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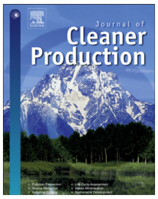

Comparing changes in productivity among private water companies integrating quality of service: A metafrontier approach

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ABSTRACT

Most previous studies evaluating the effect of ownership on the performance of water companies have ignored the fact that there are several types of private water companies. In this study, we instead recognize that private water companies can differ considerably in how they are managed, based on whether their infrastructure is privately or publicly owned. We estimated change in productivity of fully-privatized companies and concessionary companies by employing the metafrontier Malmquist Luenberger productivity (MMLP) index, which allowed us to integrate quality-of-service variables as undesirable outputs. We segregated the MMLP index to assess changes over time in relative efficiency, the use of best practice technology and the magnitude of the technological gap between technology in use and technology represented by the metafrontier. For a sample of Chilean water companies, the results indicate that during the years 2010–2016, productivity of fully-privatized water companies decreased by 7.5% which was mainly attributed to technical gap regression. By contrast, the productivity of concessionary water companies improved by 0.51% being the best-practice change the main driver of productivity. The methods we used and the conclusions of this study should be useful to water regulators because we show the relevance of both integrating quality-of-service attributes and classifying types of water companies before assessing changes in productivity over time.

1. Introduction

1.1. Problem statement

The United Nations (UN) recognizes that clean drinking water and sanitation are essential to basic human rights (UN, 2010). This recognition was emphasized in the UN's Sustainable Development Goals, which identifies "access to water and sanitation for all" as Goal 6. In spite of this goal, 663 million people (9% of the global population) are still without adequate access to clean drinking water (UN, 2018).

Over the years, public utilities have been the most common provider of clean water resources to the public (Thomas et al., 2012). However, after the paradigmatic privatization of the English and Welsh water industries in 1989, several countries have privatized some or all of their water companies. This private approach for supplying water has been promoted recently by several international institutions as well, including the World Bank, the International Monetary Fund, and the European Commission as part of conditions for obtaining financial support (Molinos-Senante and Sala-Garrido, 2016). Even though a number of municipalities have re-municipalised urban water services in recent years, private sector participation in the water industry is still widespread (McDonald, 2018). In fact, about 14% of the world's population received water services from private corporations in 2012 (Owen, 2012).

Several factors have contributed to the effort to privatise water utilities. Among these factors, the interest to improve efficiency and reduce costs are the most relevant (Guerrini et al., 2011). An extensive literature review by Suarez-Varela et al. (2017) showed that in spite data from numerous studies comparing the performance of water utilities relative to type of ownership (public vs. private), they could not conclude that either ownership type was superior to the other.

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Previous research on public-vs.-private water companies performance can be grouped into two categories, based on the time period over which the studies were conducted. Some research compared the efficiency of public and private water companies at a given moment in time (Correira and Marques, 2011; Lannier and Porcher, 2014; Suarez-Varela et al., 2017), whereas other studies compared the changes in productivity over time for water utilities, both private and public (Saal et al., 2007; Marques, 2008; Portela et al., 2011). In the framework of utilities benchmarking, productivity and efficiency are different concepts. Productivity refers to the change of performance over time. That is, unlike efficiency, productivity integrates a temporal component into performance assessment (O'Donnell et al., 2017).

Research devoted to evaluating the effect of ownership on the productivity of water companies has overwhelmingly tended to assume that there is one single type of private water company. However, Memon and Butter (2003) defined seven types of privately-owned water companies, which Molinos-Senante and Sala-Garrido (2016) later categorized into two main types: (1) full (entirely) private water companies (FPWC), owned and operated by private investors (including shareholders) and (2) concessionary water companies (CWC), those which own the right to supply water supply services for a certain time period via a concessionary contract (Petrova, 2006). To our knowledge, there are only two studies that compare changes in productivity through time for FPWCs and CWCs (Molinos-Senante and Sala-Garrido, 2015; Molinos-Senante et al., 2018).

1.2. Background

Without aiming to be exhaustive, most of the previous studies evaluating the productivity change of water companies employing non-parametric methods have computed the Malmquist productivity index and the Luenberger productivity indicator (see Table S1 in supplemental material for a literature review). In spite of the positive features of both approaches, these indicators are based on input and output variables, i.e., they do not allow integrate quality of service variables as undesirable outputs. Moreover, they assume that all water companies involved in the assessment share the same functional form which invalidates the direct comparison between FPWCs and CWCs. Focusing on the previous studies assessing and comparing the productivity change of FPWCs and CWCs, Molinos-Senante and Sala-Garrido (2015) evaluated the growth in productivity (1997–2013) for a sample of Chilean water companies (including both FPWCs and CWCs). They used the data envelopment analysis (DEA) method to compute Luenberger productivity indicators. Although these authors pioneered the method for estimating change in productivity over time for FPWCs and CWCs, their paper had two limitations. First, the authors assumed that both FPWCs and CWCs shared the same production technology even though previous studies had demonstrated the need for employing the metafrontier approach when comparing or assessing the performance (efficiency or productivity) of water companies contending with different technological restrictions (De Witte and Marques, 2009, 2010; Molinos-Senante et al., 2015; Suarez-Varela et al., 2017). [However, in a later paper, the authors did apply a DEA metafrontier model when they compared the efficiency (not change in productivity over time) of FPWCs and CWCs (Molinos-Senante and Sala-Garrido, 2016)]. The second limitation of the Molinos-Senante and Sala-Garrido (2015) study was that they did not integrate any quality-of-service variables in their evaluation of changes in productivity over time. Ignoring service quality in comparing performance usually penalizes companies that produce a higher quality output (service) because they also usually face higher production costs, which therefore reduces their efficiencies (Carvalho and Marques, 2011).

The Molinos-Senante et al. (2018) study employed a different methodological approach than did the Molinos-Senante and Sala-Garrido (2015) study in comparing changes in productivity for a sample of FPWCs and CWCs. The latter study computed a generalised parametric production index, which was based on an input distance function (translog function) integrates service quality and environmental variables into productivity assessment. However, non-parametric methods (such as DEA) provide important advantages over parametric approaches in productivity evaluations because they allow the technological frontier (representing the best-observed practices) to be flexibly constructed without imposing a given functional form or a specific technology on reference conditions (Suárez-Varela et al., 2017).

