Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making

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ABSTRACT

Construction costs of 55 municipal wastewater treatment plants in Israel (secondary, advanced secondary, and advanced treatment) were analysed in order to derive cost functions expressing the effects of design flow and treatment level on construction costs. Three equations were derived (statistically significant, \( p < 0.01 \)), one for each treatment level. These indicate that economy of scale may become weaker as treatment level rises. Analysis of the distribution of construction costs revealed negative correlation \( (p < 0.05) \) between the proportional cost of civil engineering and design flow, positive correlation \( (p < 0.05) \) between the proportional cost of electromechanical equipment and design flow, and no correlation between the proportional cost of electricity and control and design flow. Operation costs were found to be 20–70% more sensitive than construction costs to treatment level. The share of operation costs as part of the total annual costs was found to increase both with design flow and treatment level, whereas the share of construction costs concurrently decreased. The implication of the findings on policy, and consequently on treatment plants performance is discussed in the last part of the paper.

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1. Introduction

Much attention is given in the literature to engineering and process related aspects of MWWTPs (Municipal Wastewater Treatment Plants). On the other hand, although the overall costs of MWWTP (construction, operation and maintenance) play a great role in wastewater management strategies in most places, much less information is available on these and relatively few empirical studies are available. Even less attention is given to the interaction between cost, government policy and the performance of MWWTPs.

This paper tries to analyse these interactions in a systematic manner. It will be shown that the current financial support policy of the Israeli central government to local authorities may contradict public interest, since it may be a contributing factor for the poor performance of many newly built MWWTPs that were designed to produce high quality effluents (Mayson, 2005). To do so, the paper uses empirical data to analyse the relationship between construction costs of MWWTPs, their design flow, and treatment level. Then it examines the different components of MWWTP construction (namely: civil engineering, electro-mechanical equipment, and electricity and control), quantifies their proportion of the total construction costs as a function of MWWTP size, and discussed the implications of the findings on policy making. The last part of the paper analyses the effects of treatment level and design flow on construction and O&M (operation and maintenance) costs, concentrating mainly on cost distribution between these two components of treatment costs (expressed in terms of annual payment). Subsequently,
the implications of these economic aspects and financing policy of the Israeli government on the performance of MWWTPs are discussed.

Analysis of MWWTPs economics reveals that the principal determinants of treatment costs are size—expressed either by design flow or by served population size (p.e.—population equivalent), quality of raw sewage to be treated, and the required quality of the effluent. Cost functions of MWWTP often are expressed in the form of an exponential equation (Fraas and Munley, 1984; Uluatam, 1991; Balmer and Mattsson, 1994; Vanrolleghem et al., 1996; Tsagarakis et al., 2003):

\[
C = a \cdot x^b
\]  

(1)

where \(C\)—Construction costs, \(a\)—Coefficient \([\text{cost} \cdot (\text{m}^3 \cdot \text{d}^{-1})^{-b}]\) or \([\text{cost} \cdot (\text{p.e.})^{-b}]\), \(x\)—Design capacity either design flow \(\text{[m}^3 \cdot \text{d}^{-1}]\) or population served \(\text{[p.e.]}\), \(b\)—Power coefficient \([-\)].

The power coefficient of Eq. (1) is usually less than one, indicating that the specific construction costs (cost per \text{m}^3 treated or cost per p.e. served) decline with size (economy of scale). Data used in the literature as a basis for assigning values for the coefficients in Eq. (1) differs considerably. While some authors use data from real MWWTPs others use analytical estimations (Bode and Grunebaum, 2000; Tsagarakis et al., 2003). Furthermore, not always the same components are incorporated into the cost equation.

2. Sources of information

The paper uses empirical data from Israel which is a densely populated small country (population 7 \times 10^6, December 2005) having semi-arid climate. The country suffers from a severe water shortage. In order to cope with the water stress, many wastewater reuse schemes, which operate mainly for agricultural irrigation, have been introduced in the last few decades. These vary in size from small local schemes to large regional ones. To date, more than 65% of the collected municipal sewage is reused for agriculture, and by the end of the decade it is envisaged that this proportion will rise to 90% (Friedler, 2001). The dominant MWWTPs in Israel are based on the activated sludge process, thus the analyses were performed only on this type of plants. Data was gathered from several sources: applications for government support of approved projects, projects that were executed and their costs appear in governmental records, and from engineering firms.

