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Evaluation of dynamic eco-efficiency of water companies: the influence of non-revenue water and water supply interruptions

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Benchmarking the dynamic performance of water companies is a powerful tool to develop sound policies. However, it requires the use of reliable and robust methods and quality of data. In this study, the stochastic nonparametric envelopment of data (StoNED) method was employed to assess productivity change and eco-productivity change of a sample of Chilean water companies over the period 2010–2018. The StoNED approach overcomes the main limitations of stochastic frontier analysis and data envelopment analysis techniques which are the most commonly used to evaluate performance of water companies. Productivity change metric focused on the economic performance, whereas eco-productivity change evaluated economic and quality of service performance by including non-revenue water and unplanned water supply interruptions. Hence, this study analyzed the impact of quality of service variables on the dynamic eco-efficiency of water companies. The annual average productivity change and eco-productivity change estimations were 0.18% and −0.14%, respectively. It was evidenced that on average the Chilean water companies have put as priority to reduce operational costs than to improve quality of service. In both performance metrics, efficiency change was the main contributor to performance changes, whereas the role of technical change was negligible. It was illustrated that full private water companies performed better than concessionary companies and the public company. Reducing non-revenue water and unplanned water supply interruptions was particularly costly for concessionary water companies. The methodology and conclusions of this study are of great interest for water regulators and water utilities to improve the benchmarking process in the provision of drinking water services.

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INTRODUCTION

Benchmarking the performance of water companies is an invaluable tool for both companies and regulators to enhance sustainability in the provision of water and sewerage services¹. This assessment allows policymakers to compare companies' performance and identify the less and most productive companies and the factors that cause changes in productivity over time. This information could be of great significance to design policies and incentives² and to determine tariffs^{3,4}. In this context, the definition of the key performance indicators should go beyond cost outcomes to include other dimensions of water companies' performance such as non-revenue water (NRW) and water supply interruptions⁵. According to IBNET⁶, 93 out of 140 countries analyzed presented an average percentage of NRW larger than 30%. Actually, Liemberger and Wyatt⁷ estimated that the global volume of NRW was 346 million cubic meters per day which is 126 billion cubic meters per year. In the current context of climate change, where four billion people experience severe water scarcity for at least 1 month each year⁸, reducing NRW and pipe bursts are several of the major challenges faced by water utilities⁹.

Due to the importance of evaluating the performance of water utilities, the literature on this topic is large (for a review please see refs. ^{1,10–15}). Past research has focused on assessing the efficiency and productivity change of water companies in developed countries and therefore, more evidence on the performance of water utilities in developing countries is needed¹. On the one hand, efficiency is a static assessment that does not account for changes over time in the performance of water companies. The concepts of eco-efficiency and eco-productivity change have been

also used to evaluate the performance of water companies. Unlike efficiency and productivity change, which consider inputs and outputs, eco-efficiency and eco-productivity change metrics also integrate undesirable outputs, which usually refer to environmental and quality of service variables (for more details, please see the literature review by Goh and See¹⁵). On the other hand, the assessment of productivity change involves extending the notion of efficiency to an inter-temporal setting¹⁶. Moreover, productivity change allows computing efficiency for a given time period and comparing the performance among water companies evaluated¹⁷.

Focusing on past research assessing eco-productivity change of water companies, i.e., dynamic efficiency including quality of service variables as undesirable outputs, parametric and nonparametric methods have been employed¹. Data envelopment analysis (DEA) was the most commonly used nonparametric approach to evaluate the performance of water companies whereas almost all of the parametric studies used stochastic frontier analysis (SFA) technique. Although both approaches allow evaluating eco-efficiency and eco-productivity change of units, they are not exempt from limitations. On the one hand, DEA does not assume a functional form for the underlying technology but is deterministic because it does not take into account noise^{18,19}. In contrast, SFA incorporates both noise and inefficiency but it assumes a priori a functional form for the production technology²⁰. To avoid the limitations of DEA and SFA, Johnson and Kuosmanen²¹ developed the stochastic nonparametric envelopment of data (StoNED) which brings together the merits of both DEA and SFA. Like SFA, the StoNED approach takes into account both noise and

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inefficiency²². Like DEA, it does not assume a priori a functional form for the production technology, and the assumptions of monotonicity, concavity and returns to scale are maintained²³.

