

Assessing the resilience of water and wastewater utilities: A multi-criteria approach for Chile

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ARTICLE INFO

Keywords:

Operational resilience
Composite indicator
Water supply
Wastewater
Natural hazards
Performance

ABSTRACT

Ensuring the operational resilience of water and wastewater utilities (WWUs) is critical for safeguarding public health, environmental sustainability, and service continuity in the face of natural and human-induced hazards. This study develops an innovative Operational Resilience Index (ORI) to comprehensively assess WWU operational resilience from a regulatory perspective. The ORI integrates multiple resilience indicators across three key dimensions—service performance, asset management, and water security—using a Multi-Criteria Decision Analysis (MCDA) approach, incorporating expert and stakeholder preferences through the Best-Worst Method (BWM). The methodology is applied to 29 WWUs in Chile, a country with high exposure to natural disasters. The weights assigned to resilience indicators indicate a preference for short-term service performance over long-term infrastructure resilience. The estimated ORI values range from 0.524 to 0.808, with the maximum achievable score being 1.000. It was evidenced that asset management represents the most critical area for improvement, indicating a need for regulatory incentives to promote infrastructure renewal. While no statistically significant differences in ORI scores were found based on WWU ownership structure (public, private, or concessioned), concessioned WWUs demonstrated statistically superior performance in asset management (p -value = 0.012), underscoring the need for targeted regulatory measures to strengthen this dimension in other ownership models. The ORI provides a systematic benchmarking tool for regulators, enabling resilience-based performance assessments and targeted policy interventions.

1. Introduction

Access to sufficient, safe, acceptable, and affordable water for personal and domestic use, along with physical and affordable access to sanitation, are fundamental human rights [1]. These rights have been reinforced through Sustainable Development Goal 6, which aims to ensure universal access to water and sanitation by 2030 [2]. Ensuring the reliability and continuity of water and sanitation services is a critical priority for regulators, and municipalities, given their direct impact on public health, safety, and the environment [3]. However, water and wastewater utilities (WWUs) face a wide range of challenges, including natural hazards such as earthquakes, floods, hurricanes, and extreme temperatures, as well as human-made threats such as terrorist attacks, overloading, and vandalism, all of which can disrupt water and sanitation services [4,5].

Over the past few decades, resilience has emerged as a fundamental

concept for managing the performance of water supply systems in response to challenges posed by disaster events [6]. The literature offers multiple interpretations of resilience within the context of water supply systems, leading to variations in its quantification metrics and assessment approaches [7]. However, most previous research [8–11] has addressed resilience of water supply infrastructure primarily from an engineering and disaster management perspective, often as a “snapshot in time.” Moreover, they have largely focused on assessing the resilience of water supply networks, as these lifelines are exposed to a wide range of hazards that may compromise their functionality.

As an alternative approach, resilience at the utility level is conceived as a dynamic process in which operational procedures and responses are continuously reviewed against potential hazards [12]. In this context, the United Kingdom water regulator, OFWAT, defines the operational resilience of a WWU as “the ability of an organization’s infrastructure, along with the skills required to operate it, to prevent, withstand, and

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<https://doi.org/10.1016/j.seps.2025.102340>

Received 17 May 2025; Received in revised form 25 September 2025; Accepted 27 September 2025

Available online 29 September 2025

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recover from disruptions in its performance.” Additionally, operational resilience encompasses long-term adaptability to environmental pressures, demographic changes, shifts in customer behavior, and the impacts of climate change [13]. According to OFWAT [13], this study defines operational resilience as the ability of a utility’s infrastructure, together with the skills and processes required to operate it, to prevent, withstand, and recover from disruptions in its performance. This definition emphasizes resilience as a dynamic process that extends beyond engineering robustness to include service continuity, asset condition, and long-term adaptability.

Assessing the resilience of WWUs from a regulatory perspective offers several benefits, including the ability to understand and compare system resilience under different conditions. This information enables regulators to formulate policies on key topics such as climate adaptation, disaster preparedness, and emergency response. Additionally, it facilitates the identification of strengths and weaknesses within each WWU, thereby enhancing transparency in the planning and management of water and sanitation services [14]. Regulators and water managers can leverage resilience metrics to incentivize and justify investments in adaptive water and sanitation infrastructure, ensuring service continuity while safeguarding public health and the environment.

Despite the significance of this topic, research in this area remains limited, gaining increased attention during and after the COVID-19 pandemic. Farmani et al. [15] evaluated the resilience of water utilities worldwide to gain a better understanding of the current state and challenges these utilities faced during the COVID-19 pandemic. Their assessment was based on analyzing performance across key resilience-related indicators. Walker et al. [16] assessed the resilience of a sample of WWUs in the United Kingdom and Ireland using a Multi-Criteria Decision Analysis (MCDA) method, specifically Data Envelopment Analysis. In a similar context, Thelemaque et al. [17] examined a sample of small water utilities in the United States, analyzing the impact of COVID-19 on multiple performance indicators. COVID-19 was not the only hazard emphasized in assessments of water utilities’ resilience. Tiedmann et al. [18] investigated the resilience of 20 water utilities during and after a series of winter storm hazards, which triggered cascading effects across multiple critical infrastructure sectors. In this study, similar to Thelemaque et al. [17], the authors compiled and analyzed the values of multiple performance indicators. Chu-Ketterer et al. [19] developed a composite indicator to quantify the resilience of drinking water systems in New York (USA), defining resilience as the ratio of system performance during an emergency to its normal operation.

Previous studies assessing the resilience of water utilities and WWUs exhibit some drawbacks that are particularly relevant when conducting resilience assessments for regulatory purposes [20]. First, most studies have focused exclusively on the provision of water services, overlooking the sanitation services provided by many utilities, including wastewater collection and treatment. Second, these studies considered performance indicators from technical, economic, and environmental dimensions, failing to adequately address operational resilience, which is a crucial metric for the long-term planning of water and sanitation services [13]. Third, the resilience metrics presented are often highly detailed, focusing on specific components such as valves, outlets, and pumps. While valuable for technical assessments, this level of granularity limits their applicability for decision-making from a regulatory perspective [21]. Fourth, many assessments disregard key factors such as infrastructure deterioration and aging, despite their significant impact on resilience [22]. The aging and deterioration of water infrastructure increase vulnerability and the likelihood of service disruptions during and after disruptive events affecting its resilience [23]. Finally, many previous studies, particularly those focusing on water supply networks, rely on detailed datasets and computationally intensive methods that require substantial resources. This poses a challenge for their practical application, particularly in middle- and low-income countries, where data availability is limited, and resilience deficiencies are most pronounced

[24].

