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Estimating Shadow Prices of Wastewater Pollutants in Slovakia[1]

*Veronika ANTALOVÁ − Stella SLUČIAKOVÁ – Martin HALUŠ**

Abstract

The study aims to estimate shadow prices of environmental pollutants in wastewater which can under the assumption of optimal pollution levels be interpreted as environmental benefits gained from the treatment process. A directional output distance function model uses a sample of 57 medium-sized Slovak wastewater treatment plants to estimate the shadow prices for nitrogen, phosphorus, suspended solids and chemical oxygen demand. Total estimated value represents the costs avoided through undischarged pollution. Obtained shadow prices can be used in the future cost-benefits analyses of wastewater treatment investment projects.

Keywords: *distance function, economic valuation, environmental benefits, shadow prices, undesirable outputs, wastewater treatment*

JEL Classification: Q51

Introduction

According to the Slovak water legislation, wastewater is defined as any water of altered quality, e.g. containing pollutants or differing in temperature. Urban wastewater under this analysis is collected in sewer systems from households, commercial facilities, some industries and institutions and is then transferred into the wastewater treatment plant. In the sewerage system the wastewater flow is mixed with the surface runoff and rainwater and then treated.

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The removed pollution consists mainly of organic materials and nutrients, inorganic compounds and hazardous substances. Out of total wastewater volume, only 0.01% of substances needs to be removed.

A part of the wastewater released to the surface waters is despite a decline in volume still untreated and has a negative environmental impact. Furthermore, as the figure is self-reported by the polluters, the proportion of the untreated water could be even higher. To decrease the untreated portion, more wastewater treatment plants are being incorporated into the system every year (Water Research Institute, 2017) while at the same time the wastewater is becoming less and less polluted. Between 1995 and 2015, the number of pollutants released to the surface waters through effluent decreased by almost 80%, due to more modern wastewater treatment plants and more efficient purification processes (Slovak environment agency, 2015) as well as due to the decline in industrial production.

Removal of pollutants from wastewater has several indirect positive effects. First of all, the improved access to drinking water bears health benefits such as reducing the number of people affected by water-related diseases and reducing deaths (United Nations Environmental Program, 2010). Reduction of pathogens and pollutants in the water cycle decreases the number of people affected by water-borne diseases such as diarrhoea, cholera, dysentery, typhoid, and polio. Secondly, through using by-products of the treatment process additional economic profits could be created (United Nations World Water Assessment Programme, 2017).

The environmental benefits include safer and more stable aquatic ecosystems, lower pressures on the environment caused by chemical fertilizers and reduced amount of wastewater pollutants being released into the nature. The wastewater treatment might also provide a sustainable solution to water scarcity problem (Garcia and Pargament, 2015). Nutrients, such as nitrogen, phosphorus or potassium when released to surface waters cause eutrophication and excess plant growth. They are connected to the proliferation of algal blooms and an undesirable disturbance to the species composition and quantity in the water (European Environment Agency, 2012).

The risk of eutrophication is still widespread across Europe, even though it is expected to decline in the future (European Environment Agency, 2016). Freshwater ecosystems are important for global biodiversity and provide essential ecosystem services, but are vulnerable to changes in the environment (Angeler et al., 2014). Release of wastewater changes the quality of surface water and the wastewater treatment, therefore, helps to maintain the ecosystem equilibrium.

This paper focuses on the environmental benefits only, which represent a share of the total economic value of wastewater treatment. Since the economic value of wastewater treatment is not revealed through market prices, we aim to estimate the shadow prices of individual pollutants and the environmental benefits of their removal. Valuation of these non-marketed benefits is necessary to design efficient environmental policies and to provide an indicator of cost effectiveness to the benefits side of the projects. The benefits can be estimated by various methods. Among the most common ones are measurement of willingness-to-pay through stated (Hill, 1994) or revealed preference (Collier et al., 2012) methods or estimation of health benefits through the added quality-adjusted life years or potential lifetime earnings (Bradley et al., 2008).