Given the positive features of the StoNED method, it has been applied to evaluate the performance of several types of firms and services such as banks²⁴, electricity companies²³, hospitals²⁵, tax systems²⁶, and European regions²⁷. The water industry has not been left out of this from methodological innovation to evaluate performance through a synthetic index. Recently, Molinos-Senante and Maziotis²⁸ employed StoNED approach to assess the energy efficiency of a sample of wastewater treatment plants. To the best of our knowledge, only Molinos-Senante et al.²⁹ and Molinos-Senante and Maziotis³⁰ benchmarked the economic and environmental efficiency (eco-efficiency) of a sample of water companies using the StoNED method. Despite the methodological novelty of both studies, they compared the eco-efficiency of water companies during a single year, i.e., they provided a static evaluation of the performance of the analyzed water companies. To better support the regulation process of the water industry, information on the temporal dynamics of eco-efficiency is essential³¹. In other words, the assessment of the eco-productivity change (or dynamics eco-efficiency) of water companies is fundamental to regulate the water industry and to improve the performance of water companies. Despite the potential positive impact of evaluating eco-productivity change of water companies using reliable and robust methods such as StoNED, to the best of our knowledge, no prior studies have assessed the eco-productivity change of water companies using this methodological approach.

In this context, the objectives of this study are threefold. The first one is to benchmark the dynamic performance of water companies using the newly developed StoNED technique. The second objective is to analyze the impact of integrating two relevant quality of service variables such as NRW and unplanned water supply interruptions (UWSIs) on the dynamic performance of water companies, i.e., comparing productivity change and eco-productivity change. The third objective is to quantify the drivers of eco-productivity change by decomposing eco-productivity change estimations into technical change and efficiency change. The empirical application focused on a sample of Chilean water companies over the period 2010–2018. Chile is a prominent case study because it suffered a mega-drought 13 years ago³² and therefore, integrating NRW in eco-productivity change estimation is essential. It should be noted that when tariffs are set by the regulator, it assumes that the maximum percentage of water leakage of an “efficient” water company is 15% (SISS, 2022). However, no financial rewards or penalties are imposed by the regulator if companies have higher or lower levels of NRW. Moreover, no compensation is allowed to customers when the water supply is cut off due to companies’ responsibility³³. Finally, the Chilean water industry was privatized during the years 1998–2004 and therefore, the study of the relationship between privatization and eco-productivity becomes of great interest to policymakers and researchers.

This study contributes to the literature on the performance assessment of the water industry by evaluating the eco-productivity of a sample of water companies using the StoNED method. This is done by integrating NRW and UWSIs as undesirable outputs. These quality of service variables are very relevant in the current context of water scarcity. The Chilean water industry encompasses highly differentiable water companies due to structural and environmental differences across the country. Thus, although the study focused on the Chilean water industry, it provides knowledge on issues relevant to assess the performance of the water industry in several other countries.

The paper unfolds as follows. The next section presents and discusses the results of the empirical application and the final section presents the methodology used followed by a section on a

description of the sample of water companies evaluated and the variables used in this study.

RESULTS AND DISCUSSION

Parameters of the StoNED model

The first step in the assessment conducted was to estimate the production technology without integrating undesirable outputs (Eq. 11) (Model Malmquist productivity index (MPI)) and considering them (Eq. 12) (Model eco-MPI). Table 1 reports the results from the estimation of the StoNED frontier model for both approaches.

When the quality of service variables are not integrated into the assessment (Model MPI), higher volumes of drinking water delivered are associated with higher operating cost and network length and, thus, higher inefficiency. Both variables are statistically significant from zero with network length being the major driver of water delivered as indicated by the magnitude of its estimated coefficient. In particular, a 1% increase in operating costs and network length could lead to a 0.313% and 0.517% increase in the volume of water delivered, respectively. The variable time has a positive sign but is insignificant suggesting that technical progress did not have an impact on production costs. In contrast, all environmental variables had a statistically significant effect on water companies’ production efficiency. It was found that more water is delivered when the company has mixed and surface resources than groundwater resources. It appears that private companies (full private water companies (FPCs) and concessionary water companies (CCs)) produced more water than public ones as they had more customers to serve.

Dynamic eco-efficiency scores at water industry level

Results shown in Table 1 (Model eco-MPI) demonstrate the relevance of integrating quality of service variables in dynamic performance assessment because both NRW and UWSIs had a statistically significant effect on production. Higher volumes of water delivered are required to meet demand when NRW and UWSIs increase. For instance, keeping other variables equal, a 1% increase in NRW requires the abstraction, treatment and distribution of higher volumes of water, an increase by 0.161%. Moreover, ceteris paribus a 1% increase in operating costs and network length could lead to an increase in water by 0.312% and 0.311%, respectively. The sum of all input elasticities is close to unity, 0.900, implying that the Chilean water industry operates toward its optimal scale. The time variable has a negative sign which means

Table 1. Estimates of the StoNED frontier model.

