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Estimating performance and savings of water leakages and unplanned water supply interruptions in drinking water providers

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ABSTRACT

Water leakages and unplanned water supply interruptions are relevant variables in the provision of drinking water since they directly impact customers and the economic and environmental performance of water companies. For the first time, in this study, we estimated specific efficiency scores for these two quality-of-service variables using the multi-directional data envelopment analysis technique for a sample of 21 Chilean water companies over the 2007–2018 period. Unlike previous studies, this methodological approach allowed us to estimate potential savings for both quality-of-service variables. The results indicate that the Chilean water industry could improve its efficiency over water leakage and unplanned water supply interruption by 28.6% and 52.5%, respectively, while supplying the same volume of drinking water. It is estimated that water companies could save around 48 million cubic metres of drinking water per year. Savings on unplanned water supply interruptions for the Chilean water industry are estimated to be at the level of 62,419 h per year.

1. Introduction

Access to drinking water is recognized by the United Nations (UN, 2010) as a human right. Water providers (typically water utilities or water companies) are responsible for supplying drinking water to customers permanently since continuous water supply bestows significant social benefits (Brocklehurst and Slaymaker, 2015). Moreover, from the perspective of service quality, unplanned water supply interruption has been identified as one of the most relevant variables for customers' satisfaction (Blokker, 2007; Maziotis et al., 2020). Currently, 2.3 billion people live in water-stressed countries (UN-Water, 2021) and about 4 billion people experience severe water scarcity during at least one month of the year (Mekonnen and Hoekstra, 2016). Hence, within the urban water cycle, one of the main challenges that water providers face is how to reduce water leakage (Molinos-Senante et al., 2016). Past studies (European Commission, 2013; Hernández-Sancho et al., 2012) suggested that leakage is an economic, social and environmental inefficiency in the provision of drinking water. Due to the relevance of both quality-of-service variables (unplanned water supply interruption and water leakage), when the performance of water companies is assessed both variables should be considered (Cetrulo et al., 2019; Goh and See, 2021; Pinto et al., 2017).

Evaluating the performance of water providers is a useful approach for both regulators and the regulated water companies. It allows identification of the factors that have an impact on companies' costs. It can also help policy makers to design incentives and policies to encourage companies to improve their economic and environmental performance (Berg and Marques, 2011). Moreover, in some countries such as England and Wales, the output of this assessment exercise is used to set tariffs for water and wastewater services (Walker et al., 2021). Given the implications of the performance estimations for both customers and water companies, an important aspect that could not be ignored when assessing the efficiency[1] of water companies is the quality of service supplied to the customers (Cetrulo et al., 2020; Marques and Simoes,

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[1] From a policy and management perspectives, water companies and water regulators are interested in assessing the technical efficiency of water companies which in the seminal paper by Farrell (1957) was defined as the effectiveness with which a given set of inputs is used to produce a set of outputs. A firm (water company) is said to be technically efficient if it produces the same level of outputs from the minimum quantity of inputs.

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2020). The exclusion of quality of service variables in the performance assessment of water companies penalizes those companies that generate a higher quality output (service) since they also usually incur higher production costs, which therefore reduce their efficiencies (Carvalho and Marques, 2011; Sala-Garrido et al., 2019).

The integration of quality-of-service variables in the efficiency assessment of water companies has already been addressed in the literature. Several past studies (Ananda and Pawsey, 2019; De Witte and Marques, 2010; Hernández-Sancho et al., 2012; Molinos-Senante et al., 2015, 2016; Picazo-Tadeo et al., 2008; Romano et al., 2017; Sala-Garrido et al., 2021) introduced quality of service variables as undesirable outputs in the assessment of the efficiency of water companies. This approach assumes that a lack of quality (unplanned water supply interruption, water leakage, complaints or non-revenue water) can be regarded as an undesirable output which should be minimized by water companies. The limitation of the above studies is that the efficiency of water companies was derived by assuming a proportional reduction of all inputs for a given level of output. In other words, an aggregate efficiency score was calculated, and thus, it was not possible to calculate an independent efficiency score for each quality-of-service variable used in the study.

We fill in this gap in literature by using a methodology that allows us to quantify the trends in variable-specific efficiencies. An approach that calculates a separate efficiency score for each variable of interest is the multi-directional Data Envelopment Analysis (MdDEA) technique, which was developed by Bogetoft and Hougaard (1999) and Asmild et al. (2003). This approach is appropriate for situations where the target of our interest is the measurement of the efficiency and potential improvements of particular variables (Wang et al., 2013). Hence, this method is very useful to calculate the efficiency in water leakage and unplanned water supply interruptions which is the main aim of this study. Within the set of quality-of-service variables considered by previous studies evaluating the performance of water companies, water leakage and unplanned water supply interruptions are relevant from an economic, social and environmental perspective. According to Liemberger and Wyatt (2019), globally, water loss amounts to 126 billion cubic meters per year with an estimated value of USD 39 billion per year. Saving half of those losses would provide enough water to serve at least 90 million people (World Bank, 2016). Moreover, continuity of water supply is commonly used as a benchmark of utility performance and a goal to be achieved, with 24 h, 7 days a week of supply (Rawas et al., 2020).