Oh (2010) proposed the metafrontier Malmquist Luenberger productivity (MMLP) index, which is a combination of the Malmquist-Luenberger productivity index and the metafrontier concept. It was used by Chung et al. (1997) to assess productivity growth of decision-making units by considering inputs as well as desirable and undesirable outputs [i.e., it explicitly integrates deficiencies in quality-of-service as undesirable outputs in the productivity assessment (Ananda, 2018)]. The metafrontier concept was first conceived by Hayami and Ruttan (1970) and further elaborated upon by Battese and Rao (2002) to incorporate commonly perceived production frontiers, and by doing so, solve problems associated with comparing the performances of various groups with different production technologies (e.g., FPWCs and CWCs in this case study) (Battese et al., 2004).

By following a non-parametric approach that does not impose any assumption on the functional form of the production frontier, the MMLP index incorporates *ex-ante* group heterogeneities (FPWCs and CWCs) and quality-of-service variables as undesirable outputs in productivity change estimates (Li et al., 2018). According to Oh (2010), a MMLP index can be segregated into three components that typically drive changes in productivity: (1) efficiency change (EC), (2) technical change or best-practice change (BPC) and (3) technological gap change (TGC). In spite of the merits of using MMLP index to evaluate and compare changes in productivity among decision-making units employing different production technologies, empirical applications employing the MMLP index approach have been very limited and have focused on growth of carbon-sensitive productivity (Chung and Heshmati, 2015; Choi et al., 2015; Yu et al., 2017; Li et al., 2018) and microfinance institutions (Wijesiri, 2016).

1.3. Objectives

The aim of our study was to assess and compare changes in productivity for a sample of CWCs and FPWCs by incorporating group heterogeneities and quality-of-service variables into the assessment framework. In doing so, we applied the MMLP index which allowed us to segregate productivity estimates into EC, BPC and TGC components of change. This is a novel approach since, to the best of the authors' knowledge, no studies have previously compared the performance of CWCs and FPWCs based on the MMLP index. We used this empirical approach to compare 22 Chilean water companies, which together provided water and sewerage services to more than 95% of the urban population of Chile over the period 2010–2016. It should be noted that Chile provides an example of water industry privatization that has achieved near universal access to drinking water in urban areas. Because Latin America could be described as being situated at a medium level in terms of coverage and quality of drinking water services, water managers and authorities in other Latin American countries can learn some lessons from the Chilean case. Beyond the specific results for the empirical application conducted in this study, the information we provide here is relevant for policy makers and water regulators who want to adopt specific (and perhaps new policies) to improve the productivity for either FPWCs or CWCs.

2. Methods

2.1. Fundamental modelling assumptions

This section reports the fundamental assumptions required for defining the MMLP index proposed by Oh (2010). Assuming that there are $k = 1, \ldots, K$ water companies during $t = 1, \ldots, T$ time periods, the production technology for water companies producing M desirable outputs ($y \in R_+^M$) and J undesirable outputs ($b \in R_+^J$) by using N inputs, ($X \in R_+^N$) is represented by the possibility set $[P\ (x)]$ represented as:

$$P(x) = \{(x, y, b) \mid x\ \ produce\ (y, b)\} \tag{1}$$

In addition to the assumption that the production possibility set be closed and bounded and that outputs must be freely disposable, the following three axioms are required:

$$If\ (x, y, b) \in P(x)\ and\ 0 \le \theta \le 1,\ then\ (x, \theta y, \theta b)\ \in P(x). \tag{2}$$

$$If\ (x, y, b) \in P(x)\ and\ y' \le y\ then\ \left(x, y', b\right) \in P(x). \tag{3}$$

$$If\ (x, y, b) \in P(x)\ and\ b = 0,\ then\ y = 0. \tag{4}$$

The first axiom in Eq. (2) necessitates that the undesirable outputs be weakly disposable, which means that any reduction in undesirable outputs must be accompanied by the simultaneous reduction of desirable outputs. In the context of the water industry, this means that any improvements in quality-of-service uses resources that otherwise could be used to increase the production of desirable outputs. Eq. (3) expresses the strong disposability axiom, which permits desirable outputs to be reduced without any reduction in undesirable outputs (i.e., without improving the quality-of-service provided by water companies). The fourth axiom [Eq. (4)] is known as the null-jointness axiom, which requires that no desirable output can be produced unless some undesirable outputs are also produced. For example, the percentage of non-revenue water cannot be 0% because all water meters are somewhat inaccurate.

A production possibility set is conceptually well defined, but it presents difficulties when it is applied empirically. Therefore, a directional distance function is commonly used (Choi et al., 2015), which is a generalisation of the Shephard distance function. The directional distance function allows the desirable and undesirable outputs to be treated non-proportionally in a given direction (Chung et al., 1997). In addition, the directional distance function seeks to maximize desirable output production while simultaneously reducing undesirable outputs. The directional distance function is herein defined as:

$$\overrightarrow{D}\left(x, y, b, \overrightarrow{g_y}, \overrightarrow{g_b}\right) = \max\left\{\beta\ :\ \left(x, y + \beta\overrightarrow{g_y},\ b - \beta\,\overrightarrow{g_b}\right) \in P(x)\right\} \tag{5}$$

where $\overrightarrow{g} = (\overrightarrow{g_y}, \overrightarrow{g_b})$ is the vector describing the directions in which both desirable and undesirable outputs should be scaled. According to Chung et al. (1997), the direction vector selected is $\overrightarrow{g} = (y, b)$, which requires that desirable outputs increase and undesirable outputs decrease. To simplify the notation used, hereafter we define $\overrightarrow{D}(x, y, b, \overrightarrow{g_y}, \overrightarrow{g_b})$ as $\overrightarrow{D}(x, y, b)$.

2.2. The metafrontier Malmquist-Luenberger productivity index

Prior to defining and segregating terms used in the MMLP index, three benchmark technology sets must be defined: (1) contemporaneous benchmark technology, (2) intertemporal benchmark technology and (3) global benchmark technology. According to Tulkens and Vanden Eeckaut (1995), these terms are defined as follows:

Contemporaneous benchmark technology defines the production possibility set for technology type R_h for a specified time period t:

$$P_{R_h}^t = \left\{\left(x^t, y^t, b^t\right) \mid x^t\ can\ produce\ \left(y^t, b^t\right)\right\} \qquad t = 1,\ \ldots,\ T \tag{6}$$

Intertemporal benchmark technology is defined as a single production possibility set obtained from observations for a given plant type R_h throughout the time period being considered:

$$P_{R_h}^I = P_{R_h}^1 \cup P_{R_h}^2 \cup \ldots \cup P_{R_h}^T \tag{7}$$

There are H different intertemporal benchmark technologies. A water company using a given intertemporal benchmark technology is assumed to be unable to easily access other types of intertemporal benchmark technologies.

