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Estimating operational costs for enhanced continuity in water supply and sanitation services: An inverse data envelopment analysis approach in Chilean utilities

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A R T I C L E I N F O

Keywords:
Water supply and sanitation continuity
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A B S T R A C T

Study region: The largest 23 water utilities in Chile providing water and sanitation services to 97.9 % of total urban customers.
Study focus: This study introduces an innovative methodological framework based on inverse data envelopment analysis technique to quantify the additional operational costs required for water utilities to enhance their water supply and sanitation continuity while maintaining their techno-economic efficiency. This framework is pivotal for setting realistic continuity targets and assessing potential impacts on water and sanitation tariffs, thereby aiding in policy and operational planning within the water sector.
New hydrological insights for the region: The analysis was performed across four distinct continuity scenarios revealing substantial cost variability contingent on continuity targets, current service levels, and the efficiency of each utility. Results showed a median operational cost increase that varied from 28.41 % in the most stringent scenario to just 0.27 % in the most lenient. The financial implications of meeting these costs through water and sanitation tariffs would necessitate a median monthly increase in water bills, ranging from $17.24 per household in the most demanding scenarios to only $0.01 per household in the more lenient scenarios. This research provides a valuable tool for water sector regulators and managers, enabling informed decision-making by balancing service improvement objectives with economic considerations and customer willingness to pay for enhanced service continuity.

1. Introduction

The recognition of access to drinking water and sanitation as fundamental human rights by the United Nations in 2010 underscores their vital importance (UN, 2010). These rights encompass several crucial aspects: availability, accessibility, affordability, quality and safety, and acceptability (UN, 2024). In developed and middle-income nations, where the water sector is more advanced, the

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operational continuity of drinking water and sanitation services (OCWSS) becomes an additional critical component. This implies that water utilities are expected to ensure uninterrupted water and sanitation services around the clock, every day of the week. OCWSS not only serves as a crucial performance metric for water utilities (Pardal and Miguel, 2019; Meyer et al., 2023), but it also holds significance from the consumer's standpoint. Research on customer preferences, such as a meta-analysis by Van Houtven et al. (2017) involving 60 studies, demonstrates that customers' willingness to pay (WTP) for enhanced water services varies between $3 and $30 per month. Furthermore, a specific WTP study conducted in Peru suggests that customers would be willing to accept a 23 % increase in their monthly water bill to enhance the continuity of water supply (Galarza Arellano et al., 2023).

Given the relevance of OCWSS among quality of service indicators of water utilities, a research stream has focused on integrating water supply interruptions and sewerage blockages, as continuity indicators, on assessing the techno-economic performance of water utilities (e.g., Kumar and Managi, 2010; Ananda and Pawsey, 2019; Cetrulo et al., 2020; Sala-Garrido et al., 2021; 2023; Maziotis et al., 2023a; 2023b; Vilarinho et al., 2024). The main aim of these studies is to benchmark the performance of water companies based on multiple indicators being two of them the continuity in the provision of water and sanitation services. Acknowledging the significance of enhancing the OCWSS, it is pertinent to inquire about the expenses that water utilities must incur to improve OCWSS. Literature of this topic is quite limited. To the best of our knowledge, merely two prior investigations have delved into this specific area. Molinos-Senante and Sala-Garrido (2017) estimated the compensation that customers should receive in case of experiencing unplanned water supply interruptions. In doing so, they used a non-parametric approach based on the concept of shadow price of undesirable outputs. On the other hand, Maziotis et al. (2021) computed the marginal costs of unplanned water supply interruptions by estimating the cost frontier of a sample of water utilities employing a parametric method.

While these studies (Molinos-Senante and Maziotis, 2017; Maziotis et al., 2021) contribute valuable insights into the urban water sector, they primarily address the marginal costs associated with water supply interruptions, which represent the costs incurred by utilities due to outages, rather than the investment required to minimize such interruptions. This distinction is crucial as the former focuses on the consequences of service disruptions, whereas the latter pertains to proactive measures to enhance service continuity. Moreover, the existing literature focused on drinking water supply, with limited exploration into the economic aspects of managing sewerage blockages. This gap highlights a need for comprehensive analysis that encompasses both elements of the urban water cycle, providing a holistic view of the costs and strategies associated with improving overall service continuity.

This study proposes a framework, based on the inverse data envelopment analysis (Inverse DEA) method, to estimate the increase in operational costs of water companies for improving the OCWSS. DEA, a non-parametric linear programming technique, is extensively applied for evaluating the efficiency of various entities, including water utilities, by examining their input and output data (Amin et al., 2017; Goh and See, 2021). In contrast, Inverse DEA is a post-DEA sensitivity analysis approach developed initially for solving resource allocation. It employs reverse optimization to determine the necessary inputs and/or outputs for achieving set efficiency targets (Emrouznejad et al., 2023). Consequently, Inverse DEA is an effective method for calculating the additional operational costs (inputs) that water utilities require to enhance OCWSS (outputs) while preserving their techno-economic efficiency. Although DEA is widely utilized for estimating efficiency, it is not without limitations (Berg and Marques, 2011). The efficient frontier in DEA is constructed by comparing all observations, and thus, deviations due to outliers or low data quality can result in underestimation or overestimation of efficiency (Ferreira et al., 2023). Additionally, as a deterministic approach, DEA does not allow integrating environmental variables into the efficiency assessment (Pereira and Marques, 2022).

This study aims to develop and apply a methodological framework for calculating the increase in operational costs that water utilities must incur to enhance the OCWSS to meet specific goals. To demonstrate the practicality of this proposed methodology, an empirical study was carried out within the Chilean water sector. Specifically, this study calculates the anticipated increase in operational costs for a group of 23 water utilities to reach predetermined OCWSS objectives under four simulated scenarios.