Previous studies assessing the resilience of water utilities, along with OFWAT’s [13] definition of operational resilience, highlight its inherently multidimensional nature. This complexity necessitates the use of composite indicators to comprehensively capture the various aspects of operational resilience [25–27]. Given the necessity of a multi-criteria approach for assessing the operational resilience of WWUs and the previously identified limitations in the literature, this study contributes in two key directions. First, recognizing the unique characteristics of WWUs and the necessity of assessing their long-term operational resilience for regulatory integration, we propose an innovative Operational Resilience Index (ORI). This composite indicator adopts a holistic approach, providing decision-makers with a comprehensive benchmarking tool to evaluate the operational resilience of WWUs. Second, we show the practical applicability of the ORI by its estimation for the Chilean water and sanitation sector, illustrating its potential to inform resilience-based regulatory frameworks.

In the context of operational resilience of WWUs, the Chilean case study presents a compelling example for several reasons. First, due to its location within the Pacific Ring of Fire and the increasing adverse impacts of climate change, Chile is among the countries most exposed to natural hazards worldwide. According to the World Risk Index [28], Chile ranks 39th out of 192 countries, with a very high-risk index for multiple hazards, including earthquakes, tsunamis, cyclones, floods, sea-level rise, and droughts [29]. These natural hazards pose significant threats to both the short-term and long-term functionality of water and sanitation infrastructure. Therefore, computing an ORI for each WWU is crucial for benchmarking resilience performance. Second, Chile is the only country in Latin America where drinking water supply and wastewater treatment coverage in urban areas is almost universal [30]. This makes Chile a valuable reference for other middle-income countries aiming to enhance their water and sanitation services. Finally, Chilean WWUs operate under diverse ownership models, including public, concessioned, and private entities. By comparing the ORI across different ownership structures, this study contributes to the ongoing debate on the influence of ownership models on the performance of WWUs.

This study contributes to the literature in several ways. First, it extends resilience assessment beyond water supply to include wastewater services, providing a holistic evaluation of utilities’ performance. Second, the proposed ORI is explicitly designed for **regulatory benchmarking**, enabling regulators to identify resilience gaps and prioritize interventions. Third, the use of the Best-Worst Method ensures that stakeholder and expert perspectives are systematically incorporated, enhancing both robustness and policy relevance of the index. Finally, the Chilean case study illustrates the practical value of the ORI in a country highly exposed to natural hazards, offering insights that can be extrapolated to other middle- and low-income countries facing similar challenges.

2. Methods

2.1. Operational resilience index

2.1.1. Definition of resilience indicators and weights allocation

A key characteristic of the proposed ORI is its multidimensional perspective, as it integrates multiple operational resilience indicators into a composite indicator. A significant portion of the literature on composite indicators focuses on weighted methods, in which weights are assigned to each criterion (indicator) based on its relative importance in constructing the index (ORI in this study) [31]. In this context, three main methodological approaches can be distinguished: i) endogenous weighting methods; ii) stakeholder-driven weighting methods and; iii) equal weighting methods. Some MCDA methods, such as Data Envelopment Analysis and Distance-Principal Components, determine indicator weights endogenously based on the dataset of the evaluated units

(WWUs in this study) [32,33]. The key advantage of this approach is its objectivity, as the weight allocation process is data-driven, reducing subjectivity, an issue often debated in multi-criteria assessments [34]. A second approach allocates weights based on stakeholder preferences and/or expert opinions, employing techniques such as MACBETH, Analytical Hierarchy Process (AHP), or Best-Worst Method (BWM) [35–37]. This approach recognizes that the relevance of indicators, embracing the index, may vary depending on the local, regional, or national context. By integrating stakeholder perspectives, it enhances the contextual adaptability of multi-criteria assessments [38]. The third approach applies alternative MCDA techniques, such as Goal Programming, where equal weights are assigned to all indicators. This ensures that each indicator within the composite indicator carries the same level of importance [39,40]. While this approach promotes simplicity and transparency, it may overlook variations in the relative significance of different resilience indicators.

Since the ORI proposed in this study is designed for benchmarking WWUs for regulatory purposes, it is essential to incorporate the perspectives of stakeholders and decision-makers in the weight allocation process. Moreover, endogenously determined weights—where indicator weights are derived solely from the dataset—often result in some indicators receiving a weight of zero for certain units. This effectively excludes those indicators from the composite index, limiting its comprehensiveness [41]. Among stakeholder-driven weighting methods, AHP and its subsequent developments have been widely applied in various decision-making contexts, including resilience assessment [42,43]. In AHP, indicator weights are derived from pairwise comparisons conducted by decision-makers. However, a major challenge of MCDA techniques using pairwise comparisons, such as AHP, is consistency in decision-making, which often becomes an issue in practice [44]. According to Kuo & Chen [45] and Rezaei [37], inconsistencies in pairwise comparisons arise primarily from the unstructured nature of the comparison process. To address this limitation, this study employs the BWM, as proposed by Rezaei [37], to allocate weights to the set of resilience indicators constituting the ORI. This approach enhances consistency and reliability in weight estimation, improving the robustness of the estimated composite index (ORI) [46, 47].

The steps followed to allocate weights to resilience indicators according to Rezaei [37] are as follows:

Step 1. Definition of the resilience indicators for the ORI.

The first step involves selecting the resilience indicators $\{i_1, i_2, \dots, i_n\}$ that will be integrated into the ORI for the evaluated WWUs. Several criteria should be considered when selecting these indicators. While the ORI should remain simple and concise, it must also incorporate key aspects of operational resilience relevant to water regulators and WWUs. Each indicator should be preferentially independent, meaning that its performance should not influence or depend on the performance of any other criterion [38]. Furthermore, all indicators had to adhere to the SMART criteria, meaning they should be Specific, Measurable, Attainable, Realistic, and Time-sensitive [48]. Lastly, data availability is a key consideration, as the feasibility of including an indicator strongly depends on the existence of reliable statistical data [49].

Step 2. Identification of the best and worst indicators.

The decision-maker identifies the most relevant (i.e., the best) and least relevant (i.e., the worst) indicator within the framework of operational resilience of WWUs.

Step 3. Preference assessment for the best indicator

The preference of the best indicator over all other indicators is determined using a scale from 1 to 9. This results in the Best-to-Others

vector:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn}), \quad (1)$$

where a_{Bj} represents the preference of the best indicator B over indicator j , with $a_{BB} = 1$.

