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COST-EFFECTIVENESS ANALYSIS OF WASTEWATER TREATMENT BY THE ACTIVATED SLUDGE AND BIOFILTER METHODS

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ABSTRACT: The paper presents the methodology and results of cost-effectiveness analysis of selected methods of wastewater treatment: activated sludge and biofilter. The analysis concerns small municipal wastewater treatment plants with capacity of 10 to 500 m^3d^{-1} in Poland (~100 to 5000 PE). It is based on data on total investment outlays, annual operating costs and total average annual costs. It has been shown that, in the case of investment outlays, there are no statistically significant differences between technologies. However, the annual operating costs and the total average annual cost of wastewater treatment are the lowest when applying the biofilter technology. The models presented in the paper can be used for costs estimation at the initial stage of designing municipal wastewater treatment plants. The total average annual cost of wastewater treatment determines the charges for sewerage services. This charge, alongside technological and environmental factors, as well as local conditions, should be one of the criteria for choosing a method for wastewater treatment.

KEY WORDS: cost effectiveness analysis, investment outlays, operating costs, activated sludge method, biofilter method for wastewater treatment

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Introduction

Initially, when undertaking an analysis of the costs of construction and operations of a wastewater treatment plant, its objectives should be defined. In general, wastewater treatment plants in large cities were built several dozen years ago. An analysis of their construction costs should take into account the investment outlays incurred on the construction and on subsequent upgrading, updated to the price level of the year of the analysis being carried out by applying conversion rates for construction and assembly prices of the Central Statistical Office. Conducting such research is justified within framework of brenchmarking of the water supply and sewerage sector. Due to the variety of solutions applied, their results have limited application when deciding on the construction of new or upgrading of existing facilities.

The situation is different in smaller towns. Many of them, as yet, do not have wastewater treatment plants or have facilities which require overall upgrading. What is even worse, often the local authorities do not have sufficient data to estimate the total average annual costs of wastewater treatment. The level of investment outlays is usually known after a cost estimate has been made. At this stage operating costs are omitted. There is a lack of an overview of the total costs of such commonly used technologies as activated sludge and biofilter, on the basis of which an initial selection could be made.

The problem of choosing the right solution occurs when legal requirements change and upgrading of the existing facilities is required. Local authorities should at least know the approximate total annual operating costs of the wastewater treatment plants.

Both the investment outlays and the operating costs affect the total average annual cost of wastewater treatment which subsequently determines the charges for sewerage services. This charge, alongside technological and environmental factors, as well as local conditions, should be one of the criteria for choosing technologies for wastewater disposal and treatment (Bakir, 2001; Engin, Demir, 2006; Molinos-Senante et al., 2010; Sala-Garrido et al., 2011). In many cases, it may be more beneficial to use household wastewater treatment plants.

Results of the cost-effectiveness analysis allow to compare different wastewater treatment technologies and in consequence, to select a technology with a minimal total annual cost. The choice is made by assuming the fixed performance effect, e.g. the volume of treated wastewater or the degree of its treatment. This analysis, however, does not take into account other investment results, including such environmental effects as protection of the environment from pollution, maintaining human health on an appropriate level and creating conditions for the development of tourism (Karolinczak et al., 2015).

An overview of literature

The results of studies on the level of investment outlays incurred on construction of municipal wastewater treatment plants and on their annual operating costs, depending on the used technology, have not been published in the last few years. Previous research was conducted by Miłaszewski and Rauba and its results were published in 2008. Over the past 10 years this issue has not been examined. The results of research on the costs of construction and operating of the smallest facilities, where the problem is of the greatest significance, have also not been published.

The lack of systematic analysis of these issues which, in turn, is brought about by the difficulty of obtaining data. Only a few scientists are working on the economic aspects of the wastewater treatment process (Hernandez-Sancho et al., 2011). The EU Water Framework Directive assigns a very important role to economic analyses (Helming, Reinhard, 2009). Additionally, it introduces the need to conduct economic analysis in water management.

Research methods

Data examined in the paper comprise the year 2017 and were made available by municipal and public utilities authorities. The original construction investment outlays were converted to the 2017 price levels, using the price index of construction and assembly production provided by the Central Statistical Office in Poland. The analysis included the construction and operating costs of small wastewater treatment plants with a capacity of 10 to 500 m^3d^{-1}(~10 to 5000 PE), operating in activated sludge (technology I) and biofilter (technology II) technologies. The objective of the statistical analysis was to determine the significance of differences between these technologies, using regression analysis.