The methodology applied in this paper is based on the estimation of shadow prices for the pollutants removed in the process of treatment. Since pollutants removed would cause environmental harm, the shadow price of the pollutant represents the environmental damage avoided due to the process of treatment. Under the assumption of equal marginal costs and benefits, the shadow prices can be interpreted as environmental benefits gained. Previous studies estimated shadow prices of emerging pollutants (Bellver-Domingo, Fuentes and Hernández-Sancho, 2017), a shadow price for CO_2 from wastewater treatment (Molinos-Senante, Hanley and Sala-Garrido, 2015) or a shadow price for the effluent pollution being released to sensitive areas (Bellver-Domingo and Hernández-Sancho, 2018). The model approach in this study follows studies by Färe (Färe et al., 2002) and Molinos-Senante (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2011). Methodology used for the economic valuation is based on the estimation of shadow prices for the pollutants removed in the treatment process. Total estimated value represents the costs avoided through undischarged pollution.

1. Methods

The estimation of shadow price takes into account the revenue function and directional output distance function of the wastewater treatment plants within our sample. The plant aims to maximize its revenue function through maximization of the amount of treated water and minimization of the undesirable outputs while costs are fixed. The value of distance function for each plant reflects its efficiency in terms of maximizing the revenue function. The shadow price is then calculated using the effectivity, reference price of the treated water and amounts of desirable and undesirable outputs. The shadow price can be interpreted (Zhou, Zhou and Fan, 2014) as the opportunity cost of abating one additional unit of undesirable output in terms of the loss of desirable output. Assuming that the current pollution levels are optimal, marginal cost equals marginal benefit, and therefore the shadow prices of the undesirable outputs can be interpreted as an estimation of the environmental benefits gained from the treatment process.

Pricing model is based on the directional output distance function that seeks to reduce undesirable outputs and maximize desirable outputs simultaneously, using given inputs. In this particular application, the process of wastewater treatment produces only one desirable output which is the treated water, and 4 undesirable outputs: *nitrogen* (N), *phosphorus* (P), *suspended solids* (SS*)* and *chemical oxygen demand* (COD). The inputs needed to carry out the treatment are *energy, staff, reagents and maintenance* and *others.*

The directional output distance function represents the technology and bears axiomatic assumptions with properties of the output set *P(x)* (Färe et al., 2002). Output set denotes the set of desirable and undesirable outputs that can be produced from the input vector x and is defined as (1):

$$P\left(x\right)=\left\{\left(y,b\right): x\,\text{can produce}\left(y,b\right)\right\} \tag{1}$$

The directional output distance function is formally defined as (2):

$$D\left(x,y,b;g_y,-g_b\right)=\max_{\beta}\left\{\beta:\left(y+\beta*g_y,b-\beta*g_b\right)\in P\left(x\right)\right\} \tag{2}$$

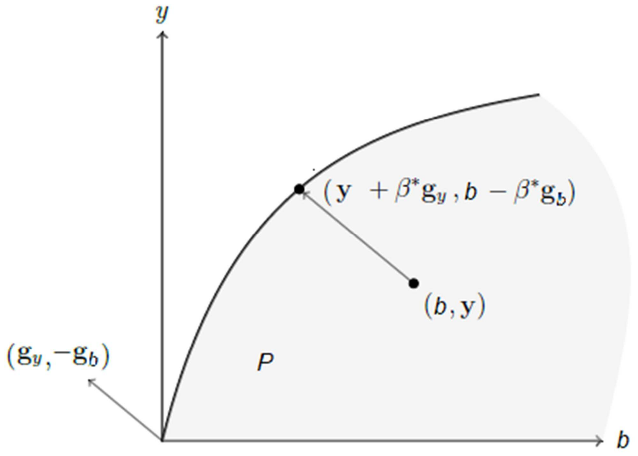
i.e., it is the largest feasible value of the projection of *(y, b)* onto the boundary of *P(x)* in the direction *g*, where *y* is desirable and *b* is undesirable output. In other words, the value β provides maximum expansion of desirable outputs and reduction of pollutants if a firm operates efficiently given the directional vector *g*. The vector $g = (g_y, - g_b)$ specifies the direction in which an output vector *(y, b)* is projected onto the frontier or boundary of output set at the point $(y + \beta*g_y, b - \beta*g_b) \in P(x)$.

