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The Technical Efficiency of Slovak Water Companies: An Application of Network DEA

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Abstract:

The technical efficiency of water companies plays a crucial role in ensuring the reliable and sustainable delivery of clean and safe drinking water. It also influences the effective management of water and wastewater services. Services of this kind, usually provided by a monopoly supplier, offer operators no market incentives to innovate, or improve their efficiency. So, the mission of the regulatory institutions is to simulate a competitive environment. The main aim of this contribution is to use Network Data Envelopment Analysis (N-DEA) to assess and benchmark the technical efficiency of 14 water and wastewater companies offering their services in Slovakia from 2019 – 2021. The methodology of N-DEA allows us to assess the activity`s cost and delivery efficiency, and its overall technical efficiency. We show that full cost efficiency was achieved by two small and one large water companies operating in different regions. Three of the largest suppliers of water and wastewater services and one small company achieved the efficient delivery of water services. Overall efficiency was achieved by one large company in 2021 and one small company in 2019 and 2020. The outcome of our

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empirical analysis demonstrates the excellent skills of managers in technically efficient companies, regardless of company size and region. That outcome may be of interest to regulatory institutions and the management of individual water companies.

Keywords:
benchmarking, network data envelopment analysis, optimisation, regulation, water

1. Introduction

In competitive sectors, the desire for market success motivates entrepreneurs to provide goods and services of comparable quality and price. Nevertheless, where, for various reasons, the competitive environment does not work, and the products are only provided by a monopoly or an oligopoly, external intervention is essential to avoid the abuse of market power. The non-market environment also includes natural monopolies in network industries that supply the population`s basic living needs. These include the supply of power and heat, drinking water, wastewater collection and treatment, and the services related to the supply of those commodities. For this reason, continuous and high-quality security of the supply of these commodities is a fundamental and critical prerequisite for a well-functioning economy.

This paper`s contribution focuses on water regulation. Water resources are finite and, in many areas, becoming increasingly scarce. We measure and compare the technical efficiency of 14 water and wastewater companies offering water-related services in Slovakia. We use a non-parametric approach, Data Envelopment Analysis (DEA). Even though the national regulators of some countries have been using benchmark techniques to evaluate water management for around twenty years, this is not true for Central and Eastern Europe.

The history of Slovak water supply relates to German colonisation in the 14th century, especially in mining areas, where water caused problems with mineral extraction. Subsequently, groundwater, drawn from mines, was used to supply the population. One of the first water mains was opened in 1886 when Bratislava`s citizens began to be supplied with drinking water.

Until 1989, the supply of Slovakia`s drinking water and the collection and treatment of its wastewater were state tasks carried out by five state enterprise water and sewerage plants. Since 1990, these services have been supplied by the municipalities. Hence, the transformation of state-owned water and sewerage enterprises began in the early nineties. In 1995, state property was transferred to cities, and three water companies were created. Subsequently, in 2001, seven more private water companies were created after government approval. This privatisation was intended to follow certain principles. For example, to protect the public interest, the shares of municipal water companies were not supposed to be publicly traded. However, this was ignored,

and the privatisation prioritised private over public interests (Supreme Audit Office of the Slovak Republic, 2019).

Creating an efficient and effective set of markets for Slovak network industries clearly required a new regulatory framework. In 2001, the Regulatory Office for Network Industries (Úrad pre riadenie sieťových odvetví – hereafter URSO, or the Authority) was established. Its purpose is to protect consumers from abuse by monopoly power in the network industries of electricity, gas, heat, power, and water management. However, at the same time, it needs to pay attention to the return on investment in network industries so that energy and water supply are reliable and secure. In exercising its powers, the intention is that the Authority shall act independently. State bodies, territorial self-administration bodies, other public authorities or persons may not influence the Authority in exercising its powers.

The Regulatory Office for Network Industries issues generally binding legal regulations, carries out price regulation, decides on the imposition of fines resulting from the regulatory law in network industries, and imposes measures to eliminate and remedy deficiencies identified during inspection. It also concludes agreements with EU Member States' regulatory authorities to promote regional cooperation. In addition, it cooperates with the European Commission, with ministries and other central government bodies and publishes an annual report on the activities of the Office (*Act No. 250/2012 Coll. On Regulation in Network Industries*, 2012).

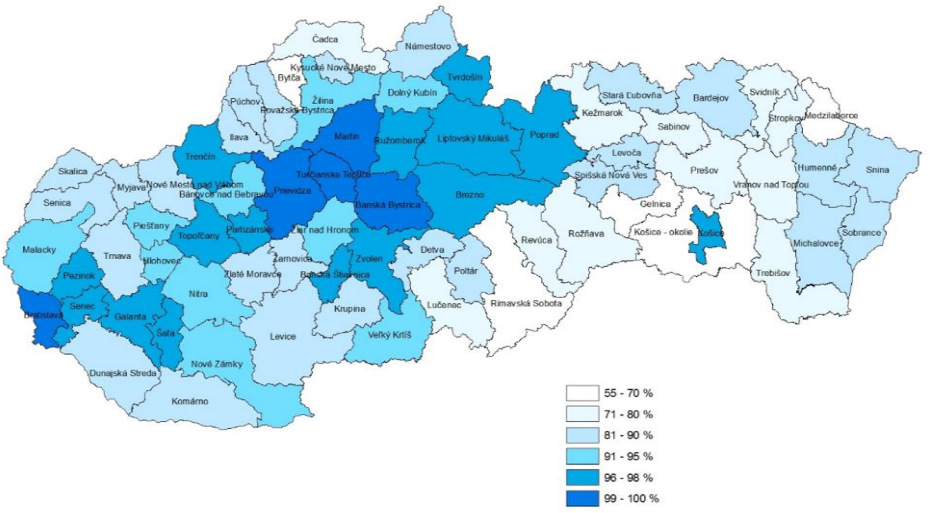
A regulated entity – for example, a water and wastewater supplier - is an entrepreneur who carries out a regulated activity. A regulated entity has the right to submit a proposal setting the price, tariff, terms and conditions, and alterations in them, to stop or interrupt the supply of goods or services, to use someone else's property for public purposes, and to request exemption from regulation, provided certain conditions are met (Regulatory Office for Network Industries, 2019, 2020, 2021).

