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RESEARCH ARTICLE

Eco-efficiency assessment under natural and managerial disposability: an empirical application for Chilean water companies

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Abstract
Getting a good understanding regarding the economic and environmental performance of water utilities is of great importance to achieve the goal of an efficient and sustainable industry. In this study, we apply the range adjusted measure (RAM) data envelopment analysis (DEA) model to evaluate the integrated (production and environmental) efficiency of several water utilities located in Chile. Integrated efficiency is evaluated using the concepts of natural and managerial disposability. This approach further allows us to quantify the contribution of each input and undesirable product on efficiency scores. The results highlighted that the Chilean water industry showed high levels of production and environmental efficiency over time. Under natural disposability, water utilities could control production costs to reduce water leakage and unplanned water supply interruptions by 3.3% on average. Under managerial disposability, water utilities could further cut down undesirable outputs by 1.4% on average by adopting best managerial practices. On average, potential savings in operating costs, employment, water leakage, and unplanned water supply interruptions were higher for concessionary utilities as they showed slightly lower efficiency scores than full private utilities.

Keywords Production efficiency · Environmental efficiency · Natural and managerial disposability · Undesirable outputs · RAM-DEA · Water utilities

Introduction

The efficiency of drinking water services measures the ability of a water utility to reduce its inputs for a given level of output if it is input oriented (Coelli et al. 2005) or to expand the generation of outputs for a given level of input in the case of output orientation (Berg and Marques 2011). Traditional studies on this topic have used operational costs as inputs whereas volume of drinking water provided and number of customers were defined as outputs (Goh and See 2021). Most of previous studies have focused on evaluating the economic performance of water utilities (Cetrulo et al. 2019). Nevertheless, in recent years, several studies have focused on the measurement of efficiency of water utilities by including environmental variables (e.g., water leakage and water supply unplanned interruptions) as undesirable outputs (e.g. De Witte and Marques 2010; Brea-Solis et al. 2017; Molinos-Senante and Sala-Garrido 2017). Considering that access to drinking water is a human right (UN 2021), water utilities are obliged to provide safe drinking water at an affordable cost. Additionally, they need to ensure that water is available to all people anytime and wastewater is treated at high standards before it is safely discharged back to the environment (Lorenzo-Toja et al. 2015). These challenges have become more important in recent years due to population and economic growth, urban development, and climate change. Understanding therefore the economic and environmental performance of water and sewerage services is of great value to utilities and water regulators to deliver these services in an efficient and sustainable way (Ananda 2018).

The inclusion of undesirable outputs (environmental variables) in an efficiency analysis can be conducted using

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parametric (econometric) and non-parametric (linear programming (LP)) approaches. The main advantage of non-parametric approaches over parametric ones is that it does not assume a functional form for the production technology (Suarez-Varela et al. 2017). For this reason, this study uses LP techniques and, in particular, data envelopment analysis (DEA) to measure the efficiency of a sample of water utilities. DEA accommodates multiple inputs and outputs, and compares the performance of a firm relative to the best industry's frontier (Ananda 2018).

There are two main groups of DEA models, namely, radial and non-radial models (Sueyoshi 2006). Radial DEA models include the models introduced by Charnes et al. (1978) under constant returns to scale (CRS) and by Banker et al. (1984) under variable returns to scale (VRS). The main limitation of these models is that they calculate the efficiency by assuming a proportional reduction of all inputs for a given level of outputs in the input-oriented case (technical input efficiency) or by assuming a proportional expansion of all outputs for a given level of inputs in the output oriented case (technical output efficiency) (Cooper et al. 2011). In contrast, non-radial DEA models can measure the efficiency using slacks and can quantify the reduction of each input or the expansion of each output (Zhang and Cui 2020). Examples of non-radial DEA models include the additive model introduced by Charnes et al. (1985), the slack-based model developed by Tone (2001), the "range-adjusted measure (RAM)" of efficiency developed by Cooper et al. (1999), and the enhanced Russel graph measure of efficiency (Pastor et al. 1999).

In the framework of water utilities, the RAM DEA-based models were used by Aida et al. (1998) to evaluate performance of entities that supply water services in Japan. However, this study did not integrate environmental variables which might impact on the performance of water companies. Subsequently, Sueyoshi et al. (2010) also used the RAM DEA approach to measure the eco-efficiency of several energy utilities. The authors used these models because they allowed the assessment of productive and environmental efficiency in a unified framework which is not suitable with traditional DEA models which assume proportional reduction of all inputs and undesirable outputs (Sueyoshi and Goto 2010, 2011a; Sueyoshi et al. 2010, 2017; Wang et al. 2013). Thus, our study applies the RAM-based DEA models to measure integrated production and environmental efficiency of water utilities.

There were several studies in the past that included undesirable products of the water cycle such as water leakage and greenhouse gas emissions in modeling water utilities' efficiency (e.g., De Witte and Marques 2010; Brea-Solis et al. 2017; Ananda and Hampf 2015; Ananda 2019; Sala-Garrido et al. 2021a). However, the main limitation of these studies was that they assumed an equi-proportional contraction of all inputs for a given level of output, i.e., the use of radial DEA models. Moreover, the empirical analysis referred to water sectors operating in developed countries. Most importantly, they did not provide separate measures of production and environmental efficiency. We overcome these limitations as follows. First, we use non-radial models to measure the contribution of each input and output on overall efficiency of water companies. Second, our case study focuses on the water and sewerage services provided by several water utilities in Chile. Thus, we provide more evidence of the environmental performance of water utilities in a middle-income country which at the moment is limited (Cetrulo et al. 2019). We note that previous studies by Sala-Garrido et al. (2019), Molinos-Senante et al. (2020), and Sala-Garrido et al. (2022) assessed the impact of environmental variables such as water leakage and unplanned interruptions on several Chilean water utilities' performance. However, they suffer from the aforementioned limitations. Moreover, and most importantly, we differentiate from any previous studies by evaluating the production and environmental efficiency of water utilities using the concepts of natural and managerial disposability (Sueyoshi and Goto 2011a, 2011b; 2012). Under natural disposability, water utilities could cut down undesirable outputs, i.e., improving the quality of service, by controlling production costs. This could be done through an efficient use of pumps while abstracting, treating, and distributing water to customers. At the same time, utilities could deliver water to a higher number of customers to satisfy increasing water demand. Moreover, they could treat more wastewater to ensure that more people have access to this service. Under managerial disposability, water utilities could increase inputs so that they could decrease undesirable outputs by various managerial efforts. At the same time, desirable products could increase as well. For instance, utilities could adopt new technologies (increased inputs) that could allow them to predict more accurately bursts and leaks in mains. Based on increased inputs, water utilities could continue to provide their water and sewerage services to more customers. Thus, we provide a thorough analysis on how water utilities could improve performance by naturally controlling resources used in the production process and by adopting better management practices. This could be an important input for policy makers to make informed decisions on asset reliability and efficiency. Finally, we go a step further and quantify the potential savings in each input and each undesirable product required so that water utilities could be considered as fully efficient.

