Decentralised wastewater treatment technologies from a national perspective: at what cost are they competitive?

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Abstract In this paper we estimate at what cost decentralised wastewater treatment can be competitive compared with conventional centralised technologies. For the current wastewater infrastructure in Western Europe and North America, typical replacement costs are 2,600 US$/cap for large countries and 4,800 US$/cap for small ones. In the same literature, average annual operating costs are reported to be 3.8% of replacement costs. However, if a long-term interest rate of 3% is consistently applied, this value increases to 4.7% for small countries and 5.5% for large ones. Assuming that alternative wastewater systems will only be accepted if their costs are similar to existing ones, the possible investments for alternative wastewater treatment technologies are calculated. Between 640 and 2,170 US$/cap can be invested in new technologies for scenarios without a sewer system. The corresponding figures for scenarios with sewer systems are between 260 and 680 US$/cap. Acceptable maintenance requirements are calculated on the basis of unit size. Transition periods are not accounted for.

Keywords Alternative wastewater treatment; competitive costs; decentralised wastewater treatment; scenarios; urine separation

Introduction

For more than a century, wastewater systems in Europe and the USA have been based on a sewage network designed to collect wastewater, which is then usually processed by a central treatment unit. This concept is now being increasingly challenged, mainly for reasons of sustainability and the difficulties of exporting the concept to water-scarce countries experiencing rapid urban growth (Larsen and Gujer, 1997). In this paper, we will examine the economic basis for a paradigm change. We claim that any new concept will have to be economically competitive with the existing one, at least in the long run. Alternatively, new systems must provide additional services for which the public is willing to pay. The former criteria will be more likely to apply to countries without an existing sewer system and the latter ones to water-scarce countries where a sewer system is less suitable. We will start by trying to determine the comprehensive cost of the current system of sewers and central treatment plants. In view of a lack of data and the distorting effect of subsidies, this is by no means an easy task. On the basis of these costs, we will compare different conceptual alternatives and determine rough estimates for the possible investment and maintenance costs that will not exceed the costs of the conventional system.

Costs for sewers and treatment plants

Although costs alone may not be a sufficient criterion to induce system changes, they play a critical role in decision-making. The following chapter gives an overview of the costs involved in centralised wastewater treatment in Europe and the USA on the basis of figures taken from the literature and aggregated for entire countries. For comparison purposes, all
local currencies are converted to US$ using purchasing power parities (PPP from OECD, 2003) and all monetary data in this publication are indexed to the year 2002 using the Chemical Engineering plant cost index (CE, 2003), which is widely used for the financial analysis of large-scale technical systems.

Replacement costs and investments
Table 1 summarises the estimated replacement costs for several national wastewater treatment systems. The figures for Switzerland are based on non-representative data of varying quality from selected regions, published by the Swiss environmental protection agency (BUWAL, 2003). The data for Germany are taken from a comprehensive study conducted by the German wastewater association (Dudey and Pecher, 1994). This work is based on a survey of 1,182 municipalities, representing almost 52% of the entire German population. The data also allows the shares for the sewer system (78.5%) and the wastewater treatment plants (21.5%) to be identified. All other data from Europe are taken from a study of the German environmental protection agency that compares costs in several European countries (Rudolph et al., 1999). In order to make the numbers comparable, adjustments were made for subsidies, tax, one-time costs, specific water consumption and public services (e.g. street runoff). No replacement costs were found for the United States. As an approximation, we base our data on previous and forecast investments designed to upgrade the system to the nationally required level. Please note that since future investments include maintenance and replacement, it may be argued that a minor part of the investments is counted twice.

Table 1 shows that replacement costs and investments range from 1,700 to 5,300 US$/cap. For a system complying with present standards, the minimum replacement costs for centralised wastewater systems seem to be around 2,600 US$/cap. It must be emphasised that these figures indicate only the public part of the infrastructure. Private sewers in particular, e.g. the connection from the house to the public sewer line, can be substantial. In a German study that covers 50,875 km of public sewers, the total length of the corresponding private pipes is estimated at about 91,850 km (Berger et al., 2002). This indicates that the non-public part of the sewer system may represent a considerable value that is not accounted for in Table 1 due to very limited reliable information about the extent, costs and condition of private sewers. The same holds true for industrial wastewater treatment plants as well as additional small decentralised ones.