The regulated entity must deliver goods or provide services per approved prices, tariffs, and business conditions and comply with the specified conditions for carrying out regulated activities. According to the URSO's decision, it may allow other entrepreneurs access to the network. It can submit proposals for changed terms and conditions to the Regulatory Office for decision at least one month before the start of their use. It informs clients about the complaint-handling procedure and keeps separate records for each regulated activity within the accounting framework according to the requirements of the URSO (Zwiebová, 2005).

The level of development of public water supply systems needs to be more balanced between regions. The decisive cause is the lack of underground water resources in areas such as the south of Central Slovakia and in Eastern Slovakia. Figure 1 shows the share of the population connected to the public water supply for 2020 in different districts of the Slovak Republic.

Figure 1:

Percentage of population supplied from public water supply in 2020



Source: Water Management Research Institute, 2021.

Overall, in 2020, 89.81% of the population got their drinking water through public water pipes, less than in most EU countries. From a regional viewpoint, the highest levels of public connection are in Bratislava, Banská Bystrica, Turčianske Teplice and Prievidza. The lowest public connection levels are in eastern Slovakia. More than 80% of drinking water comes from underground sources. Less than 20% comes from surface water sources (Water Management Research Institute, 2021).

This paper focuses on the technical efficiency of 14 Slovak water companies from 2019 – 2021. We apply a two-stage, slacked-based model (SBM) approach of Network Data Envelopment Analysis (N-DEA) to evaluate the companies` production process. The first stage assesses how cost-efficient the companies are in maintaining their infrastructure. The second stage reveals how the companies employ their infrastructure to deliver water and wastewater services to its clients. The companies studied provide water abstraction, treatment, and delivery for almost 90% of economic entities in Slovakia.

The related research questions are as follows:

1. Are Slovak water and wastewater companies using their operating costs and investments efficiently?
2. Are Slovak water and wastewater companies providing water services efficiently?
3. How technically efficient were Slovak water and wastewater companies

overall in 2019 –2021?

To the best of the authors` knowledge, this paper presents the first empirical study of the technical efficiency of the water industry in the Slovak Republic and other Central European countries. Moreover, the paper makes a significant methodological contribution through its application of advanced N-DEA to allow a phased assessment of the efficiency of the production process. While the results of the first phase of the model assess the efficiency of the operating costs and investments of the water companies, the results of the model's second phase reveal their efficiency in providing water services. In addition, the research provides evidence of economies of scale and scope in the water industry. The contribution is structured as follows. A brief literature review follows the introduction, a description of the data and model specifications, a report and discussion of the main research results, and a conclusion.

2. Literature review

To our knowledge, water management efficiency has yet to be dealt with in the scientific literature focusing on Central and Eastern Europe (CEE). Therefore, the contribution aims to fill the gap by applying the methodology of advanced non-parametric Network Data Envelopment Analysis (N-DEA) in the Slovak environment.

Compared to the CEE region, many studies on the topic exist in developed countries. A fundamental contribution to the study of technical efficiency in water management was carried out by Thanassoulis (2000a, 2000b). His papers introduced the basic DEA models for assessing efficiency under both constant and variable returns to scale. They outlined the use of DEA by the England and Wales regulator of water companies. His research introduced a productive conceptualisation of the issue, and the results are still the most cited in the academic literature. Thus, economies of scale are one of the most relevant issues to investigate.

The cost-effectiveness of Chilean water and sewerage companies, 2010-18, concerning their form of management, was examined by Molinos-Senante & Maziotis (2021). Their estimates were obtained using the stochastic non-parametric data envelopment method (StoNED). The above combines the advantages of data envelopment analysis (DEA), and stochastic frontier analysis (SFA). The results indicate the need to consider the quality of service delivered at the set water tariffs. On the one hand, the study showed that public water companies were the most price efficient, followed by fully private, and finally by concessionary water companies. On the other hand, over time, fully private water companies` efficiency showed an upward trend, while public water companies` efficiency deteriorated.

Another group of researchers, Lombardi et al. (2019), conducted an empirical DEA analysis of the Italian water sector concerning management and water loss. It focused on a selected sample of 68 Italian water companies from 2011 to 2013. They

found that public water companies were more efficient in buying and using inputs than mixed or private firms. When they focussed on water loss, the study showed that companies located in the north of Italy were more efficient than those in the centre and the south. In addition, they showed that small companies were the most efficient, followed by large and then extra-large companies.

The relationship between client satisfaction with water and wastewater services, demographic factors, communication of water companies with the clients, and perceived trustworthiness was studied by Tian et al. (2023). Through a survey of the UK public (n=760), the authors found that 77% of the respondents stated they were satisfied with their water and wastewater services. Statistical analysis highlighted significant demographic differences in the level of satisfaction, particularly by age, with higher satisfaction in older respondents. Citizens' attitudes towards local services` accountability and transparency were studied by Pita et al. (2021). The results of their binomial logit regressions indicate that in terms of perceived accountability and transparency of water supply and sewage, significant variables included gender, education, and satisfaction with the price respondents paid for the services.