The *global* benchmark technology establishes a single production possibility set based on observations made throughout the entire time period for all technology types being compared. (In this way it differs from contemporaneous and intertemporal benchmark technology sets). For all types involved in an assessment, the global benchmark technology is defined as:

$$P^G = P_{R_1}^I \cup P_{R_2}^I \cup \ldots . \cup P_{R_H}^I \tag{8}$$

The intertemporal benchmark technology of a specific group ($P_{G_k}^I$) envelops its contemporaneous benchmark technologies ($P_{G_k}^{c^t}$ and $P_{G_k}^{c^{t+1}}$), whereas the global benchmark technology (P^G) envelops all intertemporal technologies (Fig. 1).

The above definitions of benchmark technology sets allowed Oh (2010) to define the MMLP index (*MMLPI*) as an advance form of the Malmquist Luenberger productivity index, as follows:

$$MMLPI\left(x^t, y^t, b^t, x^{t+1}, y^{t+1}, b^{t+1}\right) = \frac{1 + \overrightarrow{D}^G\left(x^t, y^t, b^t\right)}{1 + \overrightarrow{D}^G\left(x^{t+1}, y^{t+1}, b^{t+1}\right)}. \tag{9}$$

where $\overrightarrow{D}^G = (x, y, b)$ is the global directional distance function defined for the global technology set as:

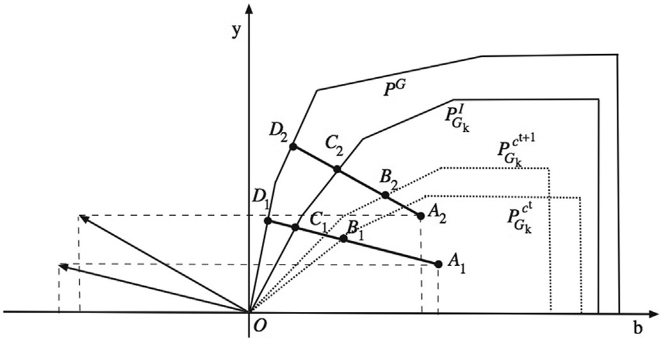

Fig. 1. Benchmark technology sets for defining the metafrontier Malmquist-Luenberger productivity index. Source: Adapted from Li et al. (2018).

$$\overrightarrow{D}^{G}(x,y,b) = \max\left\{\beta \,\middle|\, (x, y+\beta y,\ b-\beta b) \in P^{G}\right\} \qquad s = t,\ t+1 \tag{10}$$

Thus, according to Oh (2010), the MMLP index can be segregated into three components or drivers of productivity change: (1) EC, (2) BPC and (3) TGC. The mathematical deconstruction of the MMLP index is as follows:

$$\begin{aligned} MMLPI\left(x^{t},y^{t},b^{t},x^{t+1},y^{t+1},b^{t+1}\right) &= \frac{1+\overrightarrow{D}^{G}\left(x^{t},y^{t},b^{t}\right)}{1+\overrightarrow{D}^{G}\left(x^{t+1},y^{t+1},b^{t+1}\right)} = \frac{1+\overrightarrow{D}^{t}\left(x^{t},y^{t},b^{t}\right)}{1+\overrightarrow{D}^{t+1}\left(x^{t+1},y^{t+1},b^{t+1}\right)} * \frac{\frac{1+\overrightarrow{D}^{I}(x^{t},y^{t},b^{t})}{1+\overrightarrow{D}^{t}(x^{t},y^{t},b^{t})}}{\frac{1+\overrightarrow{D}^{I}(x^{t+1},y^{t+1},b^{t+1})}{1+\overrightarrow{D}^{t+1}(x^{t+1},y^{t+1},b^{t+1})}} * \frac{\frac{1+\overrightarrow{D}^{G}(x^{t},y^{t},b^{t})}{1+\overrightarrow{D}^{I}(x^{t},y^{t},b^{t})}}{\frac{1+\overrightarrow{D}^{G}(x^{t+1},y^{t+1},b^{t+1})}{1+\overrightarrow{D}^{I}(x^{t+1},y^{t+1},b^{t+1})}} \\ &= \frac{TE^{t+1}}{TE^{t}} * \frac{BPR^{t+1}}{BPR^{t}} * \frac{TGR^{t+1}}{TGR^{t}} = EC*BPC*TGC \end{aligned} \tag{11}$$

EC informs how much a technology gap has to be closed relative to the *contemporaneous* benchmark technology at time $t+1$ relative to the previous period t (Chung and Heshmati, 2015). Hence, EC is a measure of the catch-up effect relative to technical efficiency. An EC >1 implies that efficiency is improving over time, whereas (ES <1) implies that efficiency is deteriorating over time. BPC measures the change in the best practice gap ratio between the *contemporaneous* benchmark technology and *intertemporal* benchmark technology during two time periods. A BPC >1 implies that the *contemporaneous* benchmark technology frontier has shifted towards the *intertemporal* benchmark technology frontier, whereas BPC <1 implies the technology has shifted further away from the frontier. TGC represents the "technology catching-up effect" among units (e.g., water companies in this case study). TGC is related to changes in an *intertemporal* benchmark technology frontier and a *global* benchmark technology frontier during two time periods. A TGC >1 implies that the technological gap between a specific type of technology and the global frontier technology has declined over time, whereas a TGC <1 implies that the gap has widened over time. Hence, TGC provides information about how well a given type of technology is at improving performance. A MMLP index >1 implies that productivity has improved over time, whereas MMLP index <1 implies that productivity has declined over time.

2.3. Calculating the directional distance function

As illustrated in Eq. (9), a directional distance function must be estimated to calculate an MMLP index. Specifically, to segregate the MMLP index into its EC, BPC and TGC components, six directional distance functions should be estimated: $\overrightarrow{D}^{G}(x^{s},y^{s},b^{s})$, $\overrightarrow{D}^{I}(x^{s},y^{s},b^{s})$, $\overrightarrow{D}^{S}(x^{s},y^{s},b^{s})$, where $s=t$ and $t+1$.

