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Measuring operational and quality-adjusted efficiency of Chilean water companies

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The path to a sustainable management of the urban water cycle requires the assessment of both operational and quality-adjusted efficiency in a unified manner. This can be done by the use of non-radial Data Envelopment Analysis models. This study used Range Adjusted Measure models to evaluate the operational, quality-adjusted, and operational & quality-adjusted efficiency (O&QAE) scores of the Chilean water industry including water leakage and unplanned interruptions as undesirable outputs. It was found that on average water utilities presented large O&QAE scores over time. The mean O&QAE score was 0.964 which means that water utilities could further reduce costs and undesirable outputs by 3.6% on average, while trying to expand the scale of operation. This finding suggests that excellent quality-adjusted efficiency at an efficient expenditure could be feasible. It was also evidenced that customer density, mixed water resources, and ownership influenced the O&QAE of Chilean water companies.

INTRODUCTION

The path to a sustainable and efficient urban water cycle requires the water utilities to make efforts to reduce both production costs and undesirable outputs such as water leakage, carbon emissions, and unplanned water supply interruptions[1]. This issue is of great relevance as it can be used to regulate the performance of water utilities and to set the water tariffs to be paid by users[2]. Traditionally, the efficiency of water utilities was conducted by taking into account inputs and desirable outputs, i.e., operational (also known as technical) efficiency (OE). However, previous studies[3–5] evidenced that from a customers and regulatory perspective is essential that water utilities improve the quality of service provided by reducing several undesirable outputs such as water leakage and unplanned water supply interruptions that are generated as part of the drinking water production process. Dealing with these undesirable products improves the performance of water companies by reducing operational costs and improving the quality of service to customers. For instance, improving network performance by dealing with leakage could lead to lower abstraction rates reducing energy costs and ensuring, more water is available to meet extra demand in dry periods. The importance of integrated evaluation, operational and quality of service efficiency, in the water industry has received considerable interest among researchers and policy makers as it can lead to a sustainable management of water services[6,7].

Our case study focuses on assessing the operational and quality-adjusted efficiency (O&QAE) of water industry in Chile for several reasons. It is a country where water scarcity problems and conflicts for the use of water are increasing[8,9] and therefore, including water leakage in efficiency assessment is relevant. Moreover, the water industry was fully privatized during the years 1998–2004 to ensure that they would attract sufficient external funds to upgrade the infrastructure, ensure that people have access to drinking water and wastewater treatment services and pay an affordable price. Full private and concessionary water companies were established as a result of this process[10]. The first type of water companies provides water and wastewater services for an indefinite time period, whereas concessionary companies are in charge of operating and maintaining the infrastructure through a 30-year contract[11]. Finally, the assessment of performance in water industries in developing economies has received limited research[12]. Previous studies on the Chilean water industry used parametric (econometric) techniques to compare costs and efficiency among water companies[10,11,13]. However, the limitation of parametric methods was the a priori assumption of the functional form for the underlying technology. To overcome this limitation, Molinos-Senante et al.[14] and Sala-Garrido et al.[5] used nonparametric (linear programming) methods such as Data Envelopment Analysis (DEA) to analyze Chilean water industry performance. DEA compares the efficiency of each water company relative to the best industry efficient frontier[7]. Thus, our study uses DEA techniques to evaluate water utilities' quality-adjusted efficiency (QAE). However, the main limitation of the above studies was that they did not measure the QAE in a unified framework.

In order to overcome this limitation, we follow the framework developed by Sueyoshi et al.[15] and use a non-radial DEA model to evaluate the OE, QAE, and O&QAE of the Chilean water industry. The non-radial DEA model employed in this study to measure efficiency uses slacks in the objective function of the linear programming model[16,17]. The main advantage of this approach is that it does not assume proportional contraction in all inputs to generate the same level of output like radial DEA models do[18,19]. Among the different non-radial DEA methods such as the additive and slack based models, the enhanced Russel graph measure of efficiency[20–22] in this study the "range-adjusted measure (RAM)" DEA model is used which was developed by Cooper et al.[23]. This methodological approach is chosen because it allows us to integrate both operational and quality of service efficiency in a unified framework which radial and other non-radial DEA models cannot do[15,24–28]. In the context of water utilities, Aida et al.[29] employed RAM-DEA model to evaluate the OE of a sample of Japanese water companies considering inputs and outputs. Sala-

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Garrido et al.[30] also used this methodological approach to evaluate the eco-efficiency of English and Welsh water companies by integrating greenhouse gas emissions as undesirable outputs. However, none of aforementioned studies focused on evaluating operational and QAE in a unified manner.