Against this background, the objectives of this study are twofold. The first one is to estimate the efficiency of a sample of water companies focusing on water leakage and unplanned water supply interruption metrics. In order to do this, for the first time, the MdDEA approach was employed. This approach also allows us to quantify the potential savings in water leakage and unplanned water supply interruptions, which is the second objective of this study. This is a novel approach as, to the best of our knowledge, there has not been any previous study in the water sector that specifically measured the efficiency in water leakage and unplanned water supply interruptions. Our case study focuses on several water companies, public and private, that provide water services to customers in Chile over the 2007–2018 period. Thus, it is of great interest to analyze whether the ownership of water companies influences efficiency in terms of quality of service.

2. Material and methods

2.1. Methodology

In this section we present and discuss the methodology employed to estimate the efficiency and potential savings in reducing water leakage and unplanned water supply interruptions of several water companies. Radial Data Envelopment Analysis[2] (DEA) calculates the efficiency of a firm (water company) by assuming a proportional reduction of all inputs for a given level of output (input-orientation) or a proportional expansion of all outputs for a given level of input (output-orientation). Thus, it is not possible to compute the efficiency and potential improvement of each variable separately. This limitation can be overcome by using MdDEA method (Asmild et al., 2003; Bogetoft and Hougaard, 1999). MdDEA chooses the targets for input reduction and output augmentation based on specified improvement potential associated with each input and output separately, allowing therefore a particular examination of the patterns of efficiencies (Wang et al., 2013). This approach, therefore, reflects the potential improvement in each variable separately (Asmild and Matthews, 2012; Asmild et al., 2016). As the objective of this study is to assess the reduction in water leakage and unplanned water supply interruptions while keeping some other inputs and outputs (operating expenditure, volumes of water delivered and network length) constant, an input-oriented MdDEA model is used where both discretionary and non-discretionary variables are employed.

Let's assume that a firm (water company) j at any period t uses a vector of inputs $x^t_{i,j}$, $i = 1, \dots, m$ to produce a vector of outputs $y^t_{p,j}$, $p = 1, \dots, k$. To find the ideal reference point, i.e., the minimum input required to produce a given output, $(x^t_{i,j_0}, y^t_{p,j_0})$, we need to solve the following programming model for each input n (Bi et al., 2014):

$$\min \phi^t_{i,j_0} \tag{1}$$

$$s.t.$$

$$\sum_j \lambda_j x^t_{i,j} \le \phi^t_{i,j_0},$$

$$\sum_j \lambda_j x^t_{-i,j} \le x^t_{-i,j_0}, \ -i = 1, \dots, i-1, i+1, \dots, n$$

$$\sum_j \lambda_j x^t_{i,j} \le x^t_{i,j_0}, \ i = n+1, \dots, m$$

$$\sum_j \lambda_j y^t_{p,j} \ge y^t_{p,j_0}, \ r = l+1, \dots, k$$

$$\lambda_j \ge 0$$

where $x^t_{i,j}$ and $x^t_{-i,j}$ denote discretionary and non-discretionary inputs, respectively; λ_j are intensity variables that are associated with each firm j for connecting inputs and outputs (Sala-Garrido et al., 2019; Wang et al., 2013); and ϕ^t_{i,j_0} is the target value for the *ith* input reduction. The optimal solution (*) of model (1) gives the ideal reference point $(x^t_{i,j_0}, y^t_{p,j_0})$ for $(\phi^{t*}_{i,j_0}, y^t_{p,j_0})$. The excess has been interpreted as the number of times the input has been used in excess what is necessary. Hence, large excess reflects a large (absolute) slack and considerable amount of inefficiency.

We next consider the following model:

$$\max \delta^t_{j_0} \tag{2}$$

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[2] DEA is a non-parametric method which uses linear programming to compare the relative efficiency of a set of units (water companies) with multiple inputs and outputs. DEA evaluates each firm in its best merit relative to other prioritizations of units (Cooper et al., 2011).

s.t.

$$\sum_j \lambda_j x_{i,j}^t \leq x_{i,j_0}^t - \delta_{j_0}^t \left(x_{i,j_0}^t - \phi_{i,j_0}^{t*} \right), \ i = 1, \ldots, n$$

$$\sum_j \lambda_j x_{-i,j}^t \leq x_{i,j_0}^t, \ i = n+1, \ldots, m$$

$$\sum_j \lambda_j y_{p,j}^t \geq y_{p,j_0}^t, \ p = l+1, \ldots, k$$

$$\lambda_j \geq 0$$

where $\delta_{j_0}^t$ denotes the technical efficiency of firm j_0 at any time t and takes values between zero and 1 with a value of one meaning that the firm is technically efficient whereas 1-$\delta_{j_0}^t$ indicates the potential saving in comparison to the best water company in terms of performance. Moreover, the optimal solution of model (2) can be used to derive the specific MdDEA efficiency of each variable of interest which in this case study are water leakage and unplanned water supply interrutptions. It is as follows (Asmild et al., 2003; Bogetoft and Hougaard, 1999; Wang et al., 2013):

$$\frac{x_{i,j_0}^t - \delta_{j_0}^{t*} \left(x_{i,j_0}^t - \phi_{i,j_0}^{t*} \right)}{x_{i,j_0}^t} \tag{3}$$

