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Performance assessment of the Chilean water sector: A network data envelopment analysis approach

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ABSTRACT

This study applies a two-stage network structure model to evaluate water service providers cost and operational performance embracing service quality variables. An empirical analysis of the Chilean water and wastewater industries over the 2010–2018 period is presented. Moreover, in the second stage of analysis, we analyzed the impact of a set of exogenous variables on the performance of water companies. Results revealed that the Chilean water companies had notable room to reduce costs and improve operational performance. Moreover, it was found that the public water provider performed better than fully private and concessionary water providers.

1. Introduction

The water and wastewater sector plays a crucial role in society by ensuring that clean water is distributed to customers and sewage is collected and treated at high-quality standards before being discharged to the environment. Because of its monopolistic nature and to protect customer interests, the water sector is subject to regulation (Ananda and Pawsey, 2019). The regulator intervenes to ensure that the water companies collect sufficient revenue to carry out the water and wastewater services, customers' bills are affordable, and the environment is protected (Molinos-Senante et al., 2017). In order to do this, the regulator employs benchmark analysis to measure the performance of the water sector and design incentives and policies to enhance efficiency and ensure the sustainability of the urban water cycle (Lo Storto, 2018a).

Traditionally, the assessment of water companies' efficiency has been carried out using two main approaches, parametric (econometric) and non-parametric (linear programming) techniques. The advantage of the parametric approach, such as Stochastic Frontier Analysis (SFA), is that it accommodates both inefficiency and noise, whereas its disadvantage includes the specification of a functional form for the underlying technology (Coelli et al., 2005). In contrast, linear programming techniques such as Data Envelopment Analysis (DEA) accommodate multiple inputs and outputs, and the efficient frontier is constructed from the observed data without imposing any restrictions on the functional form of the underlying technology (Suarez-Varela et al., 2017). For the above reasons, several previous studies (e.g. Abbot and Cohen, 2009; Berg and Marques, 2011; Carvalho et al., 2012; Worthington, 2014; Goh and See, 2021) employed DEA techniques to assess the efficiency of water supply services. In this context, Cetrulo et al. (2019) conducted a comprehensive review of the literature focusing on studies that evaluated the performance of water companies in developing countries. They concluded that the number of studies conducted in developed countries was much higher than in developing countries. Nevertheless, Chile is considered as an exception since several past studies focused on evaluating the performance of Chilean water and wastewater service providers.

The Chilean water and wastewater industries were privatized during 1998–2004. Fully private and concessionary water companies were formed, whereas few customers received their water and wastewater services from a public company (SISS, 2021). It is considered a paradigmatic case study in Latin America (and other developing countries). Thanks to the legal and institutional reforms conducted, Chile has achieved near-universal access to water and wastewater services in urban areas (Molinos-Senante and Sala-Garrido, 2015). Several past studies assessed the efficiency of the Chilean water companies using non-parametric (DEA) techniques. For instance, Molinos-Senante and

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Sala-Garrido (2015, 2016) showed that fully private companies were more efficient than concessionary companies. The limitation of these studies was that they did not include any service quality variables in the analysis. Sala-Garrido et al. (2019) found that concessionary water companies were more efficient than fully private ones by including several service-quality variables such as water leakage and unplanned water supply interruptions in the assessment exercise. However, the limitation of the studies mentioned above is that they used conventional DEA models to assess the efficiency of the water supply and wastewater services.

In conventional DEA models, each Decision-Making Unit (DMU) (e.g., water company) is treated as a "black box," in which inputs are used to produce outputs, ignoring the intervening steps (Lewis and Sexton, 2004; Huang et al., 2014; Lo Storto, 2018b). However, some production systems have a complex network structure, and the inputs at a sub-stage of the production process can generate outputs. These outputs can then be used as inputs (intermediate products) at the next sub-stage of the production process to produce final outputs. As a result, the managers can gain more information on the efficiency of each sub-process or division (Huang et al., 2014). This approach is relevant to water companies that carry out the complete urban water cycle, i.e., water and wastewater services. In this context, wastewater produced by households is an intermediate product as it is the output of the drinking water supply service but is the input of the wastewater service as well.

The network DEA (NDEA) model was introduced by Fare et al. (1993) and further developed by Fare and Grosskopf (2000), Lewis and Sexton (2004), Sexton and Lewis (2003), Tone and Tsutsi (2009), and Pereira et al. (2021) to gain a greater understanding of the production process, i.e., urban water cycle in this study. This methodological approach allows evaluating the relative efficiencies of each DMU at each stage, including the complete production process. Fare et al. (1993) extended the NDEA model to account for undesirable outputs generated in the production process, such as pollutants. For instance, Fukuyama and Weber (2010) and Huang et al. (2014) applied a NDEA model with undesirable outputs in the banking sector; Lozano et al. (2013) in the airport sector, Iftikhar et al. (2016) and Mehmood et al. (2020) in the energy sector.

Despite the relevance of the NDEA model to evaluate water company performance from an urban water cycle perspective to the best of our knowledge, only two previous studies have been developed. Lo Storto (2018a) used both a two-stage NDEA model to measure the resource and revenue efficiency of several water and wastewater companies in Italy. The same researcher employed comparable NDEA techniques to assess the efficiency of several services in Italy, such as drinking water and wastewater collection and treatment (Lo Storto, 2020). The limitation of the above studies is that quality of service was not included in the analysis.