Step 4. Preference assessment for the worst indicator

Similarly, the preference of all indicators over the worst indicator is determined using a scale from 1 to 9, producing the Others-to-Worst vector:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T, \quad (2)$$

where a_{jW} represents the preference of the indicator j over the worst indicator W with $a_{WW} = 1$.

Step 5. Estimation of optimal weights for each indicator

The optimal weight for the indicators are derived by ensuring that, for each pair w_B/w_j and w_j/w_W , the following condition hold:

$$w_B/w_j = a_{Bj} \text{ and } w_j/w_W = a_{jW} \quad (3)$$

To satisfy these conditions for all indicators, j , we should find a solution where the maximum absolute differences $|w_B/w_j - a_{Bj}|$ and $|w_j/w_W - a_{jW}|$ for all j is minimized.

Considering the non-negativity and sum condition for the weights, the following problem should be solved:

$$\min \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\} \quad (4)$$

s.t.

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all } j$$

The optimization problem (4) can be reformulated as follows:

$$\min \varphi \quad (5)$$

s.t.

$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \varphi, \text{ for all } j$$

$$\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \varphi, \text{ for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for all } j$$

By solving Model (5), the optimal weights for each indicator $(w_1^*, w_2^*, \dots, w_j^*)$ and the optimal consistency parameter φ^* are derived. The parameter φ^* is used to compute the consistency ratio, whose details are provided in the supplemental material. The larger the φ^* value, the higher the inconsistency in the pairwise comparisons, making the weight allocation less reliable.

2.1.2. Normalization of resilience indicators

The selected resilience indicators (Stage 1 of subsection 2.1.1) may have different units of measurement and varying scales. Therefore, prior to aggregation, it is essential to normalize the indicators. Normalization ensures that all indicators are transformed into dimensionless values ranging between 0.0 and 1.0, preventing differences in units and variations across indicators from influencing the final ORI results. Additionally, normalization allows the estimated ORI values for each WWU to remain within the standardized range of 0–1, facilitating comparability across utilities.

The normalization process follows Equations (6) and (7) for positive and negative indicators, respectively. For positive indicators, higher values correspond to better resilience for the evaluated WWU. For negative indicators, lower values indicate better resilience for the evaluated WWU.

$$IN_{nj} = \frac{I_{nj} - I_j^{\min}}{I_j^{\max} - I_j^{\min}} \quad (6)$$

$$IN_{nj} = \frac{I_j^{\max} - I_{nj}}{I_j^{\max} - I_j^{\min}} \quad (7)$$

where IN_{nj} is the normalized value of the j_{th} indicator for WWU n_0 , I_{nj} represents the original value of the j_{th} indicator for WWU n_0 , $I_j^{\max}$ and $I_j^{\min}$ denote the maximum and minimum observed values, respectively, for the j indicator across all assessed WWUs.

2.1.3. Built the composite indicator, ORI

Once the optimal weights for each resilience indicator have been determined and all indicators for each assessed WWU have been normalized, the ORI for each WWU under evaluation is estimated as follows:

$$ORI_{n_0} = \sum_{i=1}^j w_j^* \cdot IN_{nj} \quad (8)$$

where ORI_{j_0} is the operational resilience index of the WWU n_0 , $i = 1, \dots, j$ where (j) is the total number of indicators comprising the composite indicator of operational resilience (ORI), w_j^* denotes the optimal weight of the indicator j , and IN_{nj} is the normalized value of the WWU n_0 for the j_{th} indicator.

2.2. Influence of ownership on operational resilience

The relationship between ownership structure and performance has long been a central topic of debate in the water industry [50]. However, empirical evidence regarding the superiority of private management over public management in urban water services remains inconclusive [51,52]. Given that Chilean WWUs operate under public, private, and concessioned ownership models, this study investigates the influence of ownership on operational resilience, aiming to contribute to this ongoing debate.

From a methodological perspective, two main approaches are commonly used to analyze the impact of exogenous variables, such as ownership,¹ on the performance of WWUs. The first approach involves the use of econometric regression models, where a performance index (e.g., ORI) is regressed against a set of exogenous variables [53]. However, this method is subject to limitations, including potential serial correlation between the error term and covariates, leading to biased estimates [54], as well as multicollinearity issues, which can distort the

statistical significance of explanatory variables [55].

As an alternative, this study employs a non-parametric statistical approach, where WWUs are grouped by ownership type, and statistical tests are conducted to determine if significant differences exist in their operational resilience. Specifically, the Kruskal-Wallis test is applied to assess whether the distributions of ORI scores differ among ownership groups [56]. This test determines whether samples originate from the same distribution. A statistically significant result would suggest that at least one group exhibits stochastic dominance, indicating differences in operational resilience. The hypothesis testing framework is as follows:

$H_0 =$ The k samples come from the same population

$H_1 =$ Some samples come from other population

The null hypothesis is rejected at a 95 % significance level when the p -value is ≤ 0.05 [57]. This statistical outcome indicates that ownership has a significant influence on the operational resilience of WWUs.

2.3. Water and wastewater utilities in Chile

In Chilean urban areas, the provision of water and sanitation services is managed by WWUs, meaning that the same utility is responsible for delivering both services to customers. Currently, 47 WWUs operate across the country, achieving drinking water service coverage of 99.94 %, while wastewater collection and treatment reach coverage levels of 99.94 % and 100.00 %, respectively. Additionally, the average per capita water consumption in Chile stands at 153.5 L per day [58].

Chile's water and sanitation sector is predominantly privatized, with over 96 % of customers served by concessionary and private WWUs. The privatization process occurred primarily between 1998 and 2004 [52]. WWUs are regulated by the Superintendencia de Servicios Sanitarios (SISS), the national urban water regulator. Although the urban water regulator existed prior to privatization, its role was significantly strengthened following the transition to private-sector management. Despite differences in ownership structures, all WWUs utilities operate under the same institutional and legal framework, ensuring regulatory consistency across the sector.

In addition to setting water tariffs and ensuring the financial sustainability of WWUs, the SISS is responsible for developing policies to manage and mitigate natural hazard risks affecting utilities. In 2015, Chile joined the Sendai Framework for Disaster Risk Reduction 2015–2030 and subsequently enacted the National Policy for Disaster Risk Reduction 2020–2030 and the National Strategic Plan for Disaster Risk Reduction 2020–2030 [59]. Within this policy framework, the SISS has been assigned a key role in planning disaster risk reduction in the water and sanitation sector. To address this challenge, the SISS restructured its organization by creating a dedicated unit responsible for developing guidelines for disaster risk management in the water and sanitation sector [60]. Additionally, in 2021, Law 21.364 was enacted, establishing the National System for Disaster Prevention and Response. Under this framework, the newly formed National Service of Prevention and Response to Disasters is required to collaborate with public and private entities, including WWUs and the SISS, to support the development of sectoral plans aimed at enhancing resilience. These regulatory and institutional advancements underscore the critical importance of assessing the operational resilience of WWUs, ensuring their ability to withstand and recover from disruptive events.