Two main approaches have been used to compute the directional distance function. Färe et al. (2007) defined the directional distance function as a quadratic form and so used linear programming to calculate it. This approach allows one to easily calculate shadow prices. However, the approach involves assuming the mathematical form of the directional distance function (Wang et al., 2018). In contrast, other studies employed the DEA approach (Färe et al., 2007; Suarez-Varela et al., 2017; Du et al., 2018), which is also calculated using linear programming. However, although DEA does not allow one to compute shadow prices, it does not require one to define a specific mathematical form to the directional distance function. DEA was highly advantageous in our study because there is no a standard mathematical form applicable to the production function for water companies. Therefore, in our study, the directional distance functions were calculated by solving the following linear programming model:

$$\overrightarrow{D}^{d}\left(x^{k\acute{,}s},y^{k\acute{s}},b^{k\acute{s}}\right) = \max\beta$$

subject to

$$\begin{aligned} &\sum_{con}\lambda^{k,s}y_{m}^{k,s} \geq (1+\beta)y_{m}^{k\acute{s}} && m=1,\ldots,M \\ &\sum_{con}\lambda^{k,s}b_{j}^{k,s} = (1-\beta)b_{j}^{k\acute{s}} && j=1,\ldots,J \\ &\sum_{con}\lambda^{k,s}x_{n}^{k,s} \leq x_{n}^{k\acute{s}} && n=1,\ldots,N \\ &\lambda^{k} \geq 0 \end{aligned} \tag{12}$$

where the superscript d in the objective function represents various types of directional distance functions (i.e., *contemporaneous, intertemporal,* and *global* functions), $\lambda^{k,s}$ is an intensity variable used to construct the production possibility set through a convex combination of observations and the *con* under the $\sum$ represents the conditions for constructing a production possibility set. Therefore, $d \equiv s$ and $con \equiv \{k \in R_{h}\}$ are conditions for the *contemporaneous* directional distance function, $d \equiv I$ and $con \equiv \{k \in R,\ s \in \tau\}$ are conditions for the *intertemporal* directional distance function, where $\tau = \{1,2,\ldots,T\}$ and $d \equiv G$ and $con \equiv \{k \in R,\ s \in \tau\}$ are conditions for the *global* directional distance function, where $\tau = \{1,2,\ldots,T\}$ and $R = R_{1} \cup R_{2} \cup \ldots \cup R_{H}$.

3. Empirical study

The empirical application conducted in this study focused on comparing the change in productivity (and its components) for a sample of Chilean FPWCs and CWCs through time (several years). The variation in technologies used by among both groups of water companies is described in Section 3.1, whereas Section 3.2 provides the variables and data used to compute the MMLP index.

3.1. Heterogeneity among water companies

Before calculating the MMLP index, the first step was to characterise the types of water companies we evaluated (i.e., FPWCs and CWCs). These two types of water companies were formed in

Chile when the urban water industry was privatized[1] from 1998 to 2004 (SISS, 2016). Before 1998, most Chilean water companies were public utilities. At that time, the urban water industry was facing two major challenges. First, most public water companies were not cost efficient and fees paid by citizens were insufficient for the utilities to cover the costs of water supply services. Second, in 1998, the wastewater treatment services covered <20% of the Chilean citizens (SISS, 2016) and so major investments were required to build new wastewater treatment plants (Frade and Sohail, 2003).

In response to these challenges, Law 19549 was enacted to privatise Chilean water companies (Molinos-Senante and Sala-Garrido, 2015). Privatization followed two different approaches. From 1998 to 2000, public water companies sold participations to private consortia with managerial and operational experience in the water industry, thus forming FPWCs (SISS, 2015). In contrast, from 2001 to 2004, the Chilean Government stopped selling shares to purchase water utility assets and instead began to transfer rights for the operation of the water companies to the private sector for a fixed term (30 years), but kept the utilities infrastructure in public ownership. This meant that assets were leased to CWCs. Currently, about 95% of urban customers in Chile are served by private water companies (SISS, 2016). FPWCs and CWCs provide both water and sewerage services to about 70% and 25% of customers, respectively.

3.2. Sample and data description

To explore how the ownership influences changes in productivity (and its components) of water companies, 22 Chilean water companies were samples from 2010 to 2016, including 12 FPWCs and 10 CWCs. The 22 water companies we analysed provided water and sewerage services in 2016 to 5,016,106 customers which represents the 96% of the total urban customers in Chile. Therefore, the empirical application conducted in this study covers almost all of the Chilean water industry. The source of our data was the “Management Reports for Water and Sewerage Companies in Chile”, published yearly by the Chilean national water regulator on its webpage for the years 2010–2016.

Both Chilean FPWCs and CWCs are considered to be multi-output producers because they provide drinking water, and collect and treat wastewater. Saal et al. (2007) and Molinos-Senante et al. (2015) determined that water companies' productivity assessment should include output parameters related to water quality. The first parameter is the volume of drinking water distributed, adjusted by its quality (y_1) (Eq. (13)), whereas the second parameter is the number of customers with access to wastewater treatment services, adjusted by the quality of the treated wastewater (y_2) (Eq. (14)).

$$y_1 = VDW * QDW. \tag{13}$$

$$y_2 = CWWT * QWWT. \tag{14}$$

where y_1 is the quality-adjusted drinking water output, y_2 is the quality-adjusted treated wastewater output, *VDW* is the volume of drinking water delivered (thousands of cubic meters), *CWWT* is the number of customers with access to wastewater treatment services, *QDW* is a quality indicator for drinking water supplied and *QWWT* is a quality indicator for treated wastewater.

QDW and *QWWT* provide data on utility compliance to water and wastewater quality standards and are provided annually by the national water board for each water company. Standards are indexed between 0.0 and 1.0, with a value of 1.0 meaning that the water company has fulfilled all legal requirements regarding safe drinking water (*QDW*) and wastewater (*QWWT*) quality. In contrast, a value lower than 1.0 for water quality indicators means that a water company's performance (desirable outputs) is less than optimal.

