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Evaluating the Sustainability of Water and Sanitation Services: A Comparative Analysis of Methodological Approaches

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ABSTRACT

Benchmarking the sustainability of water utilities (WUs) in the provision of water and sanitation services is essential for addressing global sustainability goals. This study proposes a water utility sustainability index (WUSI), which was estimated for a sample of 29 WUs in Chile. To evaluate the impact of weighting methodologies on sustainability assessments, two approaches were applied: the benefit of doubt (BoD) method and the analytic hierarchy process (AHP). The results indicate that the average WUSI score under the BoD method was 0.987, with 55.17% of WUs achieving the maximum score of 1.0, whereas the AHP approach yielded a lower mean score of 0.551, with the highest-performing WU reaching 0.737. This difference arises from the fact that the weights assigned to the indicators comprising the WUSI under the BoD approach are endogenously optimized to maximize the composite index for each WU, leading to the suppression of poor-performing indicators. In addition, the BoD method exhibited lower variance (SD = 0.035) compared to AHP (SD = 0.095), suggesting a tendency to overestimate sustainability. The ranking of WUs also varied significantly depending on the weighting methodology used. The study revealed that utility size and geographical location influence sustainability outcomes. The significant discrepancies in WUSI scores based on the weighting methodology highlight the need for regulators to adopt a hybrid approach, combining objective, data-driven methods with expert and stakeholder input to ensure more balanced and contextually relevant sustainability assessments.

1 | Introduction

The provision of drinking water and wastewater treatment services generates numerous benefits for public health, the environment, and the economy (OECD 2011). The adoption of the United Nations 2030 Agenda for Sustainable Development in 2015, particularly Sustainable Development Goal 6, has underscored the critical goal of "ensuring the availability and sustainable management of water and sanitation for all" (UN 2015). Given that water utilities (WUs) are responsible for delivering these essential services, their sustainability is pivotal in advancing global sustainability goals (Landis 2015). Moreover, sustainability has become an increasingly important factor in the regulation and governance of WUs (Agovino et al. 2021). This is because benchmarking their sustainability—that is, comparing their sustainability performance against that of other utilities—serves as an effective tool for continuous improvement (Haider et al. 2016). However, despite the recognized importance of assessing WUs' sustainability in the transition toward sustainable water and sanitation services, its implementation remains incomplete and not yet fully consolidated (D'Inverno et al. 2021; Pérez et al. 2018).

Assessing the sustainability of WUs presents several challenges, which contribute to the limited research on this topic. From a conceptual perspective, there is no universally accepted definition of sustainability within the framework of urban water and sanitation services. Sustainability has traditionally been associated with economic, environmental, and social dimensions (Argoti et al. 2019). However, additional dimensions—such as assets and governance (Marques et al. 2015), as well as tariff structures (D'Amore et al. 2024)—have also been proposed to enhance the assessment of urban water service sustainability. The selection of dimensions and performance indicators is a critical step in sustainability assessment, as the resulting sustainability index for each unit is directly influenced by them (Blancas et al. 2011). A second major challenge is the absence of a standardized methodology for evaluating WUs' sustainability. As a result, the choice of methodological approach is left to the discretion of decision-makers and analysts, who select the method they deem most suitable based on the assessment objectives and their professional experience.

Despite the use of different methodologies to assess the sustainability of WUs, all previous studies (D'Amore et al. 2024; D'Inverno et al. 2021; Gonçalves et al. 2022; Lombardi et al. 2019; Marques et al. 2015; Molinos-Senante et al. 2016; Pérez et al. 2018, 2019) share a common characteristic. They captured the multidimensional aspects of sustainability by estimating a composite indicator that integrates several performance indicators using multi-criteria decision analysis (MCDA) methods. They apply weighting techniques to determine the relative importance of each indicator embracing the composite indicator. In this context, previous studies can be categorized into three main groups. Some studies such as D'Inverno et al. (2021), Lombardi et al. (2019), Molinos-Senante et al. (2016), and Pérez et al. (2019) employed Benefit of Doubt (BoD), Data Envelopment Analysis, and Distance-principal component techniques. They are MCDA methods where indicator weights are determined endogenously based on the dataset of the assessed WUs. The key advantage of this approach is that it introduces objectivity into the weight allocation process, which is often a source of controversy (Caballero et al. 2009). A second group of studies (Gonçalves et al. 2022; Marques et al. 2015) allocated weights based on stakeholder preferences and opinions using the MACBETH method. This approach acknowledges that the relevance of certain indicators may vary depending on the local, regional, or national context. By integrating stakeholder perspectives, this method enhances the contextual adaptability of sustainability assessments. The final group of studies (Molinos-Senante et al. 2016; Pérez et al. 2018) used Goal Programming techniques to assign equal weights to all indicators, ensuring that each indicator within the composite indicator carried the same level of importance. A critical question that arises from these previous studies is: How does the choice of weighting methodology influence the sustainability of WUs?

A key limitation of previous studies assessing the sustainability of WUs is their narrow scope. To the best of authors' knowledge, all existing studies (D'Amore et al. 2024; D'Inverno et al. 2021; Gonçalves et al. 2022; Lombardi et al. 2019; Marques et al. 2015; Molinos-Senante et al. 2016; Pérez et al. 2018, 2019) have exclusively focused on the provision of drinking water services. In other words, none of these studies incorporate performance indicators related to sanitation services, including wastewater collection and treatment, despite the fact that many WUs worldwide manage both services. This omission is particularly significant given that Sustainable Development Goal 6 explicitly emphasizes both drinking water supply and sanitation, underscoring the need for a more comprehensive assessment framework.

Against this background, the main objectives of this study are twofold. First, it aims to develop and estimate a water utility sustainability index (WUSI) that integrates both drinking water and sanitation services, providing a more comprehensive measure of WUs' sustainability. Second, it seeks to evaluate the impact of the sustainability assessment framework—particularly the choice of weighting method—on WUSI estimations. In addition, this study contributes to the ongoing debate on how key factors such as utility size, ownership structure, and geographical location influence the overall sustainability of WUs.

To achieve these objectives, we estimate the WUSI for a sample of 29 WUs in Chile, all of which provide both water supply and sanitation services. In this process, we employ two distinct weighting methods: a data-driven approach, specifically the BoD method, and a preference-based approach, namely the analytic hierarchy process (AHP). The BoD method determines indicator weights in a way that maximizes the evaluated WU's performance, ensuring that no utility is disadvantaged by an externally imposed weighting structure (Vilarinho et al. 2024). In contrast, AHP allocates weights based on stakeholder or expert input, allowing the weighting scheme to reflect contextual preferences and specific local, regional, or national priorities (Ko et al. 2024).