Regarding the evaluated WWUs, the study sample consists of the 29 largest WWUs in Chile, which collectively provide water and sanitation services to approximately 98 % of urban customers (See Table S1 in Supplemental Material). These 29 utilities operate across all 16 administrative regions of the country, ensuring that the sample is representative at the national level. The selected WWUs encompass three ownership types: public (1 WWU), concessionary (8 WWUs), and private (20 WWUs). This distribution allows for a comprehensive analysis of ownership influences on operational resilience within Chile's

¹ The same methodological approach could be used to investigate the potential influence of other exogenous variables on the operational resilience of water and wastewater utilities.

water and sanitation sector.

2.4. Resilience indicators selection

The resilience indicators incorporated into the ORI were carefully selected to strike a balance between their relevance for assessing operational resilience in Chilean WWUs and the availability of statistical data. The selection process ensured that indicators represent both drinking water and sanitation services (wastewater collection and treatment), providing a comprehensive evaluation of resilience. A total of nine resilience indicators were chosen, categorized into three key dimensions: i) service performance; ii) asset management and iii) water security.

A brief description of each resilience indicator within these categories is provided below:

The service performance dimension comprises four key indicators that assess the outcomes received by customers and capture WWUs' failures to mitigate risks when they impact service provision. The four indicators embracing this dimension provide a quantitative assessment of WWUs' service reliability and quality, ensuring that operational resilience is evaluated from the customer impact perspective.

- “Drinking Water Quality Index”. This is a synthetic index computed annually by the SISS to evaluate the quality of drinking water supplied by each WWU. The index assesses compliance with the Chilean Drinking Water Quality Standard (NCh 409/2), considering parameters such as bacteriological quality, turbidity, monthly control parameters, and annual control parameters. The index is expressed as a percentage ranging from 0 % to 100 %, where 100 % indicates full compliance with NCh 409/2 throughout the year.
- “Wastewater Treatment Quality Index”. Similar to the Drinking Water Quality Index, this synthetic index is computed annually by the SISS to assess the quality of treated effluent based on concentrations of suspended solids, chemical oxygen demand, and nitrogen. The index ranges between 0 % and 100 %, where 100 % indicates full compliance with Chilean environmental regulations governing wastewater treatment (Chilean Decree 90).
- “Continuity in Drinking Water Supply”. This index, developed by the SISS, measures the continuity of water supply by considering three factors: the total number of water outages per year, the duration of each outage, and the number of customers affected. It is expressed as a synthetic index ranging from 0 to 1, where 1 indicates no water outages occurred during the year.
- “Sewerage Performance”. This indicator, also computed by the SISS, assesses the incidence of sewer collapses based on the total number of collapses per year, their duration, and the number of affected customers. It is expressed as a synthetic index ranging from 0 to 1, where 1 indicates no sewer collapses occurred during the year.

The asset management dimension consists of four key indicators that assess the ability of WWUs' infrastructure to function reliably and resist shocks and stresses. This dimension captures aspects of asset health and the capacity of infrastructure to endure variable operating conditions. The four indicators collectively assess WWUs' capacity for proactive asset management, ensuring that infrastructure is maintained and upgraded to sustain service reliability and resilience over time. It should be noted that while network renewal rates are primarily considered indicators of long-term resilience, they also generate direct short-term improvements in system performance. For instance, replacing deteriorated pipes can immediately reduce leakage, improve water pressure stability, and lower the likelihood of service interruptions. Therefore, renewal activities should be interpreted as contributing to resilience in a dual manner—by strengthening immediate operational performance and by securing infrastructure sustainability over the long term.

- “Water Leakage”. This indicator represents the percentage of water losses relative to the total volume of water abstracted. High leakage rates have been shown to correlate with increased pipe breakage rates, which compromise the resilience of drinking water distribution networks [61]. 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, as well as water scarcity challenges affecting multiple regions [62].
- “Fulfillment of the Development Plan”. Chilean WWUs are required to submit a five-year infrastructure development plan to the regulator (SISS) for approval. This plan outlines infrastructure investment commitments necessary to ensure the continuity and quality of water and sanitation services over the period, taking into account population growth, raw water availability, and other factors. The indicator used in this study measures the percentage of the development plan fulfilled in relation to the investment commitments established by each WWU.
- “Drinking Water Network Renewal Rate”. This indicator measures the ratio between the length of the drinking water network renewed and the total length of the network. It reflects the extent to which utilities are investing in infrastructure renewal to maintain service reliability and resilience.

“Sewer Network Renewal Rate”. Analogous to the drinking water network renewal rate, this indicator represents the ratio between the length of the sewer network renewed and the total length of the sewer network. In a seismically active country such as Chile, regular renewal of both drinking water and sewer networks is crucial for long-term resilience, as it mitigates risks associated with both aging infrastructure and seismic vulnerability. The water security dimension consists of a single indicator designed to assess the degree of stress experienced by each WWU in terms of raw water availability. This indicator evaluates the buffer capacity of a utility to accommodate increasing water demand or compensate for a reduction in raw water sources due to external factors such as droughts or contamination.

The proposed indicator, Raw Water Security, is estimated using the following formula:

$$\text{Raw Water Security} = 1 - \left(\frac{\text{Volume of raw water abstracted}}{\text{Volume of raw water available}} \right) \quad (9)$$

This indicator is expressed as a percentage, where a value of 0 % indicates that the WWU abstracts the entire available raw water volume, meaning it has no buffer capacity to handle increased demand or compensate for water source reductions. As the raw water security value increases, the operational resilience of the WWU improves, as it retains a greater margin of flexibility to sustain water abstraction in the event of droughts, contamination incidents, or other disruptions affecting raw water availability.

Following the conceptual framework of resilience capacities (preventive, absorptive, adaptive) [63,64], Table 1 summarizes how each of the nine indicators included in the ORI reflects different dimensions of resilience. This mapping shows that, although some indicators are derived from operational performance, they are widely recognized as proxies for the ability of utilities to prevent, withstand, and recover from disruptive events. Moreover, the selected indicators also correspond to specific types of failures or exceptional conditions faced by WUs which are also shown in Table 1.