Variables	Model MPI		Model eco-MPI	
	Coeff.	St. Error	Coeff.	St. Error
Operating cost	0.313**	0.017	0.312***	0.016
Network length	0.517**	0.018	0.311***	0.016
Non-revenue water			0.161***	0.014
Water supply unplanned interruptions			0.117***	0.011
Time	0.000	0.001	−0.000	0.001
Customer density	0.001***	0.000	0.000***	0.000
Type of water resource	0.024***	0.003	0.018***	0.003
Type of ownership	0.022***	0.004	0.027***	0.004
R ²	0.95		0.96	

***indicates that coefficients are statistically significant at 5% significance level.

**indicates that coefficients are statistically significant at 10% significance level.

that technical regress occurred in the water industry but was immaterial. All environmental variables had a statistically significant impact on water companies' production efficiency, with ownership and type of water resource being the major drivers as indicated by the magnitude of their estimated coefficients.

Figure 1 shows the estimates of dynamic performance and its decomposition for the Chilean water industry over the years 2010–2018. It is found that without the inclusion of NRW and UWSIs, average productivity increased by 0.020% per year. Productivity change was only influenced by changes in efficiency since the average technical change was 0.0% for all years evaluated. This finding is corroborated by Molinos-Senante et al.³⁴ who reported that small gains in efficiency at a rate of 0.3% on average per year contributed positively to the productivity of the Chilean water industry. Results are different when the assessment integrates quality of service variables. As it is shown in Fig. 1, eco-productivity (eco-MPI) of the Chilean water companies deteriorated. It was found that on average companies' eco-productivity reduced by 0.081% per year. This was attributed to both technical change (TC_eco-MPI) and efficiency change (EC_eco-MPI). In particular, technology deteriorated at a rate of 0.014% per year, whereas losses in efficiency were at the level of 0.067% per year on average. Our results are consistent with past studies by Molinos-Senante et al.^{34,35} and Sala-Garrido et al.³⁶ who highlighted the negative impact of technical change on water companies' productivity in Chile.

Focusing on the temporal evolution of both performance metrics, i.e., MPI and eco-MPI, Fig. 1 illustrates that productivity followed an upward trend during the years 2011–2013 but this was interrupted in the following period. During the years 2011–2012 and 2012–2013 less efficient companies slightly improved their performance relative to the most efficient ones, as they were progressing at a small rate of 0.065% and 0.105% per year on average. However, in the following period, considerable increases in operating costs and an expansion of network had an adverse impact on efficiency and productivity. The situation changed during the years 2015–2018. Productivity improved by 0.057% per year on average having less efficient companies moving closer to the frontier ones except for the years 2015–2016. Looking at the eco-MPI results, it is concluded that productivity followed a downward trend during the years 2011–2014. This implies that dealing with NRW and UWSIs was challenging for the water companies. During the period 2014–2016 less efficient companies were progressing at a rate of 0.620% on average per year. However, in the last years of our study, productivity deteriorated due to higher volumes of NRW and more frequent unplanned interruptions.

Figure 1 evidence that for almost all years evaluated, average productivity change (MPI) was larger than average eco-

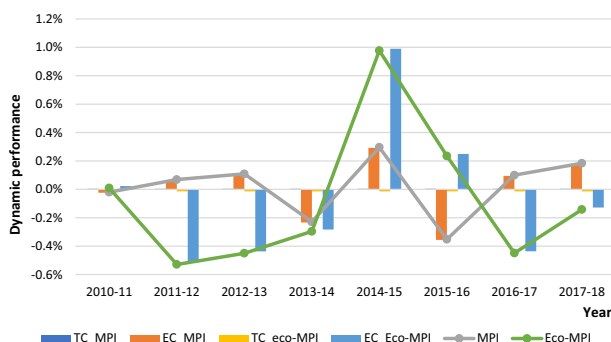


Fig. 1 Productivity and eco-productivity change of Chilean water companies. Average estimates of productivity change (MPI) and eco-productivity change (eco-MPI) and its drivers' efficiency change (EC) and technical change (TC).

productivity change (eco-MPI). This finding suggests that water companies in Chile have prioritized cost savings over improving the quality of service (NRW and UWSIs). This might be because these variables are not directly considered in the process to set water tariffs, and therefore, water companies have no direct economic incentives to reduce NRW and UWSIs. It should be noted that water tariffs in Chile are set based on the concept of an economically efficient water company. Setting tariffs based on this model operator ensures that consumers do not pay for the inefficiencies of the water company³⁷. However, it implies that water tariffs are not affected by the quality of the service provided by the water companies. By contrast, the regulation of the quality of service is indirect and only when certain thresholds are exceeded, the water regulator applies sanctions to water companies. However, not all quality of service variables are indirectly regulated. For example, NRW is not regulated directly or indirectly and therefore, they have not considerably been improved across years. To deal with this issue, the Chilean water regulator developed and adopted a long-term strategic plan which defines the target of reducing water leakage at least by 25% in 2030³⁸. In spite of this policy, results from this study reveal that the current regulatory framework applied in Chile does not encourage improvements in the quality of service provided by water companies and therefore, deep policy changes in it are required.