Against this background, the main objective of this study is to assess and compare the OE, QAE, and O&QAE of several water utilities in Chile using non-radial DEA techniques incorporating water leakage and unplanned water supply interruptions as undesirable outputs. In order to do this, we run three non-radial DEA models. The first RAM-DEA model assesses the OE by expanding desirable outputs and cutting down inputs. The second model evaluates the QAE of water utilities by reducing undesirable outputs. The third RAM-DEA model evaluates both operational and quality of service efficiency in a unified manner, i.e., O&QAE. This a novel approach as to the best our knowledge there are not any prior studies that employ RAM-DEA models to assess the O&QAE of the Chilean water utilities in a unified manner. Moreover, as we are interested in getting a better insight on what affects O&QAE, we regress each company's O&QAE scores against a set of environmental variables such as customer density and type of water resource to determine the cause of impact. Our empirical approach is implemented in several private and public water utilities in Chile and findings are discussed based on ownership type and at utility level.

RESULTS

Efficiency estimation

Figure 1 reports the average results from OE, QAE, and O&QAE during the years 2007–18 for the Chilean water utilities evaluated. It is found that on average the Chilean water industry performed well in terms of both operational and QAE. This means that on average water utilities managed to improve their managerial practices, which led to lower production costs and better quality of service. In particular, it is shown that from an operational perspective the industry reported a mean efficiency score of 0.966. This suggests that on average, water utilities could reduce their operating expenditure and employment by 3.4% while expanding the outputs by the same magnitude. In order to see the impact of quality of service on efficiency we need to look into the average QAE score. This was slightly higher, 0.981, suggesting that utilities performed well in reducing water leakage and unplanned interruptions. Nevertheless, there is small room for improvements as water utilities could further reduce costs and undesirable outputs by 1.2% to become more efficient. The O&QAE score takes into account both operational and quality of service efficiency. The average O&QAE was 0.964 which means that the potential savings in costs and undesirable outputs was 3.6% among utilities while
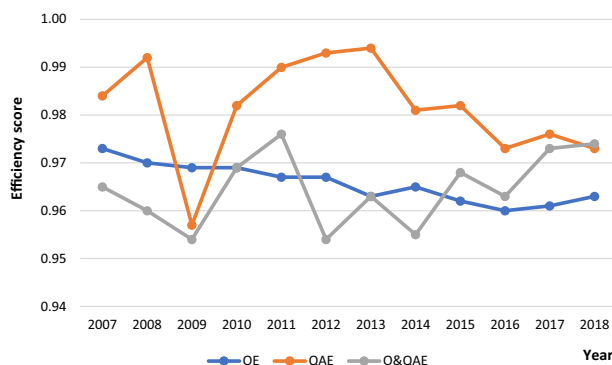
expanding their outputs by the same magnitude. Overall, it is illustrated that average OE, QAE, and O&QAE of the Chilean water companies evaluated were similar.

Looking at the trend in the OE, it is concluded that it deteriorated over time. In 2007, industry OE was 0.973 and reached the level of 0.960 in 2016. It was decreasing at a rate of 0.14% per year which was attributed to increasing operating costs and employees which might have offset any increases in the delivery of water and wastewater services. There are several factors that might explain the increase in operational costs such as the megadrought occurred in Chile and the rise of the energy costs. The downward trend in efficiency was interrupted in 2017 and finally reached the level of 0.963 in 2018. Compared to its initial level in 2007, OE slightly decreased by 1% in 2018. The trend of environmental efficiency was more volatile which was attributed to the frequency of unplanned interruptions and the changes in the levels of water leakage. During the years 2007–13 QAE followed an upward trend except for the year 2009 where efficiency declined. This was due to the large number of unplanned water supply interruptions experienced during that year. It was found that QAE increased at an annual rate of 0.19% with the year 2012 reaching its peak level. This means that any increases in costs to deal with leaks and unplanned water supply interruptions had led to higher levels of efficiency. However, a downward trend is shown in the following years. It was due to increases in the volume of water leakage. In spite of the fact that the national water regulator established that 15% of water delivered is the maximum percentage of water leakage, average value for the Chilean water industry is around 30%[31]. In 2018, water utilities needed to reduce costs and undesirable outputs by 2.7% to generate the same level of output. Thus, it appears that from 2014 onwards the higher volume of water leaks and the steady increase in levels of costs led to lower levels of efficiency.

The O&QAE scores followed the volatility showed in the QAE scores. During the years 2007–11 O&QAE was increasing a rate of 0.29% per year. In 2011, it reached the highest level compared to the other years in the sample. That year Chilean water utilities needed to reduce costs and undesirable outputs by 2.4% while expanding outputs by the same level. However, in the following years although O&QAE remained at high levels, it dropped to 0.955. An upward trend was apparent toward the end of the sample. Overall, the results indicated that water industry O&QAE remained at high levels. It demonstrated that sustainability could occur at an efficient cost. However, there is still room for improvement in efficiency. This can be done by improving daily operations, for instance by moving to a more efficient allocation of resources. This could lead to lower production costs and thus, higher OE which as indicated in the results followed a downward trend for the most of the study period. Another way to improve O&QAE is by making investments in improving the network that would allow utilities to deal with water leaks and bursts in pipes. This could lead to higher quality of service, efficiency and a more sustainable water industry.