Real construction costs and design flows of 55 MWWTPs were collected, of which 37 were designed for secondary effluent quality (design flow ranging from 1400-120,000 m^3 \cdot d^{-1}), 11 designed for advanced secondary quality (design flow 4500-120,000 m^3 \cdot d^{-1}) and 7 MWWTPs (design flow 3000-15,000 m^3 \cdot d^{-1}) were designed for tertiary quality or advanced wastewater treatment (see discussion below). Detailed information on the breakdown of construction costs to its main components—civil engineering, electromechanical equipment, and electricity and control—was available only for 9 MWWTPs in the database. The design flow of these MWWTPs ranged from 3000–37,000 m^3 \cdot d^{-1}. Data on O&M costs were taken from a study performed for the Israeli Ministry of Environment (Adan Ltd., 1999).

As the above projects were executed over several years, the construction cost of each was normalised to the same basis, $US in 2000 ($Y2K). This was performed by converting the costs (which were given in NIS) to $US according the exchange rate at the time the project was executed, and then by updating the cost obtained to $Y2K by using the change in the US Consumer Price Index—all urban (CPI) over time Eq. (2). The USEPA costs functions (Huang, 1980), were updated to $Y2K by applying Eq. (2) while using the US CPI and alternatively the US Producer Price Index—capital equipment (PPI). The change of the latter index between 1978 and 2000 was almost identical to the change of the US ENR building cost index.

\[
PV_t = HC_{t_0} \cdot \frac{I_t}{I_{t_0}}
\]  

(2)

where \(PV_t\)—Present value at year \(t\) (year 2000 in our case), \(HC_{t_0}\)—Historical cost at year \(t_0\), \(I_t\)—Present index (CPI or PPI), \(I_{t_0}\)—Historical index (CPI or PPI).

3. Effluent classification and treatment level

The minimum effluent quality required by Israeli regulations is secondary effluent quality (Fine et al., 2006). This quality is usually achieved by treatment plants operated with conventional activated sludge technology, followed by disinfection with chlorine or chlorine derivatives. Advanced secondary treatment is defined as activated sludge technology which is designed for both carbonaceous material removal and nitrification, followed by disinfection. Advanced wastewater treatment level includes a large variety of treatment technologies, among them: chemical precipitation, micro and ultra filtration, activated carbon adsorption and reverse osmosis. Table 1 lists the treatment levels that were used as benchmarks for the economical analysis.

<table>
<thead>
<tr>
<th>Treatment level</th>
<th>Effluent quality—USEPA [mg \cdot l^{-1}]</th>
<th>Effluent quality—Israel [mg \cdot l^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary</td>
<td>BOD(_5) = 25–30</td>
<td>BOD(_5) = 20; TSS = 30</td>
</tr>
<tr>
<td>Advanced secondary</td>
<td>BOD(_5) = 10–24</td>
<td>BOD(_5) = 10–15; TSS = 15–20</td>
</tr>
<tr>
<td>Advanced wastewater</td>
<td>BOD(_5) ≤ 10</td>
<td>BOD(_5) &lt; 10; TSS &lt; 10</td>
</tr>
<tr>
<td>Nitrification</td>
<td>NH(_4)-N &lt; 5</td>
<td>Performed-no numerical limit</td>
</tr>
<tr>
<td>Phosphate removal</td>
<td>P tot &lt; 3</td>
<td>Performed-no numerical limit</td>
</tr>
</tbody>
</table>

Table 1 – Effluent quality and treatment levels classification
4. Construction costs in Israel

Employing regression analysis the ‘a’ and ‘b’ coefficients (Eq. (1)) were derived for the three types of MWWTPs as a function of their design flow. Table 2 shows that the correlation coefficients of secondary treatment MWWTP and advanced secondary treatment MWWTPs were found to be statistically significant (p < 0.01). The correlation coefficient of advanced wastewater treatment MWWTPs was not proven to be statistically significant. This may be due to the small number of MWWTPs in this category for which cost data were available, as indicated by the small difference between the R value obtained (0.796) and the critical R value (0.81, for p = 0.05).