Dynamic eco-efficiency comparison by ownership

Extensive literature has compared the operational performance of private, public and concessionary water companies. However, the empirical evidence is not conclusive¹⁹. To shed light on this issue, Fig. 2 reports average estimates of productivity change (MPI) and eco-productivity change (eco-MPI) of Chilean water companies by ownership type during the years 2010–2018. Both integrating and ignoring NRW and UWSIs in performance assessment, private water companies performed better than the public one. This finding is consistent with Molinos-Senante et al.³⁵ who reported that full private companies performed better than concessionary ones. In the case of productivity change estimation, FPCs and CCs improved their productivity by 0.097% and 0.006% per year on average, respectively. In contrast, public water's productivity declined by 0.044% per year on average. When quality of service variables were included in the assessment, only FPCs improved their eco-productivity since average eco-MPI was 0.053%. By contrast, average productivity of CCs and public companies (PCs) deteriorated by 0.017% and 0.278% on average per year, respectively. Results shown in Fig. 2 indicate that dealing with NRW and UWSIs was challenging for all companies but more

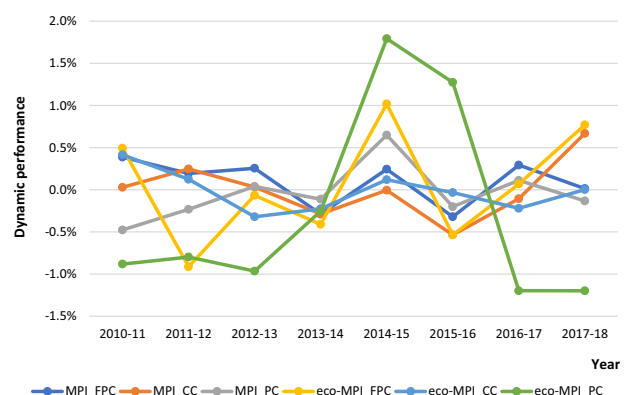


Fig. 2 Influence of ownership on productivity and eco-productivity change of Chilean water companies. Average estimates of productivity change (MPI) and eco-productivity change (eco-MPI) of Chilean water companies by ownership.

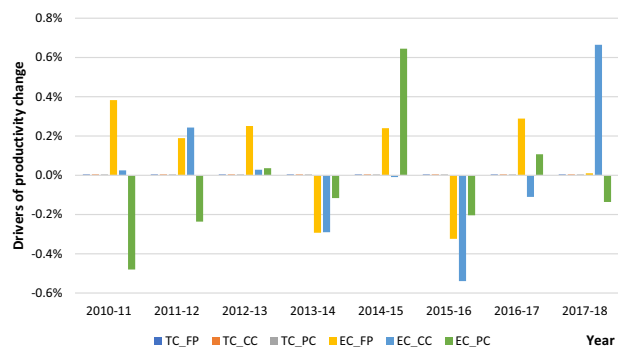


Fig. 3 Drivers of productivity change of Chilean water companies. Average estimates of technical change (TC) and efficiency change (EC) for productivity change (MPI) of Chilean water companies by ownership.

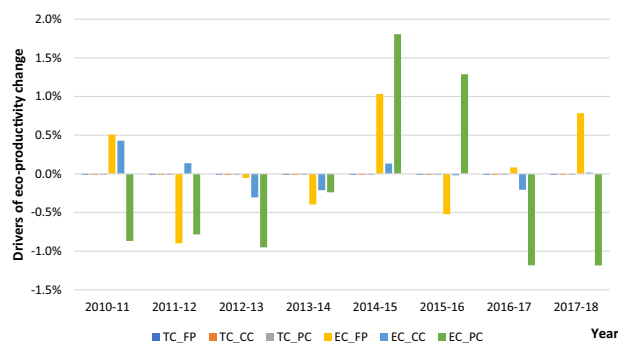


Fig. 4 Drivers of eco-productivity change of Chilean water companies. Average estimates of technical change (TC) and efficiency change (EC) for eco-productivity change (eco-MPI) of Chilean water companies by ownership.

particular for CCs and PCs. FPCs reported lower rates of eco-productivity change compared to the MPI results but they remained positive. By contrast, CCs presented positive values when performance assessment was based only on operational costs (MPI) and negative values were reported when NRW and UWSIs were integrated into dynamic performance analysis.