In Figs. 2–4, we discuss the different types of efficiency based on the type of water utility ownership. It should be noted that the sample evaluated embraces 11 full private water utilities, 9 concessionary water utilities and 1 public water utility. Hence, results should be interpreted with caution. The results indicated that the public water utility performed better than private water companies in terms of O&QAE (Fig. 4). It is found that public water utility's OE was more volatile compared to QAE and O&QAE. In particular, during the years 2007–10 OE remained at high level, an average efficiency score of 0.991 (Fig. 2). In the following years, high increases in costs led to small decreases in efficiency. In 2012, OE was 0.972 which means that public water utility should reduce costs by 2.8% while expanding output by the same level. Eventually, OE in 2018 reached the level of 0.975 showing a decrease of 1.46% compared to its level in 2007 which was 0.990. In contrast, full private and concessionary utilities reported slightly lower efficiency scores than the public water
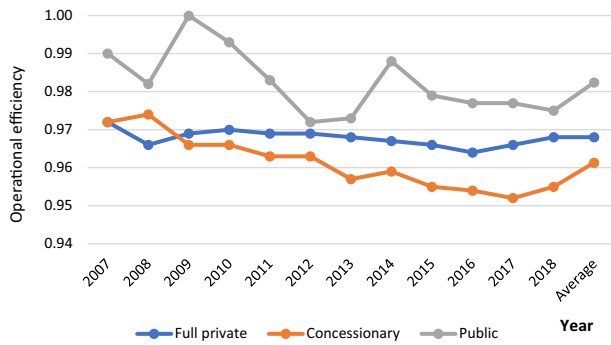

Fig. 1 Evolution over time of the efficiency of the Chilean water utilities. The trend in different types of efficiency. OE operational efficiency, QAE quality adjusted efficiency, O&QAE operational & quality adjusted efficiency.

Fig. 2 Evolution over time of operational efficiency of Chilean full private, concessionary, and public water utilities. The trend in operational efficiency based on the type of water utility.
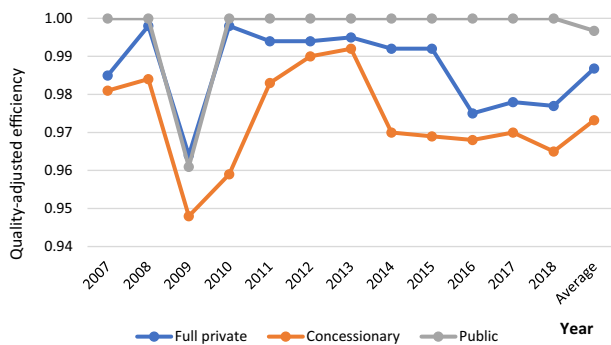

Fig. 3 Evolution over time of quality-adjusted efficiency of Chilean full private, concessionary, and public water utilities. The trend in quality-adjusted efficiency based on the type of water utility.

Fig. 4 Evolution over time of operational and quality-adjusted efficiency of Chilean full private, concessionary and public water utilities. The trend in operational and quality-adjusted efficiency based on the type of water utility.

company. From an operational point of view, it is found that full private and concessionary utilities could reduce their costs by 3.2% and 3.9%, respectively while generating more output by the same magnitudes. This finding is consistent with previous study by Molinos-Senante and Sala-Garrido[32] and Molinos-Senante et al.[13] who found that full private companies performed better than concessionary ones without the inclusion of undesirable outputs in the analysis.

From a quality of service perspective, higher QAE scores are reported for public and full private water utilities. This means that better quality of service at an affordable price could be feasible. In this case, full private utilities reported a QAE score of 0.987 on average, whereas the mean score for concessionary companies was 0.973. It involves that the potential savings in costs and undesirable outputs among full private and concessionary utilities was 1.3% and 2.7%. respectively. When both desirable and undesirable outputs are included in the analysis, the O&QAE score for full private and concessionary utilities reached the level of 0.961 and 0.963. respectively. This finding means that reducing both costs and undesirable outputs while expanding output could be challenging but it could lead to high levels of efficiency.