In order to examine the impact of technology and capacity (Q_{design}) on the investment outlays (I) a linear model (1) on logarithmic scale was developed. The model (1) utilizes independent variables used as a technology indicators (Ind_{bf} equals 1 for technology II) and their interactions with designed capacity (Q_{design}). As reference technology, technology I (activated sludge) was implemented.

$$ln\, I = A_2 + A_{2,bf} Ind_{bf} + b_2\, ln\, Q_{design} + b_{2,bf}\, ln\, Q_{design}\, Ind_{bf}. \quad (1)$$

On the linear scale it corresponds to the relationship:

$$I = e^{(A_2 + A_{2,bf} Ind_{bf})} + Q_{design}{}^{(b_2 + b_{2,bf} Ind_{bf})},$$
$$I = \left(a_2 a_{2,bf}{}^{Ind_{bf}}\right) \times Q_{design}{}^{(b_{20} + b_{2,bf} Ind_{bf})}. \quad (2)$$

As above, in order to examine the impact of technology and volume of treated wastewater (Q_{real}) on the annual operating costs (excluding depreciation) (C_e) a linear model (3) on logarithmic scale was developed. The model (3) utilizes independent variables used as a technology indicators (Ind_{bf} equals 1 for technology II) and their interactions with volume of treated wastewater (Q_{real}). As reference technology, technology I (activated sludge) was implemented.

$$ln\, C_e = A_1 + A_{1,bf} Ind_{bf} + b_{10}\, ln\, Q_{real} + b_{1,bf}\, ln\, Q_{real}\, Ind_{bf}. \quad (3)$$

On the linear scale it corresponds to the relationship:

$$C_e = e^{(A_1 + A_{1,bf} Ind_{bf})} + Q_{real}{}^{(b_{10} + b_{1,bf} Ind_{bf})},$$
$$C_e = \left(a_1 a_{1,bf}{}^{Ind_{bf}}\right) \times Q_{real}{}^{(b_{10} + b_{1,bf} Ind_{bf})}. \quad (4)$$

The total average annual cost C_a of wastewater treatment was calculated using the relationship (5) (Boruszko et al., 2013):

$$C_a = I \cdot (r + s) + C_e, \quad (5)$$

where:
C_a – total average cost of wastewater treatment [EUR year^{-1}],
I – investment outlays for construction of wastewater treatment plants [EUR],
r – discount rate [year^{-1}],
s – depreciation rate [year^{-1}],
C_e – the annual operating costs of wastewater treatment plants (excluding depreciation) [EUR year^{-1}].

In relationship (5), the depreciation rate (s) can be written as:

$$s = \frac{r}{(1+r)^n - 1} \tag{6}$$

where:
n – calculated operations time span [years].

After substituting data (6) to relationship (5) the result is:

$$C_a = I\left(r + \frac{r}{(1+r)^n - 1}\right) + C_e \tag{7}$$

After transformation, relationship (7) takes the form:

$$C_a = I\frac{r(1+r)^n}{(1+r)^n - 1} + C_e \tag{8}$$

After introducing into the equation (8) the capital recovery rate (α) (9),

$$\alpha = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{9}$$

the relationship (8) is transformed into:

$$C_a = I \cdot \alpha + C_e. \tag{10}$$

In determining the total average annual cost of wastewater treatment the following values were assumed: discount rate $r = 0.05$, operations time span $n = 20$ years, average depreciation rate $s = 0.03$, therefore coefficient $\alpha = 0.08$.

In estimating the total average cost of treatment (C_a), depending on the capacity of the wastewater treatment plant (Q), the highest correlation is shown by the general exponential regression equation (Tyteca, 1981; Miłaszewski, 2003):

$$C_a = c + a \cdot Q^b, \tag{11}$$

where:
Q – plant capacity [m^3/year],
a, b, c – exponential regression coefficients [-].

To determine a, b, c values, coefficients of the linear regression equation obtained as the result of transformation of function (11) were delineated. For this purpose, assuming that $C_a > c$ and $a > 0$, the following substitutions were made:

$$ln(C_a - c) = Y, \tag{12}$$

$$ln\, Q = X, \tag{13}$$

$$ln\, a = A, \tag{14}$$

$$e^A = a. \tag{15}$$

In result of the transformations the following linear regression equation was derived:

$$Y = A + b \cdot X. \tag{16}$$

To determine A and b values of equation (16) the smallest square method was used. The coefficient b is the value of the projected exponent function (11), coefficient a was determined by the antilogarithm of the calculated value of A. The coefficient c was determined graphically. It is the coordinate of the intersection of streak empirical points, corresponding to the level of the average annual cost of wastewater treatment with the ordinate axis.