To overcome this limitation, we extend the author's framework by including water leakage and unplanned supply interruptions in the multi-stage water production model as undesirable outputs since water companies should minimize them to improve their performance from a holistic perspective. This methodological approach allows water managers and regulators to get detailed information about water companies' economic and operational performance as overall efficiency is split into two indicators. This information is relevant to design and introduce more target-oriented measures to improve the performance of water companies. We further employ econometric techniques to study the impact of several environmental variables on the performance both at the overall company and sub-stage level.

Against this background, the main objective of this study is to assess the performance of a sample of water service providers from an urban water cycle perspective. In order to do this, we use a two-stage NDEA model to analyze the economic (cost) and operations management efficiency of water and wastewater service provision. The first stage shows how the company maintains its infrastructure by spending the minimum cost (cost efficiency), and the second stage shows how it utilizes its infrastructure to deliver water and wastewater services to its customers. We extend the above framework by considering the impact of undesirable outputs such as water leakage and unplanned supply interruptions in the multi-stage water production process. This paper contributes to the existing literature by proposing and applying an extended NDEA approach to evaluate the performance of water companies from an urban water cycle perspective. The empirical model integrates service quality variables as undesirable outputs.

Past research (e.g., Molinos-Senante et al., 2015; D'Inverno et al., 2018; Goh and See, 2021) highlighted the importance of considering service quality in assessing water companies' efficiency because ignoring service quality variables penalizes companies that deliver high service quality. To the best of our knowledge, there are no previous studies in the water and wastewater industries that included service quality variables in a multi-stage production model. Furthermore, when the overall efficiency and the efficiency at each stage is obtained, we use them as explained variables and a regression model is used to study the drivers of efficiency both at the water company and sub-stage level. We apply the above techniques to several Chilean private and public water companies over 2010–2018.

The remainder of this paper is organized as follows. The following section describes the network DEA approach employed to evaluate the efficiency of water companies. Section 3 presents the variables and the data used in this study. Section 4 reports and discusses the main results. Finally, conclusions are included in the last section.

2. Methodology

In this section, we describe the methodology used to assess the performance of water companies from an urban water cycle perspective integrating service quality variables as undesirable outputs. In particular, we use a two-stage network structure to analyze the efficiency of water and wastewater service provision. The first stage is the cost of maintaining and running the infrastructure, and the second stage is utilizing the network to deliver drinking water and collect and treat sewage (Lo Storto, 2018a). Using the network structure model, we can, therefore, calculate the efficiency of running the business, the efficiency of delivering water and wastewater services, and the process's overall efficiency (Kamarudin et al., 2018).

Considering the deterministic nature of the DEA method, it is relevant to detect potential outliers or atypical observations. In this context, De Witte and Marques (2010a) identified five complementary methodologies that can detect outliers: i) "*leverage*" concept; ii) "*peer count*" procedure; iii) "*super-efficiency*" concept; iv) order-*m* method and; v) "*peer index*" approach. In the case of the Chilean water industry, Molinos-Senante and Farias (2018) concluded that there were no atypical observations as data from water companies was collected and validated through a strict procedure by the economic water regulator.

The two-stage network model is visualized in Fig. 1. Stage 1 involves the costs of operating the infrastructure (costs), and stage 2 utilizes the infrastructure to deliver water and wastewater services to customers (operations) (Lo Storto, 2018a, 2018b). At the first stage, the water company needs to cover operating and maintaining service costs. These costs could include expenditure for employees' salaries, energy use, capital employed and are the inputs of the first stage (Lo Storto, 2018a). These expenditures allow the infrastructure (e.g., network length) to be functional (Lo Storto, 2018b). Thus, the infrastructure is the output of the first stage. From a cost point of view, a water company is efficient if it succeeds in carrying out its operations and maintenance activities using the minimum cost (Lo Storto, 2018b). At the second stage, the water company uses the infrastructure to deliver water and then collect and treat wastewater. In this case, the infrastructure is the input and, thus, the intermediate product in the two-stage network structure model. However, as Sala-Garrido et al. (2019) noted, the water and wastewater process could generate undesirable outputs such as water leakage and unplanned water supply interruptions, which the water companies want

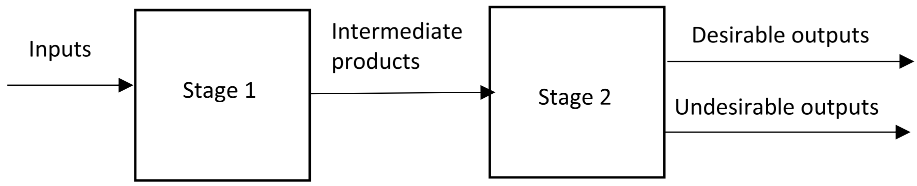

Fig. 1. Two-stage network structure model.

to minimize. Thus, at the second stage, water delivered and customers receiving wastewater treatment are the desirable outputs, whereas water leakage and water unplanned supply interruptions are the undesirable outputs (for more details, please see the next section). From the operations management perspective, efficiency goes up when the same volume of water is delivered, and the number of wastewater treatment customers can benefit from the service by utilizing a physical infrastructure having a reduced capacity regarding the network length (Lo Storto, 2018a), and from having lower water leakage and unplanned interruptions.