We next discuss the trend in efficiency for the two types of private water utilities, i.e., full private and concessionary. In terms of full private's OE, it is found that it followed an upward trend during the years 2008–2010, where it increased from 0.966 in 2008 to 0.970 in 2010 (see Fig. 2). However, it deteriorated the following years dropping to the level of 0.964 in 2016. An overall decrease of 0.416% is reported when we compared full private's OE score in 2018 with its initial score in 2007. In contrast, the OE of concessionary water companies followed a downward trend during the whole period of study. High increases in operational costs and number of employees,
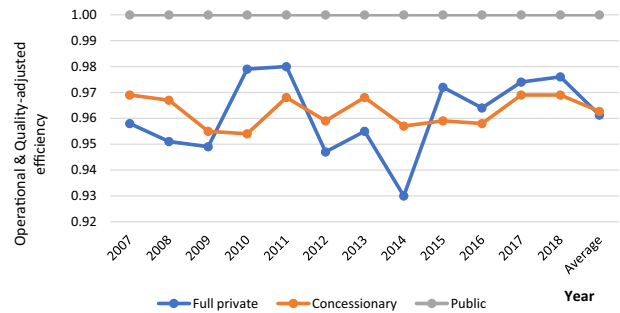
especially from 2013 onwards, offset any increases in production and thus, led to an overall drop of OE by 1.66% from 0.972 in 2007 to 0.955 in 2018. When quality of service variables are included in the analysis (Fig. 3), we found that the QAE of full private water utilities remained at high levels till 2015. Then it dropped to 0.975 in 2016 and 0.977 in 2018. This finding suggests that more frequent unplanned interruptions had a negative impact on utilities' performance. In 2018, full private utilities needed to reduce costs and undesirable outputs by 2.3% to produce the same level of services. In contrast, QAE was volatile for concessionary utilities. During the years 2007–13, it followed an increasing trend with the exception of 2009–10 where it dropped. This was mainly because of the increase in the frequency of unplanned interruptions and the steady increase in the levels of water leakage. In 2013 concessionary utilities' QAE reached its peak value, 0.992. However, a downward trend is shown in the following years.

In terms of full private utilities' O&QAE was more volatile than concessionary utilities (Fig. 4). During the years 2007–11 O&QAE was increasing at a rate of 0.963% reaching its highest value in 2011, a mean O&QAE score of 0.980. However, O&QAE deteriorated during 2012–14 but it still remained at an average level of 0.944. In the next years O&QAE followed an upward trend. Compared to its initial level in 2007, full private O&QAE increased by 1.94%. from 0.958 in 2007 to 0.976 in 2018. During the years 2007–10 concessionary water utilities' O&QAE was decreasing at an annual rate of 0.52%. In the following years, O&QAE was slightly volatile depending on the frequency of unplanned interruptions which might have offset any stable increases in costs and outputs. Its O&QAE took a mean value of 0.963 while in the last 2 years of our study showed its highest levels. This finding suggests that although it is challenging to reduce costs and deal with water leaks and bursts in pipes while trying to expand the scale of production, it can still lead to high levels of efficiency.

Table 1 reports the average efficiency scores and related rankings during the whole period at water utility level. In terms of OE, it is found that the majority of the companies reported high levels of efficiency scores. Two water utilities (Aguas Andinas and Aguas Cordillera) were fully efficient and several others had a mean OE >0.99. The two worst performing utilities (Essbio and Esval) belonged to the full private group and had a mean efficiency of 0.876 and 0.849, respectively. This means that these two utilities needed to reduce their costs by 12.44% and 15.10% to catch-up with the most efficient utilities in the industry. However, when quality of service variables are included in the analysis, these utilities showed a better performance. In terms of QAE, Essbio was fully efficient and Esval reported a mean QAE score of 0.976. Moreover, five water utilities were fully efficient with Aguas Andinas remained the most efficient utility in terms of production and QAE. The majority of the utilities improved their efficiency and ranking relative to OE with the exception of Essal which showed a lower QAE score. This finding suggests that this water utility had

Table 1. Ranking of Chilean water utilities based on operational efficiency (OE), quality-adjusted efficiency (QAE), and operational & quality-adjusted efficiency (O&QAE).

	Type water utility	OE	Rank	QAE	Rank	O&QAE	Rank
Aguas Andinas	Full private	1.000	1	1.000	1	1.000	3
Essbio	Full private	0.876	20	1.000	1	0.927	17
Esval	Full private	0.849	21	0.976	14	0.791	21
Nuevo Sur	Concessionary	0.961	14	0.946	19	0.938	16
Essal	Full private	0.942	16	0.934	21	0.900	20
Aguas del Valle	Concessionary	0.954	15	0.955	18	0.970	14
Aguas de Araucania	Concessionary	0.935	18	0.956	17	0.912	19
Smapa	Public	0.983	12	0.997	8	1.000	1
Aguas de Antofagasta	Concessionary	0.925	19	1.000	1	0.987	12
Aguas del Antiplano	Concessionary	0.940	17	0.941	20	0.913	18
Aguas Cordillera	Full private	1.000	1	0.975	16	1.000	4
Aguas Chanar	Concessionary	0.968	13	0.975	15	0.959	15
Aguas Magallenas	Concessionary	0.984	11	1.000	1	1.000	1
Aguas Decima	Full private	0.998	4	0.990	12	0.992	10
Aguas Patagonia	Concessionary	0.987	10	0.988	13	0.985	13
Aguas Chacabuco	Full private	0.994	9	0.993	10	0.991	11
Aguas San Pedro	Full private	0.995	8	0.999	6	0.999	6
Aguas San Isidro	Full private	0.998	5	0.998	7	0.998	7
Aguas Manquehue	Full private	0.997	7	0.993	11	0.995	9
Aguas Lampa	Full private	0.999	3	0.996	9	0.996	8
Coopagua	Concessionary	0.997	6	1.000	1	1.000	5