This study addresses a critical gap in the literature by examining the impact of different weighting methodologies on the sustainability assessment of WUs. By employing both data-driven and preference-based approaches, it provides a comparative analysis of how weighting schemes influence sustainability estimations. This dual-method approach enhances the robustness of sustainability assessments and contributes to the broader discourse on the role of stakeholder preferences in evaluating sustainability. Moreover, unlike previous research, which has predominantly focused on drinking water services, this study develops and applies a WUSI that integrates both drinking water and sanitation services. By incorporating both components, it offers a more comprehensive and holistic perspective on the sustainability of WUs.

2 | Case Study

2.1 | Description of the Water and Sanitation Industry in Chile

The empirical application developed in this study focuses on the water and sanitation industry in Chile. The country is characterized by a highly institutionalized and mature regulatory framework for urban water and sanitation services, which ensures consistency and comparability across utilities—an essential requirement for benchmarking sustainability using composite indicators, as proposed in this study. At present, 47 utilities operate nationwide, each responsible for both the provision of drinking water and the collection and treatment of wastewater. This dual responsibility is well aligned with the study's objective of constructing an integrated sustainability index that captures both water supply and sanitation dimensions. Furthermore, Chilean utilities are legally mandated to report standardized performance data on an annual basis, and this information is publicly accessible. The high level of data availability and consistency supports the implementation of both data-driven and expert-based MCDA methods, thereby enhancing the methodological robustness of the proposed assessment framework.

In Chile, two distinct regulatory frameworks govern the provision of water and sanitation services. In rural areas, which account for approximately 12% of the total population (INE 2025), drinking water and sanitation services are managed by local communities through their own organizational structures, resulting in decentralized, community-based management (Donoso 2018). Conversely, in urban areas, where the majority of Chileans reside—an estimated 17.2 million people (INE 2025)—water and sanitation services are provided by WUs under the regulatory oversight of the Superintendencia de Servicios Sanitarios (SISS). Thus, this study focuses on WUs providing water and sanitation services in urban areas where drinking water service coverage reaches 99.94%, while wastewater collection and treatment achieve coverage levels of 99.94% and 100.00%, respectively. The average per capita water consumption stands at 153.5 L/day (SISS 2023).

Chile's water and sanitation sector is predominantly privatized, with over 96% of customers being served by concessionary and private water companies. The privatization process took place primarily between 1998 and 2004 (Molinos-Senante et al. 2020). Although the urban water regulator existed before privatization, its role was significantly strengthened following the transition to private-sector management. Regardless of ownership, all WUs operate under the same institutional and legal framework. The current water tariff scheme does not explicitly incorporate sustainability performance indicators; instead, it focuses solely on the technical and economic efficiency of utilities, benchmarking them against a hypothetical efficient utility defined by the regulator.

Regarding the evaluated WUs, the sample assessed comprises the 29 largest Chilean WUs, which provide water and sanitation services to approximately 98% of urban customers. These 29 WUs operate across all 16 administrative regions of the country, making the sample representative at the national level. The WUs encompass three ownership types: public (1 WU), concessionary (8 WUs), and private (20 WUs). In terms of size, the assessed WUs vary significantly, ranging from the largest, serving approximately 2,160,000 customers, to the smallest, which serves fewer than 4000 customers.

2.2 | Definition of Sustainability Dimensions and Indicators

While the sustainability of urban water systems has been a subject of discussion since the 1990s (Landis 2015), there is no common and widely accepted definition of sustainable urban water systems (D'Amore et al. 2024). This lack of a universally agreed-upon definition results in the absence of a standardized set of dimensions and indicators for sustainability assessments. Sustainability is traditionally associated with the Triple Bottom Line (TBL) framework, which comprises social, environmental, and economic dimensions (Purvis et al. 2019). However, within the specific context of WUs, a pioneering approach by Marques et al. (2015) proposed two additional dimensions to the TBL framework, namely assets and governance. The assets dimension pertains to the physical infrastructure and encompasses aspects such as durability, reliability, flexibility, and adaptability of water infrastructure (Alegre et al. 2012). The governance dimension relates to transparency, stakeholder and customer participation in decision-making, accountability quality, and other institutional factors (Saxena et al. 2022).

Given that the case study focuses on the Chilean water industry, which operates under a uniform regulatory framework regarding accountability, public participation, and transparency for all WUs, the governance dimension does not exhibit significant differences among the assessed WUs. In this context, the WUSI proposed in this study embraces four key dimensions: economic, environmental, social, and assets, in alignment with the framework established by Marques et al. (2015).

The selection of performance indicators within each dimension was based on several key considerations. While the WUSI should remain simple and concise, it must also incorporate key aspects of sustainability relevant to WUs. Each indicator was required to be preferentially independent, meaning that its performance should not influence or be contingent upon the performance of any other criterion (Sofiane et al. 2023). In addition, the indicators had to adhere to the SMART criteria, meaning they should be Specific, Measurable, Attainable, Realistic, and Time-sensitive (Bjerke and Renger 2017). In other words, the selected indicators should accurately reflect progress toward or away from sustainability in a manner that is clear and easily interpretable. The eight indicators constituting the WUSI (Table 1) adhere to the SMART criteria. Specifically, each indicator is clearly defined through an unambiguous formulation (Specific); quantifiable, allowing for objective measurement (Measurable); achievable, as evidenced by the historical improvements observed in several utilities (Attainable); realistic, given its basis in routinely collected operational data reported by the utilities themselves (Realistic); and time-bound, since its evolution is systematically tracked and documented on an annual basis (Time-sensitive). Furthermore, the selection of indicators was strongly influenced by the availability of statistical data. Hence, in this case study, indicators were chosen to strike a balance between their relevance for evaluating the sustainability of Chilean WUs and the availability of statistical data necessary for their measurement.

A brief description of the sustainability indicators for the four dimensions considered in this study is provided below:

To assess the economic sustainability of WUs, the Return on Assets (ROA) and Return on Equity (ROE) were selected as key indicators. ROA measures how effectively a WU utilizes its total assets to generate net income, providing insight into the overall operational efficiency of asset management. ROE evaluates

TABLE 1 | Description of the indicators for sustainability assessment.