Finally, based on the specific efficiency scores previously computed in Eq. (3), we can derive an aggregate measure of MdDEA efficiency (total efficiency) score for the each water company $(x_{i,j_0}^t, y_{p,j_0}^t)$ as follows (Wang et al., 2013):

$$\phi_{j_0}^t = 1 - \frac{1}{n} \left[\sum_{i=1}^{l} \frac{\delta_{j_0}^{t*} \left(x_{i,j_0}^t - \phi_{i,j_0}^{t*} \right)}{x_{i,j_0}^t} \right] \tag{4}$$

2.2. *Data and sample selection*

The empirical application conducted in this study focused on the Chilean water and sewerage industry over the period of 2007–2018. The assessment of the performance of water companies in terms of quality of service is specially marked in Chile for the following reasons. First, the Chilean water industry was privatized during the years 1998–2004 and is characterized by two types of private firms, i.e., full private and concessionary water companies. Nevertheless, there is still one public water company. Full private firms provide water services to customers for an indefinite time period whereas concessionary companies supply water to customers for a limited time period (i.e., 30 years) (Molinos-Senante et al., 2018). Moreover, the current regulatory framework does not provide any incentives to the water companies in terms of financial rewards or penalties when the service quality improves or worsens. For instance, the percentage of water leakage remains high, averaging almost 30% during the last ten years (Sala-Garrido et al., 2019). Moreover, no financial compensation to customers is provided when the supply of water is unexpectedly cut off (Molinos-Senante and Sala-Garrido, 2017).

The Chilean water industry involves 54 water companies of diverse sizes in terms of population served. Due to data restrictions, our sample consists of the 21 largest Chilean water companies (11 full private companies, 9 concessionary companies and 1 public water company). Considering that the sample of water companies involves one public water company only, results about the influence of ownership on the performance of water companies should be interpreted with caution. The data is collected from the website of the national water regulator, Superintendencia de Servicios Sanitarios, (SISS).

The selection of the inputs and outputs (variables) was based on data availability, previous studies on the topic (Cetrulo et al., 2019; Pinto et al., 2017; Sala-Garrido et al., 2018, 2019; See and Goh, 2021) and the main features of the Chilean water industry (Marques et al., 2014). The two outputs employed were: i) volume of drinking water, in cubic metres per annum, that has been delivered, and ii) the network length measured in kilometres (Brea-Solis et al., 2017; Ferro and Mercadier, 2016; Molinos-Senante et al., 2016). As far as the inputs are concerned, we used the operating expenditure of the water companies' services calculated in Chilean pesos per annum and deflated by the consumer price index taken from national statistics (Molinos-Senante et al., 2018).

In the Chilean water sector, as in other water scarce countries, water leakage is a crucial topic since water companies lose about 30% of their drinking water (SISS, 2017), a value that has not improved over time (Sala-Garrido et al., 2019). Hence, water leakage and unplanned water supply interruptions were used as undesirable outputs.

The methodology proposed by Leys et al. (2013) (Eq. (5)) was applied to detect outliers because their presence distorts the efficiency results of the water companies. According to this approach, none of the 21 water companies evaluated was identified as an outlier.

$$\frac{\mathrm{x_i} - M}{\mathrm{MAD}} > |\mp 3| \tag{5}$$

where $\mathrm{x_i}$ is the original observation, M is the median of the sample and, MAD is the median absolute deviation. Table 1 reports the descriptive statistics for the variables used in the study.

3. Results

3.1. *Efficiency estimations*

Figs. 1, 2 and 3 show the temporal evolution of the average total efficiency and variable specific (water leakage and unplanned water supply interruptions) efficiency scores by ownership type over the 2007–2018 period. It is found that the average water leakage and unplanned supply interruptions efficiency for the Chilean water industry was at the level of 0.714 and 0.475, respectively. This means that the Chilean water companies to be efficient need to reduce their water leakage and unplanned water supply interruptions by 28.56% and 52.53%, respectively, while delivering the same level of drinking water with the same level of network length and maintaining the same level of operating expenditure. The total efficiency, i.e., the performance synthetic index considering all variables defined in Table 1, was at the level of 0.595, which means that on average the water industry could improve its quality of service by 40.55% while maintaining the current operating conditions, i.e., operational expenditure, volume of drinking water delivered and network length.

It is illustrated in Fig. 1 that both full private and concessionary firms presented a negative trend in total efficiency from 2007 to 2014. Both

Table 1
Descriptive variables of the Chilean water industry used in this study.

Variables	Unit of measurement	Mean	Std. Dev.	Minimum	Maximum
Volumes of water delivered	000 s m^3/year	77,336	107,208	7795	473,846
Network length	Km	5109	5449	742	21,859
Operating expenditure	EUR/year	63,616	59,478	3941	277,660
Volumes of water leakage	000 s m^3/year	25,893	33,486	1052	144,016
Water supply unplanned interruptions	hours/year	6198	7225	169	34,051

Observations: 252.
Operating expenditure was expressed in 2018 prices.