Table 2 presents the type of each resilience indicator (positive or negative) along with their key statistical measures. The data used for this analysis was sourced from the 2023 Annual Report on Water and Sanitation Services in Chile, published by the SISS, which reports performance data for the 2023 calendar year.

Table 3 presents the correlation matrix for the nine resilience indicators included in the ORI. The results indicate that the highest observed correlation is −0.48, occurring between continuity in drinking

Table 1

Mapping of resilience indicators embracing ORI to resilience capacities.

Dimension	Indicator	Exceptional condition	Resilience Capacity
Service Performance	Drinking Water Quality Index	Contamination events; treatment plant failures	Absorptive – maintaining water quality during disruptions.
	Wastewater Treatment Quality Index	Extreme rainfall; plant malfunction; discharge regulation breaches	Absorptive – ensuring effluent quality despite shocks.
	Continuity in Drinking Water Supply	Natural hazards (earthquake, flood); power outages; pipe bursts	Absorptive – ability to withstand and minimize service interruptions.
	Sewerage Performance	Sewer collapses; storm surges; blockages	Absorptive – capacity to handle system stress without collapse.
Asset Management	Water Leakage	Network fragility in droughts, seismic events, or pressure shocks	Preventive – reducing vulnerability by addressing network deterioration.
	Fulfillment of the Development Plan	Ability to implement planned adaptation to changing demand and hazards	Adaptive – proactive investment to adapt to future risks.
	Drinking Water Network Renewal Rate	Service disruptions due to aging pipes; vulnerability during seismic events	Adaptive – strengthening long-term resilience through renewal.
	Sewer Network Renewal Rate	Collapse during earthquakes or excessive inflow/infiltration	Adaptive – increasing robustness and reducing seismic vulnerability.
Water Security	Raw Water Security	Droughts; contamination of raw water sources	Preventive/Absorptive – buffer capacity to cope with droughts or contamination of sources.

Table 2

Statistics of the resilience indicators embracing the ORI for Chilean WWUs.

Dimension	Indicator	Type	Mean	St. Dev.	Min	Max.
Service Performance	Drinking Water Quality Index	Positive	98.65 %	2.25 %	90.79 %	100.00 %
	Wastewater Treatment Quality Index	Positive	98.32 %	3.64 %	81.00 %	100.00 %
	Continuity in Drinking Water Supply	Positive	0.9953	0.0092	0.9595	1.0000
	Sewerage Performance	Positive	0.9993	0.0013	0.9936	1.0000
Asset Management	Water Leakage	Negative	28.54 %	10.66 %	6.50 %	48.60 %
	Fulfillment of the Development Plan	Positive	86.10 %	22.02 %	14.00 %	100.00 %
	Drinking Water Network Renewal Rate	Positive	0.36 %	0.31 %	0.00 %	1.15 %
	Sewer Network Renewal Rate	Positive	0.20 %	0.23 %	0.00 %	0.61 %
Water Security	Raw Water Security	Positive	29.53 %	15.57 %	0.00 %	56.30 %

Table 3

Correlation matrix of resilience indicators.

	A	B	C	D	E	F	G	H	I
A) Drinking Water Quality Index	1.00								
B) Wastewater Treatment Quality Index	0.06	1.00							
C) Continuity in Drinking Water Supply	−0.07	−0.04	1.00						
D) Sewerage Performance	−0.13	−0.07	−0.03	1.00					
E) Water Leakage	0.12	−0.15	−0.02	−0.14	1.00				
F) Fulfillment of the Development Plan	−0.23	−0.12	−0.03	−0.05	−0.21	1.00			
G) Drinking Water Network Renewal Rate	0.12	−0.11	−0.30	−0.22	0.07	−0.12	1.00		
H) Sewer Network Renewal Rate	0.09	−0.25	−0.48	−0.03	0.21	−0.12	0.37	1.00	
I) Raw Water Security	0.23	−0.05	0.19	0.06	−0.18	−0.27	−0.09	−0.15	1.00

water supply and sewer network renewal rate. These two indicators focus on different services provided by WWUs, suggesting that the correlation does not imply redundancy but rather reflects distinct operational dynamics within the utilities.

3. Results and discussion

3.1. Operational resilience index of water and wastewater utilities

According to the methodology proposed for estimating the ORI for each WWU under evaluation (see Section 2.1), the first stage involves allocating weights to each resilience indicator using the BWM. To achieve this, a total of 14 experts in resilience and water and sanitation services management were consulted. The sample included six academics specializing in urban water management, two academics focusing on resilience in critical infrastructure, three professionals working in the Chilean government on water management-related issues, and three professionals from Chilean WWUs. The questionnaire used to capture expert preferences was structured in three sections: the

first provided a definition of operational resilience for WWUs² along with statistical data on water and sanitation outages in Chile over the past 10 years; the second required experts to identify the most relevant (best) and least relevant (worst) resilience indicators in the context of Chilean WWUs; and the third involved pairwise comparisons, where experts determined the preference of the best indicator over all other indicators and the preference of all indicators over the worst indicator.

Considering the preferences of the experts and solving Model (5), the weights for each resilience indicator were estimated, as presented in Table 4. The BWM estimation yielded a Consistency Ratio of 0.07, which is below the commonly accepted threshold of 0.10 [37], indicating that the pairwise comparisons provided by the experts were consistent. In

² The definition is as follows: The ability of an organization's infrastructure, along with the skills required to operate it, to prevent, withstand, and recover from disruptions in its performance. Additionally, operational resilience encompasses long-term adaptability to environmental pressures, demographic changes, shifts in customer behavior, and the impacts of climate change [13].

Table 4

Weights allocated to each resilience indicator and its aggregation for each dimension.

Resilience indicators	Weights	Dimension	Weight
Drinking Water Quality Index	0.029	Service	0.468
Wastewater Treatment Quality Index	0.029	Performance	
Continuity in Drinking Water Supply	0.205		
Sewerage Performance	0.205	Asset Management	0.366
Water Leakage	0.109		
Fulfillment of the Development Plan	0.109		
Drinking Water Network Renewal Rate	0.067		
Sewer Network Renewal Rate	0.080	Water Security	0.166
Raw Water Security	0.166		

terms of dimensions, service performance was identified as the most relevant, as it includes the two highest-weighted resilience indicators: continuity in drinking water supply and sewerage performance. This finding suggests that, while the operational resilience definition incorporates long-term resilience, there remains a preference for short-term service performance in evaluating WWUs. This emphasis is further reflected in the lower weights assigned to both network renewal rate indicators, which are more indicative of long-term infrastructure resilience. It is worth noting that, despite the academic recognition of renewal network rate indicators as contributors to resilience in both the short and long term, the experts assigned them the lowest weights. This apparent tension reflects the reality that stakeholders—particularly regulators and utility managers—tend to prioritize service continuity indicators that have immediate and visible impacts on customers (e.g., avoiding water outages or sewer collapses). In contrast, the benefits of network renewal are often deferred and less directly perceptible in the short term, which may explain their lower prioritization in the weighting process. This finding underscores the importance of complementing

expert-driven weighting approaches with academic insights, ensuring that long-term resilience investments are not overshadowed by short-term service considerations.