Dimension	Indicator	Definition	Type	Mean	SD	Min	Max
Economic	ROA (%)	Net income/total assets	Positive	5.56%	5.41%	−5.20%	24.10%
	ROE (%)	Net income/ shareholder's equity	Positive	8.78%	9.81%	−4.50%	44.00%
Social	Women representation in workforce (%)	Number of workers women/total number of workers	Positive	21.73%	8.18%	0.00%	33.30%
	Invoice reimbursement (%)	Number of invoices reimbursement/total number of invoices issued	Negative	1.28%	2.01%	0.00%	10.95%
Environmental	Water losses (%)	Volume of water lost/volume of water abstracted	Negative	28.54%	10.66%	6.50%	48.60%
	Wastewater treatment quality index	Estimated by SISS	Positive	0.983	0.036	0.810	1.000
Assets	Investment per customer (CLP/year)	Total investment per year/total number of customers	Positive	113,924	92,159	3454	371,832
	Water supply and sanitation network replacement (%)	Length of network replaced/total length of network	Positive	0.60%	0.44%	0.00%	1.32%

how efficiently a WU converts equity investments into net income, reflecting the financial profitability and sustainability of its capital structure. Both indicators are positive, meaning that higher values indicate better performance. However, since ROA and ROE can take both positive and negative values, this characteristic was accounted for in the formulation of Model (1) for estimating the WUSI.

Two key indicators were selected to assess the social sustainability reflecting both workforce diversity and customer service quality. Given the importance of gender equity in the social responsibility of WUs, the percentage of women in the total workforce of each WU was chosen as the first social indicator. This indicator reflects the commitment of WUs to inclusive employment practices and gender diversity. The second indicator focuses on customer relations and is defined as the percentage of invoice reimbursements over the total number of invoices issued. This indicator serves as a proxy for billing accuracy. It should be noted that the procedure for determining the conditions under which a WU must issue an invoice reimbursement is regulated by the SISS. Accordingly, a higher percentage of invoice reimbursements is indicative of more frequent billing errors and is therefore interpreted as a negative performance indicator. In contrast, alternative indicators such as customer satisfaction or the number of complaints are less suitable in the context of the Chilean water and sanitation sector, as they are strongly influenced by consumers' personal sensory perceptions (Denantes and Donoso 2021), rather than objective measures of service quality.

In the case of the environmental dimension, given that the assessed WUs provide both water supply and sanitation services, one indicator was selected for each service. The first indicator is water losses which represents the percentage of water losses relative to the total volume of water abstracted. In the Chilean context, this indicator is particularly relevant due to the persistent exceedance of the regulatory threshold (15%) for water losses over the past 15 years, and water scarcity issues affecting many regions of the country (Garreaud et al. 2020). The second indicator is "wastewater treatment quality index" which is computed annually by the SISS and evaluates the quality of treated effluent based on concentrations of suspended solids, chemical oxygen demand, and nitrogen (SISS 2023). This index reflects the effectiveness of wastewater treatment processes and the extent to which WUs comply with environmental regulations.

Two key indicators were selected to evaluate the assets sustainability of WUs, focusing on infrastructure investment and network renewal. The first one is the investment per customer expressed in Chilean Pesos per year. This indicator measures the annual investment per customer, reflecting the financial commitment of WUs to enhancing the robustness of both water and sanitation infrastructure. Higher investment levels indicate proactive asset management, aimed at reducing service failures and ensuring long-term system reliability. The second indicator is the network renewal rate. It represents the sum of the annual replacement percentages for both water supply and sanitation networks relative to the total network length. Regular network renewal is essential to maintaining operational efficiency, reducing failures, and extending the lifespan of infrastructure (Engelhardt et al. 2000).

Table 1 presents the definition of each indicator along with their key statistics. The data was sourced from the 2023 Annual Report on Water and Sanitation Services in Chile, published by SISS.

TABLE 2 | Descriptive statistics of the exogenous variables.

Exogenous variable	Obs	Mean	SD	Max	Min
Size (N customers)	29	208,336	430,894	2,160,340	3180
< 10,000 customers (small)	10	5454	1689	8968	3189
10,000–200,000 customers (medium)	11	82,510	67,647	188,947	17,966
> 200,000 customers (large)	8	634,949	666,677	2,160,340	208,284P
Ownership					
Public	1	3.45%			
Concessioned	8	27.56%			
Private	20	68.99%			
Geographical location					
North	4	13.79%			
Center	17	58.62%			
South	8	27.59%			

2.3 | Exogenous Variables Influencing Sustainability of WUs

The selection of potential exogenous variables influencing the sustainability of WUs was based on two main criteria. First, insights from previous studies (D'Amore et al. 2024; D'Inverno et al. 2021) and, second, the specific characteristics of the Chilean water and sanitation industry, including the availability of statistical data. Within this framework, three operational context variables were considered in the assessment (Table 2). The first variable is the size of the WU, measured by the number of households served with both drinking water and sanitation services. Based on this criterion, the 29 evaluated WUs were categorized into three groups: (i) utilities serving more than 200,000 households (large), (ii) utilities serving between 10,000 and 200,000 households (medium), and (iii) utilities serving fewer than 10,000 households (small). The second variable is the ownership structure of the utilities, classified into three types: (i) public utilities, (ii) concessioned utilities, and (iii) private utilities (Sala-Garrido et al. 2022). Finally, a geographical distinction was made for WUs operating in the northern, central, and southern regions of Chile (SISS 2023).

Table 2 presents the descriptive statistics for the variable size and the distribution of the categorical variables. The data was obtained from the 2023 Annual Report on Water and Sanitation Services in Chile, published by SISS.

3 | Methodology

3.1 | BoD

The BoD methodology is based on the Data Envelopment Analysis method, which considers multiple outputs and a single dummy input fixed at a value of 1 (May et al. 2024). DEA is a nonparametric linear programming approach that constructs a composite indicator—WUSI in this study—by forming an efficient frontier based on best-practice observations (Pishini et al. 2025; Sala-Garrido et al. 2023). In DEA, and consequently in BoD, indicator weights are determined in a data-driven manner, selected to maximize the WUSI for the evaluated WU (Sala-Garrido et al. 2021). Another advantage of the BoD methodology is its invariance to rescaling of individual indicators, allowing for the inclusion of ratio data in the analysis (D'Inverno et al. 2021).

The initial formulation of the BoD model by Cherchye et al. (2007) considered only positive indicators—that is, indicators where larger values correspond to better performance of the evaluated unit. However, in the context of WUs' sustainability, negative indicators must also be accounted for, where lower values indicate better performance, such as water losses, which are a critical factor (D'Inverno et al. 2021). To incorporate both positive and negative indicators in WUSI estimation, the BoD model proposed by Zanella et al. (2015) was applied. This model adopts a directional distance approach, enabling the simultaneous expansion (maximization) of positive indicators and contraction (minimization) of negative indicators. This adjustment is guided by a direction vector $g = (g_y, g_b)$ where g_y and g_b define the respective directions for positive and negative indicators (Vidoli et al. 2024).