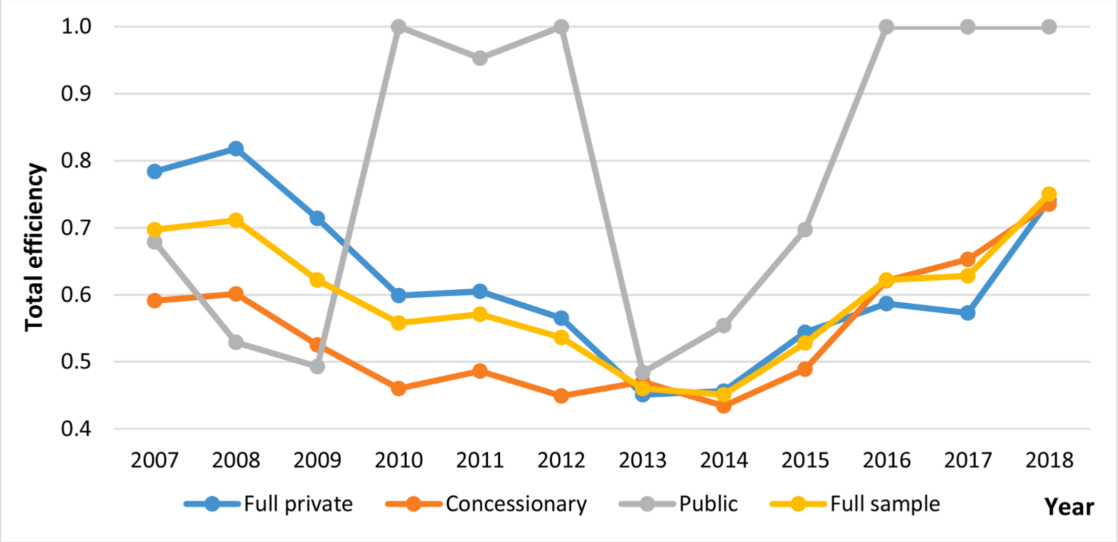

Fig. 1. Evolution of the average total efficiency of Chilean water companies (2007–2018).

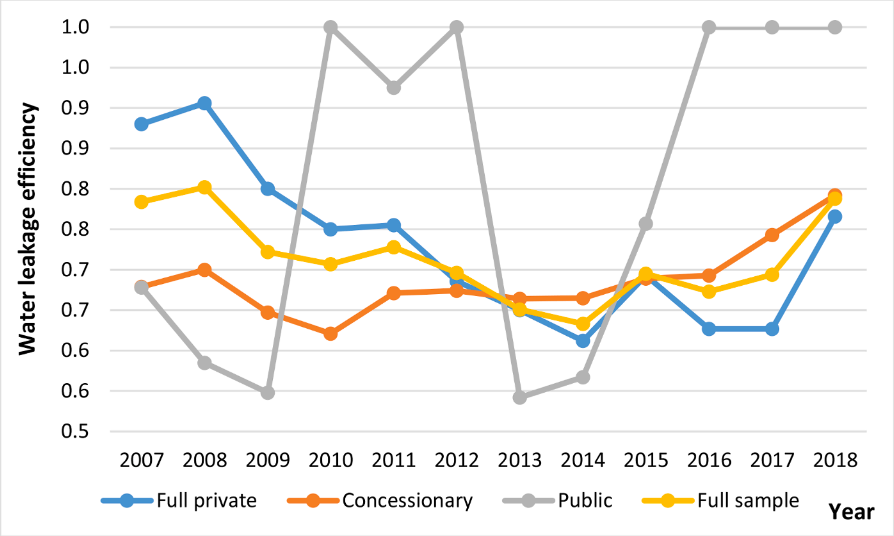

Fig. 2. Evolution of the average water leakage efficiency of Chilean water companies (2007–2018).

quality of service variables, unplanned water supply interruptions and water leakage, contributed to this decrease in total efficiency. During these years water companies in Chile might have focused on other issues such as improving wastewater treatment, removing additional pollutants from raw water or ensuring the availability of raw water sources. However, in 2014 this negative trend in total efficiency was reversed and the performance of full private and concessionary water companies year to year slightly increased. In the case of the public water company, a different pattern is observed with much greater volatility in its performance. It should be noted that only one public water company was evaluated and therefore, results shown in Fig. 1 are based only on this company.

As shown in Figs. 2 and 3, efficiency of water leakage and unplanned interruptions followed a downward trend over time with the exception being the last three years of our study. This means that quality of service deteriorated over the years. However, the water companies made efforts to reverse this situation in the last few years of our study.

Fig. 2 shows that the average water leakage efficiency was at the level of 0.802 in 2008 but reduced considerably the following years and reached the level of 0.633 in 2014. This means that the water companies suffered a regression of 17% in terms of water leakage efficiency. Only in the last two years of our sample (2017 and 2018) did the water leakage efficiency improve reaching the levels of 2007.

A similar trend is observed for the efficiency of unplanned water supply interruptions (Fig. 3). There was a considerable reduction in its efficiency during 2007–2015, from 0.609 in 2007 to 0.361 in 2015. This means that on average the water companies needed to reduce unplanned water supply interruptions by almost 64% in 2015. This situation slightly improved the following years but the companies still need to reduce their unplanned interruptions by 28.7% on average.