difficulties in reducing both costs and undesirable outputs. This was the worst performing water utility in terms of QAE with a score of 0.934 on average which means that it needed to further reduce costs, water leakage, and unplanned interruptions by 6.6% to catch-up with the most efficient companies in the industry. This utility did not improve its position when both operational and QAE were included in the analysis, i.e., O&QAE. It reported an even lower O&QAE score which was at the level of 0.900. However, the worst performing utility showed a mean O&QAE score of 0.791 suggesting that the expansion of output and the reduction of costs and undesirable outputs for this utility was challenging. The majority of the utilities reported O&QAE scores which were higher than 0.900 which means that on average they performed well in improving quality of service and reducing production costs. Five utilities appeared to be fully efficient under the O&QAE score. Aguas Andinas was fully efficient under the three different efficiency scores. Moreover, like OE, several utilities had a mean O&QAE score >0.99. These findings suggest that the rankings across the different efficiency scores were consistent.

Effect of environmental variables on operational and quality-adjusted efficiency scores

To evaluate the impact of several environmental variables on the O&QAE, we regressed the O&QAE scores of each water utility against a set of operating characteristics such as customer density, type of water resource, and type of water utility ownership. The results are reported in Table 2. It is illustrated that all variables had a statistically significant impact on water utilities' O&QAE. In particular, it is found that keeping all variables constant, a one unit increase in customer's density would decrease utility's O&QAE by 0.225 units. Most of previous studies that estimated economies of density showed positive results[33]. However, these prior studies did not integrate quality variables in efficiency assessment. By contrast, this study considers water leakage and unplanned water supply interruptions in performance assessment. As the density of customers decreases, the

length of pipes per customer increases and thus, their management from a quality perspective (i.e., water leakage and water supply interruptions) is more expensive. This might be attributed to the fact that more employees could be required to deal with network incidents impacting therefore negatively on O&QAE scores[34]. Moreover, mixed water resources, surface and groundwater resources might lead to lower efficiency compared to groundwater resources. This might be due to the higher costs involved to abstract and treat water before delivering it to customers[35]. A similar result was evidenced by Carvalho and Marques[36] whether the percentage of surface water is between 70 and 80%. Moreover, the time variable had a small but positive sign indicating that on average the O&QAE efficiency score slightly increased over time. Finally, concessionary and public water utilities present higher O&QAE scores than full private utilities as indicated by the positive and statistically significant sign of the ownership variable.

DISCUSSION

In light of climate change and population growth, water utilities are tackled with several challenges such as ensuring enough water is available for more people especially during more frequent dry periods. Thus, water utilities need to be able to minimize production costs and any undesirable outputs such as water leakage that could harm the sustainability and efficiency of the urban water cycle.

In this study, it is assessed the OE, QAE, and O&QAE of several water utilities in Chile during the years 2007–18. The use of non-radial DEA models such as the RAM efficiency model allows us to assess the O&QAE of utilities in a unified manner. The main points of our study can be summarized as follows. Firstly, it is found that the water utilities in Chile showed a similar performance in terms of production and QAE. In particular, from an operational point of view it is found that water utilities' efficiency was 0.966 on average. This means that the potential savings in operating costs among water utilities was 3.4% on average. When quality of service variables are included in the analysis, water industry

