Municipal Governance and Institutional Inefficiency in Water Supply Emergencies: Development and Validation of an Index

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Abstract

Municipal drinking water systems face increasing challenges associated with climate-related hazards, infrastructure failures, and institutional limitations that can compromise service continuity during emergency situations. Despite the growing importance of resilience-oriented water governance, existing performance assessment approaches primarily focus on technical efficiency and often overlook institutional capacities required for effective emergency response. This study developed and validated the Institutional Inefficiency Index for Water Emergencies (IIIWE), a composite indicator designed to quantify organizational inefficiencies in municipal water management systems operating under emergency conditions. The methodological framework integrates principles from institutional economics, water governance, reliability engineering, and resilience assessment. Four key dimensions were incorporated into the model: operational workforce availability, preventive maintenance compliance, equipment functionality, and emergency management systems. Variables were normalized and aggregated using a reliability-based approach to generate a single institutional inefficiency score ranging from 0 to 1. Instrument reliability and construct validity were evaluated through Cronbach's alpha, exploratory factor analysis, Kaiser–Meyer–Olkin statistics, and Bartlett's test of sphericity. Model robustness was further examined using sensitivity analysis and Monte Carlo simulation. The results demonstrated satisfactory reliability, strong construct validity, and stable performance under varying parameter conditions. The proposed IIIWE provides a practical and scientifically robust tool for identifying institutional vulnerabilities, prioritizing management interventions, supporting evidence-based decision-making, and strengthening the resilience and sustainability of municipal drinking water systems facing emergency scenarios.

Keywords: institutional inefficiency; water governance; drinking water systems; emergency management; resilience assessment; municipal water utilities.

Introduction

Water security has emerged as one of the most critical challenges for sustainable development in the twenty-first century. Increasing climate variability, accelerated urbanization, population growth, ecosystem degradation, and the rising frequency of extreme hydrometeorological events have intensified pressures on water supply systems worldwide. Beyond the physical availability of water resources, the ability of institutions to maintain service continuity, manage infrastructure, and respond effectively to disruptions has become a decisive factor in determining the resilience of water systems and the well-being of communities (Li et al., 2022; Mocholi et al., 2025). Recent evidence suggests that institutional capacity is increasingly recognized as a central determinant of water security, particularly in regions exposed to droughts, floods, infrastructure failures, and other water-related emergencies.

The growing complexity of water governance has shifted scientific attention from purely engineering-based approaches toward integrated perspectives that incorporate institutional performance, risk management, and adaptive capacity. Water supply systems are not only technical infrastructures but also socio-ecological systems whose functionality depends on administrative efficiency, organizational coordination, regulatory compliance, and strategic planning (Gain et al., 2016; Herrfahrdt et al., 2025). Consequently, deficiencies in institutional performance can significantly compromise emergency preparedness and response, increasing service interruptions, economic losses, environmental degradation, and public health risks (Pahl, 2019). Several studies have shown that weaknesses in maintenance programs, emergency planning, operational management, and inter-agency coordination frequently contribute to system failures during extreme events, even when physical infrastructure and financial resources are available (WOH, 2024).

Traditional approaches used to evaluate water utility performance have largely focused on technical, operational, and economic efficiency. Methodologies such as Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) have provided valuable insights into productivity and resource utilization within water utilities. However, these methods primarily assess efficiency under relatively stable operating conditions and often overlook institutional and organizational factors that become particularly relevant during emergencies (Butler et al., 2017; Rojas et al., 2024). As climate-related hazards increase in frequency and intensity, the limitations of conventional efficiency assessments become more evident, highlighting the need for analytical frameworks capable of incorporating institutional resilience and emergency response capacity into performance evaluation (Rockström et al., 2023).

From an institutional economics perspective, the theory of X-inefficiency proposed by Harvey Leibenstein offers a valuable conceptual framework for understanding performance gaps in public service organizations. The theory argues that organizations frequently operate below their optimal efficiency levels because of organizational rigidities, inadequate incentives, information asymmetries, weak supervision, and managerial shortcomings. Although X-inefficiency has been extensively applied in studies of firms, markets, and public-sector organizations, its application to water governance remains limited. Nevertheless, many of the operational deficiencies documented in municipal water systems—including insufficient preventive maintenance, ineffective emergency preparedness, fragmented decision-making processes, and limited technical capacity—reflect conditions consistent with institutional X-inefficiency.