This research contributes to literature by introducing an innovative methodological framework, based on the Inverse DEA technique, to project the increase in operational costs required to meet OCWSS objectives. To our knowledge, this is the inaugural study to explore this subject through an inverse optimization lens. Moreover, this study extends its analysis to assess the potential repercussions of the projected cost escalation on the water and sanitation tariffs of the scrutinized water utilities. From a policy standpoint, the findings of this investigation hold significant value for water regulators and managers as they offer a quantified assessment of the cost implications associated with enhancing OCWSS to meet various target standards. In countries where water and sanitation tariffs adhere to the cost recovery principle, understanding the economics for augmenting OCWSS is crucial not only for setting attainable goals but also for informing the tariff-setting mechanism. Essentially, gauging the financial outlay necessary for OCWSS enhancement constitutes a vital preliminary step in the formulation of long-term strategies aimed at advancing OCWSS.

2. Methodology

The selection of an inverse optimization model depends on the specific application (Chan et al., 2022). In line with the objectives of our research, we propose an inverse DEA model formulated as a design problem. This approach is characterized by designing prices, incentives, or mechanisms to induce specific agent decisions by making them optimal under the computed parameters (Gupta and Zhang, 2023). In contrast, estimation problems aim to learn a decision-making model using input data that reflects observed agent behaviour. Data-driven inverse optimization models can generate parameter estimates even if it is infeasible to render all observed decisions optimal (Chen et al., 2021). Given the aim of this study, applying an estimation problem is not suitable. Therefore, we have focused on a design problem, ensuring that all solutions for the defined scenarios are feasible and potentially applicable by water companies. Moreover, the methodological proposal relies on the advantages of DEA for assessing the efficiency of water companies and its widespread use in assessing their efficiency across many countries (Goh and See, 2021). Accordingly, the methodology is designed not only to quantify the cost of improving the continuity of water supply and sanitation services in Chile but also to be utilized by decision-makers or water managers globally. The framework for estimating the cost associated with enhancing the OCWSS encompasses three principal phases, outlined as follows:

Stage 1. Evaluation of the techno-economic efficiency of water utilities within the prevailing OCWSS conditions.

The primary goal of this stage is to assess the existing operational performance of water utilities, focusing on service continuity and the costs associated with providing drinking water, and wastewater collection and treatment. To achieve this, two main methodological approaches could be employed: i) stochastic frontier analysis (SFA) and; ii) DEA. While both methodologies offer their respective merits and drawbacks, extensive literature reviews by Cetrulo et al. (2019) and Goh and See (2021) have established DEA as the more favored approach in the context of assessing water utilities' performance. DEA is a non-parametric method which based on linear programming allows evaluating the relative efficiency of a unit (water utility in this study) by comparing it with other water utilities that use the same inputs to produce the same outputs (Gastaldi et al., 2020). The preference for DEA stems from its notable characteristics. Firstly, DEA enables the integration of multiple inputs and outputs to produce a singular measure of efficiency along the production frontier (Nithammer et al., 2022). Secondly, it allows for flexibility in assessment by not necessitating a predefined functional form of the production function (Walker et al., 2020). Consequently, this study employs the DEA methodology to assess the techno-economic efficiency of water utilities.

Consider n water utilities, $WU\_1,\ldots,WU\_n$, and the inputs and outputs for WU_j are, respectively, x^j and y^j, $j = 1,\ldots,n$. All $x^j \epsilon \Re^m$ and $y^j \epsilon \Re^s$, and $x^j > 0$, $y^j > 0$ for $j = 1,\ldots,n$. The water utility under assessment is the j_0th one. To simplify the notation, inputs x^{j_0} are denoted as x^0 and outputs y^{j_0} as y^0.

DEA models can be classified as either input-oriented, which focuses on minimizing input usage while maintaining constant output levels, or output-oriented, emphasizing the maximization of outputs while keeping inputs unchanged (Lombardi et al., 2019). Given the primary objective of this research to enhance service continuity, an output-oriented perspective was selected, aiming at improving the efficiency of service provision. Furthermore, DEA can be adapted to assume various scales of return, including constant returns to scale (CRS), variable returns to scale (VRS), non-increasing returns to scale (NIRS), and non-decreasing returns to scale (NDRS). To accommodate these diverse scenarios, a generalized output-oriented DEA model was introduced (Wei et al., 2000) for evaluating the techno-economic performance of water utilities, considering the four potential returns to scale models (Model (1)).

$$
\begin{aligned}
&(P^0)\max z^0 \qquad (1)\\
&s.t.\\
&\sum_{j=1}^{n} x^j\lambda_j \le x^0,\\
&\sum_{j=1}^{n} y^j\lambda_j \ge z^0 y^0,\\
&\delta_1\Big(\sum_{j=1}^{n}\lambda_j + \delta_2(-1)^{\delta_3}\Big) = \delta_1,\\
&\lambda_j \ge 0, \quad j = 1,\ldots,n
\end{aligned}
$$

The third constraint in Model (1) imposes CCR, VRS, NIRS or NDRS based on the values allocated to δ_1, δ_2, and δ_3 which are binary variables. The places below with * can be either 0 or 1 (Wei et al., 2000). Model (1) corresponds to:

$$
\begin{aligned}
&\text{CCR DEA model when}(\delta_1,\delta_2,\ \delta_3) = (0,*,*), \quad (P^0)\\
&\text{VRS DEA model when}(\delta_1,\delta_2,\ \delta_3) = (1,0,*), \quad (P^0)\\
&\text{NIRS DEA model when}(\delta_1,\delta_2,\ \delta_3) = (1,1,0), \quad (P^0)\\
&\text{NDRS DEA model when}(\delta_1,\delta_2,\ \delta_3) = (1,1,1), \quad (P^0)
\end{aligned}
$$

In Model (1), λ_j is a vector involving the weights allocated to inputs and outputs. The optimal value of z^0, under a particular set of δ_1, δ_2, and δ_3 values, represents the techno-economic efficiency score of the WU_j_0. $z^0 \ge 1$. A water utility is techno-economic efficient if and only if $z^0 = 1$. By contrast, if $z^0 > 1$, the water utility is inefficient, i.e., presents room to improve its techno-economic performance in comparison to their peers. Considering the diversity in the size of the water utilities assessed in our study, as evidenced by the variation in population served and volume of drinking water supplied (see Table 1), scale effects have been integrated into the performance assessment by assuming that these utilities operate under VRS technology.