Regarding ownership type, it is concluded that the public water company performed better than the private companies in terms of quality of service. In particular, on average the water leakage and unplanned interruption efficiencies were at the level of 0.800 and 0.765, respectively. Full private and concessionary water companies reported lower efficiency scores. Full private water companies needed to substantially reduce the level of water leakage and supply unplanned interruptions, on average, by 27% and 49%, respectively. Water leakage efficiency showed a downward trend throughout the entire period (see Fig. 2), whereas unplanned interruption efficiency showed some

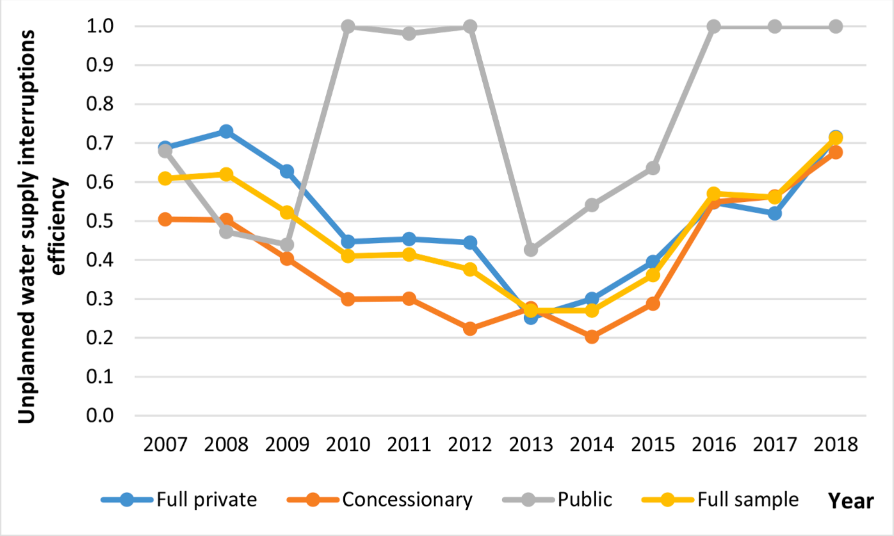

Fig. 3. Evolution of the average unplanned water supply interruptions efficiency of Chilean water companies (2007–2018).

improvement during the last three years after a significant deterioration during 2010–2015 (see Fig. 3). Concessionary water companies showed lower quality of service efficiency scores compared to full private water companies. On average, the water leakage and unplanned interruption efficiencies were at the level of 0.687 and 0.399, respectively, which means that they needed to reduce water leakage and unplanned interruptions by 31% and 60%, respectively. Some improvements in the quality of service were observed during 2016–2018. Overall, the results indicated that private water companies needed to make substantial improvements in their quality of service and particularly water supply interruptions. The same applies to the public water company although it performed better than private companies. Nevertheless, these results should be interpreted with caution given that there is only one public company in Chile.

3.2. *Potential savings estimation*

Table 2 shows the total current and potential water leakage savings by ownership type over 2007–2018. It is evident that the volume of water leakage increased over time since the level of water leakage was 324,456,000 m^3 in 2007 and 384,026,000 m^3 in 2018, which represents an increase of 15.5%. As expected, the evolution of potential water leakage savings followed the same trend as water leakage efficiency scores were shown in Fig. 2. Hence, higher values (48,405,000 m^3/year) were estimated for 2007 than for 2018 (22,763,000 m^3/year). Nevertheless, the maximum potential water leakage was reported for 2015, when a total volume of 61,165,000 m^3 of drinking water could have been saved if Chilean water companies had been efficient.

Table 2 shows that on average the Chilean water companies could achieve savings in leakage by 28.6%, or equivalently, they could save 48,166 $m^3$of water lost per year. High savings in water leakage could have been achieved during 2012–2016 which was the period where the levels of water leakage increased considerably. The public water company could have saved 4220 m^3 per year of water leakage which is equivalent to an average of 20% saving in water leakage over time. Full private water companies could have achieved 11.7% savings in water leakage on average over time, which means that they could have saved an average of 22,095 m^3 of water lost per year. During 2007–2009, where the full private water companies reported high water leakage efficiency scores as shown in Fig. 2, the savings in water leakage were at the level of 14.9% on average. However, the following years the savings in water leakage increased as the water companies became less efficient in dealing with water leakage incidents. For instance, in 2015, full private water companies could have saved 32,657 $m^3$of water lost on average per annum which is equivalent of 8.4% savings in water leakage on average. Concessionary water companies could have achieved higher savings in water leakage compared to the other companies, at the level of 31.3% per year on average. Savings in water leakage could have been achieved during 2009–2010 and 2013–2014 when concessionary water companies showed deteriorations in their water efficiency scores.

At water company level, Fig. 4 shows the average savings in water leakage over 2007–2018. The results indicated that among full private water companies (FPWC) there were two companies that reported low levels of water leakage savings on average over time. This implies that these two were the most efficient companies in terms of water leakage. The majority of full private companies reported water leakage savings that ranged from 14.32% to 34.91% on average, whereas the two companies reported water leakage savings up to 70%. This implies that the majority of water companies need to considerably improve their water leakage levels over time to catch-up with the most efficient companies. A similar situation is observed for the concessionary companies (CWC). There was one company that reported water leakage savings of 1.50% whereas the majority of them reported savings that varied from 10.53% to 29.61%. Three water companies have the potential to save more than 50% of current water leakage.