Recent studies evaluating water utilities have identified significant disparities in operational performance that cannot be fully explained by differences in infrastructure, technology, or financial resources alone. Instead, institutional characteristics frequently emerge as critical determinants of service reliability and adaptive capacity. Despite this growing recognition, the scientific literature still lacks specific instruments capable of quantifying institutional inefficiency in water emergency contexts. Existing assessments generally focus on technical efficiency, infrastructure performance, or service quality indicators, while institutional preparedness and organizational resilience remain insufficiently operationalized within quantitative evaluation frameworks (Frantz, 2013; Gain et al., 2021). This gap limits the ability of decision-makers to identify structural weaknesses that may compromise water service continuity during critical events.

Addressing this limitation requires the development of innovative methodologies that integrate institutional performance with emergency management capabilities. In this context, the present study proposes an Institutional Inefficiency Index for Water Emergencies grounded in Leibenstein's X-inefficiency theory and supported by public policy and water governance principles (Leibenstein, 1966). The proposed framework evaluates four critical dimensions associated with emergency response performance: operational workforce availability, preventive maintenance compliance, equipment functionality, and implementation of emergency management systems (Cabrera & Sarmiento, 2023; Keremidchiev, 2026). By combining these dimensions within a reliability-based analytical structure, the index seeks to quantify the gap between potential institutional performance and observed operational conditions.

The proposed approach contributes to the literature in three ways. First, it extends the application of X-inefficiency theory to the field of water governance and emergency management, an area that remains largely unexplored. Second, it introduces a quantitative instrument capable of assessing institutional vulnerabilities that are often neglected by traditional efficiency evaluation methods. Third, it provides water managers, regulators, and local governments with a practical decision-support tool for identifying weaknesses, prioritizing interventions, and strengthening the resilience of water supply systems under emergency conditions. Therefore, the objective of this study is to develop and validate an Institutional Inefficiency Index for Water Emergencies that enables the assessment of organizational performance and institutional preparedness in municipal water systems, contributing to improved water governance, emergency response capacity, and long-term water security.

Materials and Methods

This study employed a quantitative, non-experimental, cross-sectional, and explanatory research design aimed at developing and validating the Institutional Inefficiency Index for Water Emergencies (IIIWE). The methodological framework integrated concepts from institutional economics, water governance, reliability engineering, resilience assessment, and composite indicator construction to operationalize institutional inefficiency within municipal drinking water systems exposed to emergency conditions (Gain et al., 2016; Tiedmann et al., 2023).

The study was conducted in Ecuador and focused on municipal water utilities responsible for drinking water supply services in urban and peri-urban territories. Data collection was performed between January and June 2025. A purposive sampling strategy was adopted to ensure the participation of actors possessing direct knowledge of water service operations and emergency response processes.

The empirical validation involved 24 municipal water utilities distributed across different territorial contexts. A total of 312 respondents participated in the study. The sample included 187 operational and technical personnel directly involved in water supply management, maintenance activities, and emergency response operations, as well as 125 qualified users representing community organizations, water committees, and local stakeholders familiar with municipal water service performance. Sample size adequacy exceeded the minimum recommendations for exploratory factor analysis, which suggest between 5 and 10 observations per questionnaire item and a minimum sample size of 200 observations for robust psychometric validation.

The conceptual structure of the IIIWE was developed through an extensive review of the scientific literature on water utility performance, institutional efficiency, organizational resilience, emergency management, and governance systems (Butler et al., 2017; Herrfahrdt et al., 2025; Pahl, 2019). Four institutional dimensions were identified as critical determinants of municipal performance during water-related emergencies:

1. Operational workforce availability (OWA);
2. Preventive maintenance compliance (PMC);
3. Equipment functionality (EF);
4. Emergency management systems (EMS).

These dimensions were selected according to three criteria: theoretical relevance, operational measurability, and consistency with municipal responsibilities regarding drinking water service provision (Greco et al., 2019; Leštáková et al., 2024).

To determine the relative importance of each dimension, a Delphi consultation process was conducted. The expert panel consisted of 15 specialists selected according to their academic qualifications and professional experience in water governance, risk management, environmental engineering, public administration, and emergency planning (Mazziotta & Pareto, 2013; Saisana & Saltelli, 2008). The panel included five university researchers, four municipal water utility managers, three specialists in disaster risk management, and three professionals from national water governance institutions.

The Delphi process was implemented through three iterative rounds. During the first round, experts evaluated the relevance of the proposed dimensions using a five-point scale. In the second round, aggregated results were shared anonymously and participants were invited to reconsider their evaluations (Hsu & Sandford, 2007; Keeney et al., 2010). The third round focused on achieving convergence and final weight estimation. Consensus was considered achieved when at least 80% of experts assigned scores within one standard deviation of the group median (Custer et al., 1999; Hair et al., 2019).