The WUSI for each assessed WU, j_0, was computed by solving the following maximization problem (Zanella et al. 2015):

$$\max \beta \tag{1}$$

$$\sum_{j=1}^{n} b_{kj}\lambda_j \le b_{kj_0} - \beta g_b, \text{for } k = 1, \dots, l,$$

$$\sum_{j=1}^{n} y_{rj}\lambda_j \ge y_{rj_0} + \beta g_y, \text{for } r = 1, \dots, s,$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0, \text{for } j = 1, \dots, n$$

where b_{kj} represents the kth negative indicator and y_{rj} denotes the rth positive indicator and λ_j corresponds to the weights allocated to each indicator. The objective function value at the optimal solution, β, represents the maximal feasible expansion of the positive indicators and the contraction of negative ones (Matos et al. 2021). Hence, the factor β corresponds to the WUSI of the assessed WU. The WUSI ranges between zero and one, where a value of one represents the highest level of sustainability observed within the sample. In other words, WUs with a WUSI value of one demonstrate the best sustainability performance in comparison to their peers. The difference between a WU's WUSI value and one indicates its potential for improvement.

In the sustainability assessment of WUs, another critical issue is the integration of negative data, that is, indicators with negative values. Although the DEA method cannot directly handle negative data, selecting an appropriate directional vector enables overcoming this limitation (Portela et al. 2004; Silva et al. 2020). Specifically, Kerstens and Van de Woestyne (2011) and Oliveira et al. (2019) proposed incorporating negative data in DEA—and consequently in BoD—by defining a suitable directional vector $g = (-g_b, g_y) = \left(-\left|b_{kj_0}\right|, \left|y_{rj_0}\right|\right)$. Given that several assessed WUs exhibit negative values for economic indicators, we have adopted this approach.

3.2 | Analytical Hierarchy Process

The AHP is a MCDA method used to assign weights to indicators for constructing a composite indicator which in this case is the WUSI. The AHP involves three main stages. The first one is structuring the problem hierarchically: the objective (evaluating the sustainability of WUs) is placed at the top level of the hierarchy. Below this level, dimensions of sustainability are represented at intermediate levels, while indicators form the lowest level (Jiang et al. 2023). Second, decision-makers evaluate the relative importance of attributes (dimensions or indicators) through pairwise comparisons employing Saaty's nine-point scale (Saaty 1980). Each attribute is compared with others at the same hierarchical level, and decision-makers determine which attribute is more significant based on its perceived impact on the level above (Pagano et al. 2021). Finally, priorities are synthesized, and consistency is verified. In doing so, a matrix of relative weights is generated from the pairwise comparisons at each hierarchical level. Eigenvectors are computed to derive the final weights assigned to attributes (Shao et al. 2024). Given that pairwise comparisons rely on subjective judgments, consistency must be verified. This is achieved through the consistency ratio (CR), which assesses the coherence of the comparisons, ensuring logical consistency. The CR is calculated using Equation (2) (Saaty 1980).

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \tag{2}$$

where CI is the consistency ratio, defined in Equation (3), and RI is the random consistency index, which corresponds to the consistency index of a randomly generated reciprocal matrix based on Saaty's scale with forced reciprocals.

$$\text{CI} = \frac{1}{p-1}\left(\zeta_{\max} - p\right) \tag{3}$$

where p is the number of indicators in the judgment matrix, that is, the sum of l and s, and $\zeta_{\max}$ denotes the maximum eigenvalue.

Following (Molinos-Senante et al. 2014), once the weights of the indicators were determined, the WUSI for each WU was calculated as follows:

$$\text{WUSI}_{j_0} = \sum_{p=1}^{P} W_p \times IN_{jp} \tag{4}$$

where WUSI_{j_0} is the sustainability index of the WU j_0, $p = 1, \dots, P$ where (p) is the total number of indicators comprising the composite indicator of sustainability (WUSI), W_p denotes the weight of the indicator p, and IN_{jp} is the normalized value of the WU j_0 for the pth indicator. The normalization of indicators ensures the use of dimensionless scales ranging between 0.0 and 1.0, thereby preventing differences in units and ranges of variation in the initial set of indicators from influencing the final WUSI results. As in the BoD approach, the WUSI estimated for each WU ranges between 0 and 1, ensuring comparability of results.

Since the assessment includes both positive and negative indicators, normalization was conducted using Equations (5) and (6), respectively:

$$IN_{jp} = \frac{I_{jp} - I_p^{\min}}{I_p^{\max} - I_p^{\min}} \tag{5}$$

$$IN_{jp} = \frac{I_p^{\max} - I_{jp}}{I_p^{\max} - I_p^{\min}} \tag{6}$$

where IN_{jp} is the normalized value of the pth indicator for WU j_0, I_{jp} represents the original value of the pth indicator for WU j_0, $I_p^{\max}$ and $I_p^{\min}$ denote the maximum and minimum observed values, respectively, for the pth indicator across all assessed WUs.

3.3 | Influence of Exogenous Variables on Sustainability

Previous research (Gidion 2023; Molinos-Senante et al. 2023; Romano et al. 2017) has demonstrated that the background conditions in which a WU operates can influence its performance and, consequently, its sustainability. These conditions, referred to as exogenous variables, cannot be considered performance indicators since they are beyond the direct control of WUs.

From a methodological perspective, two main approaches are commonly used to analyze the influence of exogenous variables on the performance (sustainability) of WUs. The first approach, adopted in some previous studies (Ananda 2014; Villegas et al. 2019), employs econometric models in which the estimated composite indicator (WUSI in this study) is regressed against a set of exogenous variables. In this framework, the composite indicator serves as the dependent variable, while the exogenous variables act as independent variables. However, this approach presents two main limitations. First, serial correlation may arise between the error term and the set of covariates in the econometric model (Simar and Wilson 2007). Second, multicollinearity issues may also affect the regression model (Picazo-Tadeo et al. 2008). The alternative approach involves grouping WUs according to the exogenous variables under investigation and then assessing whether statistically significant differences exist between the groups in relation to their composite indicator (WUSI). To this end, the Kruskal–Wallis test is applied. This nonparametric statistical test determines whether samples originate from the same distribution (Kruskal and Wallis 1952). A significant Kruskal–Wallis test result indicates that at least one sample stochastically dominates another, suggesting differences in sustainability levels among WU groups.

