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Municipal Wastewater Treatment in Poland – Efficiency, Costs and Returns to Scale

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Municipal Wastewater Treatment in Poland – Efficiency, Costs and Returns to Scale

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Abstract

The paper reports the costs of municipal wastewater collection and treatment in Poland based on an empirical sample of 1400 operators. Treatment cost functions are investigated econometrically using the Box-Cox regression model, indicating high non-linearity and significant scale effects. Wastewater treatment costs are increasing with technology efficiency (moving from the primary, through the secondary, to the tertiary treatment), and decreasing with higher wastewater treatment plant capacity. Combining treatment and collection costs with treatment efficiency allows estimation of costs and potentials for reducing the nitrogen and phosphorus loadings to rivers by improving the efficiency of wastewater treatments plants, or building new ones, on an aggregated country-wide scale. Therefore, our results provide valuable input into any cost-benefit analyses of nutrient loadings reduction through extending or upgrading municipal wastewater treatment systems.

Keywords:
municipal wastewater treatment costs, scale effects, nutrient loadings reductions, nitrogen, phosphorus

JEL:
Q53, Q28, D61

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1. Introduction and literature review

Water quality remains one of the most significant environmental issues. Numerous local and large-scale programmes aim at providing good ecological status of fresh water and marine ecosystems. Most notably, the EU Water Framework Directive commits European Union member states to achieve good qualitative and quantitative status (both ecologically and chemically) of all water bodies by 2015. Similarly, the HELCOM Baltic Sea Action Plan is an ambitious programme to restore the good ecological status of the Baltic marine environment by 2021. These programmes aim at taking broader and more efficient actions to combat the continuing deterioration of the water environment by human activities while at the same time incorporating measures that are cost-effective in reaching these goals.

Human activities both on the seas and throughout their catchment areas are placing rapidly increasing pressure on riverine and marine ecosystems. One of the main environmental challenges, perhaps the most serious and difficult to tackle with conventional approaches, is continuing eutrophication, which leads to problems with algal blooms, lack of oxygen in the water, depletion of fish stocks, and many others (Wulff *et al.*, 2007). A number of measures to limit eutrophication have been identified, each associated with different effectiveness and costs. One of the most significant is the reduction of point source nutrient loadings, mainly through increased level of municipal wastewater treatment and increasing the proportion of households connected to treatment facilities.

Increased application and effectiveness of municipal wastewater treatment is, however, difficult to compare with other nutrient abatement measures, such as measures limiting runoff from agriculture, or atmospheric deposition, without knowing the efficiencies and costs involved. In many cases even crude cost estimates could significantly aid policy considerations. This paper aims at filling this gap by providing comprehensive estimates of cost functions for different levels of municipal wastewater collection and treatment, and reporting its effectiveness.

Existing literature related to costs of wastewater treatment is rather scarce. There were, however, several attempts to provide cost estimates and cost functions in various countries, without clear consensus on the methodology. The three most noteworthy estimates were provided by Bode and Lemmel (2001), Tsagarakis et al. (2003), and Friedler et al. (2006).

Bode and Lemmel (2001) carried out a survey of the costs of wastewater treatment in six European countries: France, Italy, Germany, the Netherlands, Switzerland and Denmark. The annual costs per population equivalent (p.e.) based on data from 34 wastewater treatment plants (henceforth WWTPs) turned out to be quite similar across the countries analysed, with an arithmetical mean equal to 46 euro per year per unit of demand which was constructed as a sum of inhabitants connected and the population equivalent coming from connected industry.

Tsagarakis et al. (2003) provide estimates of cost functions calculated from a national survey of WWTPs in Greece. Construction and land use costs are annualized, and all cost functions are estimated with p.e. being the explanatory variable. The authors apply life cycle analysis to investigate which treatment systems become the most cost-effective as the prices of inputs (labour, capital) change.

Friedler et al. (2006) calculate wastewater treatment cost functions in Israel, based on a sample of 55 plants. Unlike the two previously mentioned studies, the cost functions constructed in this paper use the design capacity in m^3 per day, rather than p.e. as an explanatory variable. They derive cost functions expressing the effects of design capacity and treatment level on construction costs. These cost functions are derived separately for each treatment type (secondary, advanced secondary, tertiary). Interestingly, they find that economies of scale may decrease as treatment level rises. In addition, they find statistical evidence that construction costs depend mostly on designed plant capacity, while operation and management costs were sensitive to both treatment levels and designed flow.