Several variables, such as continuity of service, water loss, non-revenue water, customer complaints, etc., have been employed as undesirable outputs. This enabled our analysis to integrate quality-of-service in assessing performance (Yang et al., 2016; Yagi et al., 2015; Mbuvi et al., 2012). The undesirable outputs selected for productivity change assessment must be relevant to the water companies being evaluated and the purpose of the study. In this case study, non-revenue water (b_1) and unplanned interruptions (b_2) were selected as undesirable outputs. Non-revenue water is defined as the percentage of distributed water that is unbilled (which incorporates water leakage and monetary loss). Non-revenue water has been identified as a source of economic, environmental and social inefficiencies (Colombo and Karney, 2002). In the Chilean water industry, this variable is very relevant because on average, water companies lose about 30% of their water (SISS, 2016), a value that has remained unchanged over time. This means that almost one third of the volume of treated drinking water it is not billed. Unplanned interruptions were expressed as hours in which drinking water and wastewater collection services suffered unplanned interruptions in service, which were due mainly to breaks in water mains and obstructions in sewer lines. Several factors are associated with these interruptions, including infrastructure age (disrepair), lack of an adequate management, and the occurrence of destructive natural events (e.g., earthquake, tsunamis, floods, etc.). According to the World Risk Report (2016) developed by the United Nations University, Chile presents a very high risk for being impacted by natural disasters.

Based on previous studies (Molinos-Senante and Sala-Garrido, 2015; Molinos-Senante et al., 2018) we selected two inputs to compute the MMLP index and its drivers: (1) operating costs (x_1) and (2) number of employees (x_2). Operating costs are expressed in Chilean pesos and are defined as the water and sewerage company's total operating expenditures, adjusted by the consumer price index taken from national statistics. The number of employees includes direct workers and external employees who develop tasks for water companies, but are not employed by them.

Table 1 shows descriptive statistics for the desirable outputs, undesirable outputs and inputs used in this study for FPWCs and CWCs for the 2010–2016 time period.

4. Results

4.1. Estimates for changes in productivity

MMLP index was estimated for each water company we analysed over a 7-year period to evaluate and compare changes in productivity for FPWC and CWC types of water companies. Average values for change in productivity over time for both types are depicted in Fig. 2. We also provide metafrontier Malmquist productivity (MMP) index values (*sensu* Oh and Lee, 2010), which differs from the MMLP index in that it does not integrate undesirable outputs in the assessment of productivity change. Regardless of which method we employed, productivity declined in FPWCs over the study period (2010–2016): -7.5% for MMLP index and −15.4% for MMP index (i.e. excluding undesirable outputs). However, average productivity for the FPWCs remained almost constant from 2010 to 2015, but then declined precipitously (−6%) from 2015 to 2016. In 2015, several extreme hydro-meteorological events that involved unplanned water supply interruptions and

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[1] In Chile, regulations and institutional frameworks differ for rural and urban water utilities (Donoso, 2018).

Table 1
Sample description.

		Inputs				Desirable Outputs				Undesirable Outputs			
		Operating costs (10^3CLP/year)		Number of employees		Drinking water distributed (10^3 m^3/year)		People with wastewater treatment		Non-revenue water (10^3 m^3/year)		Unplanned interruptions (hours/year)	
		FPWCs	CWCs	FPWCs	CWCs	FPWCs	CWCs	FPWCs	CWCs	FPWCs	CWCs	FPWCs	CWCs
2010	Average	24,617,865	12,989,383	681	389	62,953	19,240	813,328	312,802	20,932	7266	17,769	12,225
	SD	37,245,747	9,875,874	972	264	117,781	14,439	1,425,069	259,300	38,583	6224	34,900	15,023
	Minimum	602,704	978,501	29	42	895	698	11,947	5279	157	108	50	41
	Maximum	121,778,542	28,729,610	2879	732	412,867	35,518	4,823,716	666,301	130,872	16,178	121,347	37,440
2011	Average	26,734,502	14,150,935	666	393	63,690	19,674	785,802	309,778	21,135	7323	115,676	40,770
	SD	40,045,790	10,898,600	967	263	117,122	14,992	1,393,294	256,571	39,206	6354	237,381	52,363
	Minimum	733,181	1,017,294	29	38	1058	670	12,272	5527	192	7	48	28
	Maximum	128,845,143	32,237,440	2904	743	409,490	36,974	4,668,744	666,235	134,259	16,298	760,630	147,761
2012	Average	28,260,695	16,025,380	679	403	64,591	20,819	873,127	319,128	21,031	7360	72,608	12,971
	SD	42,102,283	12,027,755	991	270	118,433	15,797	1,614,385	245,689	37,476	6355	163,241	13,310
	Minimum	804,762	1,046,695	30	38	1150	691	12,508	5800	239	29	11	40
	Maximum	133,478,794	34,239,605	3002	766	413,937	38,526	5,529,565	633,038	127,576	16,908	568,587	41,066
2013	Average	31,322,439	17,344,081	700	425	67,497	21,812	900,659	342,944	21,658	7487	71,098	15,095
	SD	47,394,393	13,317,899	1014	289	124,381	16,466	1,660,146	264,103	38,823	6429	163,747	14,640
	Minimum	1,179,449	1,092,372	29	38	1187	707	11,770	5995	247	7	38	48
	Maximum	152,403,169	40,010,917	3014	815	435,384	39,446	5,661,187	651,058	132,819	16,899	573,322	40,774
2014	Average	34,963,729	20,058,078	713	448	68,356	22,090	942,295	350,029	22,143	7567	81,388	14,193
	SD	52,339,918	15,542,305	1030	307	124,991	16,827	1,745,178	271,201	39,449	6541	197,641	17,038
	Minimum	1,114,457	1,027,510	32	43	1472	655	12,070	5991	261	35	37	48
	Maximum	162,769,722	43,571,594	3032	844	437,365	40,681	5,979,754	668,125	135,112	17,010	690,312	45,226
2015	Average	37,732,998	22,645,793	735	466	69,485	22,528	974,320	355,331	22,862	7741	93,282	10,672
	SD	56,842,878	17,470,928	1032	324	126,488	17,312	1,817,698	276,525	41,721	6783	213,138	9580
	Minimum	1,174,862	1,061,523	40	41	1679	621	10,766	6516	218	67	7	47
	Maximum	183,757,940	53,374,551	3026	919	442,482	41,957	6,231,314	676,810	144,016	17,502	741,732	26,384
2016	Average	39,675,743	23,794,786	772	493	70,685	23,429	970,102	359,204	22,189	7666	87,982	18,365
	SD	58,795,208	18,800,187	1059	345	129,201	18,004	1,826,718	278,774	39,615	6717	209,045	33,901
	Minimum	1,241,917	1,155,063	42	47	1899	593	11,200	6752	591	92	56	48
	Maximum	188,983,189	58,655,056	2997	911	452,664	42,395	6,247,623	694,879	135,827	17,374	722,402	110,625