Looking at the drivers of dynamic performance (Figs. 3 and 4), in the case of productivity change, i.e., without considering quality of service variables, the results from the FPCs indicate that less efficient made efforts to reduce their inputs throughout the whole period of study, moving therefore closer to the most efficient ones (Fig. 3). These efficiency gains were more evident in the earlier period of our study. During the years 2015–2018 small efficiency losses existed. As for CCs, it is found that efficiency gains existed during the years 2010–2013. However, in the subsequent years, companies' efficiency deteriorated at a rate of 0.057% per year on average. Higher and more frequent negative rates of efficiency were reported by the PC. This result indicates that the PC did not manage to improve its managerial practices over time. This is particularly evident during the years 2010–2014 when efficiency losses were increasing at a rate of 0.199% per year on average. Small gains in efficiency were reported for the years 2014–2015 and 2016–2017; however, the last period of our study is characterized by losses in efficiency which were at the level of 0.132% on average per year. This result indicated that the PC needed to adopt better practices to reduce operational costs and catch-up with the most performing companies in the industry.

The improvement in the eco-productivity of Chilean water companies was attributed to an increase in efficiency change of 0.067% which offset the negative rate of technical change (Fig. 4). FPCs improved their efficiency toward the most efficient ones

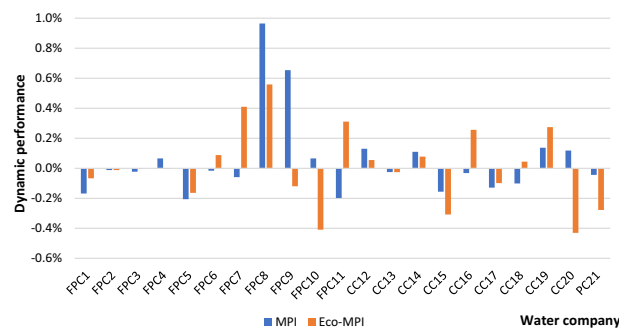


Fig. 5 Productivity change and eco-productivity change at water company level. Average estimates over the years 2010–2018 of productivity change (MPI) and eco-productivity change (eco-MPI) of Chilean water companies.

from 2014–2015 onwards. It appears that in earlier periods of our study, high levels of NRW and UWSIs had a negative impact on companies' productivity. The regression of the eco-productivity for CCs was attributed to technical regress which was at the rate of 0.014% per year, whereas efficiency change was immaterial. Efficiency change was volatile and during the years 2010–2012 gains inefficiency was reported which was at an annual rate of 0.288% on average. However, the lack of improving day-to-day operations concerning environmental and quality of service issues might have led to lower efficiencies. This was particularly evident from 2012–2014 onwards when efficiency change became negative. It was also found that during the years 2010–2014, the PC did not perform well (Fig. 4). Efficiency change was decreasing at an annual rate of 0.711% on average. Although in the next two periods the company made some improvements in their efficiency, the negative rates of efficiency change continued till the end of the period of study.

Dynamic eco-efficiency scores at water company level

Figure 5 shows the average productivity change (MPI) and eco-productivity change (eco-MPI) at the company level during the years 2010–2018. The results from MPI indicate that most of the FPCs reported negative rates of productivity which ranged from -0.206% to -0.012% per year. FPC8 and FPC9 were the top-performing companies in the entire industry with annual productivity rates of 0.965% and 0.654%, respectively. By contrast, FPC5 was the worst-performing company among all companies with an average annual rate of -0.206% . When NRW and UWSIs were incorporated into productivity analysis, then FPC8 remained the frontier company, i.e., is the Chilean water company whose performance has improved the most across years. It is a medium-size water company which is characterized by a relatively low and duration of UWSIs. By contrast, FPC9 becomes one of the worst ones with a negative annual rate of eco-productivity change of -0.120% on average. We note that this water company had the highest level of NRW in the industry. Thus, reducing leakage along with production costs proved to be a difficult task for this company.

Figure 5 also evidences that there were several FPCs that showed positive rates of productivity when undesirable outputs included in the analysis and thus, their ranking improved. A similar conclusion was found for the CCs companies. Unlike the MPI results, the worst-performing company (CC20) in the entire industry now belongs to the group of concessionary companies with an annual rate of retardation of 0.430% on average. As far as the productivity of the PC is concerned, it reported negative rates both for MPI and eco-MPI estimates. Nevertheless, dynamic performance considerably deteriorated when NRW and UWSIs were included in the assessment suggesting that improving service quality is costly.

Benchmarking the performance of water companies is a powerful tool to improve the management and regulation of water services. Water regulators in many countries use performance results in ranking water companies and in setting water tariffs. Hence, dynamic performance assessment, i.e., evaluating performance across years, is essential. Given the relevance of benchmarking in developing sound policies, robust and reliable methods should be employed to assess the performance in the water industry. Despite the large use of DEA and SFA methods to benchmark the performance of water companies, both approaches present limitations. To overcome them, in this study, we used the newly developed StoNED method to estimate dynamic performance among several water companies in Chile over the years 2010–2018. To evaluate the impact of NRW and UWSIs in dynamic performance, productivity change and eco-productivity change metrics were estimated.