Table 3 reports the actual and potential improvement for unplanned water supply interruptions by ownership type over 2007–2018. It is concluded that, on average, the Chilean water industry could reduce its unplanned water supply interruptions by 74.1% per year, which is equivalent to an average reduction of 62,419 h of unplanned interruptions per year. The level of potential savings was lower in the last three years of our study as the frequency of unplanned water supply interruptions decreased considerably during that period. The public water company reported low levels of unplanned interruptions over time in comparison to FPWCs and CWCs. The observed level of unplanned interruptions was 380 h per year on average, whereas the target value for unplanned interruptions should have been 257 h per year, which was equivalent to a 123 hour savings in unplanned interruptions (32.3%). Higher levels of savings could have been achieved for private water companies. In particular, full private could have saved 32,496 h of unplanned interruptions per year on average, whereas concessionary could have saved 29,800 h of unplanned interruptions per year on average. Both types of private companies could have obtained considerable improvements in the continuity of water supply during 2010–2015. Although the frequency of unplanned interruptions decreased in the following years, private companies could still have saved almost half of

Table 2
Actual and estimation of total potential water leakage savings for Chilean water companies.

Variable	Ownership	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
Actual water leakage (000 s m^3/year)	FPWC	236,105	237,474	246,328	251,022	255,151	253,425	259,245	265,457	274,120	266,276	272,821	273,074	3,090,499
	CWC	70,064	70,951	71,014	72,549	73,816	73,746	74,867	75,636	77,342	76,570	77,547	77,036	891,139
	PWC	18,286	18,826	20,906	20,475	22,080	22,987	22,930	23,721	20,832	18,959	24,033	33,917	267,951
	FS	324,456	327,251	338,248	344,046	351,046	350,158	357,042	364,815	372,294	361,806	374,400	384,026	4,249,588
Water leakage saving (000 s m^3/year)	FPWC	18,202	13,364	17,798	25,180	26,948	22,527	25,391	26,909	32,657	22,507	23,121	10,534	265,137
	CWC	24,316	22,310	23,957	25,728	24,630	23,411	23,551	23,513	23,444	20,657	14,464	12,229	262,210
	PWC	5888	7817	9453	0	1646	0	10,504	10,270	5064	0	0	0	50,641
	FS	48,405	43,490	51,208	50,908	53,223	45,937	59,446	60,692	61,165	43,164	37,585	22,763	577,988
% water leakage saving	FPWC	13.0	17.8	13.8	10.0	9.5	11.3	10.2	9.9	8.4	11.8	11.8	25.9	11.7
	CWC	32.1	30.0	35.3	37.9	32.9	32.6	33.6	33.5	31.1	30.7	25.7	20.8	31.3
	PWC	32.2	41.5	45.2	0.0	7.5	0.0	45.8	43.3	24.3	0.0	0.0	0.0	20.0
	FS	21.6	19.8	27.8	29.3	27.2	30.4	34.9	36.7	30.5	32.7	30.6	21.2	28.6

FPWC: Full private water companies; CWC: Concessionary water companies; PWC: Public water company; FS: Full sample.

those interruptions.

Fig. 4 shows the average potential savings in unplanned water supply interruptions over the 2007–2018 period, where large divergences among water companies are revealed. The minimum value was 17.5% whereas the maximum reached 92.1%. These figures revealed that the direct regulation applied by the Chilean regulator has failed in achieving a homogeneous quality of service for all customers. 9 out of 21 water companies (43%) could reduce more than 50% of their unplanned water supply interruptions, and therefore, they could significantly improve the quality of service to customers. This figure involved both full private water companies and concessionary water companies.

4. Discussion

The main driver of changes in water leakage efficiency (Fig. 2) and unplanned water supply interruptions efficiency (Fig. 3) was the new sanctioning policy introduced by the Chilean water regulator in 2015. Thus, in 2015, the SISS applied 107 sanctions to the water companies related to quality-of-service issues which were equivalent to around 3.2 million euro (SISS, 2015). By contrast, in 2018, the number of sanctions increased up to 121 which involved a total cost of around 6.5 million euro for the Chilean water industry (SISS, 2018).

The considerable decrease in the efficiency of water leakage might be explained by several factors. First, the cost of fixing the leaks in the pipes might be expensive for the water companies. Studies by Molinos-Senante et al. (2016, 2019) showed that the shadow price (implicit cost) of fixing water leakage in the Chilean water sector was considerably high. Other reasons could be the higher abstraction of water due to climate change and rising population which might lead to higher levels of leakage (Molinos-Senante et al., 2019). The asset age and quality of water network might be another factors that could explain the deterioration in the quality of service in terms of water leakage.

There are two main reasons behind the poor performance of water companies in terms of quality of service. Firstly, the low replacement rate of water distribution networks. According to SISS (2021), during the period 2014–2018, the average replacement rate of drinking water pipes in Chile was 0.47%. This means that more than 300 years would be needed to completely renew the drinking water distribution network at this same rate. Secondly, Chile is frequently affected by large, destructive and potentially tsunamigenic earthquakes as a result of rapid convergence of the Nazca plate beneath the South America plate (Barrientos, 2018). These earthquakes usually have significant impacts on the water network across the country (Maziotis et al., 2020).