Abbott & Cohen (2009) revealed the various measures used to gauge the levels of productivity and efficiency in the water sector regarding these measures' input and output data requirements. The literature suggests that the more advanced techniques attracted special attention. Using a DEA model and regression analysis, Liu and Fukushige (2019) investigated the efficiency of water utilities in Japan. The authors employed a two-stage analysis. The first stage involved measuring the relative efficiency of water supply and sewerage services, using DEA. In the second stage, based on regression models, the authors examined the relationships between prices and estimated efficiency scores. Salazar-Adams (2021) analysed Mexican water companies' efficiency using double bootstrap DEA. In the first stage, he calculated the efficiency of each company based on a set of inputs and outputs. In the second stage, the efficiency scores were regressed on a set of explanatory variables that influence water company efficiency. He concluded that decentralisation from the Mexican state to municipalities had not significantly increased the efficiency of water utilities because municipal and state utilities were equally efficient. However, the water reform paved the way for new organisational schemes, such as inter-municipal enterprises and privately managed enterprises. On average, the sample`s inter-municipal enterprises were more efficient than either state or municipal enterprises. On average, the sample`s several privately managed companies were the most efficient type of water utility. A possible explanation is local regulation, which may compensate for the lack of institutional capacity that often occurs in developing countries. A study by Liang et al. (2021) developed an improved two-stage network DEA model. The above assumed variable returns to scale for both weights and solution methods. In both stages the weights were determined by the share of input resources. The model was applied to eleven western Chinese provinces to measure the overall efficiency of their water resource systems, water use efficiency, and wastewater treatment efficiency, from 2008–2017. A panel Tobit regression model was

used to analyse further the key factors influencing total efficiency, water use efficiency, and wastewater treatment efficiency.

The relationships between water resources, water ecology and water environment were studied by Shi et al. (2022). A DEA window model was applied to evaluate the agricultural water resource utilisation efficiency of the (Yangtze River Economic Belt) YREB from 2010 to 2019. The paper incorporates precipitation, as an exogenous environmental variable, into analysing water resource utilisation efficiency. Lo Storto (2020) used a network DEA approach to analyse the Italian water industry. Zhou et al. (2018) investigated the efficiency of China`s water management using a non-radial, non-oriented DEA model. The Slacks-Based Measure (SBM) model can simultaneously optimise required inputs and outputs and project each unit to the "farthest" point on the efficient frontier. The regulation of the Iranian water industry, and its technical efficiency as well as productivity, measured by the Malmquist index, was researched by Nourali at al. (2014). The authors discovered that from 2008-2011, average technical efficiency reached 88% when there were variable returns to scale and 77% when there were constant returns to scale. Regarding the productivity assessment, the Malmquist index confirmed a deterioration in total factor productivity during the period analysed.

It is necessary to add that there is a vast literature revealing various determinants of efficiency of delivery of local public services. These studies began with a focus on ownership and management forms. Later, they analysed many other different aspects of service delivery, including centralisation or decentralisation, regulation, client satisfaction, economies of scale, degree of competition, contract management, and cost control.

Management forms for local public services can be classified as private management, direct public management, mixed management or inter-municipal cooperation (Albalate et al., 2021; Benito et al., 2019, 2021; Cuadrado-Ballesteros et al., 2012; Pérez-López et al., 2021; Petkovšek et al., 2021; Zafra-Gómez et al., 2020). Research papers that have studied the relationship between efficiency and the choice of service delivery mode to provide public services include Bel et al. (2021, 2010), Cuadrado-Ballesteros et al. (2012), Ferro et al. (2014), González-Gómez et al. (2014), Pérez-López et al. (2021), Zafra-Gómez et al. (2020), Mohr et al. (2010), Gradus et al. (2016) and Petkovšek et al. (2021). Privatisation of local government services is assumed to deliver cost savings, but empirical evidence from around the world is mixed. Differences in the dates of the analyses, service characteristics, and policy environment explain differences in the results of the listed studies. A genuine empirical effect of cost savings resulting from private production has not been revealed. The results suggest that to ensure cost savings, more attention should be given to the cost characteristics of the service, the transaction costs involved, and the policy environment stimulating competition rather than to the debate over public versus private delivery of these services.

Regarding other topics, Inter-Municipal Cooperation (IMC) was researched, for

example, by Teles & Swianiewicz (2018), Swianiewicz & Teles (2019), Pérez-López, et al. (2021) and Mohr et al. (2010). Czech and Slovak authors undertook most studies on the local service delivery in the CEE region. For example, Sedmihradská (2018) employed financial and accounting data of public entities to evaluate the character and magnitude of inter-municipal cooperation in the Czech Republic. She concluded that the extent of the public services provided by service contracts, or through institutionalised forms of IMC is quite limited. Most IMC was informal, e.g. exchange of experience and ad-hoc projects.

Local waste management was researched by Soukupová & Klimovský (2016) and by Soukupová et al. (2014; 2016; 2017a; 2017b; 2022). Based on data collected in 2014 from 2,065 municipalities, the regression results show that public-private partnerships are more expensive than other delivery forms. Contracting out leads to cost savings, especially for larger municipalities. The results for municipalities with fewer than 500 inhabitants show that IMC is crucial in reducing municipal costs. Meričková and Nemec (2013) and Mikušová Meričková & Nemec (2013) measured the impact of qualitative contract management factors on contracting efficiency. The results show that several important factors limit success. By far the most important is the degree of competition for the contract. Too few contracts involve a competitive bidding process. The data used to derive this conclusion cover over a decade and suggest that this problem is not improving. Change would require that our public administration systems become accountable, and intervention must focus on processes and results.

The topic we focus on – the existence of economies of scale and scope at municipal level - was also explored by Soukupová et al. (2014) and by Matějová et al. (2017). Both studies concluded that small municipalities with up to 1 000 inhabitants in the Czech Republic are likely to provide public services at higher unit costs than larger municipalities. However, there was no clear picture of the optimum size of the service delivery area. Moreover, the study by Soukupová et al. (2014), which analysed the local public services of 205 Czech municipalities with extended powers, concluded that possible economies of scale could not be clearly identified and that the size of a municipality is not a critical factor influencing the provision of local services.

A literature review reveals no research by DEA models on the technical efficiency of water companies in Central Europe. So, we applied Tone and Tsutsui's (2009) two-stage model to the Slovak water industry. The model`s first phase assesses the efficiency of the water companies` operating costs and investments. The results of the second phase reveal the efficiency of the provision of water services. Our research is also considerably influenced by the studies focusing on economies of scale and scope.