The techno-economic efficiency score (TEE) of the WU_j_0 is defined as:

$$TEE = \frac{1}{z^0} \tag{2}$$

Stage 2. Definition of the OCWSS targets for each water utility.

Previous studies (Guerrini et al., 2015; lo Storto, 2022; Sala-Garrido et al., 2023), have evidenced that variables representing OCWSS are integrated as outputs in DEA models, reflecting the objective of water utilities to maximize these aspects. This phase involves establishing the desired target(s) for outputs related to the OCWSS. These targets can be determined using various criteria, including compliance with national and/or international regulations, national water industry averages, the highest performance observed among evaluated water utilities, or specific objectives set by each utility based on their internal commitments.

From a mathematical perspective, it involves defining outputs increment(s) for each water utility evaluated, ΔY_0, that is $\beta_0 = Y_0 + \Delta Y_0$ (Jahanshahloo et al., 2004).

Stage 3. Estimation of the increase in operational costs needed to achieve OCWSS targets.

This stage aims to determine the optimal level of inputs (operational costs) necessary for one or more water utilities to enhance some or all of their output levels in alignment with the defined OCWSS targets (Stage 2), without compromising the level of TEE estimated in Stage 1. In doing so, the inverse optimization approach, particularly Inverse DEA, is utilized. Traditional optimization models, like Model (1), are designed to identify the optimal solution(s) of an objective function. In contrast, inverse optimization deals with a feasible solution that might not be optimal, with the objective to minimize data alterations to render the existing solution as optimal (Emrouznejad et al., 2023). Inverse DEA addresses inverse problems within the DEA framework, aiming to adjust inputs and/or outputs for achieving specified efficiency targets (Gattoufi et al., 2014). Therefore, employing Inverse DEA allows the estimation of required increases in operational costs (inputs) to enhance OCWSS variables, while preserving the efficiency levels of the water utilities.

To determine the level of inputs (operational costs) (α_0) of the evaluated $WU\,j_0$ when outputs (OCWSS) increase from Y_0 to β_0, the following model is solved (Jahanshahloo et al., 2004):

$$Min\alpha_0 = (\alpha_{10,\ldots,}\alpha_{m0)} \tag{3}$$

$$s.t.$$

$$\sum_{j=1}^{n} x^j \lambda_j \leq z^0 \alpha_0,$$

$$\sum_{j=1}^{n} y^j \lambda_j \geq \quad \beta_0,$$

$$\delta_1 \left(\sum_{j=1}^{n} \lambda_j + \delta_2 (-1)^{\delta_3}\right) = \delta_1,$$

$$\lambda_j \geq 0, \quad j = 1, \ldots, n$$

where the definition of all parameters included in Model (3) is the same as in Model (1).

Stages 1 and 3 of this assessment are deterministic, meaning that outliers and atypical observations could potentially influence the results. To assess the impact of such outliers and atypical observations, conditional approaches (e.g., Cazals et al., 2002; Daraio and Simar, 2007; D'Inverno and De Witte, 2020) or robust methods based on bootstrapping (Vilarinho et al., 2023) can be applied. These methods help mitigate the effect of extreme values. The choice between using a deterministic approach or more advanced robust methods will depend on the presence of outliers in the dataset, which can be verified using various techniques (Simar, 2003).

3. Case study

3.1. Urban water industry in Chile

The empirical application conducted in this study focuses on the urban water sector[1] of Chile, covering 49 water utilities that deliver water and sanitation services across 399 urban areas to a total of 5937,766 customers, representing 16,063,610 individuals. The scale of these utilities varies significantly, with the largest serving 2109,520 customers and the smallest catering to only 77 customers (SISS, 2022). Among these, 48 are operated by private entities, while a singular utility is publicly managed. The private sector is further divided into two categories: (i) fully private water companies, where both the infrastructure and the service operations are privately owned, and (ii) concessionary water companies, where the service operations are privatized under a long-term agreement, but the infrastructure remains publicly owned (Maziotis et al., 2020). The sole public utility serves 219,697 customers,

[1] The provision of water services in rural areas is conducted by rural area committees and cooperatives whose regulation differs from urban water utilities.

Table 1
Main statistics of inputs and outputs for Chilean water utilities.

		Average	Std. Dev	Minimum	Maximum
Operational_costs	1000 US$/year	57128	75905	1751	321343
Volume_of_water	1000 m^3/year	52240	96051	488	454369
People_wastewater	Number	827350	1612721	7381	7457084
CWS (Eq.4)	$hours^{-1}$	1.586	1.513	0.164	5.510
CSS (Eq.5)	$hours^{-1}$	16.501	36.207	0.253	155.161

accounting for 3.7 % of the total customer base. Fully private utilities serve 4327,294 customers (72.8 % of the total), while concessionary utilities serve 1390,775 customers (23.4 % of the total).

The 49 water utilities provide water and sanitation services to 99.40 % and 97.48 % of the urban population in Chile, respectively (SISS, 2022). In 2022, the average water consumption reached 17.06 cubic meters per month for each customer, which translates to a daily per capita consumption of 156 litters. In terms of service quality, the compliance rates for drinking water and wastewater treatment quality standards averaged 99.65 % and 98.40 %, respectively. With a focus on the OCWSS, there were a total of 10,086 water supply interruptions in 2022, of which 7044 were unplanned. On average, each water supply interruption impacted 378 customers and lasted for 3.84 hours. Regarding sewage obstructions, the utilities reported 155,546 incidents.