In this context, the main objective of this study is to evaluate the productive efficiency (PE), environmental efficiency (EE), integrated efficiency under natural disposability (IEND), and integrated efficiency under managerial disposability (IEMD) of several water utilities in a middle-income country such as Chile using an integrated approach and using the concepts of natural and managerial disposability. In order to do this, we employ non-radial LP models that allow measuring productive, environmental, and integrated efficiency. The use of non-radial LP models further allows us to quantify the potential savings in each input used in the production and the undesirable output conservation potentials.

We contribute to the existing literature for the following reasons. First, we use a novel approach to measure the performance of water utilities in terms of dealing with undesirable outputs via a natural control of production costs or improving managerial practices. In other words, efficiency scores were computed assuming natural and managerial disposability. From a regulatory perspective, analyzing the differences among both approaches is relevant since natural disposability might benefit to economically inefficient water companies which can easily save costs, whereas under managerial disposability low-cost and low-quality water companies are the most harmed. IEND and IEMD estimations could support efficient business decision making and allow policy makers to deal with network performance more efficiently and effectively. Second, this novel approach allows us to quantify the savings that could be achieved in terms of production costs, water leakage, and supply unplanned interruptions. We believe that this is an important finding to enhance the sustainability of the urban water cycle. Third, the approach adopted in this study allows identifying a separate measure of environmental efficiency of water utilities. Thus, policy makers can get a better understanding on how water utilities performed over time from an environmental perspective only. Fourth, we provide more evidence on the economic and environmental performance of the water sector in a middle-income country. Finally, we compare efficiency and savings in each input and undesirable output based on utilities' ownership type (full private, concessionary, and public water companies). For instance, policy makers can clearly identify if private utilities are more environmentally efficient than public ones. They can also conclude how much private utilities need to reduce water leakage and supply unplanned interruptions relative to public ones. Thus, we provide more evidence on the debate regarding performance and ownership of water industry.

Methodology

This section describes the methodology employed to assess the productive and environmental efficiency of the Chilean water industry in an integrated manner. In order to do this, we used the RAM DEA models previously developed by Sueyoshi et al. (2010) under natural and managerial disposability. Unlike radial DEA models where all inputs are contracted proportionally for a given level of output, the use of RAM DEA models allows us to quantify the potential contraction of each input, undesirable output, and expansion of each output in the production process.

Let us suppose that there are n water companies in the sample. Each j th water company ($j = 1, .., n$) uses a set of m inputs $X_j = \left(x_{j1}, .., x_{jm}\right)$ to generate a set of g desirable (good) outputs $Y_j = \left(y_{j1}, .., y_{jg}\right)$ and a set of p undesirable (bad) outputs $B_j = \left(b_{j1}, .., b_{jp}\right)$. Based on the literature review conducted by Cetrulo et al. (2019), variable returns to scale were assumed under natural and managerial disposability.

Under natural disposability, the following RAM DEA was solved to derive the productive and integrated efficiency for each water company (Sueyoshi and Goto 2010; 2012):

$$\begin{aligned}
&\max \textstyle\sum_{i=1}^{m} R_i^x d_i^x + \sum_{q=1}^{g} R_q^y d_q^y + \sum_{r=1}^{p} R_r^b d_r^b \\
&\textstyle\sum_{i=1}^{n} x_{ij}\lambda_{ij} + d_i^x = x_{ik} \quad (i = 1, \dots, m) \\
&\textstyle\sum_{j=1}^{n} y_{qj} - d_q^y = y_{qm} \quad (q = 1, \dots, g) \\
&\textstyle\sum_{j=1}^{n} b_{rj} + d_r^b = b_{rk} \quad (r = 1, \dots, p) \\
&\textstyle\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0 \quad (j = 1, \dots, n) \\
&d_i^x \geq 0 \quad (i = 1, \dots, m) \\
&d_q^y \geq 0 \quad (q = 1, \dots, g) \\
&d_r^b \geq 0 \quad (r = 1, \dots, p)
\end{aligned} \tag{1}$$

where λ presents intensity variables used to construct the production frontier (Sala-Garrido et al. 2021b). The use of RAM DEA model requires the use of slack variables. Thus, d_i^x, d_q^y, and d_r^b denote the slacks of inputs and desirable and undesirable outputs, respectively. The lower (min) and upper (max) bounds of inputs and desirable and undesirable outputs are used to define the range values of these variables, R_i^x, R_q^y, and R_r^b, respectively (Sueyoshi and Goto 2011a). Thus, the range values are defined as follows:

$$R_i^x = \frac{1}{(m+g+p)*(\overline{x_i} - \underline{x_i})}, R_q^y = \frac{1}{(m+g+p)*(\overline{y_q} - \underline{y_q})}, R_r^b = \frac{1}{(m+g+p)*(\overline{b_r} - \underline{b_r})} \tag{2}$$

where $\overline{x_i} = \max\left\{x_{ij}\right\}$ and $\underline{x_i} = \min\left\{x_{ij}\right\}$, $\overline{y_q} = \max\left\{y_{qj}\right\}$ and $\underline{y_q} = \min\left\{y_{qj}\right\}$ and $\overline{b_r} = \max\left\{b_{rj}\right\}$ and $\underline{b_r} = \min\left\{b_{rj}\right\}$ are the lower and upper bounds of inputs and good and bad outputs, respectively. Based on the optimal values (*) of Model (1), we can derive the PE and the IEND (Wang et al. 2013):

$$PE = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x^*} + \sum_{q=1}^{g} R_q^y d_q^{y^*}\right) \tag{3}$$

$$IEND = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x^*} + \sum_{q=1}^{g} R_q^y d_q^{y^*} + \sum_{r=1}^{p} R_r^b d_r^{b^*}\right) \tag{4}$$

As is shown in Eq. (3), PE does not incorporate undesirable outputs and measures the ability of the firm to reduce inputs while supplying services to more customers. Undesirable outputs are included in the measurement of integrated efficiency under natural disposability (Eq. 4). This efficiency therefore measures both production and environmental efficiency. It shows how undesirable products could go down through a natural control of production costs while providing services to a higher number of end users. PE and IEND take values between 0 and 1 with 1 indicating a fully efficient water company.