3. Data and model specification

As part of the analysis of technical efficiency, 14 private water companies operating in the Slovak Republic were examined. They were: Bratislavská vodárenská spoločnosť

(BVS), Trnavská vodárenská spoločnosť (TTVS), Západoslovenská vodárenská spoločnosť (ZVS), Trenčianske vodárne a kanalizácie (TVK), Podtatranská vodárenská prevádzková spoločnosť (PVPS), Severoslovenské vodárne a kanalizácie (SeVAK), Turčianska vodárenská spoločnosť (TVS), Oravská vodárenská spoločnosť (OVS), Vodárenská spoločnosť Ružomberok (VSR), Liptovská vodárenská spoločnosť (LVS), Podtatranská vodárenská prevádzková spoločnosť (PVPS), Považská vodárenská spoločnosť (PVS), Východoslovenská vodárenská spoločnosť (VVS), and Vodárne a kanalizácie mesta Komárna (KOMVaK).

Currently, there are three categories of public water operators in Slovakia. A public water operator supplying more than 50 000 inhabitants is a category I public water operator. A public water operator supplying between 2 500 and 50 000 inhabitants is a category II public water operator. A public water operator supplying less than 2 500 inhabitants is a category III public water operator. The water companies in this research are all category I operators. Currently, more than 663 regulated entities are operating public water supply and sewerage systems in the Slovak water management sector. In addition to the above 14 water companies, water infrastructure is also owned by a city, 40 municipalities, and 78 companies operating public water supply or public sewerage systems, categories I and II. Public water supplies or category III public sewage systems are currently operated by 530 small towns and municipalities (Regulatory Office for Network Industries, 2020).

The efficiency analysis uses financial and physical variables: financial data come from companies` financial statements, primarily balance sheets, and profit and loss statements. In contrast, data on physical variables was taken from the annual reports of individual water companies. Table 1 describes the variables selected for the model. They represent companies` individual inputs, outputs, and intermediate products. Variable selection was based on the empirical studies described above.

Table 1:

Description of variables

Variable	*Notation*	*Description*
Operating costs	OPEX	Costs associated with economic activity, in EURO
Investment	I	Investments in water infrastructure, in EURO
The length of the water supply network	LN	The length of the water supply network, without connections, in km
Volume of invoiced drinking water	W	Volume of invoiced drinking water intended for implementation, in m^3
Number of clients	CUS	Number of clients supplied with drinking water

Source: Authors' own, 2023.

Table 2 presents the descriptive statistics of the variables of the Slovak water companies for 2021. Tables 3 and 4 show the descriptive statistics for 2020 and 2019. In 2021, the average operating cost reached approximately € 35 232 738. As the median level of operating costs is considerably lower, this group of water companies are highly unequal in size. There are considerable differences in the minimum and maximum values for all monitored variables. In 2021, the average investment value in Slovak water companies was € 5 726 780. The average length of the water supply network in 2020 was 2 084 km. The average volume of drinking water supplied during 2021 was 14 429 319 m3.

In comparison to 2020, the observed values had slightly decreased. In 1921, the average number of clients supplied with drinking water was 326 997. The high standard deviations of all variables reflect the very wide range of sizes of water companies.

Table 2:

Descriptive statistics of variables in 2021

2021	*OPEX*	*I*	*LN*	*W*	*CUS*
Mean	35 232 738	5 726 780	2 084	14 429 319	326 997
Median	18 189 805	2 428 767	828	8 004 248	157 978
Standard Deviation	35 422 976	7 425 405	2 144	14 792 417	322 084
Minimum	5 019 779	200 000	313	2 126 563	51 271
Maximum	107 396 501	26 533 096	6 583	45 348 000	984 608
Count	14	14	14	14	14

Source: Authors' own, 2023.

Table 3:

Descriptive statistics of variables in 2020

2020	*OPEX*	*I*	*LN*	*W*	*CUS*
Mean	34 747 193	5 628 027	2 070	14 581 371	326 524
Median	17 686 475	2 416 502	814	8 403 942	157 216
Standard Deviation	9 392 155	2 074 681	571	4 000 558	86 013
Minimum	4 885 588	200 081	312	2 162 366	51 359
Maximum	106 051 110	27 491 200	6 558	47 165 000	982 313
Count	14	14	14	14	14

Source: Authors' own, 2023.

Table 4:

Descriptive statistics of variables in 2019

2019	OPEX	I	LN	W	CUS
Mean	34 832 230	7 533 512	2 059	14 431 540	325 223
Median	17 538 945	1 787 383	881	8 184 500	155 806
Standard Deviation	9 410 510	3 297 100	569	3 922 116	85 596
Minimum	4 715 481	173 777	311	2 239 569	51 280
Maximum	103 928 405	36 719 217	6 524	46 194 000	976 008
Count	14	14	14	14	14

Source: Authors' own, 2023.

As mentioned above, the literature review and data availability influenced the selection of inputs and outputs. Empirical studies generally treat operational, employee, and capital costs or investments as inputs. Outputs have generally included the drinking water supply and the number of clients connected to the public water supply. Some authors have treated the length of the water supply network as an input, others as an output. Here, we apply the network DEA model, which treats the length of the network as an intermediate product.

To answer the research questions, we use a two-level network structure. The first research question is assessed by the first phase of DEA modelling that represents the infrastructure's maintenance and operation costs. The second research question is addressed by the second phase of network DEA models, which focuses on using the network to supply clients with drinking water. The third research question is assessed by the overall technical efficiency that considers both cost efficiency and efficiency of water network utilisation.

In the first phase, the water company must cover the operation and maintenance costs. The first phase input costs include employee wages, energy consumption, and capital employed. Those expenses provide a functional water supply infrastructure – the output of the first stage. The company is cost-efficient if it supplies operational and maintenance activities at minimum cost. In the second phase, the water company uses its infrastructure to supply water. Therefore, using the network DEA model, we can calculate the cost efficiency of the enterprise, the efficiency of water service provision, and the overall efficiency of the process. The network length in this model represents the connection we have noted between the two processes. In the first phase, the length of the network enters the process as an output. In the second phase, the length of the network is represented as an input. In the research, the water companies' operating costs (OPEX) and investments (I) appear as the inputs of the first phase. In the second phase,

the volume of invoiced drinking water (W) and the number of clients connected to the public water supply (CUS) are used as outputs. The length of the network (LN) is an intermediate product that is an output in the first phase and an input in the second phase. The first stage shows how the company maintains its infrastructure cost-efficiently. The second stage shows how it employs its infrastructure to deliver water and wastewater services to its clients. When using the network SBM model, assigning weights to individual stages is important. A company has two basic equally important tasks: managing costs and providing water services. Therefore, we assign them equal weights of 0.5.