In Poland, only a few studies have investigated the issue of wastewater treatment costs to date. The Polish Chamber of Water Supply Enterprises (IGWP) is an institution which usually collects annual and quarterly data on prices of water and wastewater services. In 1999, however, they extended their publication and also included a wide spectrum of economic and technical indicators, such as unit costs of treatment, energy consumption, and labour costs of 211 water supply enterprises (IGWP, 1999). Sozański (2002) used a sample of 120 facilities to investigate similar indicators. Finally, over 400 facilities were surveyed by the National Fund for Environmental Protection and Water Management in Poland, which provides financial support for construction of all large and majority of medium capacity municipal WWTPs in Poland. The study reported mean, minimum and maximum unit costs of treatment (KPOŚK, 2004).

Our study aims to provide detailed national cost estimates for the collection and treatment of municipal wastewater. In particular we investigate the issues of (i) unit costs of collection and treatment, (ii) the effect of nitrogen and phosphorus treatment efficiency, and (iii) plant capacity on unit costs, thus providing evidence of significant scale effects.

The dataset that we use is (to our knowledge) by far the largest and the most comprehensive to date. The data comes from a survey of 1420 WWTP operators, who jointly collect and treat over 80% of wastewater in Poland.

Our results provide a comprehensive picture of municipal wastewater treatment in Poland but our estimates can potentially also be used for applications in other countries, possibly after some accounting for capital and labour costs, as the technology is fairly generic. Therefore, we provide valuable input into any cost-benefit analyses of nutrient loadings reduction through extending or intensifying municipal wastewater treatment.

The paper is organised as follows. Section 2 provides description of the sample and reports mean efficiency of nutrient removal. In section 3 we provide the results of the empirical study and estimation of cost models. Section 4 concludes.

2. Description of the Dataset

The dataset used in this study was collected as a survey distributed among municipal wastewater operators in Poland in 2008. The survey was carried out by the Regional Water Boards in Poland and aggregated by the National Water Board. The rationale of the survey was to obtain some insight into economic analysis of water management, especially in the area of water provision and wastewater collection in the municipal sector. Such an investigation was a part of the general economic analysis required by the Water Framework Directive. The questionnaire was sent to all the operators holding permissions for municipal water intake and wastewater discharge.

In total, 1420 surveys were collected, which resulted from a response rate of 87%. Of these, 1237 were eligible for further processing (the rest were incomplete). The total volume of wastewater treated by the facilities included in our dataset in 2008 was 1282 hm^3. To give some perspective, the amount of water sold by municipal operators in the same year in Poland totalled 1580 hm^3. Hence, our sample covers overwhelming majority of all municipal wastewater in Poland.

We have classified the operators in the sample according to the type of treatment that they apply – primary (mechanical), secondary (biological) and tertiary (with enhanced removal of nitrogen and phosphorus). Some operators reported joint data for more than one plant, operating at different levels of treatment. Since there was no way to disaggregate these results to levels of treatment these observations were removed from the sample. This left us with a sample of 1114 operators.

The main characteristics – capacity and unit cost[1] of the plants – are summarized in Table 1 below. The reported costs refer to collection and treatment jointly. The following cost categories were included: labor cost, operating cost, depreciation (amortization), and maintenance costs.

[1] In 2008 1 PLN ≈ 0.2844 EUR ≈ 0.4188 USD.

Table 1. WWTPs included in the dataset

	Primary	Secondary	Tertiary	All[2]
Number of operators	70	720	324	1114
Capacity $\left[m^3 \cdot \text{year}^{-1} \cdot 10^3\right]$				
Median	50.00	78.70	680.60	110.50
Mean	158.47	342.83	2 365.46	919.51
0.05 percentile	5.90	7.80	31.53	10.00
0.95 percentile	869.70	1 162.95	8 733.13	3 606.05
Standard deviation	282.50	1 417.13	6 790.99	3 942.86
Unit cost of collection and treatment $\left[\text{PLN} \cdot m^{-3}\right]$				
Median	3.23	2.90	2.44	2.72
Mean	3.55	3.66	2.94	3.44
Weighted average	2.57	2.21	2.06	2.10
0.05 percentile	1.34	1.04	1.09	1.05
0.95 percentile	7.48	8.83	6.37	8.12
Standard deviation	2.05	3.06	2.15	2.79

Surprisingly, the unit cost of treatment and collection appears to decrease as one moves from primary to secondary and from secondary to tertiary treatment. This is a counter-intuitive result. One of the possible reasons for this effect is the presence of scale effects, as different plant types have significantly different mean capacities. In general, the WWTPs applying tertiary treatment were by far larger (in terms of treatment capacity) than other plants, and secondary treatment plants were larger than primary. In order to investigate if the unit costs are indeed decreasing with an increase of treatment efficiency, we need to control for plants' capacity. We do this in section 3.