Following expert consultation, weighting coefficients were statistically calibrated using multiple linear regression analysis. Institutional performance was defined as the dependent variable, while the four normalized dimensions constituted the explanatory variables. The regression model adopted was:

$$PI = \beta_0 + \beta_1 OWA + \beta_2 PMC + \beta_3 EF + \beta_4 EMS + \varepsilon$$

Where PI represents institutional performance, β_0 is the intercept, β_i corresponds to standardized regression coefficients, and ε denotes the residual error term.

Regression diagnostics confirmed model adequacy, yielding an adjusted coefficient of determination (Adjusted R^2) of 0.81 and statistically significant coefficients ($p < 0.05$) for all explanatory variables. Variance Inflation Factors (VIF) remained below 3.0, indicating the absence of multicollinearity problems. Standardized coefficients were subsequently normalized to generate the final weighting scheme incorporated into the IIIWE model.

A structured questionnaire was developed to operationalize the four dimensions. The instrument consisted of twenty items organized into four domains, with five indicators assigned to each institutional dimension. Responses were measured using a five-point Likert scale ranging from 1 (very poor condition) to 5 (excellent condition).

Prior to implementation, content validity was assessed through expert review involving the Delphi panel. A pilot study was subsequently conducted with 30 respondents from two municipal water utilities not included in the final sample. Minor modifications were introduced to improve clarity and comprehension (Watkins, 2021).

Construct validity was evaluated through Exploratory Factor Analysis (EFA). Sampling adequacy was assessed using the Kaiser–Meyer–Olkin (KMO) statistic, while factorability was examined through Bartlett's Test of Sphericity. Factor extraction was performed using Principal Axis Factoring with Varimax orthogonal rotation. Components with eigenvalues greater than 1.0 were retained according to the Kaiser criterion (Stefana et al., 2025).

The factor analysis identified four factors consistent with the theoretical structure of the model. Factor loadings ranged from 0.71 to 0.89, exceeding the minimum threshold of 0.50 commonly recommended for construct validity. Communality values varied between 0.58 and 0.84, indicating satisfactory shared variance among observed variables. The four retained factors explained 73.6% of the total variance.

Internal consistency was evaluated using Cronbach's alpha coefficient:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{n} \sigma_i^2}{\sigma_T^2}\right)$$

Where k denotes the number of items, σ_i^2 represents the variance of each item, and σ_T^2 corresponds to the variance of the total score. Following established psychometric criteria, values greater than 0.70 were considered acceptable, values above 0.80 indicated good reliability, and values exceeding 0.90 reflected excellent internal consistency (Cronbach, 1951; Taber, 2018).

To enable comparison among heterogeneous variables, each institutional component was normalized using a min–max transformation approach that generated standardized scores ranging from 0 to 1. The normalized indicators were subsequently aggregated through a reliability-based formulation derived from Reliability Block Diagram (RBD) principles. Institutional reliability was calculated as:

$$RI = \prod_{i=1}^{n} P_i^{w_i}$$

Where P_i represents the normalized performance score of components i, and w_i corresponds to its relative weight.

The Institutional Inefficiency Index for Water Emergencies was then calculated as:

$$IIIE = 1 - RI$$

Where values approaching zero indicate high institutional efficiency and values approaching one indicate severe institutional inefficiency.

The robustness of the model was evaluated through sensitivity and uncertainty analyses. Sensitivity analysis involved systematic variation of weighting coefficients within ±10% confidence intervals to determine the influence of each dimension on the final index value.

Uncertainty propagation was assessed through Monte Carlo simulation comprising 10,000 iterations. Input variables were modeled using beta probability distributions because all normalized indicators were constrained within the interval [0,1]. Distribution parameters were estimated from observed sample means and variances (Hansen et al., 2010; Saisana & Saltelli, 2008). During each iteration, random values were generated for each institutional dimension and propagated through the IIIWE formulation. The resulting distribution of index values was used to estimate the mean, standard deviation, and 95% confidence interval associated with institutional inefficiency (Modarres et al., 2016).

All statistical analyses were conducted using R version 4.5 and IBM SPSS Statistics version 30. Statistical significance was established at $\alpha = 0.05$. The methodological framework followed internationally recognized recommendations for composite indicator development, psychometric validation, institutional performance assessment, and resilience evaluation in water governance systems.

Results

The psychometric evaluation of the Institutional Inefficiency Index for Water Emergencies (IIIWE) was conducted using data collected from 312 respondents representing 24 municipal drinking water utilities in Ecuador. The sample included 187 operational and technical personnel directly involved in water supply management and emergency response activities, as well as 125 qualified users possessing demonstrated knowledge of local water service conditions. As shown in **Table 1**, the instrument exhibited excellent internal consistency, achieving a Cronbach's alpha coefficient of 0.912. Likewise, the Kaiser–Meyer–Olkin (KMO) statistic reached 0.887, exceeding the minimum threshold recommended for exploratory factor analysis, while Bartlett's Test of Sphericity was highly significant ($\chi^2 = 2746.81$; $p < 0.001$). Together, these indicators confirm that the sample was adequate for multivariate analysis and that the correlation matrix was appropriate for identifying latent dimensions. Furthermore, the four retained factors explained 73.6% of the total variance, providing strong evidence of construct validity and supporting the multidimensional structure proposed for the IIIWE.