The hypothesis testing is as follows:

Hypothesis 0. *The k samples come from the same population.*

Hypothesis 1. *Some samples come from other population.*

The null hypothesis could be rejected at a 95% significance level when the p value was less than or equal to 0.05 (Ruxton and Beauchamp 2008). It means that the exogenous factor assessed influences the WUSI of the WUs from a statistical point of view.

4 | Results and Discussion

4.1 | Weights Allocation

In the BoD approach, the weights assigned to each indicator comprising the WUSI are determined endogenously, meaning they are optimized by solving Equation (1) in a way that is most favorable for the WU under evaluation—specifically, to maximize its sustainability index. Consequently, each WU allocates different weights to each indicator (Table 3). In contrast, the AHP approach incorporates the preferences of stakeholders or experts in the weight allocation process. As a result, all WUs are assigned the same weight for each indicator (Table 3).

In this case study, the AHP method was used to allocate weights, based on the input of 35 Chilean experts in urban sustainability from CEDEUS[1] (Center for Sustainable Urban Development). These experts were asked to complete a carefully designed questionnaire. A total of 23 out of 35 experts responded to the survey. However, after assessing the CR of the responses, 6 questionnaires were discarded, resulting in a final dataset of 17 valid responses. All experts consulted are engaged in research related to urban sustainable development. Specifically, 12 out of the 17 participants are academics holding PhDs in diverse fields, including environmental engineering, geography, environmental sciences, social sciences, and public policy. In addition, three experts are professionals working in the planning departments of WUs, while two are affiliated with the Chilean Ministry of Public Works—the governmental body responsible for overseeing the SISS. This composition reflects a predominance of academic perspectives in the expert panel. Therefore, future research would benefit from incorporating a broader representation of stakeholders from regulatory agencies and WUs, enabling a comparative analysis of preferences across different institutional contexts. To aggregate the experts' preferences, the geometric mean of their individual judgments was computed.

Under the BoD approach, the weights assigned to the indicators ROE and water supply and sanitation network replacement are 0.00% for the 29 WUs assessed (Table 3). This implies that these indicators were not incorporated into the estimation of the WUSI. Despite the analyst's recognition of their relevance in assessing WU sustainability, their exclusion is due to consistently poor performance across all WUs. The same applies to any indicator that receives a weight of 0.00% for certain WUs. It is important to note that none of the 29 WUs assign a weight greater than 0.00% to all indicators. As a result, no utility generates a sustainability composite indicator that integrates all eight indicators defined by the analyst. Furthermore, 13 out of 29 WUs (44.8%) assign the maximum weight (100%) to a single indicator—wastewater treatment quality index—while allocating 0.00% to the remaining seven indicators that comprise the WUSI. This means that for these 13 WUs, the WUSI estimated using the BoD approach is not truly a composite indicator; rather, it solely reflects the performance of the utility in terms of wastewater treatment quality.

The weights allocated to each indicator for each WU under evaluation using the BoD approach reveal two notable limitations. First, when all indicators except one are given a weight of zero, the resulting composite indicator effectively reflects a single dimension of performance. Second, if different WUs receive non-zero weights for different subsets of indicators, the resulting composite indicators may capture fundamentally different aspects of sustainability. This lack of consistency undermines comparability across units and limits the robustness of the benchmarking exercise. To address this issue, the dual formulation of Model (1) allows for the inclusion of constraints on the relative importance of each indicator (D'Inverno and De Witte 2020). These constraints ensure that the percentage contribution of each indicator falls within a predefined range, thereby guaranteeing that all indicators included in the WUSI receive a non-zero weight. However, implementing such constraints requires the incorporation of analyst-defined preferences to determine the acceptable range for each weight, thereby reducing the methodological objectivity that characterizes the original BoD approach.

When indicator weights were allocated using the AHP method—based on expert preferences—all indicators received a weight greater than 0.0%, confirming that all eight indicators were effectively considered in the estimation of the WUSI.

TABLE 3 | Weights allocated to each indicator for each water utility (WU) under evaluation under the benefit of doubt method and common for all WUs under the analytic hierarchy process (AHP) method.

Method	WU	ROA	ROE	Women representation in workforce	Invoice reimbursement	Water losses	Wastewater treatment quality index	Investment per customer	Water supply and sanitation network replacement	Number of indicators with weights equal to 0.00%
BoD	WU1	2.75%	0.00%	0.00%	0.00%	0.62%	96.63%	0.00%	0.00%	5
	WU2	2.22%	0.00%	2.06%	0.00%	0.00%	91.23%	4.49%	0.00%	4
	WU3	50.00%	0.00%	0.00%	0.00%	50.00%	0.00%	0.00%	0.00%	6
	WU4	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU5	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU6	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU7	0.00%	0.00%	1.02%	0.28%	0.47%	98.23%	0.00%	0.00%	4
	WU8	11.97%	0.00%	38.03%	39.65%	10.35%	0.00%	0.00%	0.00%	4
	WU9	0.00%	0.00%	0.00%	0.00%	48.08%	0.00%	51.92%	0.00%	6
	WU10	0.00%	0.00%	89.15%	0.00%	10.85%	0.00%	0.00%	0.00%	6
	WU11	2.72%	0.00%	0.00%	0.00%	0.13%	96.75%	0.40%	0.00%	4
	WU12	0.00%	0.00%	50.00%	32.57%	17.43%	0.00%	0.00%	0.00%	5
	WU13	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU14	0.00%	0.00%	50.00%	0.00%	50.00%	0.00%	0.00%	0.00%	6
	WU15	13.81%	0.00%	0.00%	43.17%	6.83%	36.19%	0.00%	0.00%	4
	WU16	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU17	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU18	0.00%	0.00%	0.80%	0.16%	0.42%	98.62%	0.00%	0.00%	4
	WU19	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU20	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU21	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU22	1.18%	0.00%	96.94%	0.92%	0.00%	0.00%	0.95%	0.00%	4
	WU23	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU24	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU25	0.00%	0.00%	98.08%	1.92%	0.00%	0.00%	0.00%	0.00%	6
	WU26	0.00%	0.00%	0.00%	49.77%	0.00%	0.00%	50.23%	0.00%	6
	WU27	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
	WU28	0.00%	0.00%	4.76%	3.01%	0.00%	92.23%	0.00%	0.00%	5
	WU29	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	7
AHP	All WUs	9.03%	7.39%	8.37%	9.23%	10.16%	22.93%	18.84%	14.05%	0