Table 2 presents mean efficiencies of nutrients removal in the specific types of wastewater treatment plants, according to their capacity measured in population equivalent (p.e.). These results are based on the study of Sozanski (2002). We report them here to make it possible to calculate costs with respect to the amount of nutrients removed.[3],[4]

[2] 123 operators used mixed type of treatment and we were unable to categorize them to primary, secondary or tertiary treatment – we have removed these observations from further analysis.

[3] For comparison, Mörth et al. (2007) estimate average removal rates to be 19% (N) and 15% (P) for primary, 37.5 (N) and 35% (P) for secondary and 80% (N) and 90% (P) for tertiary treatment. These results are reported to be average for the Baltic Sea drainage area.

[4] In 2008, the total p.e. of Poland was 46 million, while the amount of wastewater produced was 1963 hm^3. Therefore, 1 p.e. was equal to 42,7 m^3 of wastewater per year. There is, however, very large variation between 16 administrative districts of Poland (voivodships) resulting in p.e. ranging from 31 to 220 m^3/year.

Table 2. Efficiency of nutrients removal

Capacity (p.e.)	Pollutant	Median efficiency		
		Primary	Secondary	Tertiary
over 100000 15 000 – 100 000	N_{tot}	10% (10-20%)	55%	85% 80%
over 100 000 15 000 – 100 000	P_{tot}	15% (5-15%)	50%	90% 85%

Source: Sozański (2002)

It should be noted that the parameters for the tertiary treatment are based on legal requirements related to the national plan of implementation of the Directive 91/271/EEC (KPOŚK, 2004). If an operator declares lower level of efficiency of nutrients treatment, it is impossible to benefit from financial support of investments in wastewater treatment facilities, both from the EU and from domestic sources. We acknowledge, however, that since the the frequency of government control of the treatment efficiency depends on the plant capacity (in the case of small WWTP the legal requirements range from a few to only one verification per year) there might be incentives to overstate treatment efficiency to decrease payment for pollutants discharge.

3. Costs of Wastewater Treatment and Collection

In this section we investigate the unit costs of treatment for each type of WWTP once the capacity of a plant expressed in millions of m^3 per year is controlled for. In particular, we investigate whether there are significant and increasing returns to scale present in our dataset. In order to do this, we disaggregated the WWTPs according to their type (primary, secondary, and tertiary), and for each type we allowed for a flexible functional form of the unit cost as a function of annual treatment capacity.

Most studies model unit cost of treatment as a function of either a plant's capacity, in terms of water throughput volume (e.g. Friedler i Pisanty, 2006; Berbeka, 2009) or population equivalent (p.e.) in terms of nutrient loadings (e.g. Tsagarakis *et al.*, 2003). We argue that modelling unit costs as a function of treatment capacity in m^3 per year is a better approach than using p.e.. Capacity expressed in p.e. is not appropriate because there is usually no universal way of recalculating m^3 of wastewater into p.e.. Households' water consumption needs not be constant in time (in total value and per capita). For instance in Poland, it dropped by 50% between 1990 and 2009.[5] At the same time, the load of pollutants generated by households did not change significantly.

The treatment costs appear to depend mostly on the volume of wastewater and efficiency of treatment rather than on the size of connected population or the amount of pollutants. This is because the cost of construction of a WWTP depends mostly on the capacity expressed in m^3 per unit of time, as this parameter influences the volume of the specific technological elements, capacity of pumping devices etc..[6] Moreover, the systems of charging the consumer for wastewater services in Europe are usually based on volume. Referring to the 'user pays' principle, the charges should be based on input loads, however, since the price mechanisms are usually based on volume, we conduct the cost analysis using the same units.

3.1. Method

Most other studies reported earlier modelled unit cost as an exponential function of a plant's capacity. Since in the case of scale effects there is no theory to predict the functional relationship of cost and capacity, a researcher should be prepared to account for different forms of non-linearity in the model. Therefore, we propose a more flexible approach which nests most commonly used functional forms without specifying one a priori, and we use maximum likelihood estimates to determine the most appropriate functional form to account for the observed non-linearity in the data.