Source: own elaboration from SISS (2010–2016) data

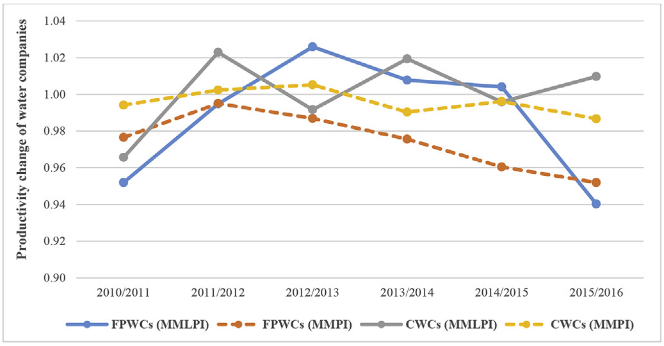

Fig. 2. Productivity change of full private water companies (FPWCs) and concessionary water companies (CWCs) considering (MMLPI) and excluding (MMPI) undesirable outputs.

obstructions in the sewerage network occurred in Chile, resulting in cost increases for water supply operations and wastewater treatment. Over the same study period, CWCs exhibited an accumulative MMLP index of 0.51%, whereas the MMP index declined (−4.78%). These results suggest that both FPWCs and CWCs have made significant progress in improving the quality-of-service provided to its customers since productivity change estimations indicate better performance when they are computed based on the MMLP index, which integrates quality of service variables, than on the MMP index.

Regression data for the MMLP index showed an average decline of 7.5% for FPWCs, which means that there was an annual decline of 1.3% for the productivity index. This decline means that if annual costs were constant over the study period, the quality-adjusted outputs must have declined by 1.3% while non-revenue water and unplanned interruptions simultaneously increased by 1.3%. In contrast, improvements in productivity for CWCs by 0.51% incorporated an improvement in quality-adjusted outputs and a reduction in undesirable outputs by 0.085% annually, thus keeping inputs almost constant. Actually, cumulative values for productivity changed from 2010 to 2016, suggesting that CWCs improved more in performance than FPWCs did across years.

We applied a non-parametric Mann-Whitney test to further analyse performance differences among FPWCs and CWCs. The null hypothesis is that MMLP index values do not statistically differ between FPWCs and CWCs. The result of this test ($p = 0.857$) means that changes in average productivity among FPWCs and CWCs do not differ. In other words, the performance of the Chilean CWCs between 2010 and 2016 was no better than the performance exhibited by FPWCs.

The present change in productivity estimates based on the MMLP index scores are somewhat consistent with the values reported by Molinos-Senante and Sala-Garrido (2015) and Molinos-Senante et al. (2018); both studies reported substantial reductions in productivity for FPWCs between 2007 and 2015: (−7.93%) and CWCs (−13.89%). Differences in productivity change estimates for CWCs demonstrate the importance of integrating quality-of-service variables as undesirable outputs in productivity assessments. As in our case study, Molinos-Senante et al. (2018) reported that the change in average productivity indices between FPWCs and CWCs did not differ statistically, thus concluding that FPWCs do not provide any better performance than CWCs over time.

Table 2 shows individual MMLP index values for each water company we analysed. This figure shows that productivity in

Table 2
Productivity change of full private (FPWCs) and concessionary water companies (CWCs) based on the metafrontier Malmquist Luenberger productivity index.

		Metafrontier Malmquist Luenberger Productivity Index						
		2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	Accumulative 2010/2016 (%)
FPWCs	WC1	1.00	1.00	1.00	1.00	1.00	1.00	0.00
	WC2	1.00	1.00	1.00	1.00	1.00	1.00	0.00
	WC3	1.00	1.00	1.00	1.00	1.00	1.00	0.00
	WC4	1.00	1.01	0.99	1.07	1.07	1.00	14.61
	WC5	1.00	0.92	1.05	0.83	0.80	1.00	−40.58
	WC6	1.00	0.97	0.99	1.00	1.00	1.00	−3.97
	WC7	1.00	1.00	1.00	1.11	1.10	1.15	34.67
	WC8	1.00	1.12	0.98	0.98	0.98	1.00	5.94
	WC9	1.00	0.91	1.04	1.00	1.00	1.00	−4.69
	WC10	0.82	1.01	1.02	1.01	0.99	1.00	−14.96
	WC11	0.73	0.93	1.17	1.05	1.06	0.54	−52.02
	WC12	0.88	1.06	1.08	1.04	1.06	0.60	−29.24
CWCs	WC13	0.72	0.94	0.95	1.03	1.01	0.98	−36.94
	WC14	1.06	1.02	1.03	1.04	0.99	0.84	−3.36
	WC15	1.01	1.12	0.98	1.00	1.00	0.99	9.96
	WC16	0.95	0.94	1.01	0.99	1.00	1.00	−11.41
	WC17	1.05	1.10	0.91	1.01	1.02	1.06	15.89
	WC18	0.98	1.06	1.00	0.98	0.97	1.00	−2.19
	WC19	1.03	0.99	1.01	1.00	0.98	0.99	1.46
	WC20	0.95	1.03	1.05	1.06	0.91	1.22	23.87
	WC21	0.88	1.00	1.00	1.04	1.07	1.03	2.47
	WC22	1.04	1.01	0.98	1.03	1.00	0.99	5.37

FPWCs varied much more over time than it did for CWCs. Estimates of cumulative productivity change from 2010 to 2016 ranged between −52.0% and 34.7% for FPWCs and from −36.9% to 23.9% for CWCs. FPWCs numbered as 1, 2 and 3 maintained their productivities over time, which means that their balances between operational costs (inputs) and the generation of both desirable and undesirable outputs did not change over time.

The most dramatic reduction in productivity occurred in FPWC 11, with 2015–2016 being its worst year (productivity declined by 46% that year). Its increase in the operational costs is what most drove its loss in productivity. From 2015 to 2016, operational costs of FPWC 11 increased by 7% and the number of employees by increased 25%. Productivity declined because neither of these increased costs (inputs) was offset by an increased generation of desirable outputs or improvements in quality-of-service (a reduction in undesirable outputs). In contrast, FPWC 7 improved its cumulative productivity by 34.7% over the period of study. This improvement occurred in the last several years we evaluated it (i.e., from 2013 to 2016). We attribute the improvement to a reduction in the hours of unplanned interruptions (which decreased by 41% between 2015 and 2016), an increase in quality-adjusted outputs (which increased by 8.4%) and drinking water and wastewater treatment services (which increased by 4.1%).