The power coefficients found in this study fall within the range reported in the literature (0.68—Aivaliotis et al., 1991; 0.71—Bode and Grunebaum, 2000; 0.89—Fraas and Munley, 1984; 0.73–0.77—Huang, 1980; 0.76—Randall and Cokgor, 2000; 0.775–0.954—Tsagarakis et al., 2003). An interesting phenomenon is that the power coefficients (b), appear to become less as treatment level rises (Table 2). This, although not tested statistically, gives an indication that the effect of economy of scale may become weaker as treatment level rises.

Fig. 1 reveals that for the range of design flows studied, construction costs in Israel exhibit very similar behavior to the USEPA models (Huang, 1980), both with respect to sensitivity to design flow, and to effluent quality. Being a small country, the sample size of MWWTPs is limited, thus the high resemblance to the USEPA models (which are based on a much larger sample size) strengthens the validity of the current findings. It should be noted that for all three treatment levels, the Israeli construction costs are somewhat lower than the USEPA cost equations. This may be due to several reasons: during the update of the USEPA construction costs, increase in process efficiency and cost reduction for specific technology, which are expected to occur in two decades, were not considered; somewhat lower standard of living in Israel that leads to lower construction costs; variation in construction regulation, and variation in building specification between the two countries.

<table>
<thead>
<tr>
<th>Treatment Levela</th>
<th>This study Israel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary treatment</td>
<td>$C = 8988 \cdot Q^{0.71}$</td>
</tr>
<tr>
<td></td>
<td>$n = 37, r = 0.908, p &lt; 0.01$</td>
</tr>
<tr>
<td>Advanced secondary+nitrification</td>
<td>$C = 2790 \cdot Q^{0.84}$</td>
</tr>
<tr>
<td></td>
<td>$n = 11, r = 0.938, p &lt; 0.01$</td>
</tr>
<tr>
<td>Advanced wastewater treatment</td>
<td>$C = 1934 \cdot Q^{0.87}$</td>
</tr>
<tr>
<td></td>
<td>$n = 7, r = 0.796, p &gt; 0.05$</td>
</tr>
</tbody>
</table>

(Critical value for p = 0.05 is 0.81)

5. Costs distribution between the main construction components

Fig. 2 illustrates that the proportional cost of the main components of MWWTPs construction reacts differently to changes in the design flow (the analysis is based on nine MWWTPs for which reliable data on cost distribution was available, see sources of information above): The proportional cost of civil engineering consists about 65% of the total construction costs in small plants, declining to 30% in large ones; the proportional cost of electromechanical equipment behaves the other way around increasing from 20% in small plants to 50% in large ones; the proportional cost of electricity and control was found to increase very moderately with design flow, from 15% in small plants to 20% in large ones. The figure further demonstrates that the proportional cost of civil engineering and electro-mechanical equipment equals at a design flow of 28,000 m$^3 \cdot d^{-1}$.

Although the sample size was very limited (nine MWWTPs), within the range of design flows analysed (3000–37,000 m$^3 \cdot d^{-1}$), the linear regressions for both civil engineering and electromechanical equipment proportional costs were found to be statistically significant (p < 0.05). On the other hand the regression of electricity and control was not proven to be statistically significant, indicating that the proportional cost of electricity and control may not change with size. It is likely that the linear regressions of the proportional costs of civil engineering and electromechanical equipment shown in Fig. 2 represent the linear part of overall theoretical curves. Had lower and higher design flows been considered, these curves might develop into an inverted S-type (civil engineering) and S-type (electromechanical equipment) curves. In this type of curves the proportional cost for low and high design flows tends towards high and low asymptotic values.

This phenomenon has two implications to policy makers and to local authorities which are responsible for wastewater treatment: 1) Due to the fact that the serviceable life of electromechanical equipment is much shorter than the serviceable life of civil engineering components (15 years compared with 40 years, Israel Water Commission, 2002), the depreciation time of the overall construction costs is significantly reduced as the design flow increases and the consequent capital costs (annual return of construction costs) become higher. 2) Construction of MWWTPs, small and large, is usually led by civil contractors due to their expertise in construction management, their capabilities in project management and co-ordination of all contractors. Authorities should realise that as the MWWTP size increases the emphasis shifts from civil works to electromechanical equipment installation, and thus select contractors who are capable to coordinate massive electromechanical works.