In context of the megadrought that Chile is suffering currently (Fuentealba et al., 2021), potential water savings from reducing water losses in the urban water cycle is not negligible (Table 2). The long-term strategic plan adopted by the Chilean water regulator has defined the target of reducing water leakage at least by 25% in 2030 (SISS, 2020). However, to the best of our knowledge, neither the water regulator nor the water companies have quantified the costs of achieving this ambitious goal. Moreover, in Chile, as in other many countries, the water leakage control strategy is based on the economic level of leakage (ELL) which is the level of leakage at which the marginal cost of reducing leakage is equal to the benefit gained from further marginal leakage reductions (Islam and Babel, 2013). However, leakage not only involves direct costs for water companies but also environmental, resource and social costs (Valis et al., 2017). To internalize these externalities in defining the optimal level of leakage, the English and Welsh water regulator (Ofwat) proposed the concept of Sustainable Economic Level of Leakage (SEEL) (Ofwat, 2007). This is the level of leakage of a water distribution network at which the unit cost of leakage control measures for the water service provider equals the unit cost of water, including the water service provider's costs and the environmental and resource costs that are external to the water service provider (European Commission, 2013). Molinos-Senante et al. (2016) estimated that the average environmental and resource costs of leakage in Chile were approximately

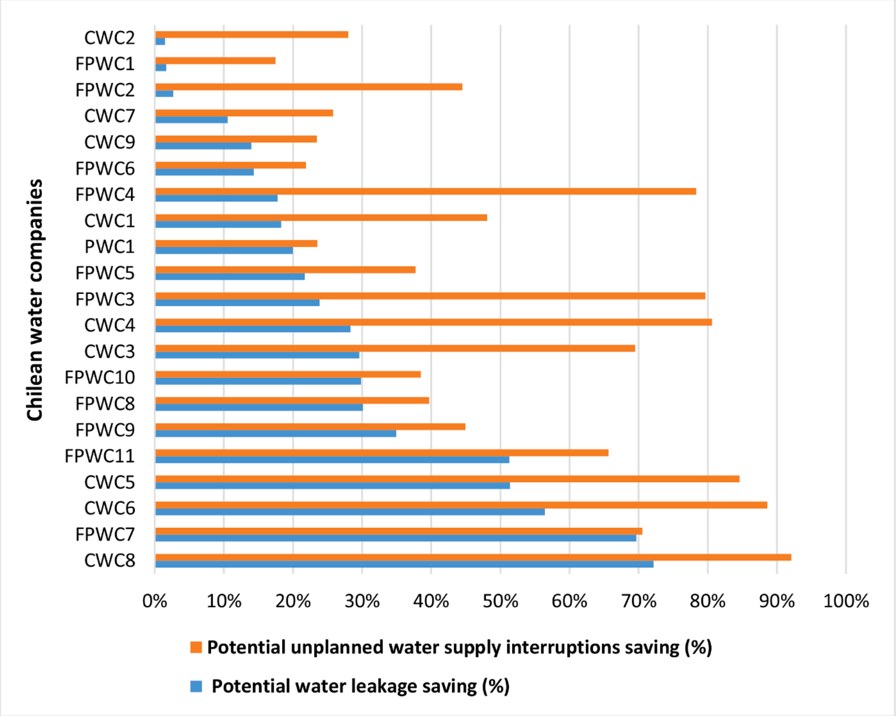

Fig. 4. Average potential savings in water leakage unplanned water supply interruptions over the period 2007–2018 for Chilean water companies.

32% of the price of the water delivered. Considering this estimation, the average tariff of drinking water in Chile and the potential water leakage savings (Table 2), the average annual environmental and resource costs of potential water leakage savings in Chile are estimated to be around 25.8 million of US$. If we consider the twelve years analyzed in our case study, these costs are estimated to be more than 309 million of US$. This figure is similar to the investment cost required to reuse 274,363,200 m^3/year which was estimated to be US$337 million (FCH, 2020), and is approximately half of the investment cost (US$636 million) of constructing six new desalinization plants to produce 63,418,896 m^3/year of drinking water (SISS, 2018). According to these figures, the environmental and resource costs of water leakage are estimated to be 535 US$/$m^3$ which is larger than the other alternative options to increase water in Chile. It should be noted that environmental and resource costs of water leakage are the negative externalities associated with the abstraction, treatment and distribution of drinking water which is not used. Hence, if the water regulator and water companies use the concept of SEEL rather than ELL to define the optimum level of water leakage, reducing current water leakage in Chilean water companies would be an economic feasible alternative compared to wastewater reuse and water desalination.

Considering the ambitious goal defined by the Chilean water regulator of reducing water leakage by at least 25% in 2030 (SISS, 2020), the largest water companies in the country, i.e., those providing drinking water in the largest cities, have defined specific plans involving non-negligible investment costs. For example, the water company providing drinking water to the capital of the country, Santiago de Chile, has implemented a plan for improving the hydraulic efficiency of the drinking water network. With a total investment of nearly US$100 million, the water company could monitor online the 13,200 km of the network through an operational control center.