Assuming that a DMU (a water company in our case) uses m inputs to generate s desirable outputs and p undesirable outputs. The "black-box" production technology, ignoring any sub-stages, can be presented as follows (Fukuyama and Weber, 2010):

$$BT = \left\{ (x, y_g, y_b) \in R_+^{m+s+p} \middle| \, x \text{ can produce } y_g \text{ and } y_b \right\} \tag{1}$$

where $x \equiv (x_1, \dots, x_m) \in R_+^m$, $y_g \equiv (y_{g1}, \dots, y_{gs}) \in R_+^s$, $y_b \equiv (y_{b1}, \dots, y_{bp}) \in R_+^p$ are the set of inputs, desirable outputs and undesirable outputs, respectively. The network production technology which uses q intermediate products can be presented as follows (Fukuyama and Weber, 2010; Kumadarin et al., 2018):

$$NT = \left\{ (x, y_g, y_b) \in R_+^{m+s+p} \middle| \begin{array}{l} x \text{ can produce } z_e \quad (\text{Stage } 1) \\ z_e \text{ can produce } y_g \text{and } y_b \ (\text{Stage } 2) \end{array} \right\} \tag{2}$$

where $z_e \equiv (z_{e1}, \dots, z_{eq}) \in R_+^q$ is the set of intermediate products.

Unlike parametric (econometric) techniques (e.g., SFA), which require the specification of a functional form for the estimation of the underlying technology, we use a non-parametric technique (i.e., DEA, to calculate the efficiency of the units under evaluation). Other advantages of DEA are that it can accommodate multiple inputs and outputs simultaneously and does not require any distributional assumptions regarding inefficiency (Suarez-Varela et al., 2017). As far as the undesirable outputs are concerned, they are treated as inputs, and we assume that the water companies want to reduce both inputs and undesirable outputs to generate the same level of output (Tyteca, 1996; De Koeijer et al., 2002; Yang and Pollitt, 2010; Halkos and Petrou, 2019).

Considering that there are n total DMUs (water companies) under evaluation, and based on previous studies (Molinos-Senante et al., 2015), constant returns to scale and input orientation, we can estimate the efficiency of any DMU k relative to the efficiency of the overall production process and the efficiency of each stage of the production process. Thus, we solve the following linear programming to estimate the efficiencies from the two-stage network structure model:

$$\theta_k = \max \sum_{g=1}^{s} u_g y_{gk} - \sum_{b=1}^{p} u_b y_{bk}$$

$$\sum_{i=1}^{m} \nu_i x_{ik} = 1$$

$$\sum_{g=1}^{s} u_g y_{gj} - \sum_{b=1}^{p} u_b y_{bj} - \sum_{i=1}^{m} \nu_i x_{ik} \leq 0 \ \forall j = 1, .., n$$

$$\sum_{e=1}^{q} w_e z_{ej} - \sum_{i=1}^{m} \nu_i x_{ik} \leq 0 \quad \forall j = 1, \dots n$$

$$\sum_{g=1}^{s} u_g y_{gj} - \sum_{b=1}^{p} u_b y_{bj} - \sum_{e=1}^{q} w_e z_{ej} \leq 0 \quad \forall j = 1, \dots, n$$

$$u_r \geq \varepsilon, \ \nu_i \geq \varepsilon, w_e \geq \varepsilon, u_b \geq \varepsilon \tag{3}$$

where ε is a small non − Archimedean number

After calculating the optimal multipliers for the inputs, intermediate products, desirable and undesirable outputs, $\nu_i^*, w_e^*, u_g^*, u_b^*$, respectively, the efficiency of each stage, θ_k^1 *and* θ_k^2 and the overall efficiency of the process, θ_k can be calculated as follows:

$$\theta_k^1 = \frac{\sum_{e=1}^{q} w_e^* z_{ej}}{\sum_{i=1}^{m} \nu_i^* x_{ik}}$$

$$\theta_k^2 = \frac{\sum_{g=1}^{s} u_g^* y_{gk} - \sum_{b=1}^{p} u_b^* y_{bk}}{\sum_{e=1}^{q} w_e^* z_{ej}}$$

$$\theta_k = \theta_k^1 * \theta_k^2 = \sum_{g=1}^{s} u_g^* y_{gk} - \sum_{b=1}^{p} u_b^* y_{bk} \tag{4}$$