Under managerial disposability, the following RAM DEA model can be solved to derive the environmental and integrated efficiency (Sueyoshi and Goto 2010, 2012):

$$\begin{aligned}
&\max \textstyle\sum_{i=1}^{m} R_i^x d_i^x + \sum_{q=1}^{g} R_q^y d_q^y + \sum_{r=1}^{p} R_r^b d_r^b \\
&\textstyle\sum_{i=1}^{n} x_{ij}\lambda_{ij} - d_i^x = x_{ik} \quad (i = 1, \dots, m) \\
&\textstyle\sum_{j=1}^{n} y_{qj} - d_q^y = y_{qm} \quad (q = 1, \dots, g) \\
&\textstyle\sum_{j=1}^{n} b_{rj} + d_r^b = b_{rk} \quad (r = 1, \dots, p) \\
&\textstyle\sum_{j=1}^{n} \lambda_j = 1, \lambda_j \geq 0 \quad (j = 1, \dots, n) \\
&d_i^x \geq 0 \quad (i = 1, \dots, m) \\
&d_q^y \geq 0 \quad (q = 1, \dots, g) \\
&d_r^b \geq 0 \quad (r = 1, \dots, p)
\end{aligned} \tag{5}$$

Note that the difference between Eqs. (1) and (5) is on the sign regarding the slack of inputs. Under managerial disposability inputs are treated as outputs and undesirable outputs are treated as inputs in mathematics (Wang et al. 2013). The optimal solution of Model (5) allows us to derive the EE and the IEMD as follows:

$$EE = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x^*} + \sum_{r=1}^{p} R_r^b d_r^{b^*}\right) \tag{6}$$

$$IEMD = 1 - \left(\sum_{i=1}^{m} R_i^x d_i^{x^*} + \sum_{q=1}^{g} R_q^y d_q^{y^*} + \sum_{r=1}^{p} R_r^b d_r^{b^*}\right) \tag{7}$$

As shown in Eq. (6), EE is measured with the inclusion of inputs and undesirable outputs only. Desirable outputs are included in the measurement of integrated efficiency (Eq. 7). This efficiency indicator (IEMD) demonstrates the ability of the water utility to invest in new technologies (better managerial practices) to reduce the production of undesirable products. At the same time, a better allocation of resources could allow utilities to deliver water and sewerage services to a higher number of customers in a more efficient way. Both efficiency indicators take a value between 0 and 1. A value less than 1 means that the water company is inefficient whereas a value equal to 1 indicates that the water company is fully efficient.

Sample and data description

Chilean water industry overview

The provision of water and sewerage services in Chilean urban areas is carried out by water companies whereas in rural settings the services are provided by local communities and cooperatives. Around 80% of Chilean people live in urban areas, and therefore, this study focused on evaluating the performance of urban water companies. The Chilean water industry was privatized during the period 1998–2004 leading to two types of private water companies, namely, full private and concessionary (Molinos-Senante et al. 2018). Under full private ownership, water utilities are obliged to provide water and wastewater services for an indefinite time period. A limited time period (i.e., 30 years) is foreseen for the concessionary utilities (Ferro and Mercadier 2016). There is also one public water utility that delivers services to a small number of customers (Molinos-Senante 2018). As a result of the privatization process, around 95% of the urban customers are currently supplied by private water companies (full private and concessionary) and only 3.9% by a public water company, cooperatives, or communities of owners (SISS 2021).

Regardless of the ownership of the water companies, all of them are regulated according to the "efficient water company" model set by the national regulator, Superintendencia de Servicios Sanitarios (SISS). This regulatory approach is used to set water tariffs and is based on the definition of a hypothetically efficient water company whose costs are compared with costs of the "real" water company. This model corresponds to a water company without assets, which must make the investment to provide water and sewerage services and establish a development investment plan every 5 years. This regulatory model does not integrate the quality of service of the water companies in the process of setting water tariffs (Sala-Garrido et al. 2021a).

Data sample

Based on past studies and literature reviews on the water industry (e.g., Carvalho et al. 2012; Pinto et al. 2017; Molinos-Senante et al. 2019; Cetrulo et al. 2019; Goh and See 2021), we defined the following inputs and desirable and undesirable outputs. The first input was presented by the operating expenditure of services provided to customers excluding staff costs. It is measured in US $ per year. The second input was the number of full-time employees per year, including outsourcing. Regarding the desirable outputs, the first output was the volume of drinking water delivered measured in thousands of cubic meters per year whereas the second desirable output was defined as the annual number of households receiving wastewater treatment services. We finally defined two undesirable outputs. The first undesirable output was the volume of water leakage measured in thousands of cubic meters per year. The second undesirable output was captured by the number of water supply unplanned interruptions measured in hours per year.