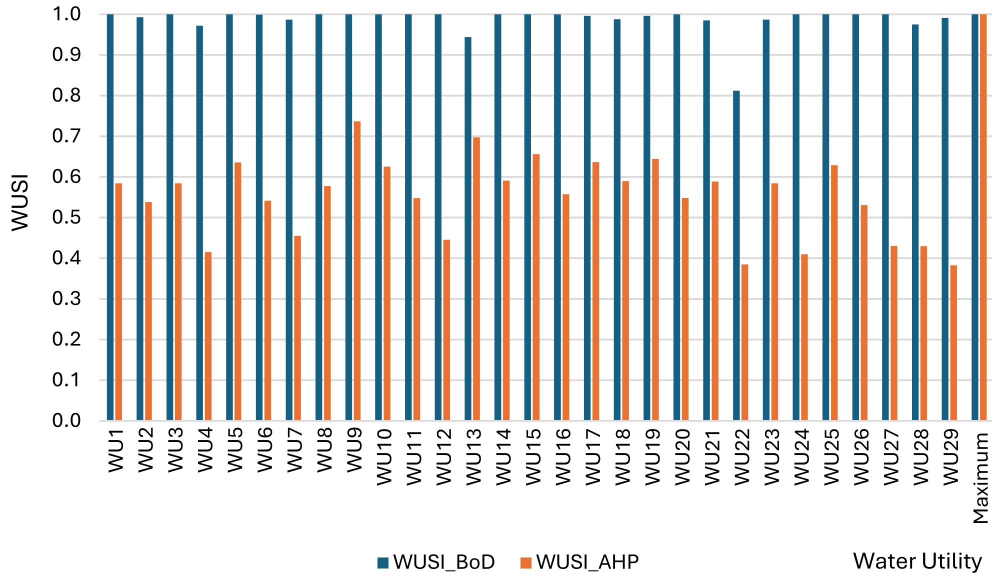

FIGURE 1 | Water utility sustainability index (WUSI) for each water utility (WU) based on BoD and AHP methods.

According to expert preferences, the two indicators representing the assets dimension are the most relevant for assessing the sustainability of WUs, with a total weight of 32.89%. This highlights the significance of long-term performance in sustainability assessment and underscores the need to consider "assets" as a distinct dimension of sustainability, rather than relying solely on the traditional TBL framework. Conversely, the two indicators representing the economic dimension were deemed the least relevant by experts, with a total weight of 16.42%. This may be influenced by the fact that most Chilean WUs are privately owned, operating under the assumption that they independently manage their financial and economic stability. However, the financial crisis of Thames Water—the largest WU in England—demonstrates that this assumption is not always valid, as the company currently faces £15.2 billion in debt (BBC 2025).

4.2 | WUSI

The WUSI of each evaluated WU was estimated using both the BoD and AHP methodological approaches (Figure 1), leading to notable differences. The average WUSI for the 29 assessed WUs was 0.987 using the BoD approach and 0.551 using the AHP approach, that is, a difference of 43.6%. As shown in Figure 1, when weights were allocated to maximize each WU's WUSI (BoD approach), 16 out of 29 WUs (55.17%) achieved the maximum score of 1.0, indicating full sustainability. In contrast, when weights were assigned according to expert preferences (AHP approach), the highest WUSI recorded was 0.737 (WU9). This suggests that even the most sustainable WU has room for improvement, as the maximum achievable WUSI is 1.0. The minimum WUSI obtained under the BoD approach was 0.812 (WU22), while the same WU had a WUSI of 0.385 under the AHP approach, indicating a significantly greater potential for improvement in sustainability under the expert-driven weighting system. Differences between the two approaches are also evident in terms of variability of WUSI values across WUs. The standard deviation for BoD-based WUSI was 0.035, whereas for AHP-based estimates, it was 0.095.

The choice of weighting approach for estimating WUSI also impacts the ranking of WUs in terms of sustainability, which can be valuable from a regulatory perspective. As shown in Table 4, when the WUSI is estimated using the BoD method, multiple utilities share the top position in the ranking, making it impossible to identify a single WU as the most sustainable. In contrast, when the AHP method is applied, each position in the ranking is occupied by a single WU. In this context, WU9 was identified as the most sustainable utility. It ranked first based on the AHP method and also achieved a WUSI of 1.0 under the BoD method. WU9 is a medium-sized utility providing water and sanitation services to approximately 189,000 households in the northern region of the country (SISS 2023). It demonstrates strong and well-balanced performance across all eight WUSI indicators, with no indicator scoring below the sample average. Moreover, WU9 stands out in the asset dimension. Its investment per customer is 2.36 times higher than the average, and its water and sanitation network renewal rate is the highest among the 29 assessed utilities, being 2.2 times greater than the average. These factors contribute to its strong sustainability performance.

The identification of the WU with the lowest sustainability differs depending on the methodological approach used. On the one hand, under the BoD approach, WU22 has the lowest WUSI. Even when weights are allocated to maximize its sustainability, its estimated WUSI is 0.812, indicating an 18.8% potential improvement compared to the most sustainable WUs. WU22 is a small utility serving approximately 3800 households in the central region of the country. Among the eight WUSI indicators, it performs above the sample average only in two: women's representation in the workforce and invoice reimbursement. This suggests that WU22 demonstrates relatively strong performance in the social dimension of sustainability but struggles in other areas. Notably, both economic indicators—ROE and ROA—are negative, and its water

TABLE 4 | Rank of water utilities (WUs) based on its sustainability estimated using BoD (Rank_BoD) and AHP (Rank_AHP) approaches.

Water utility	Rank_ BoD	Rank_ AHP	Difference Rank_AHP and Rank_BoD
WU24	1	27	26
WU27	1	24	23
WU12	1	23	22
WU26	1	21	20
WU11	1	18	17
WU20	1	17	16
WU16	1	16	15
WU8	1	15	14
WU1	1	14	13
WU3	1	13	12
WU14	1	9	8
WU10	1	8	7
WU25	1	7	6
WU5	1	6	5
WU15	1	3	2
WU9	1	1	0
WU6	17	19	2
WU17	18	5	−13
WU19	19	4	−15
WU2	20	20	0
WU29	21	29	8
WU18	22	10	−12
WU7	23	22	−1
WU23	24	12	−12
WU21	25	11	−14
WU28	26	25	−1
WU4	27	26	−1
WU13	28	2	−26
WU22	29	28	−1

and sanitation network renewal rate is 0.0%. On the other hand, under the AHP approach, WU22 ranks 28th, indicating poor sustainability but not the lowest among the assessed WUs. In this case, WU29 occupies the last position, whereas it ranked 21st under the BoD approach. WU29 is also a small utility, serving around 5220 households in the central region (SISS 2023). It performs below the sample average in seven out of the eight WUSI indicators, with the only exception being women's representation in the workforce, where it slightly exceeds the average (23.6% vs. 21.7%). Although none of its indicators represent the worst individual performance, their collective impact results in the lowest overall WUSI, as it only excels in a single indicator.