A scant amount of information on this subject is available in the literature. Adan Ltd. (1999), whose analysis was based on synthetic data, showed the same general response to design flow, i.e.: the proportional cost of civil engineering decline from 42% in small MWWTPs to 30% when the design flow reaches 35,000 m$^3 \cdot d^{-1}$, the proportional
Cost of electromechanical equipment rises from 48% to 58% with the same variation in design flow, while the proportional cost of electricity and control does not vary with design flow consisting 10% of the total construction costs.

Borboudaki et al. (2005) report on a secondary WWTP in Crete with a capacity of 8,000 m³/d civil works consisted 57% of the total capital costs of the plant. The average distribution of construction costs between civil engineering, electromechanical equipment, and electricity and control, in Germany is 65, 25 and 10% respectively (Bode and Grunbaum, 2000). These authors further state that the proportional cost of civil engineering tends to decline as the required effluent quality rises, explaining that this is the result of installation of more “high-tech”/machinery based units when MWWTPs are upgraded to reach higher effluent quality.
6. The effect of treatment level and design flow on construction and O&M costs

Both construction costs and O&M costs depend on the required effluent quality (which is a function of treatment level), where higher treatment level results in higher costs of both components. Although the above is obvious, a closer look may reveal that construction costs and O&M costs have different sensitivities to treatment level. To do so, construction and O&M costs were transformed to a relative basis, where the costs of secondary treatment (either construction or O&M) were considered as reference costs and were given a relative cost of 1. All costs of higher treatment levels were divided by the respective secondary treatment costs, and thus were expressed in a relative form to these reference costs. The treatment level examined were in increasing order in accordance with current Israeli trend in of upgrading effluent intended to increase the possibilities of effluent reuse for agricultural irrigation while protecting the environment (Fine et al., 2006). These were:

1. Secondary treatment–Reference treatment (cost considered as 1)
2. Secondary treatment followed by filtration.
4. Secondary treatment incorporating nutrients removal, followed by filtration and carbon absorption.
5. Same as the latter followed by reverse osmosis (RO).

Fig. 3 reveals that O&M costs are more sensitive to treatment level than construction costs, with the relative costs of O&M being 20 to 70% higher than the relative costs of construction (depending on the treatment level). For example, while the relative construction costs of the fourth treatment level (#4 above) are 1.4–1.7 times higher than the construction costs of secondary treatment, the relative O&M costs of the same treatment level are 2.3–2.5. This increased sensitivity is even more pronounced when effluent desalination is considered (#5 above), with relative construction costs rising to 2.2–2.7 and O&M costs rising to 3.9–4.2 times the standard costs.

Both treatment level and design flow affect not only the nominal costs, but may also affect the distribution of the overall treatment cost between its components: construction and O&M. In order to test this hypothesis, an analysis was performed on MWWTPs ranging from a design flow of 10,000 to 50,000 m³ d⁻¹, and five treatment levels from secondary to RO (see the above discussion). Fig. 4 clearly shows that the proportional O&M cost rises with increasing design flow, having a general form of an S shaped curve. This means that the proportional construction cost decline as design flow increases. For example: for secondary treatment, O&M cost consist 41% of the total treatment cost for design flow of 10,000 m³ d⁻¹ rising to 53% when design flow increases to 50,000 m³ d⁻¹. The proportional O&M cost also increases with the level of treatment, rising from 41% for secondary treatment to as much as 52% for RO (design flow 10,000 m³ d⁻¹), with no apparent effect of design flow on the difference between the proportional cost of O&M for the various treatment levels. An overall examination of Fig. 4 shows that the break even point (the point where the proportional costs of O&M and construction are equal) becomes lower as the treatment level rises: for secondary treatment this point is at a design flow of 36,000 m³ d⁻¹, below which the proportional cost of construction is higher.
than the proportional cost of O&M, and above it the other way around; for secondary treatment followed by filtration this point is at a design flow of 20,000 m³·d⁻¹; and for RO treatment this point should be around 6,000 m³·d⁻¹.