In Chile, water pricing adheres to the principle of full cost recovery, eschewing generalized subsidies.[2] The volumetric rates for drinking water, along with wastewater collection and treatment, span from 3.52 US$/$m^3$ to 1.13 US$/$m^3$. This variation is influenced by a multitude of factors, including the geographical attributes of each city, the availability and quality of raw water, and population density, among others. The setting of water tariffs is the responsibility of the urban water regulator, Superintendencia de Servicios Sanitarios (SISS), and occurs every five years. This process involves forecasting the operational costs for a techno-economically efficient water utility as well as projecting water consumption over the forthcoming five-year period (SISS, 2022).

3.2. Sample and data selection

Considering the divergent size of water utilities in Chile and the available statistical information, this study embraces the 23 main water utilities of the country in terms of customers served. The 23 utilities provide water and sanitation services to 5811,654 customers, i.e., 97.9 % of total urban customers. These 23 water utilities operate across the 16 administrative regions of the country. Moreover, the sample of water utilities embraces the public utility, 8 concessionary utilities and 14 full private utilities. Thus, the sample of water utilities assessed in this study is representative of the Chilean water industry. According to the methodological approach proposed by Simar (2003), the dataset does not include any outlier.

Based on the primary objective of the study and according to past research on this topic (Cetrulo et al., 2019; Goh and See, 2021), as well as the statistical data available, inputs and outputs for the assessment of each water utility were meticulously chosen. The data for this analysis was sourced from management reports of the Chilean water industry, accessible on the SISS website, and pertains to the year 2022. The water regulator in Chile, SISS, publishes an annual management report for water companies that includes data on key variables related to their operations and the quality of services provided. Since this data is used by the regulator in the tariff-setting process, rigorous checks are conducted to ensure the accuracy and reliability of the information submitted by the companies. As a result, the data quality is high and accurately reflects the operational conditions of each company. However, access to data disaggregated by the localities served by each water company, would be valuable for conducting more detailed studies. This level of detail would enable a more nuanced analysis of performance variations across different service areas, potentially identifying specific local challenges and opportunities for improvement.

Inputs and outputs were uniquely defined for each water utility under examination. The selected input is the operational and maintenance cost associated with providing water and sanitation services, denoted in US dollars per year. This cost encapsulates the total operational expenditure of each evaluated water utility. In the water and sanitation industry, total operational costs are often influenced by capital expenditures (CAPEX) (Kingdom et al., 2018). CAPEX represents a cash outlay used to acquire an asset that appears on the balance sheet for a specific number of years. Therefore, replacing aging infrastructure with more efficient systems presents an opportunity to reduce operational costs. For instance, in our assessment, total operational costs include energy expenses, which could be lowered if aging pumps are replaced with more efficient ones, thereby reducing energy consumption and associated costs. This insight is crucial for enhancing the TEE of the water companies assessed, marking the initial phase of the methodological approach proposed.

For outputs, four measures were identified, two of which—volume of potable water supplied and the number of customers with access to wastewater treatment services—reflect the operational capacity of each water utility. The remaining two outputs pertain to the continuity of water and sanitation services provision. Therefore, the outputs include: i) volume of potable water supplied and registered, excluding non-revenue water, which represents losses not accounted for in the water company's revenue. This is quantified in thousands of cubic meters per year; ii) population whose wastewater is collected and treated, represented by the total people count; iii) continuity in water service (CWS) delivery, as defined in Eq. (4) and; iv) continuity in sanitation services (CSS), as specified by Eq.

[2] Targeted subsidies are provided to socio-economic vulnerable customers.

(5). Both CWS and CSS consider two key parameters: the duration of service interruptions (DP_{UWSI} and DP_{SB}) and the proportion of customers affected (TC/AC_{UWSI} and TC/AC_{SB}). These parameters are are crucial for assessing the potential consequences of water and sanitation disruptions. Moreover, in the case of water supply, the study specifically focuses on unplanned interruptions, as planned interruptions are necessary for service improvements. Planned interruptions are communicated to customers in advance, minimizing inconvenience and allowing contingency plans to be implemented.

$$CWS = \left(\frac{1}{DP_{UWSI}}\right) * \left(\frac{TC}{AC_{UWSI}}\right) \quad (4)$$

$$CSS = (1/DP_{SB}) * (TC/AC_{SB}) \quad (5)$$

where CWS is the continuity of water services variable in hours^{-1}; DP_{UWSI} is the average duration of each unplanned water supply interruption in hours; AC_{UWSI} is the total number of customers affected by unplanned water supply interruptions during the evaluated year; TC is the total number of customers of each water utility; CSS is the continuity of sanitation services expressed in hours^{-1}; DP_{SB} is the average duration of each sewage blockage in hours and; AC_{SB} is the total number of customers affected by sewerage blockages during the evaluated year.

Table 1 shows a statistical summary of the input and four variables for the 23 Chilean water utilities assessed.

4. Results and discussion

The discussion of the results adheres to the methodological framework outlined in Section 2 of this study. Accordingly, the analysis unfolds in a sequential manner, beginning with the presentation of the TEE scores for the 23 water utilities under examination. Following this, the targets for CWS and CSS variables are detailed highlighting the rationale behind these objectives. The final segment of the discussion focuses on the estimated increase in operational costs required to achieve the aforementioned continuity targets. All estimations were made using GAMS (General Algebraic Modeling Software).