The “absolute level” of wastewater treatment has only a minor influence on the total investment costs. Even in countries with high requirements for wastewater treatment (Germany, Denmark, Switzerland), the investments do not substantially exceed the 20% level (Table 1). However, this changes when the “technical level” of the wastewater treatment is considered. Looking only at the WWTP fraction, there is a significant price difference in plants for BOD and nutrient removal due to the substantial increase of tank volume for nitrification. Typically, nutrient removal doubles the price of simple WWTPs (Bohn, 1997; Nolting and Dahlem, 1997).

Table 1 indicates that the specific burden for citizens of small countries is greater than in large ones (economies of scale). An appropriate explanation for this may be found in the catchment areas. Dudey and Pecher (1994) report higher specific costs for smaller cities and show that for cities with fewer than 10,000 inhabitants the specific investments are 4,300 US$, namely 60% higher than the national average. There is a 60% cost decline for the next cluster of cities (smaller than 50,000) and another 20% for cities with 100,000 inhabitants. It seems that smaller countries follow this trend, mostly because the average size of their cities is smaller (e.g. Switzerland or Denmark) or because a considerable part of the population lives in remote areas (Austria). In Switzerland for
Table 1 Estimated replacement cost of the urban wastewater system in selected countries. Local currencies are converted to US$ using PPP (OECD, 2003; listed in Table 2) and indexed for the year 2002 using the plant costs index obtained from Chemical Engineering (CE, 2003)

<table>
<thead>
<tr>
<th>Country</th>
<th>Pop.(^a) (10(^6) cap)</th>
<th>Served sewers</th>
<th>Served WWTP</th>
<th>Total (US$/cap)</th>
<th>Sewer (US$/cap)</th>
<th>WWTP (US$/cap)</th>
<th>Remarks</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>5.4</td>
<td>0.87</td>
<td>0.77</td>
<td>5,300</td>
<td></td>
<td></td>
<td>1996</td>
<td>b</td>
</tr>
<tr>
<td>Switzerland</td>
<td>7.3</td>
<td>0.96</td>
<td>0.95</td>
<td>4,400</td>
<td>3,650</td>
<td>750</td>
<td>2002</td>
<td>c</td>
</tr>
<tr>
<td>Austria</td>
<td>8.2</td>
<td>0.75</td>
<td>0.74</td>
<td>4,800</td>
<td>3,900</td>
<td>900</td>
<td>1996</td>
<td>b</td>
</tr>
<tr>
<td>Italy</td>
<td>58.0</td>
<td>0.77</td>
<td>0.63</td>
<td>3,900</td>
<td>3,200</td>
<td>700</td>
<td>1996</td>
<td>b</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>60.1</td>
<td>0.98</td>
<td>0.87</td>
<td>3,700</td>
<td></td>
<td></td>
<td>1996</td>
<td>b</td>
</tr>
<tr>
<td>France</td>
<td>60.2</td>
<td>0.81</td>
<td>0.77</td>
<td>2,600</td>
<td></td>
<td></td>
<td>1996</td>
<td>b</td>
</tr>
<tr>
<td>Germany</td>
<td>82.4</td>
<td>0.92</td>
<td>0.87</td>
<td>2,600</td>
<td>1,850</td>
<td>750</td>
<td>1993</td>
<td>d</td>
</tr>
<tr>
<td>USA today</td>
<td>275.3(^h)</td>
<td>0.71</td>
<td>1.70</td>
<td></td>
<td></td>
<td>Investments up to 2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA 2019</td>
<td>322(^h)</td>
<td>0.71</td>
<td>2,300~2,900</td>
<td></td>
<td></td>
<td>Target for 2019</td>
<td></td>
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</tr>
</tbody>
</table>

example, 60% of the population live in cities with fewer than 10,000 inhabitants, a city size category which accounts for 96% of all cities (BFS, 2003). Since our information is at national level (Table 1), we distinguish between large and small countries in this publication. The underlying assumption is that a majority of the population in large countries lives in large cities (= catchment areas) with more than 50,000 inhabitants and hence benefits from economies of scale.

Annual costs
For various reasons, finding and comparing annual costs is even more difficult than determining replacement costs. Firstly, it is difficult to track the different sources of investment capital in the wastewater sector, where public funds play a major role. Secondly, due to different lifespan assumptions, the problematic distinction between investment and maintenance, the diverse approaches to interest rates, and the frequent lack of knowledge of the depreciation rate for the total assets, it is difficult to determine the total annual costs correctly. Finally, the problem of the non-public parts of the system, such as private sewers and industrial WWTPs, is encountered again. As already discussed in the previous section, neither the investments nor the costs of these installations are accounted for in the available statistics. This makes it difficult to identify the exact capital cost, which includes depreciation and capital financing costs (such as interest payments). This session cannot give a detailed economic breakdown of the current annual costs for wastewater handling, but tries to establish a basis for discussion for the next session. To this end, the following paragraphs discuss three cost elements, namely operation and maintenance costs, depreciation and capital-financing costs.

