigated here have different treatment objectives. Most of them aim mainly at the removal of organic matter and suspended solids. The two variants incorporating maturation ponds (after anaerobic/facultative ponds and UASB reactors) are those with the higher construction costs among the processes investigated. However, it should be understood that these systems are able to remove the four categories of pathogenic organisms (practically 100% of protozoan cysts and helminth eggs, and more than 99.99% pathogenic bacteria and virus), as well as achieving substantial removal of ammonia. In a similar way, the activated sludge process is the most expensive of the compact systems, but the process is also able to remove ammonia by nitrification.

Total capital costs of collection, transportation and treatment of sewerage systems

The ranges of overall costs associated with the implementation of conventional sewerage in the towns investigated are summarized in Figure 7, which is simply an aggregation of costs presented in Tables 1–3 (25 and 75 percentiles values). The cost components are broken down and separated for the easier/less expensive and more difficult/more expensive pipe-laying conditions or treatment processes. The less expensive conditions for sewage collection are those related to soils with less than 10% rocks and less than 40% paving, and the more expensive conditions are those that do not fulfil this criterion (see Table 1). For interceptors, since per capita costs are not exactly representative of their costs, which are strictly dependent on transportation distance, the per capita values used for the less expensive and more expensive conditions are the same, reflecting the more usual situation in small cities, that is, soils with less than 10% rocks and diameters less than 300 mm (see Table 2). For treatment plants, the least expensive system

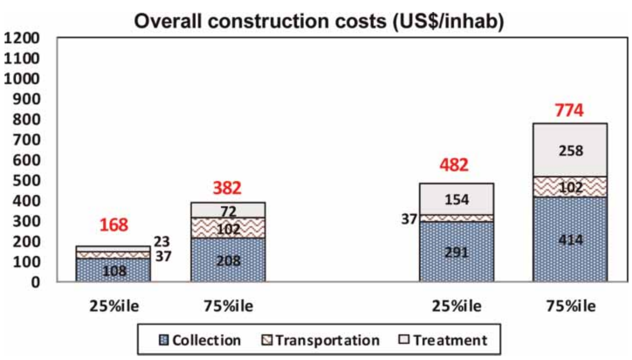

Figure 7 | Total capital costs of collection, transportation and treatment of sewage (25 and 75 percentiles), disaggregated as a function of implementation conditions – less expensive and more expensive pipe-laying conditions for sewage collectors and interceptors and process variant for treatment plant. Total costs are presented above each bar (base year: 2010).

to build was represented by the UASB reactor alone and the most expensive system was the UASB reactor followed by three or more maturation ponds (see Table 3). Total costs ranged between the 25 and 75 percentiles of US$168 and US$382/inhabitant for the less expensive conditions, and more than double, between US$482 and US$774/inhabitant, for the more expensive conditions. These values are substantially lower than those reported for European countries and the USA – typical values of US$2600 and US$4800/inhabitant for large and small countries, respectively (Maurer *et al.* 2006), which reinforces the need of this type of information for developing countries.

In all cases, the largest cost component was represented by the collection system, which accounted for between 53 and 64% of the total costs. In the less expensive conditions, interceptors represented the second largest cost component, but in the more expensive situation, the second place was taken by the treatment plants. Treatment plants accounted for between 15 and 33% of the total costs, which is in the same order of magnitude reported by Maurer *et al.* (2006).

Scenario planning for selection of wastewater treatment sites considering transportation and treatment construction costs

In preliminary studies for the implementation of new wastewater treatment plants in sewered communities (a typical situation in developing countries), a frequent decision has to be made: is it cheaper to select a nearby site, with less available land, or a faraway site, in which there is more land available? In the former case, with less area, more compact treatment systems will need to be adopted, possibly leading to higher capital costs for wastewater treatment, but to savings in sewage transportation (shorter interceptor lengths). In the latter case, in which a larger area is selected, transportation costs will be higher, but treatment costs will probably be cheaper (adoption of natural treatment processes, which require larger areas). This situation is illustrated in Figure 8, in which the two alternatives are depicted.

The following simple example will clarify the relative influence of capital costs for transportation and treatment. A small town of 1,000 inhabitants is considered, and it is assumed that less expensive pipe-laying conditions for

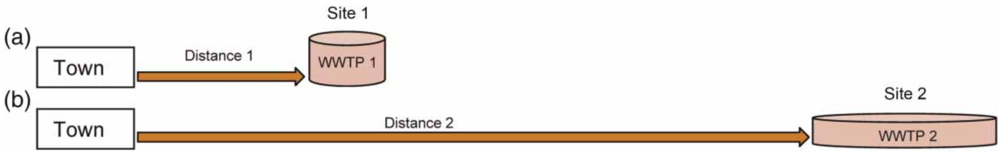

Figure 8 | Two common alternatives in preliminary studies. (a) Smaller and cheaper interceptor, more compact and more expensive treatment (site 1). (b) Larger and more expensive interceptor, natural and less expensive treatment (site 2).

interceptors will prevail and that simple treatment processes will be adopted. The sewage collection costs will not be computed here, because they are the same for both alternatives.