Figure 1 provides an illustration of the case of one desirable output *y* and one undesirable output *b*. In our estimation of the distance function we set $g = (1, -1)$, which is consistent with the environmental regulations for the generating units, which requires reduction in bad outputs. Another reason for this choice of directional vector is aggregation. The aggregate efficiency is the sum over the individual unit's efficiencies (Färe et al., 2002).

The directional output distance function takes the value of zero for technically efficient output vectors on the frontier, while positive values imply inefficiency. The higher the value, the more inefficient the output vector and the respective firm is.

Figure 1

The Directional Output Distance Function



Source: Own elaboration.

The function can be specified in several functional forms. For the purpose of this analysis, we have chosen the parametric quadratic functional form, which satisfies required properties (Färe et al., 2002). Applied to our case the formula (3) is:

$$
\begin{aligned}
&D\left(x^k, y^k, b^k; 1, -1\right) \\
&= \alpha_0 \\
&+ \sum_{n=1}^{4} \alpha_n x_n^k + \beta_1 y^k + \sum_{l=1}^{4} \gamma_l b_l^k + \frac{1}{2} \sum_{n=1}^{4} \sum_{n'=1}^{4} \alpha_{nn'} x_n^k x_{n'}^k \\
&+ \frac{1}{2} \beta_2 y^k y^k + \frac{1}{2} \sum_{l=1}^{4} \sum_{l'=1}^{4} \gamma_{ll'} b_l^k b_{l'}^k \\
&+ \sum_{n=1}^{4} \mu_n x_n^k y^k + \sum_{n=1}^{4} \sum_{l=1}^{4} \delta_{nl} x_n^k b_l^k + \sum_{l=1}^{4} \rho_l b_l^k y^k
\end{aligned}
\tag{3}
$$

where

x – the input,
y – the desirable output,
b – the undesirable output,
k – the number of units of wastewater treatment plants,
l – the number of undesirable outputs,
n – the number of inputs.

We estimate the parameters of the distance function by solving the following minimization problem (4):

$$
\begin{aligned}
& \min\sum_{k=1}^{57}\left(D\left(x^k,y^k,b^k;1,-1\right)-0\right)\\
& s.t.\, D\left(x^k,y^k,b^k;1,-1\right)\geq 0, k=1,\ldots,57\\
& \frac{\partial D\left(x^k,y^k,b^k;1,-1\right)}{\partial b_l}\geq 0, l=1,\ldots,4, k=1,\ldots,57\\
& \frac{\partial D\left(x^k,y^k,b^k;1,-1\right)}{\partial y}\geq 0, k=1,\ldots,57\\
& \beta_1-\sum\nolimits_{l=1}^{4}\gamma_l=-1, \beta_2=\sum_{l=1}^{4}\rho_l, \rho_l=\sum_{l=1}^{4}\gamma_{ll'}, \mu_n=\sum_{l=1}^{4}\delta_{nl}\\
& \alpha_{nn'}=\alpha_{n'n}, \gamma_{ll'}=\gamma_{l'l}
\end{aligned}
\tag{4}
$$

objective function minimizes the sum of deviations of the estimated distance functions for every unit from the efficient value of zero, i.e. their frontier. Constraint set ensures assumptions are fulfilled. To solve the minimization problem we used GAMS software with the CPLEX solver.

Using the values of directional output distance function we can estimate the marginal abatement costs for each pollutant per plant (Färe et al., 2002). As we consider the costs to be fixed, each plant can maximize its revenue, but not profit. The revenue function of a plant (5) may be derived as follows:

$$R\left(x,p,q\right)=\max_{y,b}\left\{p_y y-qb: D\left(x,y,b;1,-1\right)\geq 0\right\} \tag{5}$$

where

p_y – the price of the desirable output,

q – the vector of prices of undesirable outputs.