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[5] There are at least four drivers of the observed, somewhat perplexing reduction of water consumption in Poland: (a) dynamic increase of water and wastewater prices for households, (b) common adoption of metering system in the place of flat rate used before, (c) changes in water consumption patterns, such as adopting more efficient washing and bathing technologies, and (e) the changes in the difference between the population reported to live in the country and the population actually living there.

[6] We acknowledge, however, that the load of pollutants expressed in mass units could also affect treatment costs.

Specifically, we apply the Box-Cox Regression Model (Spitzer, 1982; Seaks i Layson, 1983; Sakia, 1992). This model utilizes different Box-Cox transformation parameters for the right-hand-side and left-hand-side variables of the model. The Box-Cox transformation is one of the power transform functions, in which if a variable x is transformed by the parameter γ (expressed as $x^{(\gamma)}$) it becomes:

$$x^{(\gamma)} = \begin{cases} \dfrac{x^{\gamma}-1}{\gamma} & \text{for} \quad \gamma \neq 0 \\ \ln x & \text{for} \quad \gamma = 0 \end{cases}. \tag{1}$$

The Box-Cox transformation nests a number of recognized functional forms. In particular, the linear and log-linear relationships are included for $\gamma = 1$, and $\gamma = 0$, respectively. Therefore, the Box-Cox transformation introduces flexibility in modelling non-linear relationships of unknown functional forms while also allowing for including recognized and commonly used functional forms.

The general structure of our Box-Cox regression model is:

$$UC^{(\theta)} = \alpha + \beta \cdot size^{(\lambda)}, \tag{2}$$

where UC is the unit cost of collection and treatment (in PLN/m^3), $size$ is plant's capacity (in thousands of m^3 per year), α is a constant (intercept), β is parameter associated with plant size, and θ and λ are separate Box-Cox transformation parameters for the left-hand-side and right-hand-side variables of the model. Therefore, the functional form of a relationship depends on the choice of the transformation parameters. However, rather than specifying these parameters a priori, they can be simultaneously, and therefore efficiently, estimated within the model. The usual practice is to apply a grid search over a plausible range of values or utilize continuous methods, such as maximum likelihood estimators of the parameters (Haab i McConnell, 2003).

3.2. Results

We applied the Box-Cox regression model to our data to account for non-linearity and to investigate scale effects in wastewater treatment. The maximum likelihood estimators of the transformation parameters were found for each type of wastewater treatment plant. The results are presented in Table 3 below.

The first part of the table presents models' parameters estimates and relevant test statistics. Finally, we present elasticity of the unit cost with respect to WWTP capacity for the mean capacity of each WWTP type. Elasticity is the construct that allows to measure how relative (percentage) changes in one variable affect relative (percentage) changes in another.

Table 3. Unit cost of plant types as a function of their capacity – the Box-Cox Regression Model (standard errors of parameter estimates in brackets)

Parameters:	Primary	secondary	tertiary
α – intercept (parameter)	0.64864*** (0.20963)	0.84182*** (0.08844)	1.05617*** (0.05711)
β – capacity (parameter)[7]	-0.37553 (0.24469)	-0.21940*** (0.05512)	-0.19632*** (0.02795)
θ – theta (transformation parameter)	0.06097 (0.17843)	0.38638*** (0.02084)	0.35604*** (0.03173)
λ – lambda (transformation parameter)	0.50727 (0.33235)	-0.04710 (0.09102)	0.05106 (0.08950)
Adjusted R^2	0.92670	0.87388	0.86363
$F[1, n-2]$ (probability in parentheses)	846.5 (0.0000)	4967.1 (0.0000)	2031.9 (0.0000)
$\chi^2[1]$ (probability in parentheses)	180.9 (0.0000)	1488.8 (0.0000)	643.5 (0.0000)
Elasticity of unit cost with respect to WWTP capacity[8]	-0.13825	-0.16269	-0.15606

All models display very good fit properties in terms of the adjusted-R^2 and test statistics. For all WWTP types the Box-Cox transformation parameter λ was not significantly different from zero indicating that unit cost is best modelled as a linear function of logarithm of WWTP capacity.

Surprisingly, we found that for the primary WWTPs neither their capacity nor the transformation parameter θ were not significant explanatory variables for unit costs. There was only a small number of primary treatment plants in our sample, usually old, using different mechanical treatment technologies and hence reporting very different unit cost. In addition, these plants may be expected to be remotely located (sometimes in the mountainous areas) and since the treatment and collection costs were reported jointly, it is possible that the collection costs dominate these results.