For comparison purposes, we also calculate the efficiency from the traditional "black-box" model where no intervening steps are included, i.e., no intermediate products are included in the model. The conventional DEA model takes the following form:

$$\theta_k = \max \sum_{g=1}^{s} u_g y_{gk} - \sum_{b=1}^{p} u_b y_{bk}$$

$$\sum_{i=1}^{m} \nu_i x_{ik} = 1$$

$$\sum_{g=1}^{s} u_g y_{gj} - \sum_{b=1}^{p} u_b y_{bj} - \sum_{i=1}^{m} \nu_i x_{ik} \leq 0 \ \forall j = 1, .., n$$

$$u_r \geq \varepsilon, \ \nu_i \geq \varepsilon, u_b \geq \varepsilon \tag{5}$$

where ε is a small non − Archimedean number

Finally, as previous studies (e.g., Berg and Marques, 2011; Guerrini et al., 2015; Wang et al., 2017; Pinto et al., 2017) demonstrated, there might be several operating characteristics such as density and ownership type that might have an impact on water company's efficiency and therefore, should be included in the analysis. As a result, in the final step of our analysis, we regress the efficiency scores obtained from the two-stage network structure model against a set of operating characteristics. This method allows quantifying the impact of other factors (external to the operation of water companies) that could impact companies' performance in each stage of the process, i.e., costs and operations, and the overall process.

Since the variable of interest (efficiency score) is non-negative and truncated, the ordinary least square (OLS) regression of the calculated efficiency scores may lead to inconsistent and biased conclusions (Wang et al., 2017). To deal with this limitation, we estimate a Tobit regression that considers the relationship between a non-negative dependent variable and explanatory variables.[1] The Tobit regression model takes the following form:

$$\theta_{k,t} = \alpha_0 + a_i \eta'_{k,t} + d_k + \varepsilon_{k,t} \tag{6}$$

where θ_k denotes the efficiency score from the two-stage network structure model as reported in equation (4), a_0 is the constant term, η'_{it} present a vector of operating variables of any water company k that might impact efficiency, d_k are company-specific effects that capture firm unobserved heterogeneity (e.g., managerial ability), are uncorrelated with the explanatory variables and follow the standard normal distribution, $\varepsilon_{k,t}$ denotes noise term that follows a standard normal distribution, and t denotes time. Nevertheless, the Tobit regression approach does not come without limitations because it requires the restrictive separability condition between the input-output space and the space of exogenous variables (Carvalho and Marques, 2011). Alternatively, partial frontier methods can be used to determine efficiency scores considering the influence of exogenous variables. Smoothed non-parametric regression between the ratio of conditional and unconditional efficiencies allows analyzing the influence of exogenous variables on the production process avoiding the endogeneity problem (Marques et al., 2014). Alternatively, bootstrap algorithms also allow analyzing the influence of exogenous variables on estimated efficiency scores (De Witte and Marques, 2010b).

3. Data and sample selection

Our empirical application focuses on the Chilean water sector over the 2010–2018 period. Privatization during the years 1998–2004 led to two types of ownership, fully private and concessionary water companies. One public water provider also provides water services (SISS, 2021). One of the conditions required private companies to buy public companies and make concessions to expand wastewater treatment coverage in Chilean urban areas. Thus, in 2000 only 21% of people had access to wastewater treatment services, whereas this figure increased to 99.9% in 2021 (SISS, 2021). Considering this requirement, all water companies in Chile provide water and wastewater services.

Economic regulation of the Chilean water sector is implemented by the national Superintendencia de Servicios Sanitarios (SISS) using a "model-firm" approach. According to this model, water tariffs are set assuming that water companies are technically and economically efficient based on the SISS defined "model" or efficient water company. However, this approach does not integrate service quality variables such as unplanned water supply interruptions or drinking water quality as part of setting water tariffs. The fulfillment of the national standards for quality of service is monitored by the SISS, which applies economic penalties to the water companies in case of non-compliance. Our sample consists of 11 fully private, nine concessionary water companies, and one public water provider. The data was taken from the website of the national economic regulator, SISS.

Based on previous studies of the water sector (e.g., Carvalho et al., 2012; Cetrulo et al., 2019; Goh and See, 2021), we defined the following inputs, desirable outputs, undesirable outputs and intermediate products for the two-stage network structure model. At the first stage, operating and capital expenditure of maintaining the infrastructure were the inputs, measured in Chilean pesos per year (CLP/year). This expenditure is used to ensure that the network is functional. Thus, we used the network length measured in kilometres (km) as the output of the first stage. At the second stage, where the company utilizes the network to deliver water and wastewater services, we use the network length as input. Thus, this variable is used as an intermediate product as well. As far as the desired outputs of the second stage, the volume of water delivered measured in thousand cubic metres per year and the annual number of customers receiving wastewater treatment were used.

Data about the volume of wastewater collected and treated was not available, and therefore, we used the number of customers receiving wastewater services in the efficiency assessment. Consistent with previous studies in the Chilean water sector and elsewhere (e.g., Molinos-Senante and Sala-Garrido, 2015; Sala-Garrido et al., 2019), we adjusted the water and wastewater outputs to reflect changes in the drinking and wastewater treatment quality. Our approach was to multiply these outputs with the drinking and wastewater treatment quality indicators as published by SISS. These indicators take a value from zero to one, with a value of one meaning that the water company met all legal requirements with respect to the quality of drinking water and wastewater treatment quality (e.g., concentrations of pollutants and sampling issues). Moreover, two undesirable outputs were defined at the second stage of the process. Based on past studies on the Chilean water sector (Maziotis et al., 2020), we used the volume of water leakage measured in thousand cubic metres per year and the number of water unplanned supply interruptions measured in hours per year.