The main points of our analysis are as follows. First, costs and quality of service variables affect production and efficiency. Moreover, several operational characteristics such as customer density, type of water resource and type of ownership influence the delivery of water services. The estimates of dynamic performance indicate that the Chilean water industry experienced low levels of productivity change. Moreover, when water companies need to deal with NRW and UWSIs, eco-productivity change further deteriorates. FPCs performed better than CCs who reported immaterial changes in productivity. In contrast, public companies' productivity deteriorated at a rate of 0.044% per year. When NRW and UWSIs were incorporated into the analysis, FPCs maintained positive rates of eco-productivity. This was not the case for CCs and the PC which reported high rates of retardation over time. This means that reducing NRW and UWSIs was particularly costly for these types of companies.

Overall, the findings of our study have the following policy implications. First, NRW and UWSIs influence companies' dynamic performance and therefore, the water regulator should include these variables (and other quality of service) in performance assessment. Otherwise, water companies do not have any incentives to improve the quality of service and their management focuses only on reducing operational costs. The assessment conducted over 2010–2018 revealed that on average the water industry in Chile is characterized by low levels of dynamic performance. Companies could improve performance by managing better their network and their daily operations. The adoption of new technologies that could help companies to predict and locate leaks and bursts more accurately in mains could be another strategy to improve performance.

Although the current Chilean water regulatory framework has been very successful in achieving almost full drinking water and wastewater treatment coverage in urban areas, findings from this study have evidenced that it is not enough to address the current challenges of the water companies in Chile. Hence, it is imperative to make the legal changes that allow the water regulator to establish incentives to water companies to improve the quality of service. For example, the regulator could establish benefits for those water companies that anticipate the fulfillment of the quality targets defined in the strategic long-term plan adopted by the Chilean water regulator. The benefits do not have to be only economic but can also be reputational, i.e., following a sunshine regulation approach. Moreover, the Chilean water regulator must have the power to penalize those water companies that do not comply with quality of service standards. The sanctions imposed should be exemplary in order to encourage water companies to improve their quality of service and not just to pay the sanction and continue providing water and sanitation services with poor quality.

Our research does not come without limitations. From a methodological perspective, the MPI, i.e., the synthetic index used to estimate dynamic eco-efficiency, suffers from infeasibility

and lack of circularity. To overcome both limitations, alternative indexes such as the global MPI proposed by Pastor and Lovell³⁹ could be employed in future research to estimate the productivity change of water companies. Moreover, the empirical application conducted integrates NRW and UWSIs as quality of service variables. However, additional variables such as number of complaints and sewer blockages could also be integrated into the model as undesirable outputs to assess the performance over time of the water companies.

METHODS

Methodology to compute dynamic eco-efficiency scores

This section presents the StoNED methodology which was employed to assess the eco-productivity change and its drivers for a sample of water companies in Chile. Considering the services provided by water companies, their objective is to minimize the use of inputs and the generation of undesirable outputs such as NRW and UWSIs. Hence, the following production technology is estimated^{40,41}:

$$y_{i,t} = f(x_{i,t}) \times z_{i,t} \times \text{Trend}(t) \times \exp(v_{i,t} - u_{i,t}) \quad (1)$$

where i and t denote water company and time, respectively; $y_{i,t}$ is the output produced by each water company at any year t ; and $x_{i,t}$ is a set of inputs used by each water company at any year t to produce the output. We also include a set of environmental variables, $z_{i,t}$, to capture companies' heterogeneity²³. $\text{Trend}(t)$ captures technical change whereas $v_{i,t}$ and $u_{i,t}$ denote firm-specific noise and inefficiency over time, respectively. It is assumed that noise followed the half-normal distribution, $u_i \sim N^+(0, \sigma_u^2)$, and inefficiency followed the normal distribution, $v_i \sim N(0, \sigma_v^2)$ ⁴⁰.

The StoNED approach embraces two main steps described as follows. The first step involves the minimization of the sum of the squares of the residuals, denoted as $\varepsilon_{it} = v_{it} - u_{it}$, by solving the following non-linear programming:

$$\min \sum_{i=1}^I \sum_{t=1}^T \varepsilon_{i,t}^2 \quad (2)$$

subject to:

$$\begin{aligned} \ln y_{i,t} &= \ln(a_{i,t} + \beta'_{i,t} x_{i,t}) + \gamma_{i,t} z_{i,t} + \text{Trend}(t) + \varepsilon_{i,t} & i = 1, \dots, I; t = 1, \dots, T \\ a_{i,t} + \beta'_{i,t} x_{i,t} &\leq a_{j,w} + \beta'_{j,w} y_{j,w} & i, j = 1, \dots, I; t, w = 1, \dots, T \\ \beta_{i,t} &\geq 0 & i = 1, \dots, I; t = 1, \dots, T \end{aligned}$$