For the secondary and tertiary WWTPs we observe that the capacity is a significant explanatory variable of treatment costs. This finding supports the hypothesis of the presence of increasing returns to scale – one may expect that larger plants tend to have lower unit costs. This is most likely the reason that average unit costs of primary, secondary and tertiary treatment plants (Table 1) were found to decrease – this is the result of the substantial difference in their treatment capacity, since larger plants are able to reduce unit costs.

In order to illustrate this relationship, we have calculated the unit cost of each treatment plant type as a function of its treatment capacity:

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[7] The results are presented for scaled plant sizes (in millions of m^3 per year)
[8] At mean capacity of each treatment type in the sample.

$$UC = \left[\theta \left(\alpha + \beta \cdot \frac{size^{\lambda} - 1}{\lambda} \right) + 1 \right]^{\frac{1}{\theta}} \qquad (3)$$

We graphically illustrate this relationship in Figure 1. For completeness, we have included the unit cost curve for primary WWTP – however the reader should note that this relation was not statistically significant.

Finally, we illustrate the decreasing unit cost of each type of treatment and collection by calculating the unit cost for a plant of the same capacity. We have selected two numbers reflecting plant capacities for comparison: 150 000 m^3/year, which is almost the mean capacity of primary treatment plants in our sample and close to the median size of all plants in our sample, and 1 000 000 m^3/year, which corresponds to the mean capacity of all the operators in our sample. The results are presented in Table 4.

Table 4. Unit cost of treatment and collection of wastewater for a different capacities of WWTP

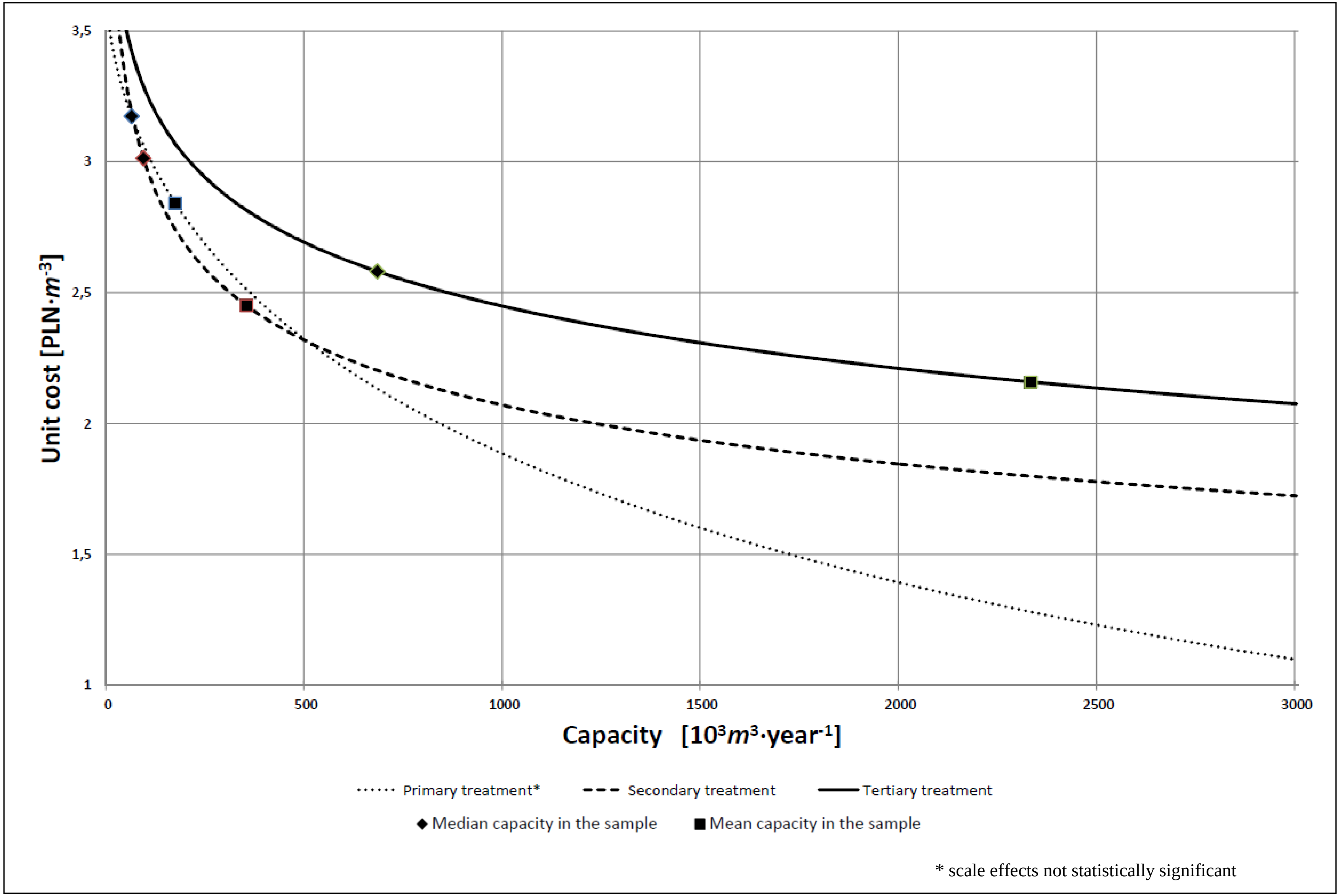
Plant capacity [m^3/year]	Unit cost [PLN/m^3]		
	Primary[9]	Secondary	Tertiary
150 000	(2.57)	2.82	3.14
1 000 000	(1.89)	2.07	2.45