An equally important issue is to specify the connection between individual decisions. There are four types of links. For example, a free link is defined as one where the connected decisions are freely determined. At the same time, continuity between input and output is maintained and is under company control. In contrast, a fixed link is defined as one with unchanged linked activities, but the intermediate product is not under the company's control. Two further types of less commonly used links are the so-called good and bad links (Tone & Tsutsui, 2009). In our analysis, we will use a free link, as all water companies can jointly determine the size of the water network.

As to model specification, Jablonský and Dlouhý (2015) characterise the stages of the production process into serial or parallel groups or a combination of the two. The serial model applied in this study assumes a multi-stage production process in which a certain output represents the input to the next stage.

In our study, a two-stage network DEA model is used. The efficiency of the first and second levels is defined as follows:

$$\max \theta_0^1 = \frac{\vec{w}' \vec{z}_0'}{\vec{v}' \vec{x}_0'} \qquad \max \theta_0^2 = \frac{\vec{u}' \vec{y}_0}{\vec{w}' \vec{z}_0} \tag{1}$$

under conditions:

$$\vec{w}'\vec{z} - \vec{v}'x \le \vec{0}' \quad \vec{u}'\vec{y}_0' - \vec{w}'\vec{z} \le \vec{0}'$$
$$\vec{v}' \ge \vec{0}', \vec{w}' \ge \vec{0}'; \vec{u}' \ge \vec{0}'$$

The overall efficiency can be expressed as:

$$\max \theta_0^0 = \frac{\vec{u}' \vec{y}_0}{\vec{v}' \vec{x}_0'} \tag{2}$$

under conditions:

$$\vec{u}'Y - \vec{v}'X \le \vec{0}'$$
$$\vec{v}' \ge \vec{0}, \vec{u}' \ge \vec{0}$$

If we assume that the output of the first stage is also the input to the second stage,

then the overall efficiency is expressed by the following equation:

$$\theta_0^0 = \frac{\vec{w}'\vec{z}_0'}{\vec{v}'\vec{x}_0} \times \frac{\vec{u}'\vec{y}_0'}{\vec{v}'\vec{x}_0} = \frac{\vec{u}'\vec{y}_0'}{\vec{v}'\vec{x}_0} \tag{3}$$

under conditions:

$$\vec{u}'Y - \vec{w}'Z \le \vec{0}'$$
$$\vec{w}'Z - \vec{v}'X \ge \vec{0}'$$
$$\vec{v}' \ge \vec{0}, \vec{u}' \ge \vec{0}, \vec{w}' \ge \vec{0}$$

If the model is written as a linear programming problem, we get the following form:

$$\max \theta_0^0 = \vec{u}' y_0 \tag{4}$$

under conditions:

$$\vec{v}'\vec{x}_0 = 1$$
$$\vec{u}'Y - \vec{w}'Z \le \vec{0}'$$
$$\vec{w}'Z - \vec{v}'X \ge \vec{0}'$$
$$\vec{v}' \ge \vec{0}, \vec{u}' \ge \vec{0}$$

If $\vec{v}'^*, \vec{u}'^*, \vec{w}'^*$ represent an optimal solution, we express the overall efficiency of the 1st and 2nd stages as follows:

$$\theta_0^1 = \frac{\vec{w}'^*\vec{z}_0}{\vec{v}'^*\vec{x}_0}$$
$$\theta_0^2 = \frac{\vec{u}'^*\vec{y}_0}{\vec{w}'^*\vec{z}_0} \tag{5}$$
$$\theta_0^0 = \frac{\vec{u}'^*\vec{y}_0}{\vec{v}'^*\vec{x}_0}$$

Where: X = input matrix, Y = output matrix, Z = intermediate product matrix, $\vec{x}_0$ = input´s vector of DMU, $\vec{y}_0$ = output´s vector of DMU, $\vec{z}_0$ = intermediate product vector of DMU, $\vec{v}'$ = input weight vector, $\vec{u}'$ = output weight vector, $\vec{w}'$ = intermediate product weight vector, θ_0^0 total efficiency of DMU, θ_0^1 efficiency of the first stage of DMU, θ_0^2 efficiency of the second stage of DMU.

The traditional DEA model cannot systematically analyse the relationship between overall efficiency and the efficiency of each stage. However, the network DEA model considers the interactions between different stages and can integrate the efficiency evaluation of the network node in the system into an overall efficiency evaluation of the system. It is one of the methods applicable to the comprehensive assessment of

structural efficiency within the DMU (Tone & Tsutsui, 2009).

4. Results, discussion and recommendations

The technical efficiency of the Slovak water companies from 2019 to 2021, measured by the two-stage network SBM model, is summarised in table 5. The water companies' operating costs (OPEX) and investments (I) are the inputs of the first phase. In the second phase, the volume of invoiced drinking water (W) and the number of clients connected to the public water supply (CUS) are used as outputs. The length of the network (LN) is an intermediate product that is an output in the first phase and an input into the second phase. The first stage shows how the company maintains its infrastructure cost-efficiently. The second stage shows how the Slovak water companies employ their infrastructure to deliver water and wastewater services to their clients.

Table 5 shows that in Phase 1, many companies did not perform their operations and maintenance activities at minimum cost. In fact, most were not cost-efficient. From the results shown in Table 5, focusing on the values of the technical efficiency in the first phase, it can be observed that the efficiency of operating costs and investments was achieved in two small companies (Vodárne a kanalizácie mesta Komárna – KOMVaK, Vodárenská spoločnosť Ružomberok – VSR) and one large company (Východoslovenská vodárenská spoločnosť – VVS). While the eastern Slovakia company VVS is amongst the largest water companies operating in Slovakia, KOMVaK, operating in north Slovakia, and VSR, operating in central Slovakia, are amongst the smallest water companies. The first phase efficiency results strongly suggest that most water companies have much scope to improve their performance.