The third most relevant indicator identified is raw water security, highlighting the challenges Chilean WWUs have faced over the past decade due to severe and prolonged droughts affecting the country. In contrast, both quality-related indicators—drinking water quality and wastewater treatment quality—were considered the least relevant in the context of operational resilience. This finding indicates that resilience is primarily perceived as a service continuity issue, rather than a quality concern, aligning with previous research on the subject [22,65].

Once the weights for each resilience indicator were determined and the indicators were normalized for each WWU (Table 5), they were integrated into the ORI, with the resulting values presented in Fig. 1. Analyzing the average values of the normalized indicators, the highest value (0.912) corresponds to the wastewater treatment quality index, indicating that most WWUs under evaluation perform optimally in this area. Additionally, this indicator exhibits the lowest standard deviation, suggesting a relatively homogeneous performance across utilities. In contrast, the lowest average performance is observed for the drinking water network renewal rate, with an average normalized value of 0.316. A similar average performance is found for the sewer network renewal rate (0.335), but this indicator has the highest standard deviation (0.336), highlighting notable variations in performance among the assessed utilities. The low performance in these two resilience indicators reveals significant shortcomings in infrastructure renewal among WWUs.

The estimated ORI ranges from 0.524 (WWU2) to 0.808 (WWU15), while the maximum achievable ORI is 1.000 (Fig. 1). This indicates that the assessed utilities have the potential to improve their operational resilience by 19.2 %–47.6 %. The WWU with the highest ORI (WWU15) is a concessioned utility, characterized by maximum performance in two

Table 5

Normalized indicators for each resilience indicator across all assessed water and wastewater utility (WWU).

Water and wastewater utility (WWU)	Drinking Water Quality Index	Wastewater Treatment Quality Index	Continuity in Drinking Water Supply	Sewerage Performance	Water Leakage	Fulfillment Development Plan	Drinking Water Network Renewal Rate	Sewer Network Renewal Rate	Raw Water Security
WWU1	0.910	0.995	0.926	0.359	0.390	0.983	0.330	0.787	0.060
WWU2	0.950	0.979	0.904	0.000	0.347	0.900	0.626	0.000	0.630
WWU3	0.987	0.979	0.689	0.984	0.271	0.767	0.409	0.934	0.817
WWU4	0.883	0.932	0.948	0.828	0.185	0.894	0.600	0.000	0.134
WWU5	1.000	0.753	0.978	0.969	0.420	1.000	0.496	1.000	0.212
WWU6	0.979	0.953	0.933	0.859	0.257	0.590	0.296	0.459	0.580
WWU7	0.960	0.853	0.995	0.906	0.000	0.000	0.252	0.639	0.626
WWU8	0.985	0.926	0.933	0.984	0.525	0.837	0.252	0.361	0.629
WWU9	0.831	0.947	0.000	0.984	0.525	0.773	0.643	0.951	0.199
WWU10	1.000	0.995	0.198	0.875	0.432	0.924	0.461	0.721	0.315
WWU11	0.953	0.853	0.951	0.781	0.727	0.926	0.400	0.770	0.658
WWU12	0.691	0.000	0.864	0.906	0.382	1.000	0.504	0.721	0.732
WWU13	0.000	0.979	0.914	0.938	0.758	1.000	0.296	0.623	0.199
WWU14	1.000	1.000	0.988	0.953	0.641	0.044	0.452	0.426	0.617
WWU15	1.000	0.889	0.872	0.984	0.561	1.000	0.443	0.393	0.851
WWU16	0.979	1.000	0.946	0.906	0.078	1.000	0.487	0.770	0.577
WWU17	1.000	1.000	0.980	0.969	0.482	0.913	0.000	0.000	0.770
WWU18	0.650	0.937	0.968	0.984	0.594	0.755	1.000	0.000	0.489
WWU19	0.869	1.000	0.919	0.859	0.819	0.706	0.130	0.148	0.924
WWU20	1.000	1.000	0.975	0.938	0.200	0.627	0.391	0.000	0.948
WWU21	1.000	1.000	0.993	1.000	0.938	1.000	0.696	0.000	0.450
WWU22	0.754	0.853	1.000	0.875	0.371	1.000	0.000	0.000	0.538
WWU23	1.000	1.000	0.963	0.891	1.000	0.837	0.000	0.000	1.000
WWU24	0.315	1.000	0.965	1.000	0.131	1.000	0.000	0.000	0.257
WWU25	0.976	1.000	0.891	0.984	0.587	1.000	0.000	0.000	0.642
WWU26	0.704	0.911	1.000	1.000	0.371	0.837	0.000	0.000	0.436
WWU27	0.382	1.000	1.000	1.000	0.843	1.000	0.000	0.000	0.693
WWU28	1.000	1.000	0.963	0.984	0.613	1.000	0.000	0.000	0.000
WWU29	1.000	0.705	1.000	1.000	0.371	1.000	0.000	0.000	0.224
Average	0.854	0.912	0.885	0.886	0.476	0.838	0.316	0.335	0.524
St. Dev.	0.240	0.188	0.224	0.206	0.249	0.252	0.263	0.365	0.272

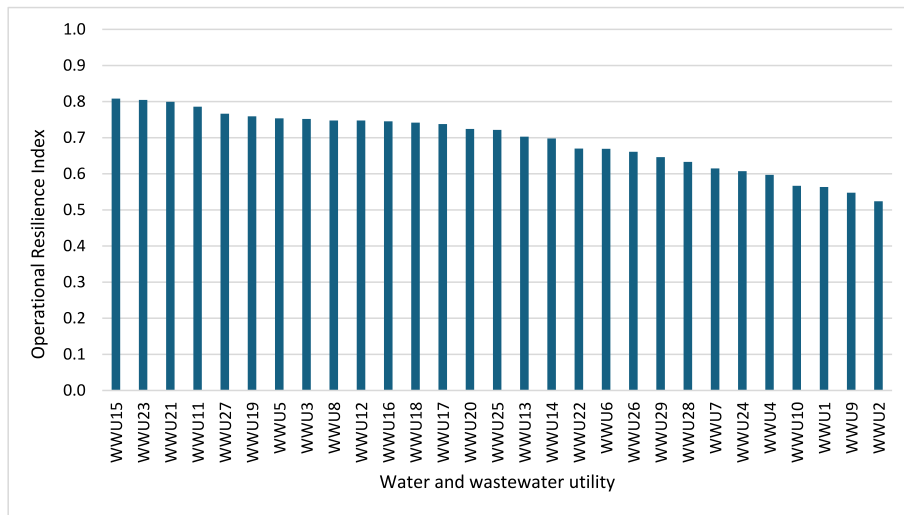


Fig. 1. Operational Resilience Index (ORI) for each assessed water and wastewater utility (WWU).