Furthermore, we ran the "black-box" model for comparison purposes without any intervening steps (Eq. (5)). In this case, the inputs were operating and capital expenditure, whereas the desirable outputs were the network length and the quality-adjusted volumes of water delivered and the number of customers receiving wastewater treatment. The undesirable outputs were the volumes of water leakage and the number of water unplanned supply interruptions.

It should be noted that the number of inputs and outputs (desirable and undesirable) is limited by the number of water companies evaluated in this study. According to the rule of thumb, the number of observations (water companies) should be equal to or greater than $\max\{m\,x\,s; 3\,x\,(m+s)\}$ where m is the number of inputs and s is the number of outputs. If the number of observations is less than the minimum defined according to the rule of thumb, a large portion of the observations will be defined as efficient, and efficiency discrimination among observations is questionable due to an inadequate number of degrees of freedom (Cooper et al., 2011). For this reason, in this study, inputs and outputs (desirable and undesirable) were selected based on restrictions in the data sample size.

Finally, we assess the impact of several operating characteristics on a water company's efficiency by selecting the following exogenous variables: i) customer density defined as the ratio of the number of customers to the network length (Molinos-Senante and Maziotis, 2020); ii) type of water resource which is a categorical variable to capture whether raw water is surface water, groundwater and mixed (Molinos-Senante et al., 2020), and iii) the type of ownership to denote if the company is a public, fully private or concessionary water company. The descriptive statistics are reported in Table 1.

4. Results and discussion

4.1. Efficiency estimation

The two-stage network structure model (network model) and the "black-box" model, shown in Eqs. (3) and (5), respectively, were estimated using GAMS software (General Algebraic Modeling System) with CPLEX solver. The main results are reported in Table 2, showing the pooled descriptive statistics of efficiency scores measured by the two different models. It is concluded that, on average, the overall efficiency under the two-stage network structure was 0.527. Thus, on average, the water companies needed to substantially reduce their inputs by 47.3% to

[1] The advantages of using a Tobit regression when someone wants to research the impact of operating characteristics on efficiency was demonstrated in previous studies (see for instance Garcia-Sanchez, 2006; Kirpatrick et al., 2006; Renzetti and Dupont, 2006; Byrnes et al., 2010; Guerrini et al., 2015; Wang et al., 2017; Ananda, 2019; Wang et al., 2020) as well as its effectiveness compared to alternative approaches, such as the OLS (Hoff, 2007; Guerrini et al., 2015).

Table 1
Descriptive statistics.

Variables	Unit of measurement	2010	2011	2012	2013	2014	2015	2016	2017	2018
Quality-adjusted volumes of water delivered	000s m3/year	43,527	45,255	46,280	47,097	48,017	48,747	49,715	50,371	51,879
Quality-adjusted customers receiving wastewater treatment	nr	654,147	664,552	653,959	671,092	688,142	705,013	733,786	745,249	757,051
Operating expenditure (opex)	000s CLP/year	26,293,518	27,447,040	28,011,038	30,822,059	32,739,563	33,731,813	34,306,940	34,276,516	35,678,723
Capital expenditure (capex)	000s CLP/year	16,021,763	16,570,004	16,714,264	16,902,718	17,791,958	19,311,993	18,481,986	18,177,477	18,013,396
Network length	km	2994	3040	3076	3112	3141	3182	3192	3251	3338
Volumes of water leakage	000s m3/year	14,966	15,271	15,236	15,534	15,874	16,199	15,747	16,293	16,717
Water supply unplanned interruptions	hours/year	4937	3535	5745	7208	6190	6961	1573	1565	1395
Customer density	km/nr	57	57	57	57	57	57	57	57	57

Observations: 189.
Costs are expressed in 2018 prices.

Table 2
Pooled descriptive statistics of efficiency scores.

		Mean	Std. Dev.	Minimum	Maximum	Efficient water companies (%)
Network model	Stage 1 efficiency	0.686	0.223	0.205	1.000	14.81
	Stage 2 efficiency	0.788	0.208	0.288	1.000	37.56
	Overall efficiency	0.527	0.209	0.205	1.000	4.23
Black-box model		0.856	0.198	0.326	1.000	55.02

maintain the same level of output. In order to understand what explains the low overall efficiency in the NDEA model, we need to look at the efficiency scores of each stage. The mean efficiencies at stages 1 and 0.686 and 0.788, respectively. These findings suggest that at stage 1, several water companies did not carry out their operations and maintenance activities using the minimum (efficient) expenditure. Most of the water companies were identified as cost-inefficient (stage 1). It is reported that only 28 out of 189 observations (15%) were efficient. This result implies that the water companies needed to allocate their resources better to improve daily operations, maintain infrastructure and catch up with the most efficient companies.

The mean efficiency at stage 2 was higher than the one reported at the previous stage, indicating that more water companies were efficient. This finding suggests that reducing inputs such as water leakage and unplanned supply interruptions could lead to higher efficiency. However, substantial efforts still need to be taken by the water companies at the operations stage on average to improve efficiency. Almost two-thirds of water companies were inefficient. On average, a water company needed to reduce its inputs by 22%, whereas the worst water company needed to reduce its inputs by 71% to maintain the same level of water and wastewater services.