The condition for the distance function ensures feasibility, i.e. 100% efficiency cannot be exceeded. In our case, p_y is the price of treated water which is marketable and the price q is a vector of shadow prices of the five pollutants. Forming the Lagrangian form of revenue function and taking the first order conditions yields to find shadow prices. Assuming that the price of the desirable output, the treated water, is known and coincides with its shadow price, the absolute shadow prices of undesirable outputs are given by (6):

$$q_l=-p_y\frac{\partial D\left(x,y,b;1,-1\right)/\partial b}{\partial D\left(x,y,b;1,-1\right)/\partial y}, l=1,\ldots,4 \tag{6}$$

The minus sign in the equation ensures shadow prices are negative to reflect the environmental damage avoided during the treatment process.

Using our parametrization of distance function the equation of the shadow prices for each pollutant for every plant becomes (7):

$$q_l^k = -p_y \frac{\gamma_l + \sum_{l'=1}^{4} \gamma_{ll'} + \sum_{n=1}^{4} \delta_{nl} x_n^k + \rho_l y^k}{\beta_1 + \beta_2 y^k + \sum_{n=1}^{4} \mu_n x_n^k + \sum_{l=1}^{4} \rho_l b_l^k}, l = 1, \ldots, 4, k = 1, \ldots, 60 \qquad (7)$$

2. Data

The sample used in this analysis consists of 57 wastewater treatment plants in the Slovak republic (described in Table 1). All the plants use secondary treatment to remove nitrogen and phosphorus from the wastewater. Statistical information by each plant has been limited to the year 2016 and might differ over a longer period of time. We considered medium-sized plants with the volume of wastewater treated varying between 1 and 12 million m^3 per year. Since we experienced convergence problems of our model due to the numerical size of outputs and inputs, we normalized the data by dividing each output and input by its mean value before estimating the model (Färe et al., 2002).

Table 1

Description of the Sample

			Mean	**Standard deviation**	**Min**	**Max**
Inputs (€/year)	Energy	x_1	139 810	101 309	51 597	639 042
	Staff	x_2	189 894	88 897	62 886	503 896
	Reagents maintenance	x_3	113 694	111 957	4 207	554 145
	Others	x_4	526 725	415 946	38 236	2 252 756
Desirable output (m^3/year)	Treated water	y	2 851 831	2 293 168	944 685	12 233 360
Undesirable outputs (kg/year)	Nitrogen	b_1	90 718	91 574	14 997	539 452
	Phosphorus	b_2	16 421	19 492	347	85 710
	SS	b_3	647 201	809 349	123 076	4 806 722
	COD	b_4	1 254 598	1 464 031	52 200	9 870 639

Source: Own elaboration based on water management companies.

3. Model Results

The estimates of parameters of directional output distance function are provided in the Annex 1. The values of the distance functions give us the estimates of technical inefficiency for each plant (Annex 2). The value of inefficiency does not give any information on the economic management of the plant. The plant is not able to decide about the amount of pollutants that occur in the incoming water and has to reach a certain treatment level to meet the limits of pollutants in the released water.

The mean of estimated value of the directional output distance function is 0.109, which means that at the fixed costs the amount of treated water could be on average expanded by 309 999 m^3 per year and the amount of all pollutants could be contracted by 218 375 kg per year simultaneously. It implies quite high level of efficiency of wastewater treatment plants within the sample.

Table 2 shows the average shadow prices of four undesirable outputs. We have to inflate the ratio of derivatives of distance function by multiplying by the mean value of y to mean value of b to get original dimensions of data. For the calculation of these shadow prices the reference price for the desirable output needs to be assigned. Reference price of the treated water in the amount of 0.991 euros per cubic meter was provided by the Slovak regulation authority. A single value is used for all the treatment plants, since the destination of the effluent is the same for all of them.

It can be seen that the main environmental benefits of treatment are the elimination of *phosphorus and nitrogen*, which is in line with the previous studies (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2010; Molinos-Senante, Hernández-Sancho and Sala-Garrido; 2011; Chambers, 1998). For the shadow price of *the chemical oxygen demand* the obtained value is much lower which may be because water bodies have a certain capacity to self-purify this pollutant (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2011).

Table 2

Average Shadow Prices for the Undesirable Outputs – Pollutants (€/kg)

	Shadow prices for undesirable outputs (€/kg)			
Reference price of water (€/m^3)	N	P	SS	COD
0.991	–31.942	–82.433	–10.706	–2.277

Source: Own elaboration.