Operation and maintenance (O&M) costs. The literature typically specifies values of between 26 and 65 US$/cap annually (or 0.7–1.8% of replacement costs) as average national O&M costs. The variances are mainly caused by differing costs of labour and sludge disposal, as well as the tricky distinction between maintenance and investments costs. Within the variations, no clear tendency can be discerned for different WWTP sizes. Only the expenses for labour differ significantly, from 50% for plants of less than 100,000 population equivalent (PE) to 25% for plants bigger than 1 million PE (Bohn, 1997). No detailed information about the costs split between WWTP and sewer systems can be found in the literature. For this publication we use a plausible assumption that approximately 25% of the total operating costs are accounted for by the sewers and the other 75% by the WWTP (BUWAL, 2003).

Depreciation. The average lifespan of the urban water infrastructure depends on many factors and is in general very difficult to estimate. Besides the pure physical aging or wearing due to environmental stresses, functional aging also needs to be considered. This occurs when a required performance exceeds the technical specifications, e.g. if an increase of population overloads the hydraulic capacity of the main sewer or the WWTP. In addition, other problematic issues include the definition of the end-of-life of a sewer pipe, a clear distinction between maintenance and replacement or the real depreciation rates that are used from an accounting point of view. The German guideline (ATV, 1996) recommends linear depreciation factors of 1% to 2% for sewers and 4% to 5% for wastewater treatment plants. On the basis of these guidelines and the information in Table 1, therefore, we assume a lifespan of 80 years for sewers and 25 years for WWTP plants, and an investment-cost split of 80:20 for sewers and WWTP respectively. For the linear depreciation model, we calculate an annual depreciation rate for the entire system of 1.8% (1/80·0.8 + 1/25·0.2 = 1% + 0.8%) of annual investment costs.
Capital-financing costs. These are normally costs for accessing the capital market to finance investments, such as interest payments in the case of loans or profits in the case of equity (“return on equity”). These costs can generally have a substantial impact on the annual cost of a system, considering the high investment costs and long life cycles of the assets. From an economic standpoint, there is no imperative need to charge the customer for capital-financing costs based on the replacement costs of the entire system; indeed it might even be questionable to do so. The financing structure, i.e. the share of loans, equity and public grants used for the original investment, is decisive for the exact determination of the capital financing costs. However, the aim of this paper is to provide an estimate of the acceptable costs for alternative technologies. We therefore assume that there will be no equity-based financing, so the only capital-financing costs we have to consider are the interest payments.

An average capital-financing rate, derived from a net present-value analysis, is used. The integral of the interest payments over the entire financing period is divided by the lifespan in years and expressed as an average discounted annual capital-financing rate. At an interest rate of 3% and a lifespan of 80 years, for example, the net present value of all interest payments is 165% of the investments, which yields an average annual capital-financing rate of 2.06%. For comparison purposes (subsequently with alternative scenarios) we make the assumption that the loan for the investment has the same duration as the lifespan of the assets, rather than being a normal long-term loan of 15–20 years taken out on a revolving basis.

An average annual capital-financing rate of 2.0% can be calculated for the entire wastewater treatment system on the basis of a typical annual interest rate of 3% and the various lifespans for the different assets discussed in the last section. The average annual payment for capital financing costs is therefore between 52 and 96 US$/cap. A comparison of this with the figures in Table 2 shows clearly that neither the costs nor the fees represent the full amount for depreciation, capital financing and O&M costs.

Conclusion: Replacement and running costs

Table 3 summarises the typical figures for the annual and replacement costs of the wastewater treatment systems of an entire country. Typical costs for large and small countries are 2,600 US$/cap and 4,800 US$/cap respectively, and 80% of the value is locked in the sewer system. If we include the costs of capital, the estimated annual operating cost relative to the replacement cost of the wastewater treatment infrastructure is 4.7% for small countries and 5.5% for large ones (Table 3), based on a long-term interest rate of 3%.