In the second phase, water is distributed through the supply network, and the outputs are the volume of drinking water supplied to clients and the number of clients connected to the public water supply. For the whole period under consideration, three companies were recorded as technically efficient in providing their water and wastewater services: Bratislavská vodárenská spoločnosť (BVS), Západoslovenská vodárenská spoločnosť (ZVS), and Východoslovenská vodárenská spoločnosť (VVS). All three companies, BVS, offering services in the capital Bratislava; ZVS, operating in the western part of Slovakia; and VVS, supplying water services in eastern Slovakia, are amongst the largest water and wastewater services suppliers. These three large companies were joined in 2019 and 2020 by a small Vodárenská spoločnosť Ružomberok – VSR operating in central Slovakia. The above validates that the efficiency of water and wastewater companies can also be achieved by smaller companies.

Table 5:

Technical efficiency of water companies in 2019 – 2021 assessed by a two-stage DEA model

DMU 2021	Efficiency of phase 1	Efficiency of phase 2	Overall efficiency	Ranking
BVS	0.18	**1.00**	0.59	11
TTVS	0.23	0.26	0.25	27
ZVS	0.11	**1.00**	0.55	12
TVK	0.37	0.16	0.19	29
PVS	0.38	0.16	0.19	32
SeVaK	0.18	0.31	0.28	22
TVS	0.56	0.14	0.19	33
OVS	0.51	0.12	0.16	38
VSR	0.89	0.54	0.66	8
LVS	0.48	0.09	0.12	42
SVPS	0.16	0.78	0.51	18
PVS	0.44	0.35	0.37	19
VVS	**1.00**	**1.00**	**1.00**	3
KOMVaK	**1.00**	0.35	0.51	16
DMU 2020	**Efficiency of phase 1**	**Efficiency of phase 2**	**Overall efficiency**	**Ranking**
BVS	0.22	0.99	0.61	10
TTVS	0.26	0.26	0.26	25
ZVS	0.08	**1.00**	0.54	14
TVK	0.36	0.16	0.19	31
PVS	0.40	0.16	0.19	30
SeVaK	0.17	0.31	0.28	23
TVS	0.53	0.14	0.19	34
OVS	0.51	0.12	0.16	39
VSR	**1.00**	**1.00**	**1.00**	**1**
LVS	0.49	0.09	0.12	41
SVPS	0.17	0.78	0.51	15
PVS	0.42	0.35	0.37	20
VVS	0.63	**1.00**	0.82	5
KOMVaK	**1.00**	0.52	0.68	6
DMU 2019	**Efficiency of phase 1**	**Efficiency of phase 2**	**Overall efficiency**	**Ranking**
BVS	0.25	**1.00**	0.63	9
TTVS	0.26	0.26	0.26	26
ZVS	0.10	**1.00**	0.55	13
TVK	0.36	0.17	0.20	28
PVS	0.38	0.16	0.19	35
SeVaK	0.17	0.31	0.27	24
TVS	0.54	0.14	0.19	36
OVS	0.53	0.12	0.16	37
VSR	**1.00**	**1.00**	**1.00**	1
LVS	0.51	0.09	0.12	40
SVPS	0.17	0.78	0.51	17
PVS	0.21	0.35	0.31	21
VVS	0.97	**1.00**	0.98	4
KOMVaK	**1.00**	0.51	0.67	7

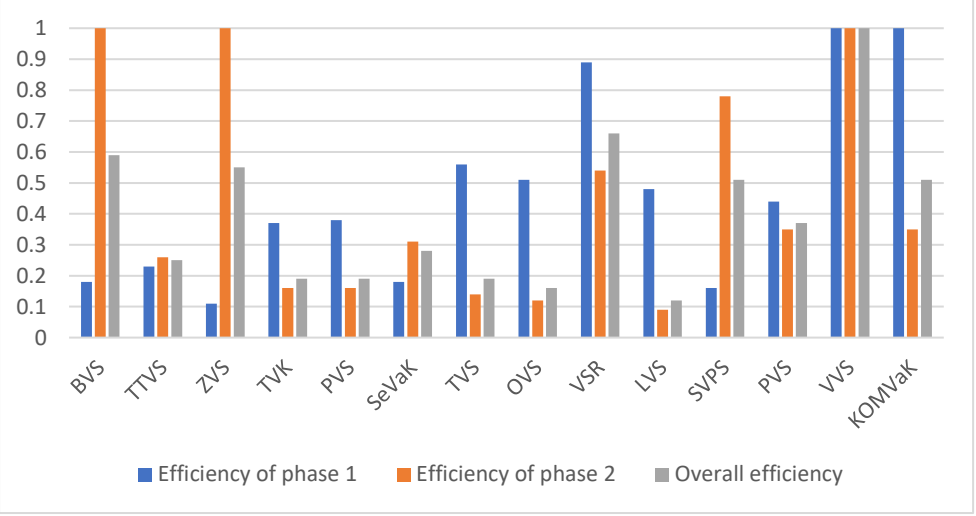
Note: Bratislavská vodárenská spoločnosť (BVS); Trnavská vodárenská spoločnosť (TTVS); Západoslovenská vodárenská spoločnosť (ZVS); Trenčianske vodárne a kanalizácie (TVK); Podtatranská vodárenská prevádzková spoločnosť (PVPS); Severoslovenské vodárne a kanalizácie (SeVAK); Turčianska vodárenská spoločnosť (TVS); Oravská vodárenská spoločnosť (OVS); Vodárenská spoločnosť Ružomberok (VSR); Liptovská vodárenská spoločnosť (LVS); Podtatranská vodárenská prevádzková spoločnosť (PVPS); Považská vodárenská spoločnosť (PVS); Východoslovenská vodárenská spoločnosť (VVS); Vodárne a kanalizácie mesta Komárna (KOMVaK).