4.1. Techno-economic efficiency of water utilities

The TEE evaluation of the 23 water utilities, as depicted in Fig. 1, reveals that four utilities achieved an efficiency score of 1.0, signifying their status as top performers within the assessed group. These efficient entities comprise a diverse mix in terms of ownership, including the sole public utility, two fully private utilities, and one concessionary utility, indicating that ownership type does not necessarily correlate with efficiency levels. Geographically, three of the efficient utilities are located in the central region of Chile, while the remaining operates in several regions of the country, suggesting that the geographical location and associated conditions do not have a decisive impact on techno-economic efficiency. This finding aligns with the research conducted by Molinos-Senante and Farías (2018), which highlighted the significant influence of water utility management on performance outcomes. The current study corroborates this conclusion, underscoring the importance of effective management practices over geographic or ownership factors.

Conversely, WU2 emerged as the least efficient entity with a score of 0.222 (Fig. 1). This indicates a potential for increasing outputs by as much as 77.8 % to match the performance of the efficient utilities. The operational challenges faced by this utility might be influenced by its location in the northern region of Chile, where water availability and quality issues are prevalent. This case

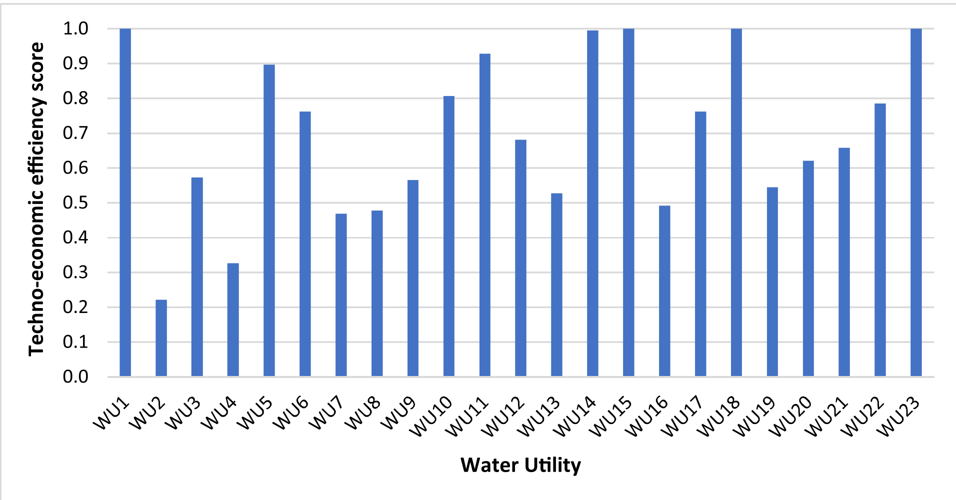

Fig. 1. Techno-economic efficiency scores of Chilean water utilities.

underscores the critical role of local environmental conditions in shaping the operational efficiency of water utilities, highlighting the need for tailored management strategies to overcome such challenges.

The computed average TEE score for the 23 evaluated Chilean water utilities stands at 0.699. This indicates that, on an aggregate level, it exists a potential for these utilities to enhance their outputs by approximately 30.2 % to reach the benchmark set by the efficient entities. Notable divergences in TEE scores are observed among water companies, highlighting a heterogeneous performance across the sector. This finding aligns with previous research endeavours that have also scrutinized the efficiency of Chilean water utilities, incorporating service quality variables into their assessments. Different DEA models and the inclusion of varied service quality outputs have yielded comparable outcomes in past studies, underscoring the consistency of efficiency challenges across the sector. Mocholi-Arce et al. (2022) determined an average efficiency score of 0.527. Meanwhile, Maziotis et al. (2023a) and Sala-Garrido et al. (2023) reported slightly higher average efficiency scores of 0.623 and 0.618, respectively. These variations in efficiency estimates highlight the sensitivity of DEA outcomes to the selection of inputs and outputs, as well as the underlying models used in the analysis. Nonetheless, the consensus across these studies points to a significant room for improvement in the operational and economic performance of water utilities in Chile.

4.2. *Definition of water and sanitation continuity targets*

Under the framework of Chilean urban water regulations, water utilities are mandated to ensure the continuous provision of water and sanitation services throughout the year, 24 hours a day. This regulatory requirement implies that the ideal values for the OCWSS variables used in this study, i.e., CWS and CSS, should be zero (zero customers affected by water and sanitation interruptions). However, achieving these targets is not entirely feasible due to multiple factors beyond the control of water utilities, including pressure fluctuations, external loads, soil movement, extreme natural disasters, or interference from third parties, among others. In recognition of these challenges and to pragmatically assess the impact of striving towards these continuity targets on the operational costs of water utilities, four distinct scenarios were conceptualized.

To evaluate the impact of varying OCWSS targets on the operational costs of water utilities, four distinct scenarios, have been delineated: i) Restrictive Scenario: It posits the most stringent conditions, setting the ceiling for water supply interruptions and sewer blockages duration at 1 hour, and limiting the maximum number of affected customers to 5 % of the utility's total customer base for water services and to 1 % for sanitation provision; ii) Average Scenario: This intermediate scenario aligns the continuity indicators (CWS and CSS) of all assessed water utilities to at least the sample average. Utilities with performance above this average maintain their current levels, whereas those below the threshold aim to meet the average values of IWS and ISS; iii) Conservative Scenario: In this scenario, every utility is expected to enhance its continuity of water and sanitation services by 10 % relative to their current state. This scenario sets a modest improvement target, acknowledging the challenges while striving for incremental progress and; iv) Advanced Scenario: This scenario ambitiously aims for a 30 % improvement in service continuity across all utilities compared to their present performance. This scenario represents a significant commitment to elevating service standards and reducing interruptions.

The four scenarios defined (Table 2) provide a structured framework to assess the operational and financial implications of

Table 2
Targets for operational continuity water supply and sanitation services for the four scenarios defined. All variables are expressed in hours^{-1}.