The quantification of the potential redundancies in water leakage and water supply unplanned interruptions based on the optimal slack variables of the models discussed in the

Table 1 Descriptive statistics of the variables used

Variables	Unit of measurement	Mean	Std. dev	Minimum	Maximum
Volumes of water delivered	000 s m^3/year	50,856	92,398	991	473,846
Households receiving wastewater treatment	nr/year	735,230	1,292,820	3563	6,497,126
Operating expenditure (opex)[2]	000 s US $/year	33,601	44,230	670	221,671
Employees	nr/year	630	758	22	3375
Volumes of water leakage	000 s m^3/year	16,469	28,750	127	142,922
Water supply unplanned interruptions	Hours/year	4034	6474	3	34,051

Observations: 252

Costs are expressed in 2018 prices

[2]The conversion rate on 6th July 2022 was 948 Chilean pesos ≅ 1 US $

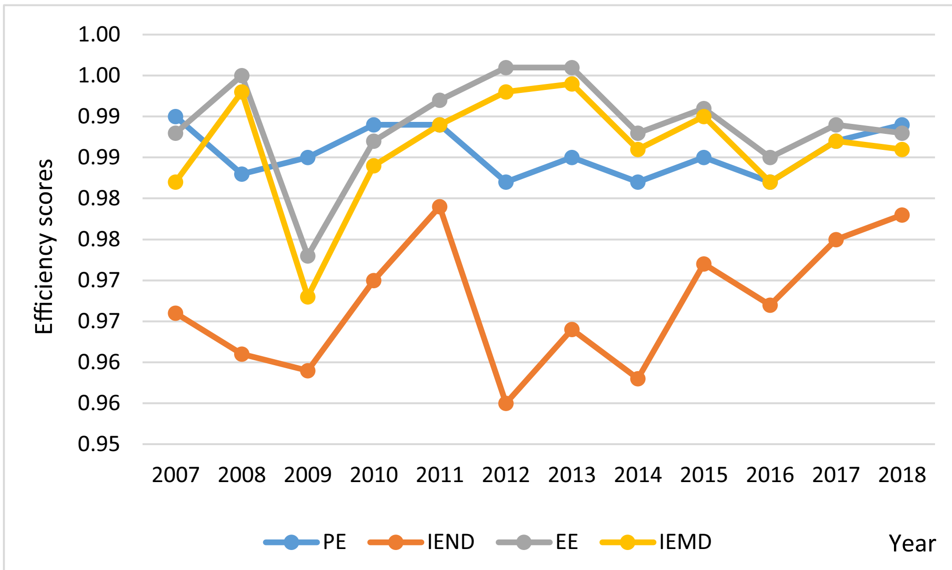

Fig. 1 Evolution of efficiency scores of Chilean water companies under natural and managerial disposability (PE: production efficiency; IEND: integrated efficiency under natural disposability; EE: environmental efficiency; IEMD: integrated efficiency under managerial efficiency)

previous could be of great interest to policy makers. This is particularly important in the Chilean water industry where there is no incentive scheme in place, in terms of financial rewards, for the utilities when they reduce leakage. The data used in this case study are publicly available in the management reports published by the SISS[1] (Molinos-Senante et al. 2018). We report the descriptive statistics of the variables used in our empirical study in Table 1.

Results and discussion

Efficiency score estimation at water industry level

Figure 1 reports the results from the estimation of the different efficiency indicators. The results indicate that during the years 2007–2018 the Chilean water industry showed high levels of efficiency from a production and environmental perspective. In particular, on average PE was 0.986 which means that on average water utilities could reduce operational costs and employment by 1.4% to provide their services to customers. It should be noted that efficiency scores estimated are relative and, therefore, the large average PE computed means that all water companies presented a similar performance. It does not mean that they performed extraordinarily well in absolute terms. PE remained quite stable during the period of study. It fell from 0.990 in 2007 to 0.983 in 2008, but then it started to increase and remained at high levels reaching its peak values in the years 2010 and 2011. This finding suggests that on average utilities made some improvements in their daily operations which allowed them to control production costs while supplying water and treating wastewater to a higher number of customers. From 2013 onwards, PE was increasing at a small annual rate of 0.11%. We note that the measurement of PE did not include any undesirable outputs. These are included in the measurement of integrated efficiency. The results indicate that when water

[1] Data is available at https://www.siss.gob.cl/586/w3-propertyvalue-6415.html.

leakage and unplanned interruptions were incorporated in the analysis, then the magnitude of efficiency was lower. It is found that IEND was 0.967 on average which means that water companies should further reduce leakage and unplanned interruptions by 3.3%. Integrated efficiency was quite volatile which was mainly attributed to the frequency of unplanned interruptions. It followed a downward trend at the beginning of our study as it fell from 0.966 in 2007 to 0.959 in 2009 on average. We note that during that period water leakage was increasing at an annual rate of almost 8%, putting therefore pressure to the water utilities who needed to reduce production costs and improve service quality. In the subsequent years, integrated efficiency improved mainly due to the reduction in the frequency of unplanned interruptions. This was also apparent in 2011 where mean IEND reached its peak value which was at the level of 0.979. From 2013 onwards, efficiency was quite volatile, but it remained at high levels. Overall, the findings suggest that to further improve efficiency, water utilities could continue to provide water and sewerage services to their customers and reduce undesirable outputs by decreasing production costs such as a more optimal use of network. Figure 1 also illustrates that at the end of the period, there is a convergence between PE, IEND, IEMD, and EE. It should be noted that in 2017, the Chilean urban water regulator started to work on developing the "Agenda 2030." It is the long-term strategic plan of the regulator whose main goal is to identify the main challenges of the Chilean water industry and propose targets for them. Although the "Agenda 2030" was formally approved and launched in 2020 during the previous years, many water companies started to adopt measures to improve the quality of service anticipating the requirements by the regulator.

We next discuss the outcomes from the efficiency indicators under managerial disposability, i.e., EE and IEMD. It is shown that water utilities performed well in terms of EE showing a mean score of 0.989. This finding implies that investing in technologies to better predict leakage or bursts in pipes could have a positive impact on the performance of water companies. Some well-known technologies to detect burst are listening sticks, leak noise correlators, vibro-acoustic techniques, gas injection techniques, and ground-penetrating radar (Cheng et al. 2019). A more innovative technology is the use of drones with remote sensing (pulsed laser). Differences in laser return times and wavelengths are used to make digital 3D representations of the landscape and indicate the amount of water in the ground (Lang et al. 2017).