Table 2.	Estimates of the Tobit regression.			
Variables	Coff.	St.Err.	T-stat	*p* value
Constant	0.461	0.154	**3.000**	0.003
Customer density	−0.225	0.015	**−14.570**	0.035
Ownership	0.034	0.020	*1.730*	0.085
Wsource	−0.176	0.036	**−4.885**	0.000
Time	0.007	0.002	**3.461**	0.001
Firm-specific Dummy 1	−0.081	0.043	*−1.889*	0.060
Firm-specific Dummy 2	−0.134	0.031	**−4.388**	0.000
Firm-specific Dummy 3	0.173	0.045	**3.852**	0.000
Firm-specific Dummy 4	−0.041	0.019	**−2.137**	0.021
Firm-specific Dummy 5	−0.049	0.026	*−1.902*	0.058
Firm-specific Dummy 6	−0.140	0.044	**−3.163**	0.002
Firm-specific Dummy 7	0.252	0.077	**3.271**	0.001
Firm-specific Dummy 8	−0.432	0.062	**−6.951**	0.000
Firm-specific Dummy 9	0.067	0.034	**1.990**	0.048
Firm-specific Dummy 10	−0.131	0.031	**−4.173**	0.000
Firm-specific Dummy 11	0.052	0.024	**2.163**	0.031
Firm-specific Dummy 12	0.351	0.091	**3.845**	0.000
Firm-specific Dummy 13	0.083	0.048	*1.729*	0.085
Firm-specific Dummy 14	0.106	0.057	*1.853*	0.065
Firm-specific Dummy 15	0.159	0.027	**5.769**	0.000
Firm-specific Dummy 16	0.146	0.054	**2.703**	0.007
Firm-specific Dummy 17	0.186	0.035	**5.231**	0.000
Firm-specific Dummy 18	−0.191	0.090	**−2.137**	0.033
Firm-specific Dummy 19	−0.172	0.041	**−4.195**	0.000
Firm-specific Dummy 20	0.054	0.031	*1.742*	0.083
$X^2(24)$	**207.700**			
p value	0.000			
Log-likelihood	224.140			

Dependent variable = efficiency score.
Bold indicates that coefficients are statistically significant at 5% significance level.
Bold italic indicates that coefficients are statistically significant at 10% significance level.

efficiency improved. The mean efficiency score was 0.981, which suggests that the industry performed well in dealing with leaks and unplanned interruptions. When both operational and QAE are assessed, then it is found that that the mean O&QAE was slightly lower, 0.964. This finding suggests that reducing costs and undesirable outputs while expanding the scale of production might be challenging. However, the high levels of efficiency showed that better service quality at a minimum cost could be feasible.

Looking at the results at an ownership type, it is concluded that the public water utility performed better than private utilities. In particular, in terms of production point of view it is reported that full private and concessionary utilities could contract their costs by 3.2% and 3.9%, respectively to catch-up with the most efficient utilities in the industry. Higher QAE scores are reported for both types of companies, 0.987 and 0.973, respectively. This finding suggests that utilities made efforts to reduce both costs and undesirable outputs. When both operational and QAE are assessed, then the mean O&QAE for full private and concessionary utilities reached the level of 0.961 and 0.963, respectively. The findings from this study showed that several operating

characteristics beyond water utilities' control could influence O&QAE. High customer density and mixed (surface and groundwater) water resources could lead to higher employment and operational costs resulting therefore, to lower efficiency.

Overall, the methodology employed in this study and its conclusions are of great interest to policy makers for several reasons. First, water regulators and utilities can assess the performance of their peers from both a production and quality of service point of view. Thus, they can identify the worst and best performers and strategies to improve efficiency. This study showed that although the Chilean water industry present high levels of O&QAE over time, there is still room for improvement. Water utilities could further improve their managerial practices by moving to an efficient allocation of resources. This could be done, for instance, by adopting technologies that could allow utilities to predict leakage and bursts in pipes more accurately. This could embrace the sustainable management of urban water cycle. Dealing with incidents associated with water leakage and repairs in pipes to maintain the supply of water has an impact on efficiency. Moreover, this study showed that when a utility takes water from both surface and groundwater might require more inputs. Thus, reducing water leakage and use energy more efficiently to abstract and treat water might be crucial in reducing production costs and enhancing efficiency from a production and quality of service perspective. Finally, the methodology employed in this study allows the regulated water utilities to evaluate if there might be other operating characteristics that could affect efficiency.

METHODS

Efficiency assessment

This section outlines the methodology used to evaluate the OE, QAE, and O&QAE of the Chilean water industry. Under OE, water utilities are assumed to contract inputs and expand outputs at the same time[24]. Thus, this measure does not incorporate undesirable outputs. Under QAE, water utilities are assumed to contract undesirable outputs[25]. O&QAE integrates both operational and quality of service variables and therefore, water utilities are assumed to expand desirable outputs whereas at the same time undesirable outputs are contracted. Let's suppose that there are m water utilities and the jth water utility ($j = 1, .., m$) employs a vector of n inputs $X_j = (x_{j1}, .., x_{jn})$ to produce a vector of q desirable outputs $Y_j = (y_{j1}, .., y_{jq})$ and a vector of p undesirable outputs $B_j = (b_{j1}, .., b_{jp})$. The OE of the particular kth water utility is derived using the following RAM-DEA model: [Eqs. 1–6]

$$\max \frac{\left(\sum_{i=1}^{n} \frac{d_i^x}{R_i^x} + \sum_{s=1}^{q} \frac{d_s^y}{R_s^y} \right)}{(n+q)} \tag{1}$$