The first equation is the logarithmic version of the regression equation. It should be noted that the term $a_{i,t}$ captures the presence of returns to scale. The evidence about the presence of economies of scale in the Chilean water industry is mixed. On the one hand, some previous studies evidenced that water companies operate under constant returns to scale^{36,42,43}. On the other hand, there is also empirical evidence of the presence of economies of scale in the Chilean water industry⁴⁴. In this study, it is assumed that water companies operate under constant returns to scale and therefore, we set $a_{i,t} = 0$. This means that an increase in inputs will lead to the same proportional increase in outputs. The parameter $\beta_{i,t}$ present the marginal product of inputs⁴⁵. Moreover, the regression equation includes a set of environmental variables, $z_{i,t}$, which could impact companies' performance. The first constraint ensures that the function is concave and the third constraint that the function is monotonic increasing⁴⁰. Hence, the first step of StoNED approach provides the estimators for the inputs, environmental variables and time trend employing convex nonparametric least squares as developed in ref. ⁴⁶.

In the second step, the StoNED approach employs the method of moments (MoM) to estimate the expected value of inefficiency along with the variances of inefficiency and error terms^{22,47,48}. Firm-specific inefficiency estimates are derived using the following

approach:

$$E(u_i|\varepsilon_i) = \mu_* + \sigma_* \left[\frac{\phi(-\mu_*/\sigma_*)}{1 - \Phi(-\mu_*/\sigma_*)} \right] \quad (3)$$

where ϕ is the standard normal density function; and Φ is the standard normal cumulative distribution function, $\mu_* = -\varepsilon_i \sigma_u^2 / (\sigma_u^2 + \sigma_v^2)$ and $\sigma_*^2 = \sigma_u^2 \sigma_v^2 / (\sigma_u^2 + \sigma_v^2)$ (see Kuosmanen and Kortelainen²³, for more details). Equation (3) gives firm-specific inefficiency estimates, $\hat{u}_i$ which could be converted into firm-specific technical efficiency estimates as follows:

$$TE_{it} = \exp(-\hat{u}_{i,t}) \quad (4)$$

We further extended the efficiency analysis with the StoNED method into a productivity framework by adopting the traditional MPI, which is the most common total factor productivity index used in the literature⁴⁹. This index measures the productivity change between two time periods, t and $t + 1$, and was originally defined by Caves et al.⁵⁰. Then, Fare et al.⁵¹ defined and decomposed the productivity index in terms of Shephard input distance functions. An input distance function measures the maximum contraction of input required to produce the same output. The input distance function, $D(x, y)$, is defined in the input set $L(y)$ as follows:

$$D(x, y) = \max \left\{ \mu : \left(\frac{x}{\mu} \right) \in L(y) \right\} \quad (5)$$

where μ denotes the technical efficiency score of the water company implying that it can contract its inputs by $1/\mu$ to generate the same output⁵². The input set $L(y)$ presents all the set of input vectors required to produce the set of output vectors.

Based on the input distance function, $D(x, y)$, Fare et al.⁵¹ defined the MPI as follows:

$$MPI(t, t + 1) = \left(\frac{D^t(x^t, y^t)}{D^t(x^{t+1}, y^{t+1})} \times \frac{D^{t+1}(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})} \right)^{1/2} \quad (6)$$

Equation (6) is further decomposed into efficiency change, EC , and technical change, TC , as follows:

$$EC(t, t + 1) = \frac{D^t(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})} \quad (7)$$

$$TC(t, t + 1) = \left(\frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^{t+1}, y^{t+1})} \times \frac{D^{t+1}(x^t, y^t)}{D^t(x^t, y^t)} \right)^{1/2} \quad (8)$$

$$MPI(t, t + 1) = TC(t, t + 1) * TEC(t, t + 1) \quad (9)$$

For the StoNED approach, and without any loss of generality, Eq. (9) can be re-stated as follows^{41,48}:

$$MPI(t, t + 1) = \exp(Trend + \varepsilon(i, t + 1) - \varepsilon(i, t)) \quad (10)$$

where $\exp(Trend)$ and $\exp(\varepsilon(i, t + 1) - \varepsilon(i, t))$ present technical change and efficiency change, respectively. Technical change is captured by the estimated coefficient of the regression Eq. (2). Efficiency change is derived from the estimation of Eqs. (2)–(4). If technical change is positive then technical progress occurs which contributes positively to productivity change. In contrast, a negative value for technical change implies technical regress and impacts negatively on productivity change. In an analogous manner, a negative value for efficiency change implies that less efficient companies improved their efficiency toward the most efficient (frontier) ones. Thus, it contributes positively to productivity change. In contrast, a negative value for efficiency change implies losses in efficiency which negatively affects productivity change.