EE remained stable and at high levels during the whole period of study and approached the value of unity (full efficiency) during the years 2011–2013. High levels of efficiency were also apparent when the utilities put efforts to provide water and sewerage services to more customers. The mean efficiency score was 0.986 which means that the industry could provide services to more customers by 1.4% while reducing undesirable outputs by the same amount by various managerial methods such as the adoption of new technologies. Thus, high levels of PE can be combined with high levels of service quality. IEMD started to increase from 2009 onwards reaching its highest levels in 2013. Then it followed a small downward trend, but the mean efficiency score was 0.986. Average IEMD was higher than average IEND. This finding suggests that higher savings can be achieved by controlling overall production costs. Utilities could also continue to improve their management because it is a strategy that has already been proven to be efficient.

Figure 2 displays the results from the efficiency indicators under natural disposability according to water companies' ownership. Public utility appeared to be fully efficient during the whole period of study, whereas full private and concessionary water utilities reported similar levels of efficiency. Full private utilities performed slightly better than concessionary in terms of PE. Reducing inputs by 1.5% on average could further improve the efficiency of private sector. PE for full private utilities was increasing at an annual trend of 0.04% during the years 2007–2011. Then it followed a downward trend suggesting that increases in operational costs and employment offset any increases in outputs. This was interrupted in the following years where PE substantially increased suggesting that improvements in daily operations allowed utilities to become more efficient. In contrast, PE for concessionary utilities was less volatile during the period of study implying that steady changes in production costs and outputs kept the trend in productive efficiency stable over time.

Results from this study are consistent with previous studies by Ferro and Mercadier (2016) and Molinos-Senante et al. (2018, 2019) who reported high levels of efficiency for the Chilean water industry. These studies found an efficiency score of 0.91 on average for the private utilities. Additionally, the public water utility reported an efficiency score of 0.998 (Ferro and Mercadier 2016). The differences in the efficiency scores between those studies and our study lies on the methodology employed. We used a non-parametric approach which does not require a functional specification for the underlying technology whereas the studies by Ferro and Mercadier (2016) and Molinos-Senante et al. (2018, 2019) employed econometric techniques by specifying a Cobb–Douglas and translog function for the production technology.

As is shown in Fig. 2, the inclusion of undesirable outputs reduced the integrated efficiency of private water utilities. This implies that reducing undesirable output, i.e., improving the quality of service, might be challenging for both type of utilities (full private and concessionary). A natural control of production costs could result in contraction of water leakage and unplanned interruptions by 3.5% and 3.4% for full private and concessionary water utilities, respectively. It is found

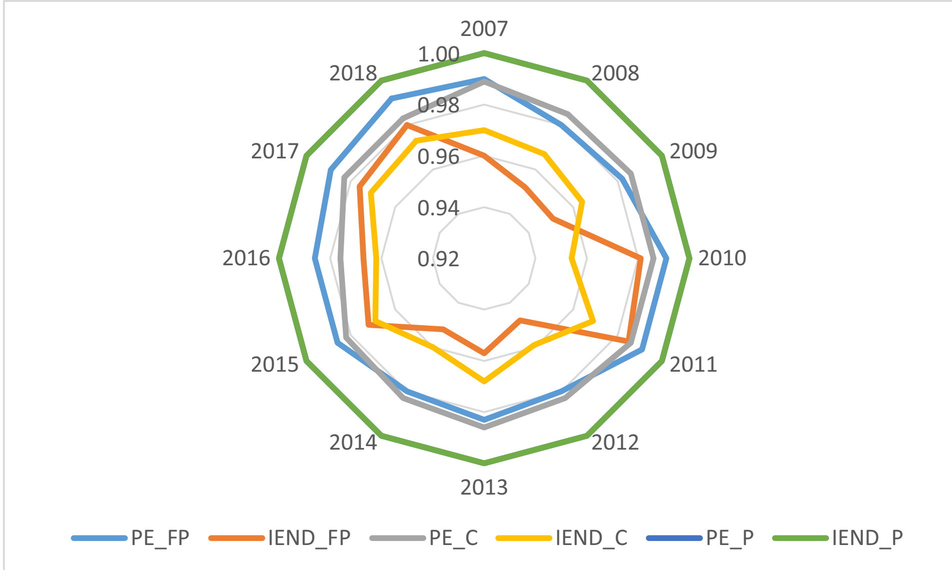

Fig. 2 Evolution of efficiency scores of Chilean water companies by ownership type under natural disposability (FP: full private; C: concessionary; P: public)

that during the years 2007–2009 IEND followed a downward trend for both type of utilities. However, concessionary utilities reported higher levels of efficiency than full private ones. This implies that full private utilities needed to deal with more frequent incidents in the network. The situation changed in the following years mainly due to the reduction in the frequency of unplanned interruptions for full private water companies. Overall, both types of utilities reported similar levels of integrated efficiency. However, we note that on average full privates' efficiency increased by 2.1% over the period of study when compared to its initial level, from 0.960 in 2007 to 0.980 in 2018. In contrast, concessionary utilities' efficiency slightly increased by 0.3% on average during the same years. Moreover, an upward trend in both types of utilities' efficiency was evident in the last years of our sample. These findings suggest that full private appeared to have achieved higher gains in efficiency than concessionary. Although private utilities showed high levels of efficiency from a production and environmental perspective, there is still considerable room for further improvements. These could be achieved by reducing leakage and unplanned interruptions by running network operations more efficiently.

Results based on managerial disposability are shown in Fig. 3. The public water utility was found to be fully efficient. However, full private and concessionary reported high levels of efficiency with full private utilities performing better than concessionary. The mean EE score was 0.993 and 0.983 for full private and concessionary utilities, respectively. This means that the potential reduction in water leakage and unplanned water supply interruptions among full private and concessionary was 0.7% and 1.7%, respectively. This finding suggests that the adoption of technologies that could accurately predict malfunction in pipes could result in high levels of efficiency. EE for full private water companies was mainly stable reaching its peak levels during the years 2010–2015 suggesting that improvements in management allowed utilities to become efficient in reducing undesirable outputs. On average, concessionaries' EE was slightly lower suggesting that this type of utilities needed to put more efforts in reducing leakage and bursts in pipes using best industry practices. However, both types of utilities reported similar levels of efficiency in 2018 indicating that to improve efficiency they could cut down undesirable outputs by almost 1.2% on average. IEMD for full private did not change considerably when desirable outputs were included in the analysis. In contrast, concessionary's mean integrated efficiency slightly fell to 0.978 relative to its mean EE, which was 0.983. This finding suggests that the delivery of water and sewerage services to more customers while adopting new technologies to reduce undesirable outputs could bring more cost savings for full private than concessionary utilities. Integrated efficiency was more volatile for concessionary utilities which could be mainly attributed to more frequent incidents in network. We note that the years 2009–2010 were challenging, showing the lowest levels of efficiency; however, it was increasing at an annual rate of 0.3% on average. An upward trend was observed in the following years indicating that concessionary utilities put efforts to improve environmental performance while delivering water and treating wastewater to catch-up with the most efficient utilities in the industry.