Adopting a compact treatment system comprised by UASB reactor followed by trickling filters will incur for 1,000 inhabitants × US$109/inhabitant = US$109,000 (median value of US$109/inhabitant – see Table 3). If the treatment plant is close to the town (site 1 in Figure 8) and the overall interceptor length is only 1,000 m, the total transportation cost will be 1,000 m × US$94/m = US $94,000 (median of US$94/m – see Table 2). In this case, the total costs will amount to US$94,000 + 109,000 = US $203,000.

However, if, for instance, natural treatment systems are employed, with a lower median cost of US$81/inhabitant (see Table 3), the treatment capital costs will reduce to US $81,000. In this case, since a larger area for treatment will be required (site 2 in Figure 8), probably longer transportation distances will be necessary in order to arrive at a suitable site. If the interceptor length becomes, for instance, 3,000 m, the transportation costs will change to 3,000 m × US$94/m = US$282,000, and the overall costs will amount to US$81,000 + 282,000 = US$363,000, a value that is greater than that from the previous alternative, offsetting the advantage of adopting a cheaper treatment process. Of course, for larger interceptor lengths, the difference will be even greater.

Figure 9 illustrates the resulting transportation and treatment costs for different population sizes, for the same conditions as the example above (interceptor costs = US$94/m; low treatment costs = US$81/inhabitant; high treatment costs = US$109/inhabitant). It is seen that, for small populations such as the one from the example (1,000 inhabitants), capital costs for transportation are likely to be higher than treatment costs. For larger towns, the relative weight of the transportation costs tends to decrease. For instance, for a population around 10,000 inhabitants, capital costs for transportation will only be higher than treatment costs if the interceptor length is larger than 12 km, which is seldom the case in practice for a town, of such a size. Similar graphs can be plotted for different unit costs for transportation and treatment.

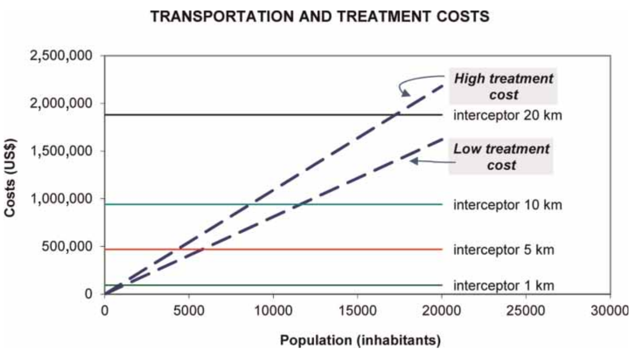

Figure 9 | Capital costs for transportation (solid horizontal lines) and treatment (dashed lines), for different combinations. Data are the same as the one presented in the example in the text (interceptor costs = US$94/m; low treatment costs = US$81/inhabitant; high treatment costs = US$109/inhabitant).

As a general comment, it can be said that for small towns (fewer people), in terms of capital costs, it is more advantageous to treat the wastewater at short distances, even if the treatment process is more expensive. Only for larger populations, does it start to be more advantageous to transport the sewage to larger distances, in order to find sites that can accommodate cheaper treatment plants. In summary, for small towns, transportation costs play a decisive role, whereas for medium to large towns the capital costs may be dominated by the treatment.

It should be pointed out that the analysis as done here is very simplistic, because it takes into account only capital costs. In the present example, the treatment processes selected may have somewhat similar operation and maintenance costs, since none of the treatment processes is highly mechanized and consume energy. But if this is not the case, net present value studies for a certain planning horizon need to be made in order to convert annual operating costs to the present value, which can be summed with the capital costs in order to come to the overall (capital plus operation and maintenance) cost of each alternative.

CONCLUSIONS

The paper presents the breakdown of the capital costs of the three major components of a conventional separate sewerage system (collection, transportation and treatment) in a developing country (Brazil). Under more favourable pipe-laying conditions (soil with less than 10% rocks and less than 40% of pavement in the streets), capital costs for collection systems range from US$100 to US$200 per inhabitant, and can more than double if the site conditions are more difficult. In the case of interceptors, for the more common case of favourable site conditions and pipe diameters less than or equal to 300 mm (which prevail in small towns), unit capital cost figures are from US$75 to US$130 per metre length, but can reach US$300 per metre in case of more difficult pipe-laying conditions. Regarding wastewater treatment plants, eight different processes were investigated, and per capita capital costs ranged from US$25 to US$260/inhabitant, depending on the treatment process applied, which are in the broad range of values available in the literature.

Total capital costs for the implementation of the overall sewerage system (collection, transportation and treatment) range from around US$170 to US$770/inhabitant, depending on pipe diameter and on the degree of difficulty in pipe laying, as well as on the treatment process employed. In all cases, approximately 60% of the total costs are represented by the collection system.

From the cost figures presented, it is likely that, for small populations, the capital costs associated with the interceptors may be larger than those linked to the treatment plants, depending on the transportation distance. Therefore, finding suitable close sites for the wastewater treatment plants, thus reducing the costs associated with the interceptors, may lead to the overall lowest implementation costs. However, one should note that this comment only applies to capital costs, and operation and maintenance costs, which have not been considered in this research, may lead to different conclusions.

It is expected that this paper will bring contributions to increasing the database of construction costs of sewerage systems in developing countries. In terms of wastewater treatment, the cost values of systems incorporating UASB reactors with or without post-treatment are of particular interest, as such systems are a very significant alternative for warm climate regions and developing nations, and their costs are not easily found in the literature.

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