Water Utility	Original values		Restrictive Scenario		Average Scenario		Conservative Scenario		Advanced Scenario	
	CWS (Eq.4)	CSS (Eq.5)	Target CWS	Target CSS	Target CWS	Target CSS	Target CWS	Target CSS	Target CWS	Target CSS
WU1	1.33	0.25	20.00	100.00	1.59	13.08	1.47	0.28	1.73	0.33
WU2	0.43	22.81	20.00	100.00	1.59	22.81	0.48	25.09	0.56	29.65
WU3	1.63	4.79	20.00	100.00	1.63	13.08	1.79	5.27	2.11	6.23
WU4	0.57	1.68	20.00	100.00	1.59	13.08	0.63	1.85	0.75	2.19
WU5	2.00	0.81	20.00	100.00	2.00	13.08	2.20	0.89	2.60	1.05
WU6	0.58	1.55	20.00	100.00	1.59	13.08	0.64	1.71	0.76	2.02
WU7	0.70	21.36	20.00	100.00	1.59	21.36	0.77	23.50	0.91	27.77
WU8	3.33	3.68	20.00	100.00	3.33	13.08	3.66	4.04	4.32	4.78
WU9	0.79	6.47	20.00	100.00	1.59	13.08	0.87	7.12	1.03	8.41
WU10	4.37	0.67	20.00	100.00	4.37	13.08	4.81	0.73	5.68	0.87
WU11	0.16	155.16	20.00	100.00	1.59	76.39	0.18	84.03	0.21	99.30
WU12	1.58	20.68	20.00	100.00	1.59	20.68	1.73	22.74	2.05	26.88
WU13	2.76	3.08	20.00	100.00	2.76	13.08	3.04	3.39	3.59	4.01
WU14	2.78	5.53	20.00	100.00	2.78	13.08	3.06	6.08	3.61	7.19
WU15	5.51	3.76	20.00	100.00	5.51	13.08	6.06	4.14	7.16	4.89
WU16	0.34	1.16	20.00	100.00	1.59	13.08	0.37	1.28	0.44	1.51
WU17	0.51	0.34	20.00	100.00	1.59	13.08	0.56	0.37	0.66	0.44
WU18	0.45	94.90	20.00	100.00	1.59	94.90	0.49	104.39	0.58	123.37
WU19	0.26	21.05	20.00	100.00	1.59	21.05	0.28	23.16	0.34	27.37
WU20	1.07	1.67	20.00	100.00	1.59	13.08	1.18	1.84	1.40	2.18
WU21	0.28	3.02	20.00	100.00	1.59	13.08	0.31	3.32	0.37	3.93
WU22	0.96	4.81	20.00	100.00	1.59	13.08	1.05	5.29	1.24	6.25
WU23	4.08	0.29	20.00	100.00	4.08	13.08	4.49	0.32	5.30	0.37

improving service continuity in the water sector, reflecting a range of ambitions from conservative enhancements to ambitious overhauls. Nevertheless, alternative OCWSS targets can be defined depending on the objectives of the water regulator and/or water utilities.

4.3. Operational costs increment to achieve OCWSS targets

The methodological framework outlined in this research enables the estimation of total operational costs, as well as the incremental costs relative to existing operational expenses, required to meet OCWSS targets across various scenarios. Table 3 presents the necessary operational costs to attain OCWSS benchmarks for the four evaluated scenarios. These costs are contingent upon the existing operational expenses, the specified continuity targets for each scenario, and the requisite efficiency standards each utility must uphold. It should be noted that since the methodological approach employed is based on the DEA method, the estimated costs of the evaluated water utilities might be influenced by their operating environments (Carvalho and Marques, 2011; Pinto et al., 2017). Consequently, the estimated operational costs required to meet continuity targets for water supply and sanitation services vary significantly among water companies. This variation is primarily driven by differences in current total operational costs, which are largely influenced by the varying number of customers served by each utility.

As it was expected, the most significant rise in operational costs is linked to the restrictive scenario, which sets the highest OCWSS goals for all evaluated water utilities. According to Table 4, the average projected cost increases for water utilities under this scenario is 28.41 % with a median value of 122.24 %. This indicates that to enhance water supply and sanitation continuity to 20 hours^{-1} and 100 hours^{-1}, respectively, while maintaining efficiency levels, the examined utilities would need to augment their costs by an average of 122.24 %. Conversely, the conservative scenario, which stipulates the smallest enhancement in OCWSS, shows the lowest operational cost increment, with an average of 1.49 % and a median of 0.27 %. The advanced scenario presents an average operational cost increase of 4.47 % and a median of 0.80 %. A comparison between the conservative and advanced scenarios reveals that transitioning from a 10 % improvement (conservative) to a 30 % improvement (advanced) entails an average operational cost increase of 2.98 % and a median increase of 0.53 %.

Comparing operational increase among water utilities, notable diverges are observed among utilities specially in the restrictive scenario where the increase in operational costs ranges between 2.35 % (WU1) and 578.29 % (WU15) (Table 4). As it is shown in Table 2, OCWSS targets for the restrictive scenario are equal for the 23 assessed water utilities. Thus, the divergence among water utilities illustrates the different effort in terms of operational costs that water utilities should be carried out to achieve restrictive OCWSS targets keeping its current efficiency. Because one restriction of the models employed to estimate the change in inputs (operational costs) when outputs change (OCWSS targets) is keeping the current performance (efficiency score) of each water utility, there is no direct relationship between the gap in OCWSS between current and targeted values and the estimated increase in operational costs. This issue is clearly exemplified for the restrictive scenario. As it is shown in Table 2, WU15 is the one with the best CWS indicator (5.51 hours^{-1}) whereas the WU1 value for this indicator is limited to 1.33 hours^{-1}. The situation is even more evident for sanitation continuity indicator as the CSS value for WU1 is 0.25 hours^{-1} being the maximum 155.16 hours^{-1} (WU11). However,

Table 3
Current operational costs and estimated operational costs to achieve continuity targets on water supply and sanitation services for each scenario. Costs are expressed in US$/year.