In contrast, considerably higher efficiency scores are reported when the urban water cycle is considered a “black-box”, i.e., when efficiency is estimated using the traditional DEA model (Table 2). The average efficiency was 0.856, having more than half of DMUs efficient. It means that several water companies operated on the efficient frontier, indicating that they were performing well in managing their network. However, this is not the case when a two-stage network structure is chosen. The appendix shows that mean differences calculated either between different stages or between overall process and black-box process, and between different stages and black-box process, were statistically significant. A negative and statistically significant correlation between stages 1 and 2 was found, suggesting that trade-offs are necessary to improve overall efficiency. These findings imply that sub-process efficiency (network model) might be more informative than company level efficiency (black-box model). Overall, these findings imply that the inclusion of intervening steps gives a better understanding of where inefficiencies in the production process occur, which is critical for delivering water and wastewater services to the customers. The results showed that the companies needed to achieve substantial cost savings when operating and maintaining the infrastructure. Expenditures to lower levels of water leakage and unplanned interruptions might drive further efficiencies in delivering services to the final customers.

Focusing on results based on the network model, Fig. 2 gathers the trend in the efficiency scores during the years 2010–2018. The results indicate a downward trend in the overall efficiency of the production process considering the urban water cycle perspective, from 0.582 in 2010 to 0.503 in 2018. The reduction in the overall efficiency over time was attributed to the low inefficiency of stage 1, whereas the efficiency of stage 2 remained stable. It appears that during the years 2010–2014,

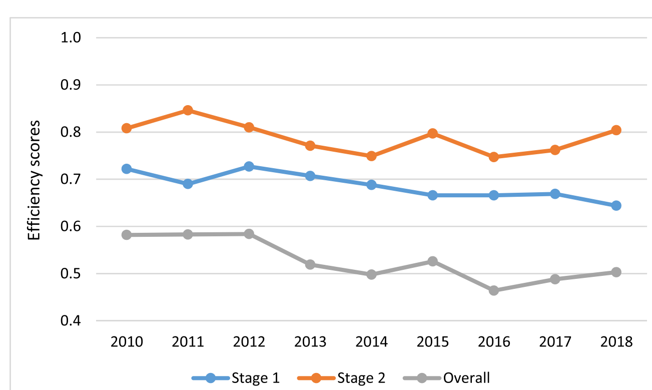

Fig. 2. Evolution of average efficiency scores based on network model for Chilean water companies.

water companies' efficiency at stage 1 was declining at a rate of 1.13%, which was attributed to the lack of savings in operating and capital expenditure to maintain the infrastructure. No substantial cost savings were achieved in the subsequent years (2015–2018) as the mean efficiency continued to decline at a rate of 1.62% per year. From a cost point of view, in 2018, the water companies still needed to considerably reduce their costs by 35.6% to maintain the same level of output.

In contrast, the efficiency of the water companies at stage 2 fluctuated over time. It appeared that during the years 2010–2014, companies' efficiency decreased, mainly attributed to an increase in the number of water supply unplanned interruptions. However, in the following years (2015–2018), the mean efficiency of the companies increased at a rate of 1.91% per year. This finding is attributed to a lower frequency of unplanned water interruptions, whereas water leakage levels were increasing at a lower rate. From an operational point of view, water companies apparently could further reduce their inputs by almost 22% on average to improve the delivery of water and wastewater services to the customers. The company's overall efficiency could be improved by maintaining its business and operations using the most efficient expenditure and reducing leakage and unplanned interruptions in its network.

Considering that the relationship between ownership and performance has long been at the core of the debate in the water sector (Suárez-Varela et al., 2017), Fig. 3a–c shows the efficiency scores from the network model by ownership type. The results indicate that, on average, public water appeared to be more efficient than private water companies, with fully private companies being more efficient than concessionary ones. It is noted that the mean overall efficiency of the public water provider was 0.719, meaning that it could further reduce its inputs by 28% to maintain the same level of output. Improving public water's performance could be achieved by better managing the costs of running its business (stage 1). This finding is particularly evident from 2014 onward, where the efficiency regarding the costs of operating and maintaining its activities (stage 1) reduced from 0.798 in 2014 to 0.615 in 2018. During the study period, the water company's efficiency reduced by almost 16%, indicating that a better allocation of its resources is of great significance to improve performance.

Delving into the efficiency scores of the private companies, we conclude that the overall mean efficiency of fully private and concessionary water companies was low, at the level of 0.569 and 0.455, respectively. Fully private and concessionary companies needed to substantially reduce their inputs by 43.1% and 54.5%, respectively, to maintain the same level of output. The costs of maintaining and operating the business (stage 1) and the operations stage (stage 2) impacted the company's overall efficiency, with stage 1 being the most inefficient stage of the process. In particular, from a cost perspective (stage 1), the mean efficiency of fully private and concessionary companies was at the level of 0.705 and 0.660, respectively. Both types of water companies could not run their business by spending the minimum cost. Fully private and concessionary companies needed to reduce further their costs by 30% and 34%, respectively, to improve performance. We note that from 2013 onward, there was a downward trend in fully private companies' efficiency, suggesting that achieving cost savings during that period was challenging. During the whole study period, fully private companies' efficiency reduced by almost 8.2%, from 0.736 in 2010 to 0.675 in 2018. The same pattern in the efficiency of stage 1 was also evident for concessionary water companies. Their average efficiency reduced by almost 13.4% during the years 2010–2018, indicating that the need to allocate resources efficiently is of utmost importance for this type of company.