Quantification of potential improvements at water industry level

To get a better insight on how inefficient water utilities could adjust their inputs and undesirable outputs to reach

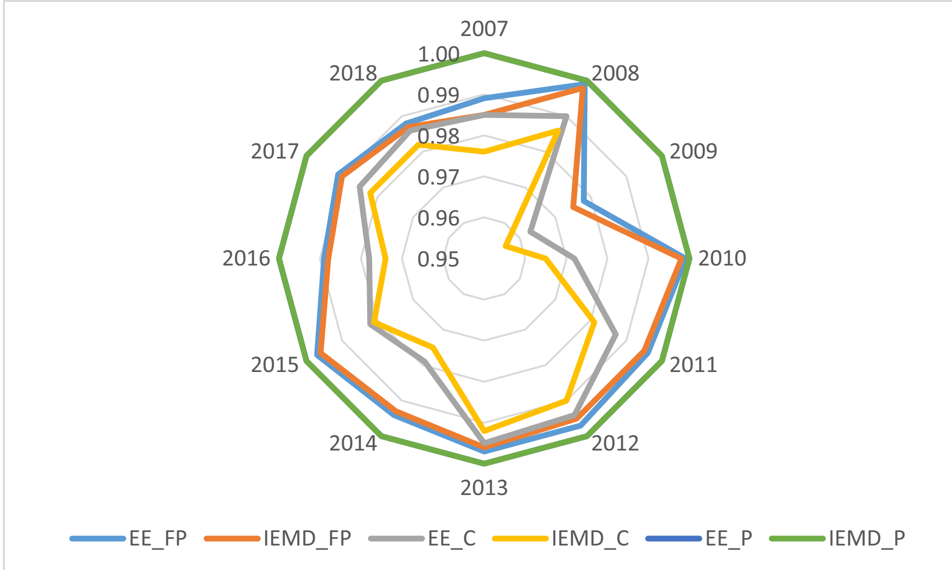

Fig. 3 Evolution of efficiency scores of Chilean water companies by ownership type under managerial disposability (FP: full private; C: concessionary; P: public)

the most efficient ones, we need to discuss the results shown in Table 2. This table shows the potential redundancy in operating costs, employment, water leakage, and unplanned water supply interruptions derived from the slacks under natural disposability (Wang et al. 2013). The results indicate that the theoretical maximum potential conservation for full private utilities in operating costs and labor could be at the level of 12% and 20%, respectively. Equivalently, they could reduce operating costs by 4621 thousands of CLP and 151 employees, respectively. The highest savings in operating costs could have been achieved in 2008 and in 2012 which were 20% of the actual operating costs. Full private could have saved more than 25% of actual employment during the years 2012–2014. We note that during the last years of our sample, the potential reduction in operating costs and employment followed a downward trend suggesting that the utilities moved closer to the frontier inputs.

As for undesirable outputs, the results indicated that the potential conservation in water leakage could be 580 Mg of water per year on average. The water savings ranged from 0.2 to 6.5% on average during the period of study. This figure is very relevant in the framework of the megadrought that Chile is suffering since 13 years ago (DGA 2021). Moreover, water utilities could further improve efficiency by reducing unplanned interruptions. It is found that on average the savings in unplanned interruptions could have been at the level of 50% or equivalently, 2403 h of interruptions per year on average. Hence, utilities need to make considerable efforts to reduce unplanned interruptions as the savings in this factor are substantial. Reducing the number of water supply interruptions is essential to improving the quality of service provided by water companies to customers (Pinto et al. 2017).

Higher savings in costs and undesirable outputs are apparent for the concessionary water utilities. Savings in operating costs and labor could amount to 28% and 34% of the actual inputs, respectively. This is equivalent to 6539 thousands of CLP per year and 158 employees on average. Since 2013, there has been an upward trend in the amount of operating costs that could have been achieved every year suggesting that utilities were moving away from the most efficient costs. The largest operating costs and employment conservation potential was reported in 2016, which is consistent with the results in Fig. 2 where PE was the lowest in the sample. The savings in water by fixing the leaks could be at the level of 7.4% on average or equivalently, 584 thousands of cubic meters per year on average. With the exception of the years 2009–2011 where savings in water amounted to 3% of actual water leakage, the savings for the rest of the years were more than 6% on average. This finding suggests that dealing with water leaks should be on utilities' agenda. Enhancing efficiency requires a substantial reduction in unplanned water supply interruptions. It is found that the unplanned interruptions conservation potential could be 2217 h per year or savings could be at the level of 54%. Overall, our findings suggest that the path to an efficient and sustainable water industry requires a better allocation of resources and considerable reductions in water supply unplanned interruptions and leakage.