Table 2 Average fees and estimated annual costs per capita for sewer and wastewater treatment plants.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>102</td>
<td>102</td>
<td>65</td>
<td>8.66</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>63</td>
<td>102</td>
<td>34</td>
<td>1.91</td>
<td>c</td>
<td></td>
</tr>
<tr>
<td>Austria</td>
<td>155</td>
<td>155</td>
<td>26</td>
<td>0.94</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>92</td>
<td>79</td>
<td>n.a.</td>
<td>0.85</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>135</td>
<td>153</td>
<td>33</td>
<td>0.63</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>128</td>
<td>134</td>
<td>n.a.</td>
<td>0.91</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>127</td>
<td>147</td>
<td>64</td>
<td>0.99</td>
<td>d</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>103</td>
<td>n.a.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>96</td>
<td>109</td>
<td>1.00</td>
<td>1.19</td>
<td>e</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>27</td>
<td>109</td>
<td>1.19</td>
<td>Based on estimated margin costs</td>
<td>i</td>
<td></td>
</tr>
</tbody>
</table>

References: i: Renzetti (1999), other references are listed in Table 1
For the eight countries listed in Table 2, the averaged figure taken from the literature is 3.8%.

The WWTP plays a significant role for the operation costs, whereas the investments costs are mainly dominated by the sewer system. Approximately one third of the annual costs are assigned to operating the plants, another third for the depreciation and the last third for interest (3% interest rate). It is self-evident that in reality operating costs are subject to strong variations due to local regulations (e.g. sludge disposal) and cost structures (e.g. labour cost). The analysis shows clearly that capital-financing costs can have a very significant influence on the annual costs of wastewater treatment and must be included if new systems or alternatives are compared with each other.

### Future treatment systems: possible end-point scenarios

In this session we identify some of the framework conditions needed for the successful implementation of a completely new wastewater treatment approach based on a national or super-regional framework. The financial considerations presented here may not apply to regional or small-scale implementation and may need to be adapted. We will discuss various technical scenarios.

- **Scenario 1 (A and B): decentralised wastewater treatment without a sewer.** A radical scenario which reduces the requirement for a sewer system to the absolute minimum, deals with the entire polluted wastewater in the household itself and disposes of storm water and treated wastewater locally. We look at an **A-situation** ("from scratch") without an existing sewer and a **B-situation** ("existing sewer") with an existing, well-maintained sewer. The technical basis for such radical scenarios is discussed in the literature (e.g. Larsen and Gujer, 2001).

- **Scenario 2 (A and B): decentralised wastewater treatment with a sewer.** The (existing) sewer remains as it is. In **scenario A** ("decentralised WWTP"), the wastewater is treated in decentralised facilities as close as possible to the source, thus obviating centralised wastewater treatment systems. **Scenario B (urine separation)** is a urine-separating scenario with minimal changes to the existing sewer-based system, operating on the principle of waste design (Henze, 1997). For simplicity, we will look only at the most straightforward case: thanks to urine separation, a new treatment plant can be built without nutrient elimination (for various urine separation scenarios, see e.g. Larsen and Lienert, 2003).

Due to the existing wastewater infrastructure, transition scenarios are always critical when discussing the costs of new technologies. However, such a discussion is beyond the scope of this paper. In all scenarios, we consider that a new treatment plant has to be built. For the sewer system, only scenario 1B is critical with respect to transition. In this special case, we will discuss our assumptions within the scenario itself.
Scenario 1: Alternative solutions without a sewer system

Scenario 1A: “from scratch”. Since there is no existing infrastructure in this case, the full costs of establishing a new conventional wastewater treatment system can be assigned to an alternative solution. The acceptable annual costs per capita are therefore assumed to be similar to the costs summarised in Table 3: 142 US$/cap·yr for large countries and 227 US$/cap·yr for small countries. In each case the operation costs are 44 US$, while 98 US$ represent capital costs for large countries and 183 US$ for small countries.

Scenario 1B: “existing sewer”. In this scenario, we consider the situation that a sewer network is abandoned and radically decentralised wastewater treatment technology introduced. Since the investments in the sewer are not recovered, possible capital-financing costs remain and are not available for an alternative system. We consider that in a mature sewer system depreciation corresponds to the ongoing replacement of the sewer, keeping the average life expectancy constant. This replacement can be abandoned, so that the depreciation costs become available for alternatives. The same is of course true for the operating costs. We made the assumption that a new WWTP has to be built, which results in the same allocation of cost elements to new and old infrastructure. Based on these assumptions and Table 3, the acceptable annual costs per capita are 99 US$/cap·yr for large countries and 149 US$/cap·yr for small countries.