Table 4 also presents the ranking differences for each WU based on WUSI estimates derived from the AHP and BoD approaches. The results indicate that only WU9 and WU20 maintain the same ranking position under both methodologies. Furthermore, no clear trend of over-position or under-position emerges when comparing the two approaches. A total of 17 out of 29 WUs (58.6%) achieve a higher ranking when WUSI is estimated using the BoD method rather than the AHP approach. This is largely influenced by the fact that 16 WUs share the top position under the BoD method. Conversely, 10 WUs (34.5%) exhibit the opposite trend, ranking lower under the BoD method compared to the AHP approach.

The estimation of WUs' sustainability using the AHP method allows for the computation of each dimension's contribution to the WUSI (Figure 2). By comparing these values with their maximum achievable scores—determined by the weights assigned to each indicator—it is possible to identify the strengths and weaknesses of each WU across the different sustainability dimensions. As illustrated in Figure 2, none of the evaluated WUs achieved the maximum score in the economic, social, or assets dimensions, indicating that all utilities have room for improvement in these areas. In contrast, WU23 attained the maximum score (0.33) in the environmental dimension. This is due to its exceptionally low percentage of water losses (6.5%)—the lowest among all assessed WUs—and its wastewater treatment quality index of 1.00, the highest possible score. However, as shown in Table 3, WU23 does not rank as the most sustainable utility overall, as its performance in other dimensions, particularly the economic and assets, falls significantly below the maximum achievable scores.

Figure 2 also highlights WU22 as the weakest performer in the assets dimension, with a contribution of 0.0 to the WUSI. This is because it has the lowest performance in both indicators within this dimension. Similarly, WU27 has a contribution of 0.0 to WUSI in the economic dimension, reflecting its poor performance in this area. This detailed analysis enables the identification of specific dimensions where each WU should focus its efforts to enhance sustainability, as well as those in which it already demonstrates strong performance.

4.3 | Impact of Exogenous Variables on Sustainability

To examine the potential influence of exogenous variables—size, ownership, and geographical location—on the sustainability of WUs, we applied the Kruskal–Wallis test for each variable. Table 5 presents the average WUSI for each WUs' group based on both BoD and AHP estimations, along with the corresponding *p* values from the Kruskal–Wallis tests. In addition, box plots illustrating the statistical distribution of each WU group are provided as supplemental material.

Regarding the size of the assessed WUs, the BoD-based WUSI estimations reveal no statistically significant differences

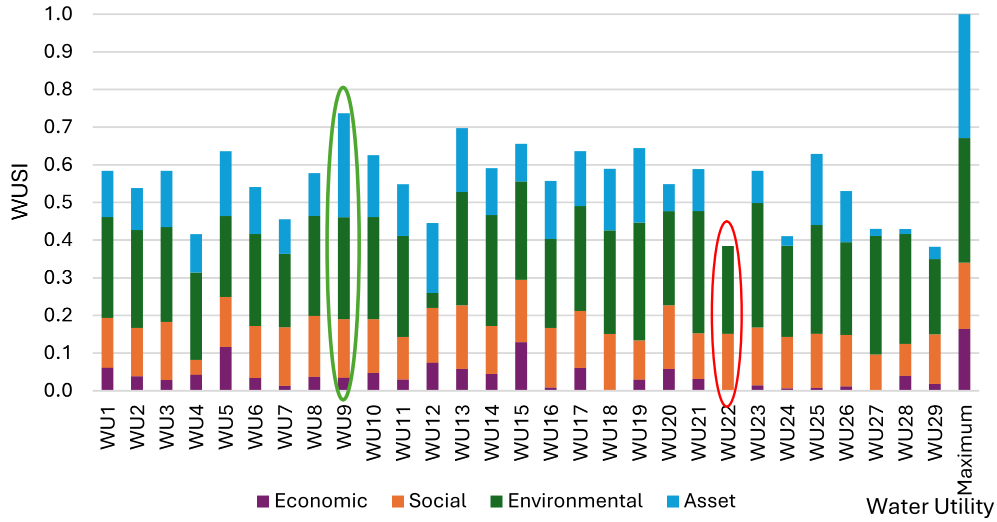

FIGURE 2 | Contribution of each dimension of sustainability to WUSI in comparison with its maximum.

TABLE 5 | Average water utility sustainability index (WUSI) for each group of water utilities, estimated using BoD and AHP methods, along with the *p* value of the Kruskal–Wallis test.

Explanatory variable	Average WUSI_BoD	*p* (BoD)	Average WUSI_AHP	*p* (AHP)
Size				
< 10,000 customers (small)	0.975	0.591	0.492	0.030
10,000–200,000 customers (medium)	0.993		0.612	
> 200,000 customers (large)	0.994		0.541	
Ownership				
Public	0.987	0.317	0.455	0.316
Concessioned	0.990		0.599	
Private	0.986		0.537	
Geographical location				
North	1.000	0.032	0.596	0.044
Center	0.984		0.522	
South	0.988		0.589	

among the three utility size groups (Table 5). This suggests that utility size does not influence sustainability when using this approach. However, when WUSI is estimated using the AHP method, the greater variability among WUs leads to statistically significant differences among size groups. The results, shown in Table 5, indicate that medium-sized utilities exhibit the highest WUSI, while small utilities have the lowest sustainability. These findings contrast with those of D'Inverno et al. (2021), who reported the highest sustainability levels for larger WUs. Nevertheless, the influence of utility size as an exogenous variable remains a topic of debate. Previous studies have shown that the "optimal" utility size varies significantly across different countries, highlighting the context-dependent nature of this relationship (Carvalho and Marques 2016; Molinos-Senante et al. 2023).

Regarding the ownership of the assessed WUs, no statistically significant differences in sustainability were observed among public, concessioned, and private utilities, as the *p* values obtained for both the BoD and AHP approaches are larger than 0.05 (Table 5). This finding aligns with previous research (González-Gómez and García-Rubio 2018; Peda et al. 2013; Romano et al. 2015), which also found no statistical differences in the performance of WUs based on ownership structure. In the case of Chilean WUs, this lack of difference may be attributed to the fact that all utilities, regardless of ownership, operate under the same legal and institutional framework and are subject to identical regulatory obligations.