The value of coefficients a, b, c of function (11) was determined in accordance with the discussed algorithm, based on the actual data on investment outlays and the annual operating costs (excluding depreciation) of municipal wastewater treatment plants.

Results of the research

a) investment outlays

The regression analysis showed that the annual capacity of the plant (Q_{pro}) affects the level of investment outlays (I) in all the analyzed technologies. The effect of the technologies proved to be statistically insignificant. The relationship finally defined between the level of investment outlays (I) and the annual capacity of wastewater treatment plants (Q_{pro}) for both treatment technologies is as follows (price level 2017):

$$I = e^{4.83} \times Q_{pro}{}^{0.73} = 124.58 \times Q_{pro}{}^{0.73} \text{ [EUR]}. \tag{17}$$

Coefficient of linear determination is high (0.95) and whole model is significant. Figure 1 shows the identified relationship and its diagnostic graphs.

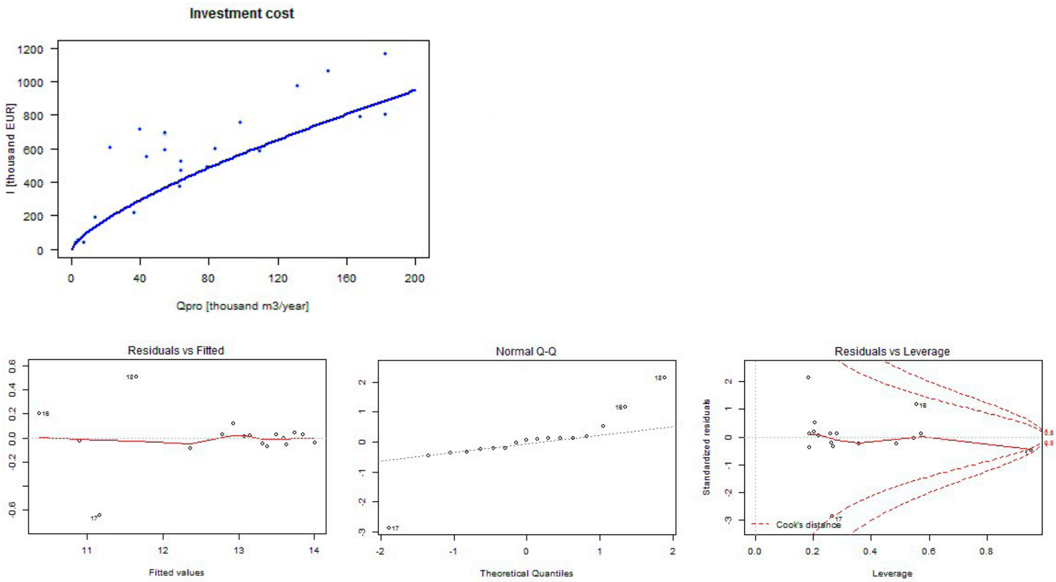

Figure 1. The relationship between the level of investment outlays incurred on the construction of small municipal wastewater treatment plants and their capacity and its diagnostic graphs

Source: author's own work.

The reviewed models illustrate that, in the analyzed capacity of small municipal wastewater treatment plants operating in the activated sludge and the biofilter technologies, there are no statistically significant differences in the level of investment outlays. For both technologies an increase of investment outlays has been observed together with an increase in their capacity.

The relationships of the impact of technologies on the investment outlays calculated in the paper comply with the conclusions of research conducted by Coleman (1997) and Kłoss-Trębaczkiewicz et al. (1998), Fraasa, Munley (1984) and Rauba (2008). The total investment outlays for construction of wastewater treatment plants grow with the increase of their capacity. In addition, with the increase of wastewater treatment capacity, there are more significant differences in the investment outlays in particular treatment technologies. The same conclusion were made by Muga, Mihelcic (2008). Moreover, they observed that investment outlays incurred on all kinds of mechanical-biological treatment plants are much greater than those incurred on construction of the lagoon and land treatment systems. In the case of a large land reserve, when choosing wastewater treatment technology, constructed wetlands should also be taken into account.