Because one of the objectives of this study is to compare the dynamic performance of water companies without and with the presence of undesirable outputs such as NRW and UWSIs (for

more details, please see the next section), Eq. (10) is calculated twice. Firstly, without the inclusion of undesirable outputs, the MPI (Eq. 8) is calculated by minimizing inputs (operating expenditure and network length in our case) for a given level of output. This is the traditional MPI and measures productivity change of water companies. Secondly, when undesirable outputs are integrated, Eq. (10) is estimated by minimizing both inputs and undesirable outputs (NRW and UWSIs in our case) for a given level of output. We define this index as the eco-MPI⁴¹ which estimates eco-productivity change.

The traditional MPI is calculated using the following production technology:

$$\ln y_{i,t} = \ln f(OPEX_{i,t}, LENGTH_{i,t}) + z_{i,t} + Trend(t) + \varepsilon_{it} \quad (11)$$

When undesirable outputs are present, the following production technology is estimated to derive the eco-MPI:

$$\ln y_{i,t} = \ln f(OPEX_{i,t}, LENGTH_{i,t}, WLEAK_{i,t}, WUPL_{i,t}) + z_{i,t} + Trend(t) + \varepsilon_{it} \quad (12)$$

If productivity change (MPI and eco-MPI) takes a positive value, then it means that improvements in productivity occurred. Negative values of productivity suggest productivity retardation. If productivity takes a value of zero, then productivity did not change between the evaluated periods.

Data and sample selection

Our empirical approach focused on the Chilean water industry during the years 2010–2018. In particular, productivity change and eco-productivity change of 21 water companies, which provide water services to more than 90% of the Chilean urban population, were assessed. In Chile, two main types of water companies exist, FPCs and CCs. Under full private ownership, water companies are in charge for the maintenance and upgrade responsible for delivering water and sanitation services for a particular time period, i.e., 30 years. There is also a small proportion of customers that receive their water from a PC⁵³. More information about the water industry privatization process is available on the website of the Chilean water regulator (Superintendencia de Servicios Sanitarios (SISS))⁵⁴.

The selection of the variables to assess productivity change and eco-productivity change was based on past studies and literature reviews on this topic (see for instance refs. 1,13,15, and data availability for Chile. Two inputs were considered. The first one was the annual operating expenditure (costs) of the water companies to provide drinking water. It is expressed in thousands of CLP per year. As the water and sanitation industry is capital intensive, capital is an important component of the industry's inputs⁵⁵. Hence, the second input was the water network length measured in kilometers. It was selected as a proxy to capital expenditure because the water industry tends to have non-regular investments over time. This means investment fluctuates widely from year to year depending on the occurrence of major projects⁵⁵.

The (desirable) output was defined as the annual volume of drinking water delivered measured in thousands of cubic meters per year. Following past practice (e.g., 36,56) the volume of water delivered was multiplied by the drinking water quality index reported by the SISS to reflect quality improvements. This indicator takes a value between zero and one with one meaning that the companies met all drinking water quality standards. Two undesirable outputs were included in the analysis. The first was the annual volume of NRW measured in thousands of cubic meters per year and the second was the total number of UWSIs measured in hours per year.

As noted by past studies (e.g., 14,57,58) there might be several structural and operating characteristics that could impact water

Table 2. Descriptive statistics of the Chilean water companies for 2010–2018.

Variables	Unit of measurement	Average	Std. Dev.	Minimum	Maximum
Volume of water delivered	000 s m ³ /year	52,328	94,251	1064	473,846
Operating expenditure	000 s US\$/year	52,813	67,909	1267	323,299
Network length	km	3439	4968	88	21,859
Drinking water quality indicator	Index	0.974	0.052	0.700	1.000
Volumes of non-revenue water	000 s m ³ /year	17,049	29,530	104	142,922
Water supply unplanned interruptions	h/year	4345	7031	3	34,051
Customer density	nr/km	57.890	14.618	19.407	89.237

Observations: 189.
 Costs are expressed in 2018 prices.
 The conversion rate applied was 650 CLP $\cong$ 1US\$.

companies' performance and should be included in the analysis. We therefore incorporated the following variables: (i) customer density defined as the number of customers divided by water network length; (ii) main source of raw water which is a categorical variable to capture surface, groundwater and mixed water resources and (iii) ownership of the water company which is a categorical variable to capture FPCs, CCs and the public water company. Table 2 shows the descriptive statistics for the variables used in this study. The data comes from the Chilean water regulator as published on its website.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CODE AVAILABILITY

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

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AUTHOR CONTRIBUTIONS

A.M.: methodology; software; writing—original draft. M.M.-S.: conceptualization; writing—review and editing. R.S.-G.: data curation; writing—review and editing. M.M.-A.: formal analysis; writing—review and editing.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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