We have compared our results with previous studies conducted on wastewater treatment plants located in the Spanish region of Valencia using data for different years and different samples of plants (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2010; Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2011; Chambers, 1998). The study by Molinos-Senante (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2011) used the same 4 pollutants and directional distance function parameterization with a quadratic form as our study. We obtained similar results for the shadow price of *nitrogen* and *phosphorus*.

However, results for the shadow price of *suspended solids* and *chemical oxygen demand* are much higher. These differences may arise from the significant differences in outputs between Slovak and Spanish treatment plants. Comparing values of outputs, *nitrogen* and *phosphorus* are similar, but values for *suspended solids* and *chemical oxygen demand* are half the values in the previous study. The removal of *suspended solids* and *chemical oxygen demand* in the treatment process is more expensive in Slovakia due to different volumes of these pollutants.

Comparing the results of other Spanish studies by Hernández-Sancho (Hernández-Sancho, Molinos-Senante and Sala-Garrido, 2010) and Molinos-Senante (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2010) the estimated shadow prices for nitrogen and phosphorus are lower in our model, while SS and COD are much higher. Even though the mean values of pollutants are similar across all three Spanish studies, the results of shadow prices differ significantly. The reason for inconsistency in results can be a different form of distance function used in studies. We considered the parametric quadratic functional form of distance function, while Hernández-Sancho (Hernández-Sancho, Molinos-Senante and Sala-Garrido, 2010) and Molinos-Senante (Molinos-Senante, Hernández-Sancho and Sala-Garrido, 2010) used the translog (transcendental logarithmic) function. While the translog function offers the greatest flexibility, the quadratic function can be restricted to satisfy the translation property (Chambers, 1998). Furthermore, our model didn’t include the biological oxygen demand even though it was included in the Hernández-Sancho’s study (Hernández-Sancho, Molinos-Senante and Sala-Garrido, 2010), since biological oxygen demand and chemical oxygen demand measure the same pollution through different means. Incorporation of both indicators would result in double counting of this pollution.

Considering the volume of pollutant removal in the treatment process within our sample and the shadow prices of pollutants, we can calculate the value of overall environmental benefits resulting from treatment of wastewater per year or per cubic meter of treated water. The biggest proportion of environmental benefits (49%) comes from the removal of the *suspended solids* and the *chemical oxygen demand.* Even though, *phosphorus* has high shadow price, it contributes to the value of benefit by only 10% because the volume removed in the treatment process is relatively low. The overall environmental benefits of the treatment stand at 4.922 euros per cubic meter. The biggest contribution in environmental sense is still the removal of phosphorus and nitrogen, which could cause serious eutrophication problems within the recipient water, had they not been removed in the process of treatment.

Table 3

Environmental Benefit of Treatment within the Sample

Pollutants	Pollutant removal	Environmental value pollution		
	kg/year	€/year	€/m3	%
N	5 170 954	165 168 538	1.016	21
P	936 050	77 161 627	0.475	10
SS	36 890 462	394 949 183	2.430	49
COD	71 512 119	162 834 184	1.002	20
Total		800 113 532	4.922	

Source: Own elaboration.

4. Conclusions and Policy Implications

Environmental benefits of treating the wastewater released into surface waters in 2016 are estimated to be 1.96 billion euros. The approximation of the results for all the wastewater treatment plants through multiplication of the environmental benefits per unit by the amount of domestic wastewater released into surface waters provided by Slovak Hydrometeorological Institute can be used to estimate overall environmental benefits of wastewater treatment in Slovakia. It represents a lower bound estimate of costs to remove the pollution from the environment, had the wastewater not been treated. It would have to be invested in cleaning and reconstruction programs, such as removal of nutrients to stop eutrophication of water bodies or to save the water organisms and ecosystems. There are, however, many other polluting substances being removed from the wastewater throughout the process that would further increase the benefits, had they been included in the study.

Figure 2

Estimated Benefits (size of the dot) of Each Wastewater Treatment Plant

Source: Own elaboration.