The geographical location of WUs significantly influences their sustainability, with utilities in the central region of

Chile facing the most challenging conditions, while those in the north experience the most favorable ones. Although the differences in average WUSI values are not extremely large, they are statistically significant, as indicated by p values below 0.05 for both BoD- and AHP-based estimations. The central region of Chile is home to the majority of the country's urban population. In the Metropolitan Region of Santiago alone, 6,849,310 people reside (BCN 2025), accounting for approximately 40% of the national population. This high population density may exert pressure on WUs, negatively impacting their sustainability.

The findings of this study provide critical insights into the sustainability assessment of WUs, particularly regarding methodological differences, weighting criteria, and the influence of exogenous variables.

The significant discrepancies in WUSI estimations between the BoD and AHP methods highlight the importance of selecting an appropriate sustainability assessment framework. The BoD method allows WUs to optimize weights, thereby maximizing their WUSI values. Under this approach, utilities with lower sustainability scores cannot argue that the prioritization of criteria negatively impacts their performance. However, the results demonstrate that this method tends to overestimate sustainability. In contrast, the AHP method provides a more balanced and rigorous evaluation by incorporating expert judgment, which introduces some subjectivity into the assessment.

5 | Policy Recommendations

The policy implications drawn from the analysis conducted in this study are not only relevant to the Chilean case but can also be generalized to the global water and sanitation industry.

Given the differences in WUSI estimations based on BoD and AHP methodological approaches, it is recommended that sustainability assessment frameworks could integrate stakeholder preferences, including not only policymakers and regulators but also utility managers and consumers. The recommendation to use MCDA methods incorporating stakeholder preferences is further supported by the fact that, under the BoD method, several indicators receive a weight of 0.0. This means that these indicators are in practice excluded from the WUSI calculation, leading to potential biases in sustainability estimation. As a result, the composite indicator varies across WUs, making direct comparisons challenging. Moreover, the ranking of WUs is highly sensitive to the weighting approach used, and the fact that the BoD method results in multiple WUs sharing the top position complicates benchmarking efforts. This is particularly problematic if sustainability considerations are to be integrated into regulatory frameworks.

Consistent with Marques et al. (2015), this study suggests that traditional sustainability frameworks, such as the TBL, may not fully capture the long-term sustainability of WUs. The findings highlight the importance of incorporating "asset management" as a distinct sustainability dimension, necessitating revisions to regulatory guidelines and performance assessment metrics. In this context, policymakers should enforce stricter regulations on asset renewal and promote financial mechanisms to support long-term investments in water and sanitation infrastructure.

In this context, water regulatory bodies should consider incorporating the WUSI—or alternative sustainability indices—into tariff-setting procedures to ensure that pricing frameworks reflect not only efficiency considerations but also broader sustainability objectives. WUs that demonstrate proactive asset management practices or achieve higher sustainability scores could be granted preferential tariff treatment or prioritized for investment incentives. Furthermore, the publication of WUSI-based rankings or scorecards would enhance transparency and accountability across the sector. Such measures would also help raise public awareness regarding the importance of sustainability in water and sanitation service provision, thereby creating additional pressure on utilities to improve their long-term performance.

For the effective estimation of sustainability indicators such as the WUSI, WUs should be required to periodically report data on a comprehensive set of indicators encompassing all dimensions of sustainability—not only financial and operational metrics, as it is commonly the case. This practice would enhance transparency and enable consistent monitoring of performance improvements over time. Given the complexity of this task, it is essential that the water regulator provides support to utilities in developing the necessary technical capacities and data management systems required to operationalize the WUSI, particularly in low-capacity or rural contexts. This support should include the implementation of standardized data collection protocols and the development of digital platforms for systematic performance tracking.

Regarding the influence of exogenous variables, the lower WUSI values observed for small WUs underscore the need for targeted policies to enhance their sustainability. Relevant measures may include financial assistance programs, investment incentives to improve infrastructure, and capacity-building initiatives to strengthen technical and managerial capabilities. In addition, the observed impact of geographical location on WU sustainability suggests that, in countries with significant climatic, socioeconomic, or demographic variability, location-specific regulatory adaptations could help address diverse operational challenges and promote sustainable water management.

6 | Conclusions

Benchmarking the sustainability of water and sanitation services is essential for achieving Sustainable Development Goal 6 and addressing the global sustainability challenges faced by society. However, the absence of a standardized methodology for measuring sustainability hinders its effective assessment. This study proposes and estimates a WUSI for a sample of WUs that provide both water and sanitation services. By comparing a data-driven approach (BoD) with a preference-based approach (AHP), the study underscores the critical role of methodological choices in evaluating sustainability performance.

The results demonstrate that while the BoD method allows utilities to maximize their sustainability scores by optimizing indicator weights, it often leads to overestimations. In contrast, the AHP method, which incorporates expert judgment, provides a more balanced and rigorous assessment, though it introduces some level of subjectivity. These findings suggest that sustainability assessments should integrate both data-driven and stakeholder-informed methodologies to ensure accuracy and fairness in utility benchmarking. Another critical insight from this study is the significant influence of weighting criteria on sustainability outcomes. Under the BoD approach, some indicators received a weight of zero, effectively excluding them from the assessment. This raises concerns about the comparability of WUSI scores across utilities. In contrast, the AHP approach ensures that all sustainability indicators contribute to the final score, enhancing both comparability and policy relevance. Furthermore, the variability in utility rankings between the two approaches underscores the need for transparency in sustainability assessment frameworks, particularly if these indices are to inform regulatory or policy decision-making.

Regarding the influence of exogenous factors on WUs' sustainability, the findings indicate that utility size and geographical location play significant roles in shaping sustainability outcomes. Small utilities tend to have lower sustainability scores, emphasizing the need for targeted policies to support their transition toward more sustainable practices. In addition, the observed geographical disparities in sustainability performance suggest that location-specific regulatory adaptations may be necessary to address region-specific challenges effectively.

From a policy perspective, this study provides valuable insights for regulators and decision-makers. The significant discrepancies in WUSI scores based on the weighting methodology highlight the need for regulatory agencies to adopt a hybrid approach that balances objective, data-driven methods with expert and stakeholder input. Furthermore, integrating sustainability performance into regulatory and tariff-setting frameworks could serve as a powerful incentive for WUs to adopt more sustainable practices, particularly in asset management and environmental stewardship. By linking sustainability metrics to policy and financial mechanisms, regulators can promote long-term multidimensional performance within the water and sanitation sector.

Endnotes

[1] https://en.cedeus.cl/.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.