Results at water company level shown in Fig. 4 indicate that the Chilean water companies presented a very uneven performance in terms of water leakage. This finding proves that the policies adopted by the water regulator have not been effective enough to incentivize water companies to reduce their water leakage and therefore additional measures are required. The divergence in the potential of water savings among water companies (Fig. 4) suggests that they might have voluntarily decided to reduce their water leakage, and not as a consequence of a regulatory policy, which might generate differences in terms of quality of service for customers.

According to the Chilean regulation for water companies, customers do not receive any compensation from unplanned water supply interruptions. Nevertheless, economic sanctions on water companies are imposed in case of water supply interruptions (Molinos-Senante and Sala-Garrido, 2017). The large percentage of potential unplanned interruptions savings estimated (Table 3) suggests that the sanctions applied by the regulator are not enough to incentivize water companies to provide a highly reliable service in terms of continuity.

5. Conclusions

Evaluating the quality of service in terms of water leakage and unplanned water supply interruption is of great interest to regulated companies who want to improve network performance and to regulators who want to introduce policies that incentivize companies to provide a good quality of service to customers at a low cost. In contrast to previous performance assessment studies, we estimated specific efficiency scores for variables of water leakage and unplanned water supply interruption. Following a pioneering approach in the context of assessing the performance of water companies, we used MdDEA method which also allowed quantifying potential savings for each quality-of-service variable.

The main findings of our study can be summarized as follows. First, the Chilean water industry needed to substantially improve its water leakage and unplanned interruption efficiency. In particular, it was found that during 2010–2018 the Chilean water companies could have improved its efficiency in terms of water leakage and unplanned supply interruptions by, on average, 28.56% and 52.53%, respectively, to produce the same level of output. Secondly, large divergences among water companies were identified which reveals that policies adopted by the Chilean regulator had failed in achieving a homogeneous quality of service for all customers. Thirdly, on average, Chilean water companies could save around 48,166,000 m^3 of drinking water per year. This figure

Table 3
Actual and estimation of total potential unplanned water supply interruptions for Chilean water companies.

Variable	Ownership	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total
Actual unplanned water supply interruptions (hours/year)	FPWC	36,031	42,720	33,375	48,087	44,713	70,055	87,280	71,702	71,240	23,588	23,138	20,970	572,900
	CWC	27,935	23,169	24,644	55,350	29,258	50,284	63,543	57,761	74,533	9196	9473	8124	433,270
	PWC	456	604	537	248	258	296	545	525	403	250	246	192	4561
	FS	64,422	66,493	58,556	103,686	74,229	120,635	151,368	129,988	146,176	33,034	32,857	29,286	1,010,730
Unplanned water supply interruptions saving (hours/year)	FPWC	19,687	24,296	19,752	34,240	30,168	53,341	72,919	57,487	56,928	8694	7719	4722	389,953
	CWC	22,937	16,241	17,777	47,814	23,963	45,584	54,028	52,237	66,273	4025	4110	2614	357,603
	PWC	146	319	301	0	5	0	313	241	147	0	0	0	1471
	FS	42,770	40,856	37,831	82,054	54,136	98,924	127,260	109,965	123,347	12,719	11,829	7335	749,027
% unplanned water supply interruptions saving	FPWC	54.6	56.9	59.2	71.2	67.5	76.1	83.5	80.2	79.9	36.9	33.4	22.5	68.1
	CWC	82.1	70.1	72.1	86.4	81.9	90.7	85.0	90.4	88.9	43.8	43.4	32.2	82.5
	PWC	32.0	52.8	56.1	0.0	1.9	0.0	57.4	45.9	36.4	0.0	0.0	0.0	32.3
	FS	66.4	61.4	64.6	79.1	72.9	82.0	84.1	84.6	84.4	38.5	36.0	25.0	74.1

is substantial in comparison to other measures evaluated by the Government to increase water supply. In terms of continuity of service, it has been estimated that from 2007 to 2018, Chilean water companies could have reduced their unplanned water supply interruptions by 74.1%, which is equivalent to 62,419 h per year.

The findings of this study are of great interest to policy makers for several reasons. We provide a methodology that identifies the efficiency of specific variables which, in our case, were associated with quality of service and were presented by water leakage and unplanned water supply interruptions. Thus, water companies can understand how efficient they have been in each of these quality-of-service variables over time, quantify the ideal target level and the potential improvements for each variable. This could allow them to make more informed decisions on how to improve network performance and provide good quality of service to customers. Moreover, the findings of our methodology could be useful to regulators when setting performance targets and designing incentives in the form of financial rewards or penalties to encourage companies to improve quality of service to customers.

Considering that the number of water companies evaluated in this study was 21, only two quality of service variables (unplanned water supply interruptions and water leakage) were considered in efficiency assessment. However, in case of a larger sample of water companies, the number of variables integrated in the assessment might also be higher. Additional quality of service and environmental variables such as greenhouse gas emissions and quality of wastewater treated could be integrated in the assessment. This information would be very useful for both water companies and regulators to improve the quality of service from a holistic perspective.

CRediT authorship contribution statement

Maria Molinos-Senante: Formal analysis, Funding acquisition, Project administration, Writing – review & editing. **Alexandros Maziotis:** Conceptualization, Data curation, Methodology, Writing – original draft. **Ramón Sala-Garrido:** Data curation, Validation, Software. **Manuel Mocholi-Arce:** Investigation, Methodology, Validation.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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