Water Utility	Current Operational Costs	Operational Costs Restrictive Scenario	Operational Costs Average Scenario	Operational Costs Conservative Scenario	Operational Costs Advanced Scenario
WU1	321,343	328,900	321,935	321,377	321,444
WU2	140,053	170,432	140,970	140,525	141,469
WU3	57,172	68,318	57,472	57,253	57,414
WU4	41,458	64,765	43,490	41,511	41,617
WU5	48,335	55,413	48,619	48,387	48,490
WU6	55,728	71,559	56,762	55,764	55,838
WU7	68,298	82,471	68,625	68,515	68,949
WU8	10,891	18,791	11,147	11,006	11,237
WU9	16,738	28,365	17,313	16,793	16,905
WU10	16,350	23,539	16,629	16,488	16,765
WU11	11,905	13,041	11,905	11,905	11,905
WU12	8490	17,433	8493	8609	8846
WU13	4473	22,533	4866	4612	4889
WU14	2079	11,939	2236	2158	2316
WU15	1751	11,880	2347	1927	2277
WU16	71,652	87,280	73,133	71,675	71,719
WU17	175,656	185,735	176,607	175,658	175,685
WU18	6194	11,880	6505	6813	8052
WU19	147,729	160,260	148,105	147,897	148,233
WU20	59,340	69,936	59,905	59,384	59,473
WU21	7213	18,266	8003	7232	7270
WU22	2238	15,142	2650	2280	2364
WU23	38,859	44,792	39,131	38,963	39,172

Table 4
Increase in operational costs (%) to achieve continuity targets on water supply and sanitation services for each scenario.

Water Utility	Restrictive Scenario	Average Scenario	Conservative Scenario	Advanced Scenario
WU1	2.35	0.18	0.01	0.03
WU2	21.69	0.65	0.34	1.01
WU3	19.50	0.52	0.14	0.42
WU4	56.22	4.90	0.13	0.38
WU5	14.64	0.59	0.11	0.32
WU6	28.41	1.86	0.07	0.20
WU7	20.75	0.48	0.32	0.95
WU8	72.54	2.35	1.06	3.17
WU9	69.46	3.43	0.33	1.00
WU10	43.97	1.71	0.85	2.54
WU11	9.54	0.00	0.00	0.00
WU12	105.33	0.04	1.40	4.20
WU13	403.73	8.78	3.10	9.29
WU14	474.30	7.57	3.80	11.39
WU15	578.29	34.01	10.00	30.00
WU16	21.81	2.07	0.03	0.09
WU17	5.74	0.54	0.00	0.02
WU18	91.81	5.03	10.00	30.00
WU19	8.48	0.25	0.11	0.34
WU20	17.86	0.95	0.07	0.22
WU21	153.25	10.97	0.27	0.80
WU22	576.60	18.40	1.88	5.65
WU23	15.27	0.70	0.27	0.80
Average	122.24	4.61	1.49	4.47
Median	28.41	1.71	0.27	0.80

currently, the WU1 is fully efficient, i.e., its efficiency score is 1.0 (Fig. 1). Thus, this water utility could still being efficient and improve its OCWSS with a moderate increase in their operational costs. By contrast, the WU15, which is also fully efficient (Fig. 1), in spite of having better CWS and CSS indicators than WU1 (Table 2) needs an increase in operational costs much higher than WU1 to achieve OCWSS targets and at the same time still being efficient.

Table 4 reveals that, within the average, conservative, and advanced scenarios, 8 out of the 23 water utilities analyzed could meet the OCWSS targets with an increase in operational costs of less than 1 % relative to their current expenditures. This finding is crucial

Table 5
Impact of improving continuity of water and sanitation services on the monthly average water and sanitation bill paid by customers.

Water Utility	Monthly average water consumption (m^3/household)	Average volumetric water and sanitation tariff (US$/$m^3$)	Monthly volumetric water and sanitation bill ($/household)				
			Current	Restrictive Scenario	Average Scenario	Conservative Scenario	Advanced Scenario
WU1	14.67	1.42	20.83	21.32	20.87	20.84	20.84
WU2	12.50	3.01	37.64	45.80	37.88	37.76	38.02
WU3	14.71	2.11	31.04	37.09	31.20	31.08	31.17
WU4	14.16	3.34	47.32	73.92	49.64	47.38	47.50
WU5	29.41	2.21	65.00	74.52	65.39	65.07	65.21
WU6	12.70	2.40	30.48	39.14	31.05	30.51	30.55
WU7	14.77	2.03	29.98	36.21	30.13	30.08	30.27
WU8	14.54	2.00	29.09	50.19	29.77	29.39	30.01
WU9	14.77	2.41	35.60	60.32	36.82	35.72	35.95
WU10	57.00	4.15	236.57	340.59	240.61	238.58	242.58
WU11	12.64	3.52	44.50	48.75	44.50	44.50	44.50
WU12	15.44	2.07	31.97	65.64	31.98	32.42	33.31
WU13	15.02	2.23	33.51	168.81	36.46	34.55	36.63
WU14	50.45	2.07	104.43	599.75	112.34	108.40	116.33
WU15	14.13	2.10	29.69	201.37	39.79	32.66	38.59
WU16	13.50	2.44	32.95	40.13	33.63	32.96	32.98
WU17	15.75	1.88	29.61	31.31	29.77	29.61	29.62
WU18	30.33	1.99	60.36	115.78	63.40	66.40	78.47
WU19	15.69	2.41	37.82	41.02	37.91	37.86	37.95
WU20	15.24	2.02	30.80	36.30	31.09	30.82	30.86
WU21	12.18	2.28	27.79	70.37	30.83	27.86	28.01
WU22	13.44	2.72	36.57	247.42	43.30	37.26	38.63
WU23	15.01	1.13	16.96	19.55	17.08	17.01	17.10
Average	19.05	2.35	46.98	107.19	48.93	47.77	49.35
Median	14.77	2.21	32.95	50.19	36.46	32.96	35.95

for water regulators as it demonstrates the feasibility of setting continuity targets that do not necessitate substantial increases in operational costs, thereby mitigating the potential for significant rises in water tariffs that could impact user affordability. By contrast, the substantial increase in operational costs for other water utilities, particularly under the restrictive scenario, underscores the need of developing flexible and adaptative policy frameworks. Such frameworks should accommodate different levels of ambition and resource availability, enabling utilities to set realistic OCWSS improvement targets.