Efficiency scores estimation at water company level

We turn our discussion in the results of the efficiency indicators obtained at utility level. This information is very relevant for regulatory purposes as it allows benchmarking the performance of water companies under different assumptions. Results are shown in Table 3. It is found that five utilities were fully efficient, and four utilities had an efficiency score close to unity under both natural and managerial disposability. Average PE ranged from 0.906

Table 2 Evolution of potential improvement in inputs and undesirable outputs by water utility ownership

	Operating cost reduction potential		Employment reduction potential		Water leakage reduction potential		Unplanned interruptions reduction potential	
	000 s CLP/year	%	nr/year	%	000 s m^3/year	%	Hours/year	%
Full private								
2007	2650	8%	113	16%	1222	6.5%	1884	49%
2008	5818	20%	191	27%	811	3.8%	2502	64%
2009	4706	13%	180	25%	576	2.6%	2635	87%
2010	2785	8%	98	13%	631	2.8%	1347	31%
2011	3259	9%	87	12%	540	2.4%	664	16%
2012	7531	20%	185	25%	982	4.3%	5089	80%
2013	5954	14%	182	25%	750	3.2%	5147	65%
2014	8218	18%	201	26%	801	3.4%	5370	82%
2015	5181	12%	159	20%	419	1.7%	2458	38%
2016	4380	10%	161	19%	123	0.5%	788	37%
2017	3111	7%	145	17%	41	0.2%	537	26%
2018	1854	4%	112	12%	61	0.2%	418	22%
Average	4621	12%	151	20%	580	3%	2403	50%
Concessionary								
2007	2211	16%	128	34%	1458	21%	1161	37%
2008	3320	24%	148	38%	520	6.9%	1654	64%
2009	4367	23%	127	31%	237	3.1%	1911	70%
2010	4229	22%	130	30%	263	3.3%	4688	76%
2011	4378	21%	135	31%	265	3.3%	1868	57%
2012	6928	32%	163	37%	666	8.3%	3777	68%
2013	5529	23%	151	32%	592	7.2%	3375	48%
2014	7458	29%	165	34%	630	7.6%	4562	71%
2015	8129	29%	180	35%	538	6.3%	2264	27%
2016	12,218	44%	233	43%	570	6.8%	553	54%
2017	9983	35%	160	29%	633	7.4%	462	44%
2018	9716	33%	172	29%	637	7.5%	330	37%
Average	6539	28%	158	34%	584	7.4%	2217	54%

*Because the public water company is full efficient, it does not present potential savings to be efficient

to 0.997 which means that the potential reduction in inputs could range from 0.03% to almost 10%. Considerable savings could be achieved if utilities make efforts to allocate their resources more efficiently to reduce undesirable outputs. This is particularly evident for WC3 whose reduction in costs, leakage, and unplanned water supply interruptions could be contracted by almost 20.9% on average. Investing in new technologies to improve environmental performance had a positive impact on WC3's efficiency as shown by the integrated efficiency score under managerial disposability. Average savings in efficiency under natural disposability varied from 0.07 to 20.9%. Enhancing environmental performance is a major concern for several other utilities as their integrated efficiency under natural disposability varied from 0.912 to 0.943 on average.

Several utilities (WC2, WC3, WC4, WC5, WC7, WC10, WC12) had an integrated efficiency under natural disposability which was higher than managerial disposability. This means that these utilities should focus on not only continuing to offer services to their customers and but also reducing their undesirable outputs by controlling production costs. In contrast, the mean integrated efficiency under managerial disposability was lower than natural disposability for several other utilities (WC6, WC14, WC15, WC16, WC19, WC20). This means that these utilities could improve efficiency by reducing undesirable outputs through managerial efforts such as the use of new technologies that could better predict leaks and burst in pipes.

Quantification of potential improvements at water company level

Finally, we discuss the input and undesirable output conservation potential at utility level under natural

Table 3 Average efficiency indicators (2007–2018) under natural and managerial disposability at water company level

Water company	Type	PE	Rank	IEND	Rank	EE	Rank	IEMD	Rank
WC1	Full private	1.000	1	1.000	1	1.000	1	1.000	1
WC2	Full private	0.970	18	0.927	17	1.000	1	1.000	1
WC3	Full private	0.906	21	0.791	21	0.984	15	0.978	15
WC4	Concessionary	0.975	16	0.943	16	0.963	19	0.950	21
WC5	Full private	0.973	17	0.905	20	0.957	21	0.952	20
WC6	Concessionary	0.995	12	0.988	13	0.979	17	0.978	16
WC7	Concessionary	0.958	20	0.912	19	0.970	18	0.961	18
WC8	Public	1.000	1	1.000	1	1.000	1	1.000	1
WC9	Concessionary	0.988	14	0.987	14	1.000	1	1.000	1
WC10	Concessionary	0.969	19	0.913	18	0.962	20	0.954	19
WC11	Full private	1.000	1	1.000	1	1.000	1	1.000	1
WC12	Concessionary	0.981	15	0.961	15	0.982	16	0.977	17
WC13	Concessionary	1.000	1	1.000	1	1.000	1	1.000	1
WC14	Full private	1.000	6	1.000	6	0.993	13	0.992	13
WC15	Concessionary	0.992	13	0.988	12	0.991	14	0.987	14
WC16	Full private	0.997	11	0.996	11	0.995	12	0.993	12
WC17	Full private	1.000	8	0.999	8	0.999	8	0.999	8
WC18	Full private	0.999	10	0.999	10	0.999	9	0.998	9
WC19	Full private	1.000	1	1.000	1	0.996	11	0.995	11
WC20	Full private	0.999	9	0.999	9	0.997	10	0.996	10
WC21	Concessionary	1.000	7	1.000	7	1.000	1	1.000	1

disposability during the years 2007–2018 (Table 4). For inefficient utilities, the savings in operating costs could range from 1 to 53% on average. Several utilities (WC3, WC4, WC5, WC10, WC12, WC15) should reduce operating costs by more than 20% on average if they want to become more efficient. In addition, these utilities could further reduce the number of employees between 95 and 1021 on average to catch up with the most efficient firms in the industry. Thus, the mean savings in employment could amount up to 60% of the actual employment levels. The less efficient utilities from a production point of view appeared to be inefficient from an environmental point of view as well. For instance, WC3, WC4, and WC7 needed to make substantial savings in reducing the amount of water lost in the network. These savings were found to vary between 10.5 and 15% of the actual water leakage levels on average. This is equivalent to save up to 6128 thousand of cubic meters per year on average. The rest of the utilities needed to make considerable savings in water ranging from 0.8 to 6.9% on average.

It appears that 9 out of 21 utilities were doing in well in terms of controlling water leakage. However, water utilities need to act in terms of unplanned interruptions. Several utilities (WC3, WC4, WC7, WC10, WC12, WC15) needed to make savings in unplanned interruptions which could range between 80 and 93% on average. The theoretical maximum unplanned interruption conservation potentials for these utilities were more than 2360 h per year on average. Dealing with burst in pipes should be a priority for water utilities. For instance, during the years 2007–2018 one of the less efficient utilities (WC3) in the sample could have reduced on average the hours of unplanned interruptions by 12,641 and saved 6128 thousand of cubic meters of water per year and by reducing operating costs and employments by 40% and 54%, respectively.