Our results indicate that there are indeed significant scale effects in municipal wastewater treatment – the WWTPs with large capacities are being able to collect and treat wastewater more cheaply than their smaller counterparts. On the other hand, as the type of treatment becomes more sophisticated, the cost of treatment increases.[10]

[9] Since our data did not allow to estimate the significant influence of capacity on costs for primary treatment plants, we calculated weighted average unit costs for these plants (2.57 PLN/m^3). This value is presented as a unit cost for the plant capacity of 150 000 m^3/year which was close to the mean capacity of all the primary treatment plants included in the sample. For the capacity of 1000 000 we present the results predicted by our model, however, we note that these results were not statistically significant.

[10] These results remain, however, only indicative. Most WWTPs are tailored to specific conditions and needs, i.e. WWTPs with the same treatment performances do not inevitably incur the same costs, especially since our results do not separate the cost of collection from the cost of treatment. For more discussion of this issue and simulation results see Benedetti et al. (2006).

Figure 1. Unit cost of treatment and collection as a function of capacity of WWTP



4. Summary and Conclusions

The aim of this study was to provide detailed national cost estimates for the collection and treatment of municipal wastewater as a means of reducing nutrient loads to rivers. We used a very large dataset derived from a survey of 1420 WWTPs which jointly treat over 80% of wastewater in Poland. This allowed us to estimate cost functions for wastewater treatment and collection, for the three standard treatment levels (primary, secondary, tertiary). The estimated cost functions for secondary and tertiary treatment display considerable scale effects.

Our results provide a comprehensive description of municipal wastewater treatment costs in Poland and as such can be useful for future policy applications, such as estimating costs and effectiveness of improving wastewater treatment on a country scale, in reference to the implementation of the EU Water Framework Directive or the Baltic Sea Action Plan.

Several extensions of our work could make it more precise or easier to apply. The estimated cost functions that we provide can easily be used to calculate unit cost of treatment for plants of different capacities and treatment levels Integrating our approach with spatial analysis of the number of people connected to each type of treatment would allow estimation of the national level costs and effects functions for reducing nutrient loadings through improved type of treatment. When combined with the estimated wastewater transport cost (through connecting new people to sewerage networks or transporting wastewater with sanitation equipment) and the potential for household-level treatment, more insight could be provided into efficiency and costs of reducing nutrient loadings through connecting the additional households to wastewater treatment system.

Our work could also be extended with more in-depth analysis of major cost drivers of selected WWTPs in order to gain insight into the sensitivity of the cost functions to e.g. capital versus labour costs. Such analysis would make it possible to properly adjust our cost functions for use in other countries, where such comprehensive datasets on WWTPs are not available and therefore local cost functions cannot be estimated.

In summary, our results provide a comprehensive description of municipal wastewater treatment costs in Poland, based on a large sample of WWTPs. As our literature review showed, such cost estimates are very scarce, not only in Poland but also internationally. Our results will therefore provide valuable input into cost-benefit analysis of nutrient loadings reduction through extending or intensifying municipal wastewater treatment. In this regard, our results could be used to improve the earlier, much coarser calculations used in cost-benefit analyses, such as e.g. Gren et al. (1997; 1997). Overall, our study provides useful inputs for various policy assessments, and a basis for future work aiming at improving and extending our estimates.

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