Variations in the increase of operational costs among different water utilities to meet the OCWSS targets, as outlined in the four scenarios, are also reflected in the changes in water and sanitation bills (Table 5). Initially, a significant disparity is noted in the average monthly water consumption across utilities, with the highest being 57.00 m^3/month (WU10) and the lowest at 12.18 m^3/month (WU21). Given that water and sanitation pricing in Chile adheres to the full cost recovery principle, considerable variations in the volumetric tariffs for water and sanitation services are evident among the utilities (Table 5). The average cost per cubic meter of water varies from 4.15 US$ (WU10) to 1.13 US$ (WU23). Consequently, the prevailing average monthly bill for water and sanitation services paid by Chileans ranges from 236 US$/month (WU10) to 16.96 US$/month (WU23). Therefore, the incremental operational costs required to reach the OCWSS targets (Table 3) will have a differential impact on the bills of water users. Particularly in the most restrictive scenario, which predicts the highest increase in water bills, customers' average payment would escalate from 46.98 US$/month to 107.19 US$/month. As anticipated, the rise in costs for the average, conservative, and advanced scenarios is considerably more modest, with an increase of less than 1 US$/month for the conservative scenario and under 2 US$/month for the average scenario. In this context, Maldonado et al., (2023) calculated that the WTP for residents of the Metropolitan Region of Santiago, Chile, to enhance the continuity of water supply in the event of extreme natural climate conditions averages at 1.81 US$/month. When this figure is juxtaposed with the projected bill increments for WU1, the principal utility delivering water and sanitation services in the aforementioned region, it is apparent that even the restrictive scenario is economically feasible from the standpoint of customer WTP.

The findings of this study underscore the critical role of engaging diverse stakeholders—especially customers—in meaningful discussions about the trade-offs between service improvements and the associated cost increases in water utility services. In doing so, multi-criteria decision analysis-based approaches should be considered (Pereira et al., 2023). Transparent and proactive communication is essential in building public support for necessary rate adjustments or alternative funding mechanisms to cover the higher costs. Such engagement is particularly important given the policy implications of improving OCWSS. Decision-makers should weigh the immediate financial impacts against the broader, long-term benefits that include enhanced public health outcomes, increased economic productivity through reliable water infrastructure, and strengthened resilience to environmental challenges such as climate change, drought, and population growth. The need for such foresight cannot be overstated, as water companies often operate within tight financial constraints while simultaneously being responsible for providing an essential public good. The findings of the study can guide investments in infrastructure that should be designed not only to meet present demands but to ensure the future sustainability of the system, ultimately contributing to social equity, environmental protection, and economic growth.

5. Conclusions

Enhancing the OCWSS is a goal shared by water utilities and regulators, as it pertains to elevating the service quality delivered to the population. Nevertheless, such advancements entail associated costs. This research introduces an innovative methodological framework that leverages the inverse DEA technique to quantify the additional operational expenses water utilities must undertake to meet specific OCWSS benchmarks while maintaining their TEE. This approach is crucial not only for setting attainable OCWSS objectives but also for assessing the prospective effects on the water and sanitation tariffs and bills, providing valuable insights for both policy formulation and operational planning in the water sector.

The usefulness of the proposed methodological framework was demonstrated via a case study that calculated the costs associated with enhancing the OCWSS for 23 Chilean water utilities across four distinct scenario targets. The estimated costs exhibited substantial variability, influenced by the specific OCWSS targets, the existing service continuity levels, and the current TEE of each utility. Notably, the median operational cost increase required to meet the continuity targets for water supply and sanitation services varied significantly, ranging from 28.41 % for the restrictive scenario to 0.27 % for the conservative scenario. Additionally, marked discrepancies were observed among the evaluated water utilities, which were also reflected in the changes to water and sanitation bills. These changes showed a median monthly increase ranging from 17.24 US$/household in the most demanding scenarios to as low as 0.01 US$/household in the more lenient one.

The methodological approach introduced in this research holds substantial value for water regulators and managers, offering a proactive tool to evaluate the economic implications of enhancing the OCWSS at the individual water utility level based on various targets. This capability is crucial for informed decision-making, aiding in the delineation of OCWSS objectives. The variable costs associated with enhancing OCWSS highlight the need for strategic investment planning by water utilities. Policymakers must consider both the financial implications and the potential improvements in service quality when setting OCWSS targets. The significant variability in cost across different scenarios and utilities suggests that a one-size-fits-all approach may not be appropriate. Instead, targeted investments based on specific utility performance and regional service demands may be more effective. Results from the empirical application evidence the importance of balancing service quality improvements with the economic burden on consumers. The considerable increase in operational costs for the restrictive scenario and its direct reflection on tariffs and bills necessitate a careful approach to rate setting. Policymakers should consider mechanisms to mitigate the impact on households, particularly in more demanding scenarios. This could include phased tariff adjustments, targeted subsidies for vulnerable groups, or cross-subsidization within the utility's customer base. Furthermore, the methodological approach proposed enables the juxtaposition of estimated costs with customers' WTP for service continuity enhancements. Such comparative analysis is instrumental in establishing OCWSS targets that align with both the operational goals of water utilities and the expectations and necessities of their customers, fostering a balanced and informed approach to service improvement and economic planning in the water sector.

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

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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