Additionally, the second stage of the process showed some encouraging findings; however, there is still room for improvement for both types of private companies. From the operator point of view, fully private and concessionary water companies showed higher efficiency scores on average, 0.821 and 0.725, respectively. This finding means that they could further reduce their inputs and undesirable outputs by 18% and 27.5%, respectively, to deliver the same level of water and wastewater activities. We note that during the years 2010–2014, fully private companies did not perform well in their service delivery as the mean efficiency was deteriorating at a rate of 2.46% per year.

However, an upward trend in efficiency was evident during the last years of our sample, suggesting that the companies might have reduced the frequency of unplanned water interruptions and the level of water leakage. In contrast, concessionary water companies showed an increase in the efficiency at stage 2 over time. In particular, it increased from 0.722 in 2010 to 0.761 in 2018, an increase of 5.44%. This finding suggests that concessionary water companies performed well in delivering water and wastewater services over time, but they still needed to improve their performance as the mean efficiency was low, 0.725.

4.2. Influence of exogenous variables on efficiency scores

The final step of our analysis is to assess the impact of several exogenous variables such as population density, water resources and ownership in the efficiency of each sub-process and overall efficiency of water companies. The results are depicted in Table 3. It is found that

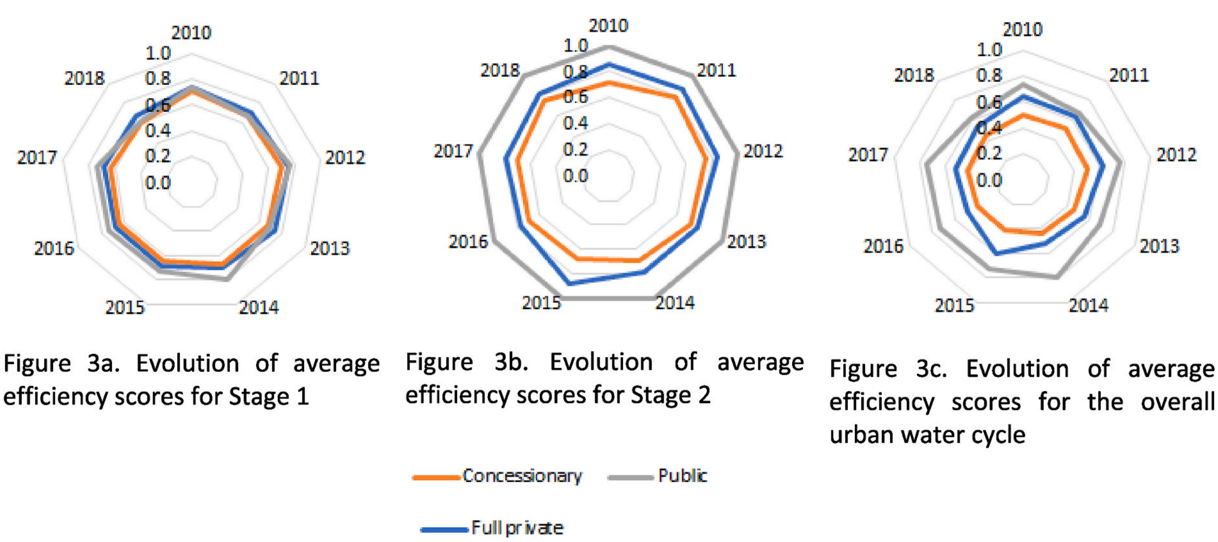

Fig. 3. a. Evolution of average efficiency scores for Stage 1, Fig. 3b. Evolution of average efficiency scores for Stage 2, Fig. 3c. Evolution of average efficiency scores for the overall urban water cycle, Fig. 3c. Evolution of average efficiency scores for the overall urban water cycle.

Table 3
Estimates of Tobit regression.