resilience indicators such as the drinking water quality index and fulfillment of the development plan (Table 4). However, despite some utilities (WWU21, WWU23, WWU27, and WWU29) achieving the maximum normalized value (1.000) for four resilience indicators, they do not exhibit the highest ORI. This is because their moderate or poor performance in other resilience indicators affects their overall score. In contrast, WWU15, despite having its lowest normalized indicator at 0.39, maintains relatively strong performance across all resilience indicators. This balanced performance contributes to its high ORI, rather than excelling in only a few indicators. Notably, WWU15 is a medium-sized utility serving approximately 260,000 customers in the southern region of Chile. On the other hand, the WWU with the lowest ORI (WWU2) does not achieve the maximum normalized value in any resilience indicator (Table 4), indicating that it has room for improvement across all indicators. Additionally, it exhibits the lowest performance among its peers in two indicators namely, sewerage performance and sewer network renewal rate. This suggests that its poor performance in sanitation services is the primary factor contributing to its low ORI. Moreover, WWU2 is one of the largest private utilities in Chile, providing services to approximately 900,000 customers in the central-southern region of the country.

The contrast between WWU15 (highest ORI, 0.808) and WWU2 (lowest ORI, 0.524) illustrates the real-world implications of resilience differences. WWU15's superior continuity of water supply and strong investment fulfillment translate into fewer interruptions for its 260,000 customers, higher service reliability, and reduced leakage losses, which in turn lower operational costs and environmental impacts. Conversely, WWU2's weaker sewerage performance and limited renewal measures increase the likelihood of service failures for nearly 900,000 customers, raising public health risks, environmental compliance costs, and customer complaints. These differences demonstrate that higher resilience is directly associated with tangible social benefits (greater service reliability), economic savings (lower non-revenue water and repair costs), and environmental improvements (enhanced wastewater treatment and reduced leakage). Hence, ORI scores provide not only a benchmarking tool but also a proxy for the broader economic and social value of resilience.

To further analyze the strengths and weaknesses of each WWU across the three resilience dimensions of the ORI, Fig. 2 compares the maximum achievable scores for each dimension with those effectively achieved by each WWU. Regarding service performance, none of the 29 WWUs reached the maximum possible score of 0.468. The average gap

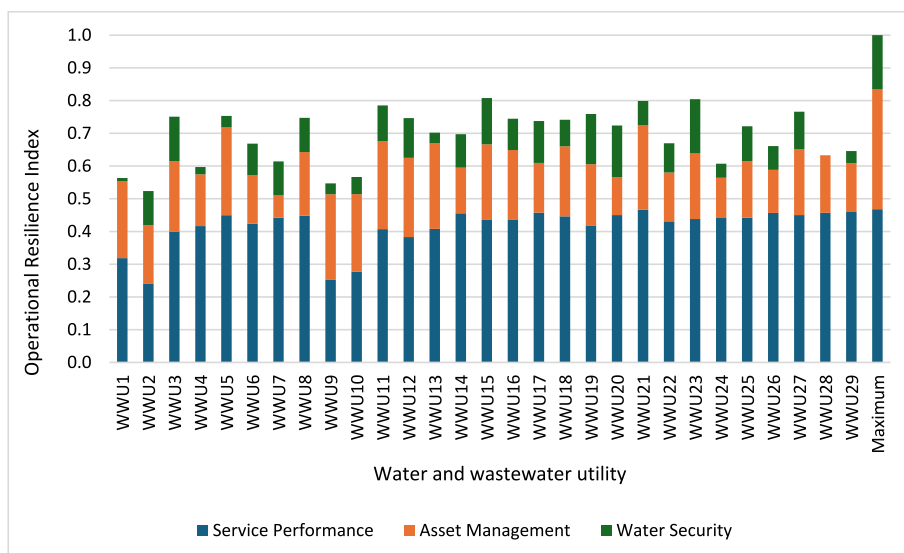


Fig. 2. Contribution to resilience dimensions to operational resilience index (ORI).

between the maximum score and the actual scores achieved is 11.48 %, with variations ranging from 0.32 % (WWU21) to 48.46 % (WWU2). In the asset management dimension, not only did no WWU reach the maximum score, but the performance gaps in this dimension are notably larger, with an average deviation of 47.74 %, ranging from 26.62 % to 81.41 %. Finally, in the water security dimension, which consists of a single indicator, the average deviation from the maximum score is 47.55 %. These findings highlight that the asset management dimension represents the greatest opportunity for improvement in WWUs' operational resilience. This dimension encompasses long-term resilience indicators, focusing on infrastructure management and renewal, areas where utilities show significant gaps. In contrast, service performance exhibits the highest scores, indicating that WWUs tend to prioritize short-term resilience, emphasizing continuity and immediate service delivery over long-term infrastructure resilience.

3.2. Influence of ownership on operational resilience

The evaluation encompassed 29 WWUs, comprising 1 public WWU, 8 concessioned WWUs, and 20 private WWUs. To assess the potential influence of ownership type on operational resilience, the Kruskal-Wallis test was applied. Table 6 presents the key statistics of the ORI and its dimensions for each WWU type, along with the Kruskal-Wallis test results. The average ORI values are relatively similar across the three ownership types, with private utilities exhibiting the highest operational resilience and the public utility the lowest. However, the Kruskal-Wallis test results indicate that these differences are not statistically significant. This finding is consistent with previous research [66–68], which also reported no significant performance variations among water utilities based on ownership structure. In the case of Chilean WWUs, this lack of distinction may stem from the fact that all utilities, irrespective of ownership, operate within the same legal and institutional framework and are subject to identical regulatory requirements.