Source: Authors' own, 2023.

According to the results shown in Table 5, the Slovak water and wastewater companies` overall efficiency levels were reached only by Východoslovenská vodárenská spoločnosť (VVS) in 2021 and by the small Vodárenská spoločnosť Ružomberok (VSR) in 2019 and 2020. The outcome of our empirical analysis of overall technical efficiency demonstrates excellent managerial skills concerning cost efficiency, efficient use of their capital and efficient water service provision, regardless of their size and the region in which they operate.

Figure 1:

Technical efficiency of the water companies in the Slovak Republic 2021

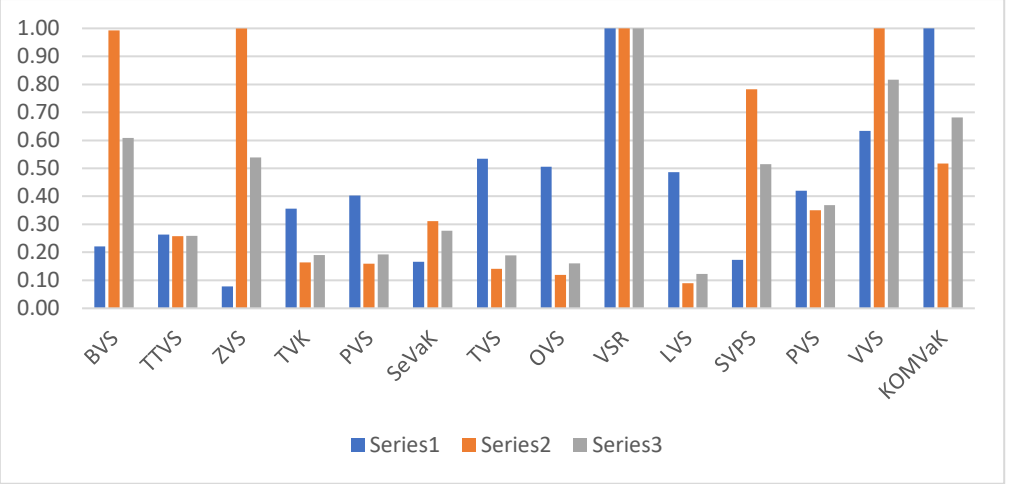


Source: Authors' own, 2023.

Figure 1 shows the 2021 efficiency ranking of water companies. The best result was achieved by Východoslovenská vodárenská spoločnosť (VVS), which was a fully efficient production unit in both phases of the process, and therefore also in overall efficiency. VVS is one of the largest water companies operating in eastern Slovakia. The supplier Liptovská vodárenská spoločnosť (LVS) recorded the lowest efficiency score, only 12%.

Figure 2:

Technical efficiency of water companies in the Slovak Republic 2020

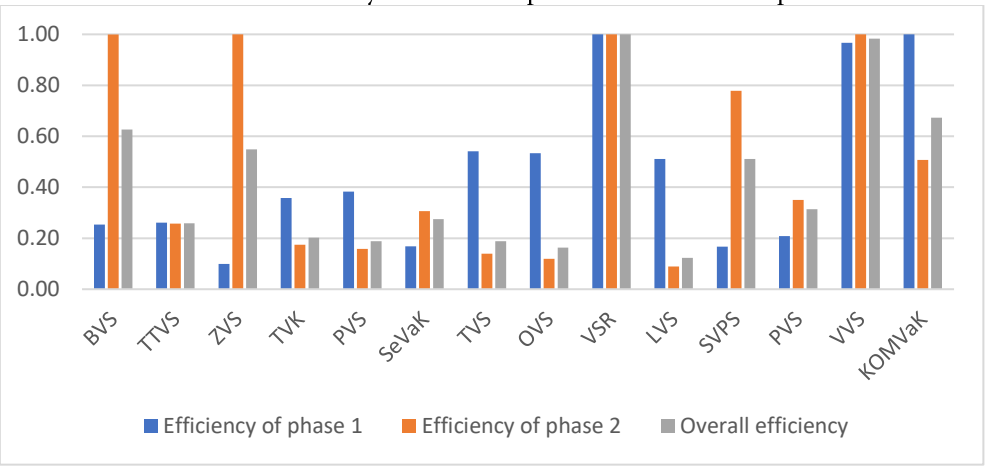


Source: Authors' own, 2023.

Figure 2 shows the 2020 ranking of Slovak water companies by the two-stage DEA model. Overall efficiency was reached by the small Vodárenská spoločnosť Ružomberok (VSR), while again the worst performing water company was Liptovská vodárenská spoločnosť (LVS).

Figure 3:

Technical efficiency of water companies in the Slovak Republic 2019



Source: Authors' own, 2023.

Figure 3 illustrates the 2019 ranking of water companies, and it is interesting to note that the best performing water company was Vodárenská spoločnosť Ružomberok (VSR), and the worst performer, as in the COVID-19pandemic year, was Liptovská vodárenská spoločnosť (LVS).

The results reported above confirm the importance of cost management for water companies' performance. However, price and other regulations are also critical in determining outcomes. The Regulatory Office for Network Industries regulates the water management sector. The regulation covers a series of areas, including the public water supply and public sewerage, as well as the services dealing with the use of surface water. The regulated activity is the production, distribution, and supply of drinking water through the public water supply system, and the removal and purification of wastewater through the public sewer system. Also covered is the abstraction of standing and flowing water from watercourses and their hydroelectric power potential. If sufficiently economically important, the Banska Stiavnica-headquartered Slovak Water Management Company (Slovak Vodohospodársky podnik), a regulated state monopoly, manages surface water in lakes and rivers.

Our analysis period covered the period of the COVID-19 pandemic. Water companies adopted measures to minimise its negative impacts in a situation where the required volume of drinking water, wastewater removal and treatment was little changed from the pre-pandemic period. However, there were unexpected, challenging situations, including an increase in costs, including a significant increase in the costs of construction works and materials, increases in the cost of personal protective equipment and testing employees, employee absences due to COVID-19 or related quarantines. The pandemic had widespread negative impacts throughout the industry, some of which may adversely affect future capacity.