b) operating cost (excluding depreciation)

The regression analysis showed that the annual volume of treated wastewater (Q_{real}) has impact on the final operating cost (K_e) in both technologies (p-value less than 0.0001). In addition, the effect of the biofilter technology, i.e. Ind_{bf} variable (p-value 0.02) and its interaction with the capacity (p-value 0.03) proved to be statistically significant. The ultimately identified relationship between the level of the annual operating costs (K_e) and the volume of annually treated wastewater (Q_{real}) is as follows (price level 2017):

- for technology I (activated sludge technologies):

$$K_e = e^{1.05} \times Q_{real}{}^{0.94} = 2.87 \times Q_{real}{}^{0.94} \text{ [EUR year}^{-1}\text{]}, \tag{18}$$

- for technology II (biolfilter):

$$K_e = e^{-3.26} \times Q_{real}{}^{1.31} = 0.04 \times Q_{real}{}^{1.31} \text{ [EUR year}^{-1}\text{]}. \tag{19}$$

Coefficient of linear determination was high (0.93) and whole model is significant (p-value for F test less than 0.0001). Figure 2 shows the identified relationship and its diagnostic graphs.

The annual operating treatment costs are lower in the biofilter technology. Augmented operating costs are observed when the volume of treated wastewater increases.

The level of the annual operating costs of wastewater treatment plants depends on the technology, capacity and effectiveness of the treatment plants and the composition of pollutants in wastewaters. The most difficult is to describe by means of statistical model the impact of treatment effectiveness and composition of the pollutants in wastewater on the treatment cost (Hernandez-Sancho et al., 2011; Muga, Mihelcic, 2008). The total operating costs increase together with an increasing volume of wastewaters treated. These costs are lower when the wastewater treatment technology uses biofilters. Currently, biofilters are used for wastewater treatment in rural wastewater treatment plants to 1,000 PE (Person Equivalent), and in Western Europe even up to 20,000 PE (Q ~5,000 m^3d^{-1}) (Ignatowicz, Puchlik, 2011).

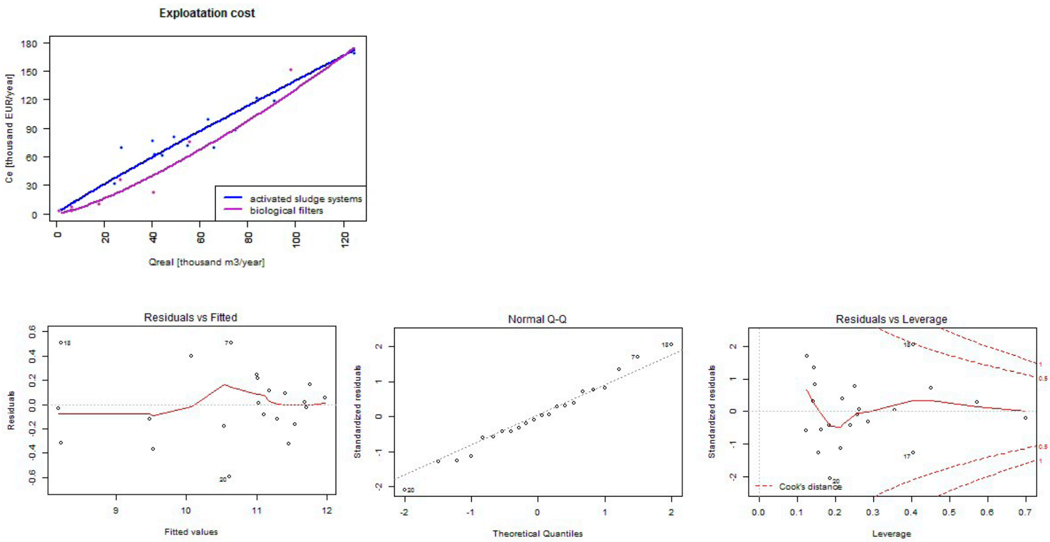

Figure 2. The relationship between the level of annual operating costs of small municipal wastewater treatment plants and volume of treated wastewater and its diagnostic graphs

Source: author's own work.