The resilience dimensions of Service Performance and Water Security follow a similar pattern. In both cases, the public WWU exhibits the highest scores, while concessioned WWUs show the lowest average scores. However, the Kruskal-Wallis test results indicate that these differences are not statistically significant ($p\text{-value} > 0.05$). Conversely, in the Asset Management dimension, the public WWU performs significantly below its peers (0.068), whereas concessioned utilities exhibit the highest performance (0.231). This difference is statistically significant ($p\text{-value} = 0.012$), confirming that concessioned utilities demonstrate stronger asset renewal and infrastructure management practices. This finding suggests that concessioned WWUs outperform both private and

public utilities in terms of infrastructure management and renewal rate.

The methodological approach proposed in this study, along with the results of assessing the operational resilience of WWUs from a holistic perspective, carries several policy implications for regulatory authorities, WWUs, and policymakers involved in urban water management. The key policy implications are as follows:

The proposed ORI integrates multiple resilience indicators into a synthetic index that incorporates the opinions and preferences of stakeholders and experts. This approach is particularly suitable for middle- and low-income countries, where access to detailed datasets is limited. The ORI enables the systematic and comparable benchmarking of WWUs' resilience, providing essential information for water regulators to assess the short- and long-term preparedness of utilities against natural and human-induced hazards. Based on ORI estimations at the WWU level, regulators can implement enforcement mechanisms or incentives to enhance resilience in water and sanitation service provision. The findings reveal that not all indicators contribute equally to the resilience of water and sanitation services.

Focusing on the Chilean water and sanitation industry, the findings highlight that asset management represents the most critical area for improvement in WWUs' operational resilience. In this context, the water regulator should consider implementing incentive mechanisms, such as targeted subsidies or performance-based funding, to encourage WWUs to invest in network renewal, leakage reduction, and wastewater infrastructure upgrades. This issue is particularly relevant for Chile, given its high exposure to natural hazards (e.g., earthquakes, droughts), to ensure that WWUs adopt measures that enhance their long-term resilience.

The study also reveals that WWU ownership does not influence operational resilience, underscoring the crucial role of regulation in monopolistic services such as water and sanitation provision [69]. Consequently, the Chilean water regulator should continue prioritizing policies that enhance resilience across all WWUs, rather than implementing ownership-specific policies. However, given that concessioned utilities demonstrate superior performance in asset management, regulators should introduce targeted policies for other utilities to strengthen this dimension of resilience.

4. Conclusions

Ensuring the reliability and continuity of water and sanitation services is a critical priority for regulators and municipalities, given their direct impact on public health, safety, and the environment. In this context, assessing the operational resilience of WWUs is essential, as resilience metrics enable regulators and water managers to justify and incentivize investments in adaptive infrastructure, ensuring service continuity. This study develops and applies an innovative composite indicator, the ORI, to assess the resilience of WWUs. The ORI integrates multiple resilience indicators across three key dimensions: service performance, asset management, and water security. By employing a MCDA approach and incorporating stakeholder preferences through the BWM, the ORI provides a comprehensive and systematic tool for benchmarking WWU resilience from a regulatory perspective.

The case study focuses on the Chilean water and sanitation industry. The findings reveal a substantial gap between the maximum achievable resilience and the actual performance of WWUs, with potential improvements ranging from 19.2 % to 47.6 %. While service performance exhibits the highest scores, asset management emerges as the most critical area for improvement, suggesting that WWUs prioritize short-term service continuity over long-term infrastructure sustainability. This underscores the need for regulatory incentives to promote proactive asset management and infrastructure renewal. Additionally, although no statistically significant differences in overall ORI scores were found based on WWU ownership structure, a critical exception was observed in the asset management dimension, where concessioned utilities outperformed both public and private utilities. This result highlights a robust and policy-relevant insight: concessioned WWUs are more

Table 6

Average ORI and resilience dimension scores based on water and wastewater utility ownership.

Operational Resilience dimensions and Index	Statistical parameters	Type of water and wastewater utility		
		Public	Concessioned	Private
Operational Resilience Index (ORI)	Average	0.614	0.683	0.700
	St. Dev.		0.099	0.077
	p-value	0.619		
	Kruskal-Wallis			
Service Performance	Average	0.442	0.384	0.425
	St. Dev.		0.077	0.054
	p-value	0.178		
	Kruskal-Wallis			
Asset Management	Average	0.068	0.231	0.181
	St. Dev.		0.038	0.044
	p-value	0.012		
	Kruskal-Wallis			
Water Security	Average	0.104	0.068	0.094
	St. Dev.		0.047	0.046
	p-value	0.428		
	Kruskal-Wallis			

effective in infrastructure renewal and asset management. Regulators should therefore consider targeted measures to ensure that public and private utilities strengthen this dimension of resilience, in order to reduce long-term vulnerabilities across the sector.

The proposed ORI serves as a valuable decision-support tool for evaluating WWU preparedness against natural and human-induced hazards. Regulatory authorities can utilize the ORI to establish resilience-based performance benchmarks, implement enforcement mechanisms, and develop incentive structures to encourage long-term resilience investments. Given Chile's high exposure to natural disasters, strengthening regulatory frameworks to promote sustainable asset management and water security is imperative for ensuring the long-term functionality of water and sanitation services. The ORI represents a novel contribution to the field by integrating water and wastewater services into a single resilience framework, adopting a regulator-oriented perspective, and incorporating structured expert preferences through the Best-Worst Method. These features distinguish the ORI from previous resilience assessments, which have been predominantly infrastructure-specific, data-intensive, and less suitable for policy applications. Future research should focus on refining the ORI methodology by incorporating additional resilience indicators that capture emerging risks, such as cybersecurity threats and utilities' response to water shortages. Moreover, assessing temporal changes in ORI scores over time could provide valuable comparative insights into trends in WWU operational resilience.

CRedit authorship contribution statement

Alexandros Maziotis: Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Maria Molinos-Senante:** Writing – original draft, Methodology, Data curation, Conceptualization.

Funding

This work was supported by the Department of Education of the Regional Government of Castilla y León and co-financed by the European Union through the European Regional Development Fund (ERDF) (Reference: CLU-2025-2-06) and by the Research Center for Integrated Disaster Risk Management (CIGIDEN), ANID/FONDAP/1522A0005 in Chile.

Acknowledgement

The authors would like to acknowledge the National Agency of Research and Development of Chile (ANID) for funding the Research Center for Integrated Disaster Risk Management (CIGIDEN) (Grant no. ANID/FONDAP/1522A0005) and the Research Centre for Sustainable Urban Development (CEDEUS) (Grant no. ANID/FONDAP/1523A0004).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seps.2025.102340>.

Data availability

Data will be made available on request.

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