$s.t$

$$\sum_{j=1}^{m} x_{ij}\lambda_{ij} + d_i^x = x_{ik} \ (i = 1, \dots, n)$$

$$\sum_{j=1}^{m} y_{sj} - d_s^y = y_{sk} \ (s = 1, \dots, q)$$

$$\sum_{j=1}^{m} \lambda_j = 1, \lambda_j \geq 0 \ (j = 1, \dots, n)$$

$$d_i^x \geq 0 \quad (i = 1, \dots, n)$$

$$d_s^y \geq 0 \ (s = 1, \dots, q)$$

where d_i^x and d_s^y present the slacks for the inputs and desirable outputs, respectively. The term λ are intensity variables that are used to construct the efficient frontier[5]. Moreover, R_i^x and R_s^y are ranges of inputs and desirable outputs, respectively, which are calculated based on the upper and lower bounds of inputs and desirable outputs. These ranges take the

following form:

$$R_i^x = \overline{x_i} - \underline{x_i} \text{ and } R_s^y = \overline{y_s} - \underline{y_s} \tag{2}$$

where $\overline{x_i} = \max_j\{x_{ij}\}$ and $\underline{x_i} = \min_j\{x_{ij}\}$ are the upper and lower bounds of inputs, respectively, and $\overline{y_p} = \max_j\{y_{pj}\}$ and $\underline{y_p} = \min_j\{y_{pj}\}$ are the upper and lower bound of desirable outputs, respectively[15]. Then, we calculate the OE as follows:

$$OE = 1 - \frac{\left(\sum_{i=1}^n \frac{d_i^{x*}}{R_i^x} + \sum_{s=1}^q \frac{d_s^{y*}}{R_s^y}\right)}{(n+q)} \tag{3}$$

where the subscript (*) presents the optimal values obtained from Model (1)[15]. Unlike the OE, the evaluation of QAE requires the inclusion of undesirable outputs. Therefore, the QAE of specific kth water utility is derived by solving the following RAM-DEA model:

$$\max \frac{\left(\sum_{i=1}^n \frac{d_i^x}{R_i^x} + \sum_{r=1}^p \frac{d_r^b}{R_r^b}\right)}{(n+p)} \tag{4}$$

$s.t.$

$$\sum_{j=1}^m x_{ij}\lambda_{ij} - d_i^x = x_{ik} \ (i = 1, \dots, n)$$

$$\sum_{j=1}^m b_{rj} + d_r^b = b_{rk} \ (r = 1, \dots, p)$$

$$\sum_{j=1}^m \lambda_j = 1, \lambda_j \geq 0 \ (j = 1, \dots, m)$$

$$d_i^x \geq 0 \ (i = 1, \dots, n)$$

$$d_r^b \geq 0 \ (r = 1, \dots, p)$$

where d_r^b present the slacks for the undesirable outputs. In addition, R_r^b denotes the range for undesirable outputs which is derived based on the lower and upper bounds of the undesirable outputs:

$$R_r^b = \overline{b_r} - \underline{b_r} \tag{5}$$

where $\overline{b_r} = \max_j\{b_{rj}\}$ and $\underline{b_r} = \min_j\{b_{rj}\}$ are the upper and lower bound of undesirable outputs, respectively[26]. The QAE is calculated as follows:

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

Finally, Sueyoshi et al.[15] and Sueyoshi and Goto[24] developed the following RAM-DEA model to estimate the unified efficiency (operational and quality-adjusted efficiency) of the particular kth water utility. This model takes into account the negative and positive parts of the slack variables of inputs, the slack variables of desirable and undesirable

outputs. It is as follows:

$$\max \frac{\left(\sum_{i=1}^n \frac{(d_i^{x+}+d_i^{x-})}{R_i^x} + \sum_{s=1}^q \frac{d_s^y}{R_s^y} + \sum_{r=1}^p \frac{d_r^b}{R_r^b}\right)}{(n+q+p)} \tag{7}$$

$s.t.$

$$\sum_{j\neq1}^m x_{ij}\lambda_{ij} - d_i^{x+} + d_i^{x-} = x_{ik} \ (i = 1, \dots, n)$$

$$\sum_{j\neq1}^m y_{sj} - d_s^y = y_{sk} \ (s = 1, \dots, q)$$

$$\sum_{j\neq1}^m b_{rj} + d_r^b = b_{rk} \ (r = 1, \dots, p)$$

$$\sum_{j=1}^m \lambda_j = 1, \lambda_j \geq 0 \ (j = 1, \dots, m)$$

$$d_i^{x+} \geq 0 \ (i = 1, \dots, n)$$

$$d_i^{x-} \geq 0 \ (i = 1, \dots, n)$$

$$d_s^y \geq 0 \ (s = 1, \dots, q)$$

$$d_r^b \geq 0 \ (r = 1, \dots, p)$$

The unified O&QAE is defined as follows:

$$O\&QAE = 1 - \frac{\left(\sum_{i=1}^n \frac{(d_i^{x+*}+d_i^{x-*})}{R_i^x} + \sum_{s=1}^q \frac{d_s^{y*}}{R_s^y} + \sum_{r=1}^p \frac{d_r^{b*}}{R_r^b}\right)}{(n+q+p)} \tag{8}$$