Variables	Stage 1				Stage 2				Overall			
	Coef.	Std. Err.	Z- stat	p-value	Coef.	Std. Err.	Z- stat	p-value	Coef.	Std. Err.	Z- stat	p-value
Constant	1.284	0.172	**7.470**	0.000	0.855	0.302	**2.830**	0.005	0.933	0.143	**6.540**	0.000
Customer density	−0.004	0.001	**−2.540**	0.011	0.007	0.004	***1.940***	0.053	0.000	0.002	0.200	0.841
Ownership	−0.054	0.078	−0.700	0.485	−0.192	0.122	−1.570	0.115	−0.122	0.053	**−2.320**	0.020
Type of water resource	−0.179	0.065	**−2.750**	0.006	−0.041	0.092	−0.440	0.659	−0.143	0.042	**−3.430**	0.001
Year												
2011	−0.037	0.019	***−1.940***	0.053	0.056	0.057	0.970	0.333	−0.003	0.033	−0.090	0.928
2012	0.005	0.019	0.270	0.786	0.017	0.058	0.290	0.769	0.003	0.033	0.100	0.922
2013	−0.016	0.019	−0.800	0.423	−0.053	0.057	−0.930	0.350	−0.069	0.033	−2.090	0.036
2014	−0.035	0.019	***−1.780***	0.075	−0.093	0.057	−1.640	0.102	−0.090	0.033	**−2.730**	0.006
2015	−0.054	0.020	**−2.770**	0.006	−0.016	0.058	−0.280	0.779	−0.057	0.033	***−1.710***	0.088
2016	−0.042	0.021	**−1.960**	0.050	−0.123	0.059	**−2.070**	0.038	−0.125	0.034	**−3.660**	0.000
2017	−0.040	0.021	***−1.940***	0.053	−0.083	0.059	−1.410	0.157	−0.098	0.034	**−2.880**	0.004
2018	−0.069	0.021	**−3.340**	0.001	−0.030	0.059	−0.510	0.611	−0.086	0.034	**−2.550**	0.011
$X^2(11)$	**59.11**				***18.06***				**50.46**			
Prob > $X^2(11)$	0.000				0.080				0.000			

Efficiency score is the dependent variable.
Bold coefficients are statistically significant from zero at the 5% level.
Bold italic coefficients are statistically significant from zero at the 10% level.

customer density and type of water resource had a negative and statistically significant impact on the efficiency of the water companies from a cost perspective. This means that as customer density increases and more water is taken from mixed and groundwater resources, the higher the costs of upgrading and maintaining the business and thus, the lower the efficiency could be. However, when the infrastructure is upgraded and maintained to meet the extra demand due to increases in customer density, the cost of delivering services to the customers will go down. Other things being equal, one unit increase in customer density could lead to a 0.007 unit increase in the company's efficiency from an operations management point of view.

Moreover, it appears that ownership and type of water resource had a statistically significant impact on water companies' overall efficiency. Regarding ownership, private companies' efficiency decreased relative to public companies. When more water is taken from mixed and groundwater resources than surface water, then water companies are faced with higher costs and thus lower efficiency. Finally, the negative sign of the year dummies suggests that efficiency was decreasing over time.

5. Conclusions

Performance evaluation is of great significance for the sustainable development of water and wastewater companies as they can identify factors that can help them reduce costs while maintaining the same level of output. The output of this assessment can also be used as an input to set tariffs for customers. A water company is likely to gain more information on sub-process or divisional efficiency than company level efficiency.

In this paper, we employed a two-stage network structure model to assess the efficiency of water and wastewater service provision, including service quality variables in the analysis. The first stage estimated the cost efficiency of the water company, i.e., its ability to maintain the infrastructure at minimum cost. The second stage estimated the operational efficiency of the water company, i.e., its ability to improve the quality of service for a given level of water and wastewater services. The final step of our analysis used a regression model to explore the determinants of efficiency both at the company and sub-stage levels. We applied this methodology to the Chilean water sector over the 2010–2018 period.

The results can be summarized as follows. First, it was found that the mean overall efficiency under the two-stage network structure was low, 0.527, which means that, on average, water companies needed to reduce their inputs by 47.3% to maintain the same level of output. The low overall efficiency level was attributed both to low costs and operational efficiency. On average, the water sector needed to reduce its costs by almost 31.4% and quality of service by 21.2% to provide customers with the same service levels. Higher efficiencies were reported for the black-box model, but this might not provide accurate results as it ignores the intervening steps.

Regarding water companies' ownership, the public water provider performed better than private ones, with fully private companies being more efficient than concessionary ones. The public water provider could further improve its performance by managing better the costs of running its business. In contrast, fully private and concessionary water companies should improve their performance by improving cost and operational efficiency. Finally, it was found that, on average, water companies' cost efficiency could mainly improve by taking less water from mixed and groundwater resources, whereas its operational efficiency could increase by delivering services to densely populated areas.

Overall our results could be of great interest to policymakers for several reasons. First, the multi-stage production model of the water and wastewater services provides a better understanding of the efficiency of each sub-stage and overall process in the framework of the urban water cycle. Managers and water regulators can determine if the water companies are efficient from a cost perspective, i.e., whether they can run their business by spending the minimum expenditure. They can also see if the water companies are efficient from an operational point of view, i. e., whether service delivery to customers has improved by reducing undesirable outputs such as water leakage and unplanned supply interruptions.

Taking into account that the regulatory model applied to the Chilean water sector assumes that water companies are technically and economically efficient, the two-stage DEA approach applied in this study is of great relevance for the Chilean water regulator to support the regulatory process. The methodology applied in this study also explored factors beyond companies' control that could affect their cost and operations' efficiency, such as population density and type of water resource. The findings at the divisional level can also help regulators design incentive-based policies in the form of financial rewards/penalties when companies outperform/underperform. This information is relevant for improving the efficiency of the urban water cycle as well as promoting strategic planning aimed toward increasing sustainability and resilience.

Future research on this topic might involve evaluating the productivity change of water companies and its drivers to understand whether improvements or setbacks on the performance of water companies occurred at specific stages of the production process. Additionally, other quality of service and environmental variables could be included in the assessment depending on the study's specific objectives.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jup.2022.101350.

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