Research conducted by Muga and Mihelcic (2008) shows that the operating costs of the mechanical-biological wastewater treatment plants are significantly higher than those of the lagoon and land treatment systems. This is associated with increased energy consumption as well as with more highly mechanized equipment. In addition, Hernández-Sancho and Sala-Garrido (2009) showed that larger facilities are operated with greater technological and cost efficiency than smaller ones.

c) total average annual cost of wastewater treatment

Since the total average annual cost of wastewater treatment (C_a) depends on the level of investment outlays (I) and the operating costs (C_e), models (17), (18), (19) are transferred to the relationship (10). The capacity (Q_{pro}) and the volume of treated wastewater (Q_{real}) are the main factors which determine the total average annual cost of wastewater treatment (C_a). Biofilter technology (Ind_{bf}) has significant impact on the operating costs (K_e) and thus, indirectly, on the total average annual cost of wastewater treatment (C_a). Finally, the relationship between the total average annual cost of treatment (C_a), the capacity of the wastewater treatment plant (Q_{pro}) and the volume of treated wastewater (Q_{real}) takes the form (price level 2017):

- for technology I (activated sludge technologies):

$$C_a = 0.08 \times 124.58 \times Q_{pro}{}^{0.73} + 2.87 \times Q_{real}{}^{0.94} \text{ [EUR year}^{-1}\text{]}, \quad (20)$$

- for technology II (biofilter):

$$C_a = 0.08 \times 124.58 \times Q_{pro}{}^{0.73} + 0.04 \times Q_{real}{}^{1.31} \text{ [EUR year}^{-1}\text{]}. \quad (21)$$

Figure 3 shows the identified relationship.

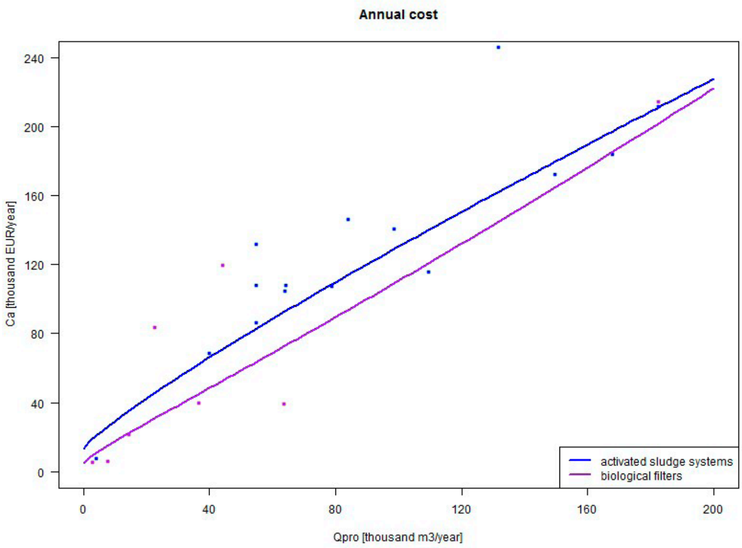

Figure 3. The relationship between the level of total average annual cost of wastewater treatment and their capacity

Source: author's own work.

The total average annual costs of wastewater treatment are lower in the biofilter technology. They increase with the growth of the wastewater treatment plant capacity.

Results of the research conducted by Sala-Garrido et al. (2011), based on data envelopment analysis (DEA), show a similar average technological and economic efficiency of systems such as activated sludge, aerated lagoon, trickling filter and rotating biological contactor. In this paper, in accordance with the guidelines of cost-efficiency analysis, it was assumed that the technological efficiency of all the analyzed systems is the same. Taking into account the criterion of the lowest average annual cost of wastewater treatment, the biofilter technology proved to be the most effective in small plants.

Conclusions

The data presented in this study give a view on the possible impact of wastewater treatment technology, wastewater treatment plant capacity and volume of treated wastewater on the construction and operating costs of small municipal wastewater treatment plants. The resulting mathematical models can be used at the initial stage of designing municipal wastewater treatment plants. In the following years, they need to be updated using the price index of construction and assembly production.

The reviewed models illustrate that, in the analyzed capacity of small municipal wastewater treatment plants operating in the activated sludge and the biofilter technologies, there are no statistically significant differences in the level of investment outlays. However, the annual operating costs and total average annual cost of wastewater treatment are lower in the biofilter technology. For both technologies, an increase of investment outlays has been observed together with an increase in their capacity. Increased operating costs are observed when the volume of treated wastewater increases.

Data regarding construction and operating costs should be collected systematically, thus allowing to enhance the credibility and reliability of the developed cost models. This, as well, will allow for the application of the probabilistic approach to cost analysis.

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