Influence of environmental variables on efficiency
In this study we are also interested in identifying the factors that could impact water utilities' O&QAE. Thus, after we obtain the O&QAE scores from Eqs. (7 and 8), we regressed them against a set of environmental variables (see next section for more details). Since the O&QAE score takes a value between zero and one, we use Tobit regression[7,37–39]. Hence, the model takes the following form: [Eq. 9]

$$\beta_{j,t} = \gamma_0 + \gamma_j \zeta_{j,t}' + \delta_j t + \eta_j + \upsilon_{j,t} \tag{9}$$

where $\beta_{j,t}$ denotes the O&QAE of each water utility j at any time t, γ_0 is the intercept (constant) term, ζ_{jt}' is the vector of environmental variables and t captures time. Moreover, in the above regression model, η_j captures firm-specific dummies and $\upsilon_{l,t}$ is the error (noise) term, which follows the standard normal distribution. Several studies in the past used the Tobit regression model to evaluate the impact of several environmental variables on utilities' efficiency[40–43]. Nevertheless, this approach is not exempt of limitations since it requires the restrictive separability condition between the input-output space and the space of exogenous variables[36]. Alternatively, partial frontier methods can be used to determine efficiency scores considering the influence of exogenous variables. Smoothed nonparametric regression between the ratio of conditional and unconditional efficiencies allows analyzing the influence of exogenous variables on the production process avoiding the endogeneity problem[44].

Data and sample selection
Our case study focuses on 21 water utilities in Chile during the years 2007–18, which provide water and wastewater services to around 93% of

Table 3. Descriptive statistics of the variables used.

Variables	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Volume of water delivered	m³ per year	50,856	92,398	991	473,846
Customers receiving wastewater treatment	Nr per year	735,230	1,292,820	3563	6,497,126
Operating expenditure	000 s CLP per year	31,854,033	41,930,089	635,228	210,144,159
Employees	nr per year	630	758	22	3375
Volume of water leakage	m³ per year	16,469	28,750	127	142,922
Water supply unplanned interruptions	Hours per year	4034	6474	3	34,051
Customer density	nr per km	57.06	14.64	18.43	89.24
Source of water	Categorical	1.38	0.72	0.00	2.00
Ownership	Categorical	0.62	0.58	0.00	2.00

Observations: 252.
Cost are expressed in 2018 prices.

the Chilean urban people[31]. The sample consists of 11 full private water utilities, 9 concessionary water utilities, and 1 public water utility. Being natural monopolies, an economic regulator was set up to monitor financial and quality of service performance and set tariffs[45]. The data employed to estimate OE, QAE, and O&QAE came from the website of the economic regulator, Superintendencia de Servicios Sanitarios (SISS)[11].

The inputs, desirable and undesirable outputs were chosen based on past studies in the water industry and the available statistical information[12,46–48]. We used two inputs in our analysis. The first input was the operating expenditure (costs) measured in thousands of Chilean Pesos per year (CLP per year). It integrates all the operational costs incurred by the water companies except for labor costs. Hence, the second input was the number of employees per year. We used two desirable outputs. The first output was proxied by the volume of water delivered in cubic metres per year. The second desirable output was the annual number of customers receiving wastewater treatment services. Quality of service variables, i.e., undesirable outputs, were defined as the volume of water leakage measured in cubic metres per year and the number of unplanned water supply interruptions measured in hours per year.

Past studies demonstrated the importance of including environmental variables in the efficiency analysis as they impact water companies' input requirements and thus, inefficiency[49,50]. Hence, we included the following environmental variables: (i) customer density derived as the ratio of number of customers to the network length; (ii) type of water resource which is a categorical variable and captures surface, groundwater and mixed water resources; (iii) the type of ownership to capture if the water utility is public, full private and concessionary owned. Descriptive statistics of the variables used in our study are depicted in Table 3.

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

CODE AVAILABILITY
The codes generated and/or used during the current study are available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

R.S.G.: Data curation; methodology; software. M.M.A.: Validation; methodology; formal analysis. A.M.: Conceptualization; data curation; validation; writing-original draft; methodology; software. M.M.S.: Project administration; resources; writing-review & editing; Formal analysis.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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