Scenario 2: Alternative solutions with a sewer system

Scenario 2A: decentralised WWTP. We see from Table 3 (by replacing the centralised WWTPs and their associated costs) that the acceptable annual costs for decentralised systems are 62 US$/cap·yr for large countries and 90 US$/cap·yr for small countries. They comprise a capital cost (depreciation and capital financing costs) of 29 US$ for large countries and 57 US$ for small countries. The operating costs are 33 US$ (for both large and small countries).

Scenario 2B: urine separation. This scenario is designed for areas with sensitive surface waters that require nutrient elimination. By collecting and treating urine separately, it is possible to avoid implementing nutrient removal in central WWTPs. Switching from nutrient removing plants to high loaded WWTP halves the investment requirements for the treatment plant (14 US$/cap·yr for large countries and 29 US$/cap·yr for small countries) and decreases the operating costs by 25% (8 US$/cap·yr; data from Nolting and Dahlem, 1997; Bohn, 1997; Table 3). Hence, the total funds available for the urine separation are 22 US$/cap·yr for large countries and 37 US$/cap·yr for small countries.

Conclusions for alternative scenarios

If we accept similar O&M expenditures to those in conventional systems (Table 3), we can estimate the possible investments in new technologies and their corresponding unit sizes. We assume that the lifespan of all decentralised treatment systems (rain and wastewater) is 15 years, which results in a depreciation rate of 6.7%. For interest rates of 3% over 15 years, an annual capital financing rate of 1.7% is calculated. The total annual capital costs will then be 8.4%. Without significantly exceeding the current annual cost level, we can use these figures to determine the possible investments for new treatment technologies in the various scenarios (Table 4).
Discussion and conclusions

In this paper, we have estimated the cost of decentralised wastewater treatment technologies in order to be competitive with conventional centralised technologies on a national level. We made the assumption that, on the basis of equivalent performance, alternative wastewater systems will be accepted only if their costs correspond to the savings resulting from abandoning the existing system. In view of this objective and given the length restrictions of this paper and the problems frequently encountered with the database, it is obvious that the calculations and approaches described here must be seen as purely indicative and not as being fully reliable at micro level in an empirical sense. The following comments might represent useful steps towards comparing centralised and decentralised solutions.

Capital-financing costs. We emphasize that there is a substantial difference between our aim and the typical aim of an economist who may calculate the correct fee to be charged for the services of an existing sewer system. For example, it is questionable to charge the customer for capital-financing costs based on replacement costs. However, in order to make the different technical approaches comparable, capital-financing costs are a very good measure for the amount of capital tied-up in the form of hardware. Smaller investments with short lifespans can then be compared with buildings that last several generations. Finally, this approach makes the difference between the private and public operation of wastewater removal transparent.

Lifespan. Scenario 1 clearly shows that the lifespan of the wastewater infrastructure corresponds directly to the amount of potential investments in hardware. Switching from the current centralised system with an average lifespan of 56 years to a decentralised concept with an assumed lifespan of 15 years reduces the equivalent per capita replacement costs by more than 50%. On the other hand, it brings benefits from the possibility of competition (as in any other market) and the potential for innovation due to shorter life cycles.

Operation & maintenance. One major concern of decentralised technology is the unknown costs for appropriate O&M. Maintenance costs correlate directly with the economical unit size. This leads to the not very surprising consequence that at the level of households (typically comprising three people), a treatment system with a lifespan of 15 years must be inexpensive (less than 2,000 US$ for scenario 2A) and should have low professional maintenance requirements (less than 3 hours per year). Looking at common household appliances, these requirements look fairly reasonable but require mass production.
Transition. Conventional centralised systems are investment-intensive and the sewer infrastructure is responsible for 80% of the replacement costs. Any larger investment in a sewer system leads very quickly to a technological lock-in, as adding a new customer to the system reduces the average per capita costs. Investments in a sewer system are sunk costs and cannot be recovered if the system is abandoned. We would like to argue that this lack of flexibility is a highly problematic aspect of sewer-based centralised wastewater treatment. Consequently, it would be important to develop transition scenarios for breaking out of this situation. Scenario 2B, urine separation, represents a possible attempt to develop such transition scenarios. However, since the urine separation technology discussed here involves only waste design and no changes to the basic concept of sewer-based wastewater treatment, it can only be a very first step towards a decentralised system.

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