The worst case of performance over time occurred at CWC 13, whose productivity declined for four of the six years over which we evaluated performance. The 2010–2011 year showed the largest reduction in productivity (28%). In this water company, all variables, except the volume of non-revenue water, contributed to the reduction of productivity. For example, the number of unplanned interruptions doubled and the number of employees increased by 19%. In contrast, CWC 20 improved its productivity the most (24%), with 2015–2016 being the most productive year (22% improvement) due to a reduction in the loss of non-revenue water (17%) and an improvement in quality-adjusted output of wastewater treatment (4%).

In examining the changes over time of all MMLP index values, there was no common temporal trend among water companies (Table 2). That is, the variations from year-to-year were unpredictable. Moreover, with the exception of water companies 1, 2 and 3, whose productivity remained consistent over time, and water company 7, whose productivity continually improved over time, productivity for the remaining 18 water companies fluctuated unpredictably between periods of declines and increases in productivity. This suggests that the policies and regulations adopted by the water regulator and implemented by water companies to improve the productivity have had a limited effect on productivity for either type of privately-operated water companies (FPWs and CWC). Moreover, neither type of Chilean water companies was similar in the manner in which its productivities fluctuated over time.

4.2. *Components of productivity change*

In order to gain a better understanding of what drives changes in Chilean water companies productivity, we graphed fluctuations in average EC, BPC, and TGC values over time, by water companies type (Figs. 3 and 4). Individual values for each water company are provided as supplemental material. The average annual efficiency change (EC) was −0.04% for FPWCs and −1.03% for CWCs. These results indicate that efficiency declined over time for both types of water companies. EC represents a catching-up index and so a value of −0.04% means that the technology gap widened by 0.04% per year. A deterioration in EC is due to either (1) the catching-up rate

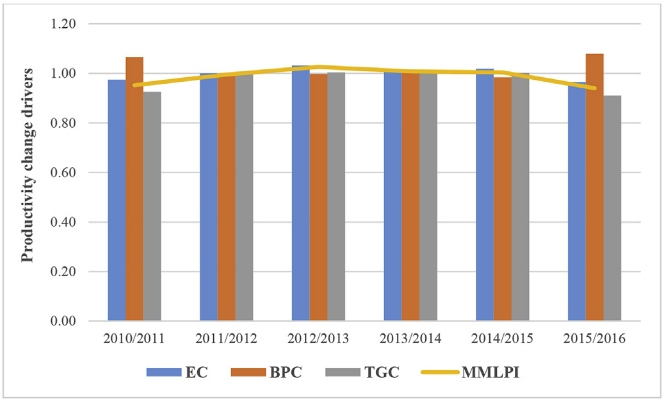

Fig. 3. Annual average productivity change drivers for FPWCs.

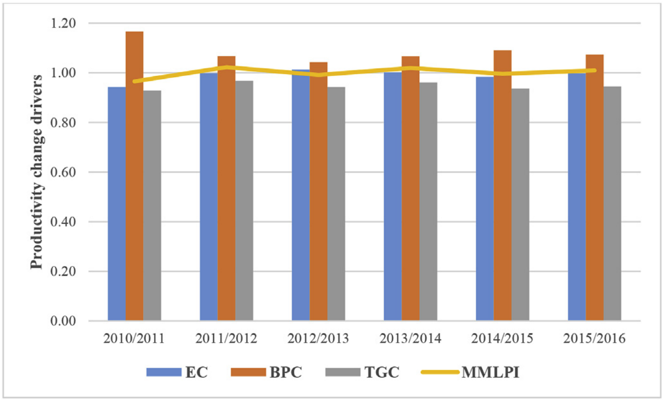

Fig. 4. Annual average productivity change drivers for CWCs.

of a water company is slower than the rate that the frontier technology improves or (2) rate at which the a plant's technology deteriorates is more rapid than the rate at which the frontier technology deteriorates (Oh, 2010). The change in EC over time was positive from 2011 to 2015, which means that the *average* performance of FPWCs moved closer to the contemporaneous production frontier over that period and so EC contributed positively to the growth in productivity (Fig. 3). In contrast, EC was positive for CWC plants only from 2012 to 2014, which means that EC contributed negatively to productivity for most of the years we evaluated CWCs.

The average annual rate of technological improvements (BPC) contributed to 2.1% of growth for FPWCs and 8.5% of growth for CWCs, indicating that both types of private companies have benefited by improving their technologies. Positive values for BPC (for both FPWCs and CWCs) imply that the contemporaneous benchmark technology frontiers shifted towards the intertemporal benchmark technology frontiers. Our results suggest that concerns and policies directed at improving quality of service and reducing operational costs have stimulated water companies to improve their technologies. In fact, for CWCs the average BPC score was >1.0 for all years we analysed. Fig. 4 illustrates that technological improvement (BPC) was the main driver of productivity gains in CWCs. In contrast, technological progress and lack of progress in FPWCs were related (on average) to positive and negative shifts in the efficient frontier. BPC values indicated that CWCs advanced more in their use of technology than did FPWCs for the years we analysed. When losses in efficiency are combined with advances in technological progress, we found that, on *average*, FPWCs and CWCs have lagged relative to advances in the technology frontier. In other words, the rate at which companies incorporated technological advancement did not keep pace with the technological advance of the efficient frontier.

The annual change in the technological gap ratio (TGC) was −2.6% for FPWCs and −5.3% for CWCs, indicating that for both types of companies, the technological gap increased between the technology used by the group and the technology defining the metafrontier. This widening of the technological gap suggests the failure of both types of water companies to incorporate advanced technologies (represented by the global frontier), which has contributed to their forfeiture of productivity gains that could have been made, but were not because the advanced technologies were not embraced. A time-specific examination of the average TGC reveals differences between the two types of water companies we examined.

For CWCs, the TGC value was <1.0 for all years we evaluated, whereas TGC was >1.0 for FPWCs from 2012 to 2015. This suggests that FPWCs have embraced new technology (relative to the global norm) more than have CWCs, whose infrastructure is publicly-owned. When BPC and TGC values are examined against their peers (within the same type of company), it appears that CWCs are more successful than FPWCs in improving their performances over time. However, from a wider, more global perspective based on the technological frontier (what is possible), it appears that the perceived higher CWC gains are actually due to the fact that their baselines (starting points) of performance (including quality of service parameters) were lower for CWCs than they were for FPWCs.