As declared in studies by Pita et al. (2021), Tian et al. (2023) and Lombardi et al. (2019), the role of technical efficiency in water companies covers several important aspects, such as limited resource utilisation and sustainability, client satisfaction, infrastructure maintenance and water quality, energy efficiency, reduction of water losses, data monitoring and analysis, cost control, and compliance with regulations.

Technical efficiency involves maximising available resources, such as water sources, treatment facilities, energy, and human resources. Efficient water companies optimise these inputs to produce the desired outputs, minimising waste and costs. Technical efficiency is crucial for the long-term sustainability of water resources. Efficient water management practices, such as water recycling and reuse, can help conserve water supplies, especially in regions facing water scarcity. In the case of the Slovak water companies, Figure 1 reveals the lack of underground water resources in areas such as the south of Central Slovakia and in Eastern Slovakia.

As stated by Pita et al. (2021) and Tian et al. (2023), efficient water services contribute to client satisfaction. Reliable water supply, consistent water quality, and responsive client service are all aspects of technical efficiency that can enhance client

trust and loyalty. Unfortunately, in the case of Slovakia, no available data exists that would allow access the client satisfaction; it might be one of the research gaps for the future.

Water companies must maintain and upgrade their infrastructure, including pipes, pumps, treatment plants, and distribution systems, to ensure they operate at overall efficiency. Regular maintenance and investment in infrastructure are essential to prevent leaks Lombardi et al. (2019), reduce energy consumption Chen et al. (2023), and extend the lifespan of assets. Technical efficiency is closely linked to the quality of the water supplied. Water treatment processes must efficiently remove contaminants and pathogens to ensure safe drinking water for consumers. Efficiency in this context means achieving high water quality standards while minimising waste and energy use.

Water treatment and distribution can be energy-intensive processes. Water companies should strive to use energy-efficient technologies and practices to reduce their carbon footprint and operational costs. Energy-efficient pumps, renewable energy sources, and optimised treatment processes can contribute to technical efficiency. Energy-efficient production processes became inevitable in light of the climate crisis and war conflicts.

Water companies often face challenges related to water loss through leakage in distribution systems Lombardi et al. (2019). Technical efficiency involves minimising these losses through effective monitoring, maintenance, and replacement of ageing infrastructure. Reducing water losses not only conserves resources but also saves money. Technical efficiency relies on data collection, monitoring, and analysis. Water companies need accurate data on water quality, consumption patterns, infrastructure performance, and energy use to identify areas for improvement and make informed decisions.

Water companies must adhere to regulatory standards and environmental guidelines. Achieving technical efficiency is essential for meeting these requirements designed to protect public health and the environment. Compliance can also help avoid costly fines and legal issues. Achieving technical efficiency helps control operational costs, which is critical for public and private water companies. By optimising processes and resource utilisation, water companies can provide affordable services to consumers and maintain financial stability.

5. Conclusion

Water is the most essential resource of the planet, without which no human can survive. However, water resources are finite, and are becoming increasingly scarce in many areas. The technical efficiency of water companies is essential for delivering reliable and safe water services while minimising environmental impacts and costs. It encompasses various aspects of operations, infrastructure, and resource management to ensure the

sustainability and effectiveness of water supply and wastewater treatment systems.

To the best of the authors' knowledge, the paper is the first empirical study on the technical efficiency of the water industry not only in the Slovak Republic but also in the Central European countries. Moreover, it is an application of advanced N-DEA that allows the assessment of the efficiency of the production process in its following phases. The two-stage network DEA (N-DEA) model provides a thorough overview of the efficiency of the individual process of 14 water and wastewater companies offering water related services in Slovakia. Managers can use information on overall efficiency, the efficiency of individual phases, the efficiency of operating costs and investments of the water and wastewater utilities and the efficiency of the water and wastewater-related services. The technical efficiency of operating costs was achieved in two small companies (Vodárne a kanalizácie mesta Komárna – KOMVaK, Vodárenská spoločnosť Ružomberok – VSR) and one large company (Východoslovenská vodárenská spoločnosť – VVS). The efficiency of water services delivery was recorded by Bratislavská vodárenská spoločnosť (BVS), Západoslovenská vodárenská spoločnosť (ZVS), and Východoslovenská vodárenská spoločnosť (VVS). All three companies, BVS, offering services in the capital Bratislava; ZVS, operating in the western part of Slovakia; and VVS, supplying water services in Eastern Slovakia, are amongst the largest water and wastewater services suppliers. Three large companies were joined in 2019 and 2020 by the small Vodárenská spoločnosť Ružomberok – VSR operating in Central Slovakia. Overall efficiency was reached only by Východoslovenská vodárenská spoločnosť (VVS) in 2021, and by the small Vodárenská spoločnosť Ružomberok (VSR) in 2019 and 2020. The outcome of our empirical analysis demonstrates excellent managerial skills concerning cost efficiency and efficient water service provision, regardless of their size and region in which they operate. It should be stressed that economies of scale and scope were not proved in our empirical investigation.

Our results are relevant for the water companies` managements and water sector policymakers. As to the Slovak institutional framework, in 2001 the Regulatory Office for Network Industries was established and, among other tasks, was ordered to protect consumers from abuse by monopoly water suppliers. At the same time, it was instructed to pay attention to the return on investment of business entities so that the supply of energy and water is reliable and secure. This fact should be appreciated, as usually in Central and Eastern European countries, the regulation of the water industry is divided between several ministries.

The results of network DEA can also motivate strategic planning by managers of the Slovak water companies aimed at increasing sustainability and resilience. For example, they could introduce incentives to improve the cost-effectiveness and efficiency of water management services. The results, at the individual stages of the production process, could help the regulatory body design policies based on financial and other incentives. We recommend using the outputs of such an analysis to determine customer price tariffs. Our future research plans aim to extend our results to the technical efficiency of Slovak water management enterprises by examining the

productivity of the water industry in greater detail.

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