Health benefits are not considered within this analysis. Wastewater treatment significantly decreases the number of people infected by water-related diseases and saves premature deaths. It was not within the scope of this analysis to estimate the monetary value of improved health level. The overall benefits of wastewater treatment would therefore be even higher. The quality of water has a positive impact on the local economy as well, both in terms of creating jobs in tourism, fisheries or agriculture and employing locals at wastewater treatment plants. Moreover, some of the treatment plants could generate energy and reduce the country's dependency on imported fossil fuels by use of biogas.

In the future, possible implications of these results may be in cost-benefits analyses of wastewater treatment investment projects. While some of the partial data, such as the efficiency of removal of pollutants, is already considered, shadow prices might provide a different perspective. The environmental benefits included in this analysis don't have a direct market price and hasn't been considered in the financial sense in any cost-benefit analysis. This led mostly to the underestimation of the total benefits of the wastewater treatment. Moreover, this value could serve as a comparison base for decision makers to decide which project in diverse areas to fund in order to achieve the greatest benefits.

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Annex A

Parameter Estimates of Distance Function

α_0	0.144	α_{24}	0.234	μ_3	0.073	δ_{44}	–0.073
α_1	0.248	α_{33}	0.119	μ_4	–0.118	ρ_1	–0.159
α_2	0.056	α_{34}	0.055	δ_{11}	0.343	ρ_2	–0.063
α_3	–0.227	α_{44}	–0.153	δ_{12}	0.209	ρ_3	0.036
α_4	–0.276	β_2	–0.195	δ_{13}	–0.381	ρ_4	–0.009
β_1	–0.451	γ_{11}	–0.081	δ_{14}	0.114	ρ_1	–0.073
γ_1	0.335	γ_{12}	–0.038	δ_{21}	–0.104		
γ_2	–0.024	γ_{13}	–0.050	δ_{22}	0.024		
γ_3	0.135	γ_{14}	0.009	δ_{23}	0.33		
γ_4	0.104	γ_{22}	0.004	δ_{24}	0.039		
γ_5	–0.241	γ_{23}	–0.047	δ_{31}	0.027		
α_{11}	–0.895	γ_{24}	0.018	δ_{32}	0.059		
α_{12}	–0.386	γ_{33}	0.177	δ_{33}	–0.009		
α_{13}	0.388	γ_{34}	–0.044	δ_{34}	–0.004		
α_{14}	–0.098	γ_{44}	0.009	δ_{41}	–0.072		
α_{22}	0.232	μ_1	0.285	δ_{42}	–0.049		
α_{23}	0.144	μ_2	0.290	δ_{43}	0.076		

Source: Own elaboration.

Annex B

Estimates of Inefficiency of Each Plant

Považská Bystrica	0.161	Dolný Kubín	0.096
Púchov	0.14	Nižná	0.045
Dubnica nad Váhom	0.54	Námestovo	0
Liptovský Mikuláš	0	Bardejov	0
Brezno	0.255	Humenné	0
Lučenec	0	Snina	0.048
Handlová	0.054	Michalovce	0.529
Prievidza	0.195	Prešov – Kendice	1.084
Rimavská Sobota	0.489	Sabinov	0.122
Veľký Krtíš	0.061	Rožňava	0
Detva	0	Revúca	0
Zvolen	0	Svidník	0.019
Banská Štiavnica	0.022	Trebišov	0
Žiar nad Hronom	0.003	Vranov – Lomnica	0.004
Spišská Nová Ves	0	Čadca	0.076
Kežmarok	0.113	Kysucké Nové Mesto	0.135
Stará Ľubovňa	0.078	Nitra	0
Levoča	0.113	Zlaté Moravce	0.281
Krompachy	0.008	Dunajská Streda – Kútniky	0
Devínska Nová Ves	0	Galanta	0
Modra	0.129	Sereď	0
Senec	0.449	Šaľa	0
Hamuliakovo	0	Levice	0
Malacky	0	Nové Zámky	0.038
Myjava	0.03	Šurany	0
Senica	0.165	Bánovce nad Bebravou	0.581
Holíč	0.021	Partizánske	0
Skalica	0	Topoľčany	0.112
Komárno	0	**Average**	**0.109**

Source: Own elaboration.