The novel way we deconstructed factors that contribute to productivity allowed us to identify of the main factors responsible for changes in productivity over time for two very different types of water companies (those that own their infrastructure and those whose infrastructure is publicly owned). This insight should enable water regulators to identify specific measures and policies to improve the performance of the two types of water companies it regulates.

5. Discussion

In the case of the Chilean water industry, unlike previous studies for English and Welsh water industry (e.g. Maziotis et al., 2017), productivity change estimations are not directly linked to regulatory cycles since Chilean water companies do not update their tariffs simultaneously, i.e., the same year. Moreover, according to the World Risk Report (2016), Chile exhibits large exposure to natural hazards which impact water and sanitation infrastructure and therefore, also impacts on the productivity of water companies. Thus, results on Fig. 2 evidenced that from 2015 to 2016 Chilean water companies suffered a marked productivity regression which can be attributed to the extreme hydro-meteorological events and earthquakes occurred in Chile in 2015. Just to name a few of these extreme events, in March 2015 unusual ocean and atmospheric conditions produced many years' worth of rainfall in a ~48 h period over northern Chile's Atacama Desert, one of Earth's driest regions. The toll of the flooding included 31 deaths, as well as widespread damage to homes, roads, bridges and water and sanitation infrastructure (Wilcox et al., 2016). In September 2015, an earthquake of magnitude 8.4_{ML} affected the central area of the country causing numerous water supply interruptions and sewerage pipe obstructions. It should be noted that the MMLP index integrates unplanned interruptions and non-revenue water, which includes water losses due to pipe breaks, as variables to evaluate productivity change of water companies. This finding evidences that management practices of the water companies and regulations are not the only variables to be considered when productivity change of water companies is analysed. This issue is even more relevant in countries exposed largely to natural hazards such as Chile where for improving the productivity of water companies is essential reduce the vulnerability of the water and sanitation infrastructure.

Performance comparison between FPWCs and CWCs (see Table 2) illustrates that productivity in FPWCs varied notably more over time than it did for CWCs although both types of private water companies operate under the same regulatory framework. Results indicate that CWCs have improved the quality of service more than FPWCs, which has involved better productivity change vales. Results on Fig. 4 evidenced that BPC was the main driver of productivity gains in CWCs which involves that the shift of the efficient frontier for this type of water companies was positive. According to SISS (2012), since 2012 the coverage of wastewater treatment in urban areas of Chile was larger than 95% and therefore, water companies have focused on improving the quality of service which has involved a positive shift of the efficient frontier (BPC>0). Results shown in Table 2 also evidenced that productivity change variations for the 22 water companies evaluated did not follow a common temporal trend. This finding suggest that managerial decisions are made following a short-term criterion rather than a large one which hinders productivity improvements across years. As it was reported by Molinos-Senante and Farias (2018), there are two main figures supporting this idea. First, from 2004 to 2015, the average turnover rate of the chief executive officers of Chilean water companies was 17 months which is very low to make long-term strategic decisions. Second, the infrastructure replacement rate, which is essential for reducing unplanned interruptions and non-revenue water, is extremely low being 0.5% and 0.2% for water and sewerage networks when according to the model firm defined by the Chilean water regulator, both rates must be 2% (SISS, 2015).

6. Conclusions

To assess and compare changes in productivity of CWCs and FPWCs, the metafrontier Malmquist Luenberger productivity index (MMLP index), was employed since it provides consistent productivity measures in the presence of undesirable outputs. Moreover, this approach allowed us to segregate productivity estimates into the three main factors attributable to changes in performance over time: (1) relative efficiency, (2) use of best-practice technology and (3) the magnitude of the technological gap between technology in use and technology represented by the metafrontier.

The empirical assessments we performed illuminated three primary insights. First, CWCs in Chile performed better than FPWCs over time when productivity assessment not only considers traditional inputs and outputs but also integrates some quality of service variables, such as non-revenue water and unplanned interruptions, as undesirable outputs. Thus, during the years 2010–2016, productivity of FPWCs decreased by 7.5% which was mainly attributed to technical gap regression (−15.6%). By contrast, the productivity of concessionary water companies improved by 0.51% being the best-practice change the main driver of productivity which improved by 51% across years. Second, changes in productivity over time were extremely variable among the water companies we evaluated, which reveals that Chilean water companies are not homogeneous relative to performance, but rather differ widely even within a given type of company. Third, factors responsible for productivity drove change in the same direction over time for both CWCs and FPWCs. For example, values measuring changes in efficiency and changes in the magnitude of the technological gap were both negative, which suggested that they contributed to a relative loss in productivity over time in both FPWCs and CWCs. In contrast, changes in use of best-practice technologies were positive for both types of water companies, which implies that best-practise technologies contributed to the improvement of productivity over time.

The methods we used and conclusions of this study should be useful to water regulators. We show that it is important to integrate *ex ante* group heterogeneities in productivity change estimations to avoid biased results. In this case study, group heterogeneities refer to types of private water companies. The same classification approach could be used to reduce other sources of variation, such as among countries, services provided or demographic differences among customer populations. This study represents the first empirical application of the MMLP index to evaluate productivity change of water companies. In spite of the usefulness of the case study conducted, a limitation is the sample size, i.e. the number of water companies evaluated which restricts the number of variables (inputs, desirable outputs and undesirable outputs) to be considered in the analysis[2]. Future research will focus on repeating the productivity analysis considering additional water companies which will allow to integrate additional quality of service variables. From a methodological point of view, in this study the directional distance function was estimated using a non-parametric approach. Thus, the study could be repeated using parametric methods to estimate the directional distance function to judge the sensitivity of productivity change results to the choice of the methodological approach.

In developed countries, where drinking water and wastewater treatment services serve close to 100% of their populations, the focus of regulation is on improving the quality-of-service to end users. Therefore, it is essential to include quality-of-service variables in performance assessments, especially in developed countries. Results have revealed that in Chile, the water industry is not homogeneous relative to changes in productivity over time, but we did identify notable differences between water companies, which suggest that additional regulatory and policy efforts are needed to balance the performance over time among water companies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.12.034.

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[2] According to "Cooper's rule", the number of units (water companies) must be higher than or equal to $max\{m \bullet s; 3(m+s)\}$, where m is the number of inputs and s is the number of outputs (desirable plus undesirable) involved in the productivity assessment (Cooper et al., 2007).

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