These findings conform with the few citations on the subject available in the literature. Bode and Grunebaum (2000) in a survey of 34 European MWWTPs showed that the operating costs consist 41–75% of the total annual costs. Based on data of secondary MWWTP (design flow of 8000 m³·d⁻¹) in Crete reported by Borboudaki et al. (2005), it was estimated that construction cost consists 30–35% of the overall treatment cost.

7. The combined effect of economy and government policy on the performance of MWWTPs

In Israel, local authorities are responsible for wastewater treatment and consequently to the construction and operation
of MWWTPs. The central government supports local authorities in the form of subsidised loans for construction, while no direct financial support is given for the operation of MWWTPs. This form of responsibility and financial support is common in other countries too (Aivaliotis et al., 1991). Since the proportional cost of construction (which is financially supported by the central government) decreases as treatment level rises and the proportional cost of O&M (which is not supported by the central government) increases, the outcome of this policy is that the overall support of the central government decreases as the treatment level rises. Such policy is clearly problematic and actually contradicts the interest of the general public, which is a higher treatment level of wastewater, leading to wider reuse possibilities at lower negative environmental effects.

The conduct of the municipal wastewater treatment sector in Israel during the last decade is an example of the consequence of this policy. During the last decade about 1 billion US$ were invested in Israel in construction of new MWWTPs all around the country. Most of the funds for the construction of the plants were allocated by the central government to local authorities in the form of low interest loans or grants. However, according to a recent report of the Israeli Ministry of Environment (Mayson, 2005), much of this vast investment in new MWWTPs has failed to achieve the expected results. Mayson (2005) further states that this is due to the fact that quite a few local authorities (municipalities and or regional councils), due to financial difficulties, have not paid their share of the O&M costs of the MWWTPs. The managers of the effected MWWTPs are reluctant to report these facts to the central government, since they are actually employed by the municipalities. As a consequence, these MWWTPs are not operated as they should, and thus produce effluent of quality much poorer than what they were designed for. Different structure of the financial support policy of the central government, where MWWTPs operation and not only construction is supported directly, may help solving this problem. The central government, in an effort to solve this problematic situation, lately started to demand the formation of financially independent water and wastewater corporations within local authorities. By doing so, the government tries to ensure that revenue received from water and sewerage bills is used only for water and wastewater related projects even if the local authority suffers from financial difficulties. It seems that the combination of these two measures (changing the financial support policy of the central government and formation of independent municipal water and wastewater corporations) may lead to better performance of MWWTPs and will best serve the interest of the general public.

8. Conclusions

Data from municipal wastewater treatment plants in Israel were used in order to analyse the interactions between cost, government policy and the performance of MWWTPs.

- Exponential regression equations, expressing construction costs as a function of design flow were derived for three treatment levels (i.e. secondary treatment, advanced secondary, and advanced treatment), and were found to be statistically significant ($p < 0.01$). The power coefficients of the equations appear to become higher as treatment level rises, giving an indication that economy-of-scale may become weaker as treatment level rises.
- Analysis of cost distribution between the main construction components revealed that as design flow increases the proportional cost of civil engineering declines significantly ($p < 0.05$), while the proportional electromechanical equipment cost rises ($p < 0.05$). The proportional electricity and control cost was found to be rather insensitive to design flow. This implies that the depreciation time of the overall construction costs is significantly reduced as the design flow increases and the consequent capital costs (annual return of construction costs) become higher. Further, authorities should realise that as the MWWTP size increases the emphasis shifts from civil works to electromechanical equipment installation.
- O&M costs were found to be more sensitive to treatment level than construction costs, with the relative O&M costs (relative to O&M costs of secondary treatment) being 20–70% higher than the relative construction costs, depending on the required treatment level.
- The proportional O&M cost as part of the total treatment cost was found to increase both with treatment level and design flow, while the proportional construction cost (expressed in terms of annual payment) was found to decrease as these two factors rose.
- Considering the above findings it was demonstrated that the current financial support policy of the Israeli government to local authorities, which directly supports only MWWTPs construction, contradicts public interest, since it is may be one of the causes of poor performance of many newly built MWWTPs.

REFERENCES