Conclusions

Traditionally, the evaluation of a water utility's efficiency focuses on its efforts to reduce inputs while ensuring that all people have access to water and sewerage services (increase desirable outputs). However, several undesirable outputs could be generated as part of the production process. Reducing these outputs is of great importance as it could lead to an efficient and sustainable urban water cycle. In this study, we assess the integrated production and EE of several water utilities in Chile during the years 2007–2018. The assessment of efficiency is conducted using RAM DEA–based models under the concepts of natural and managerial disposability.

The main results of the empirical application conducted can be summarized as follows. It is found that the Chilean industry reported high levels of both PE and EE. Under natural disposability, PE was 0.986 on average which means that costs could reduce by 1.4% while offering services to end users. The reduction in production costs could further

Table 4 Evolution of potential improvement in inputs and undesirable outputs at water utility level

Water company	Type	Operating cost reduction potential		Employment reduction potential		Water leakage reduction potential		Unplanned interruptions reduction potential	
		000 s CLP/year	%	nr/year	%	000 s m^3/year	%	Hours/year	%
WC1	Full private	0	0%	0	0%	0	0.0%	0	0%
WC2	Full private	9510	10%	291	15%	102	0.2%	7054	43%
WC3	Full private	33,305	40%	1021	54%	6128	15.0%	12,641	87%
WC4	Concessionary	10,781	34%	206	36%	1731	10.5%	3654	83%
WC5	Full private	6810	22%	290	38%	18	0.1%	6515	79%
WC6	Concessionary	1170	4%	62	9%	82	0.8%	779	13%
WC7	Concessionary	13,727	43%	484	60%	2473	15.9%	4521	87%
WC8	Public	0	0%	0	0%	0	0.0%	0	0%
WC9	Concessionary	9135	19%	80	11%	0	0.0%	48	1%
WC10	Concessionary	11,503	38%	322	46%	810	6.9%	8106	93%
WC11	Full private	0	0%	0	0%	0	0.0%	0	0%
WC12	Concessionary	10,189	53%	166	48%	132	2.4%	2360	87%
WC13	Concessionary	0	0%	0	0%	0	0.0%	0	0%
WC14	Full private	0	0%	0	0%	0	0.0%	8	2%
WC15	Concessionary	2331	43%	95	58%	29	1.6%	477	80%
WC16	Full private	622	16%	36	32%	95	5.2%	170	60%
WC17	Full private	239	7%	4	5%	0	0.0%	20	25%
WC18	Full private	251	14%	14	24%	22	3.1%	10	22%
WC19	Full private	0	0%	0	0%	0	0.0%	0	0%
WC20	Full private	89	8%	7	18%	12	2.6%	17	20%
WC21	Concessionary	13	1%	4	7%	0	0.0%	8	13%

lead to a reduction in water leakage and unplanned water supply interruptions by 3.3% as indicated by the mean integrated efficiency score under natural disposability. Under managerial disposability, the mean EE was at the level of 0.989, which means that utilities could reduce undesirable outputs by 1.1% by investing in new technologies that could better predict malfunctions in the network. Integrated efficiency was 0.986 on average which means that providing water and sewerage services to more people while reducing undesirable outputs by adopting best industries' technologies does not put much pressure on utilities' costs. The results at ownership type indicated that the public water utility performed slightly better than private utilities. Full private and concessionary utilities reported similar levels of integrated efficiency under natural disposability, an average efficiency score of 0.985. This finding suggests that controlling production costs could lead to a further reduction in undesirable outputs by 1.5%. Under managerial disposability, full private utilities appeared to be more eco-efficient than concessionary utilities, 0.991 versus 0.978. This means that concessionary utilities could achieve substantial savings in undesirable outputs if they invest in new technologies that improve network performance. The potential savings in operating costs and employment for full private utilities could be at the level of 12% and 20% on average, respectively. The savings in water leakage and unplanned interruptions could be up to 3% and 50% on average, respectively of the actual levels.

Overall, the findings of our study could be of great interest to policy makers for the following reasons. Our study provides a methodology that allows the regulator and regulated utilities to identify the best and worst performers in terms of productive and environmental efficiency. It also shows strategies that water utilities could adopt to improve eco-efficiency. Utilities could not only continue to provide water and treat wastewater to a higher number of customers but also reduce undesirable outputs by various managerial efforts such as the adoption of technologies that better predict leakage and bursts in pipes. Other strategies to reduce undesirable outputs in the production process could be through control of production costs. Moreover, we quantified the costs, leakage, and unplanned interruption conservation potentials, which demonstrated the need of policy makers to act. The regulator has an important role to play as it can set performance targets and introduce financial rewards or penalties when utilities meet or do not meet these targets. Thus, the path towards an efficient and sustainable water industry requires collaboration of both regulators and regulated utilities.

In spite of the positive features of RAM DEA models, they do not fulfil the "unique projection for efficiency comparison" property introduced by Sueyoshi and Sekitani (2009) which guarantees that the efficiency measure selects a unique projection onto the efficient frontier, as a benchmark for the evaluated firm. To overcome this limitation, Aparicio et al. (2021) proposed the multiplicative RAM (MRAM) model. However, it does not fulfil the property of indication. Recently, Aparicio and Monge (2022) developed the generalized RAM (GRAM) method which satisfies the six properties defined for efficiency measurement in DEA. Future research on this topic could focus on evaluating and comparing efficiency of water companies using the RAM, MRAM, and GRAM DEA methods.

Author contribution RSG: methodology; conceptualization. MMA: conceptualization; software. MMS: project administration; resources; writing—review and editing; formal analysis. AM: conceptualization; data curation; validation; writing—original draft; methodology; software.

Data availability The datasets generated and/or analyzed during the current study are not publicly available due to they were developed from primary sources of data but are available from the corresponding author on reasonable request.

Declarations

Ethics approval This manuscript has been developed in compliance with ethical standards.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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