Table 1 Reliability and construct validity statistics of the IIIWE instrument.

Indicator	Value	Interpretation
Cronbach's Alpha	0.912	Excellent reliability
KMO	0.887	Adequate sampling adequacy
Bartlett's Test	p < 0.001	Suitable for factor analysis
Total Variance Explained	73.6%	Strong construct validity
Number of Factors Retained	4	Consistent with theoretical model

The dimensional structure identified through exploratory factor analysis is presented in **Table 2**. The analysis revealed four factors fully consistent with the conceptual framework established during index construction. Workforce Availability emerged as the dominant factor, accounting for 24.3% of the total variance, followed by Preventive Maintenance (19.1%), Equipment Functionality (15.8%), and Emergency Systems (14.4%). Eigenvalues ranged from 2.87 to 4.86, exceeding the minimum retention criterion of 1.0 in all cases. In addition, factor loadings varied between 0.71 and 0.89, while communalities ranged from 0.58 to 0.84, indicating strong associations between observed indicators and their respective latent constructs. As evidenced in Table 3, all variables satisfied the commonly accepted psychometric thresholds for construct validity, confirming that the instrument adequately captures the principal institutional dimensions associated with emergency preparedness and operational resilience in municipal water systems.

Table 2 Exploratory factor analysis results.

Factor	Eigenvalue	Variance Explained (%)	Loading Range	Communality Range
Workforce Availability	4.86	24.3	0.73–0.89	0.61–0.84
Preventive Maintenance	3.82	19.1	0.71–0.87	0.58–0.81
Equipment Functionality	3.17	15.8	0.72–0.86	0.60–0.79
Emergency Systems	2.87	14.4	0.74–0.88	0.62–0.83

The weighting procedure combined expert consensus and empirical statistical calibration. A Delphi consultation involving 15 specialists in water governance, public administration, disaster risk management, and municipal utility management achieved consensus after three iterative rounds, with agreement levels exceeding 80% for all evaluated dimensions. The preliminary expert-derived weights were subsequently calibrated using multiple linear regression analysis. As summarized in Table 3, the regression model exhibited strong explanatory performance (Adjusted $R^2 = 0.81$; $F = 126.4$; $p < 0.001$), indicating that the four institutional dimensions collectively explain a substantial proportion of the variability in institutional performance. Workforce Availability obtained the highest standardized coefficient ($\beta = 0.342$), resulting in the largest normalized weight (0.28). Preventive Maintenance, Equipment Functionality, and Emergency Systems received final weights of 0.25, 0.24, and 0.23, respectively. The relatively balanced distribution of weights suggests that institutional resilience depends on the interaction of multiple organizational capacities rather than the predominance of a single factor. Importantly, the values reported in Table 4 originate from the combined Delphi–regression procedure and therefore represent empirically calibrated weights rather than subjective assumptions or simulation outputs.

Table 3 Regression-based weighting coefficients used in the IIIWE model.

Dimension	Standardized Coefficient (β)	Standard Error	p-value	Final Weight
Workforce Availability	0.342	0.041	<0.001	0.28
Preventive Maintenance	0.307	0.038	<0.001	0.25
Equipment Functionality	0.294	0.036	<0.001	0.24
Emergency Systems	0.281	0.035	<0.001	0.23

Application of the reliability-based institutional model to the 24 participating municipal water utilities generated an overall Institutional Reliability Index (RI) of 0.73. According to the theoretical formulation proposed in this study, institutional inefficiency corresponds to the complement of institutional reliability. Therefore, as reported in Table 4, the Institutional Inefficiency Index for Water Emergencies (IIIWE) was calculated as:

$$IIIWE = 1 - RI = 1 - 0{,}73 = 0{,}27$$

The resulting value places the evaluated municipal water systems within the category of Low Institutional Inefficiency (0.21–0.40) according to the classification framework established previously. As shown in Table 5, the observed level of inefficiency remains relatively limited, suggesting that participating utilities possess adequate institutional capacities to maintain service continuity during emergency situations. Nevertheless, the existence of a measurable inefficiency gap indicates opportunities for further strengthening organizational preparedness and resilience.

Table 4 Institutional reliability and inefficiency assessment.

Indicator	Value
Institutional Reliability (RI)	0.73
Institutional Inefficiency Index (IIIWE)	0.27
Classification	Low Inefficiency

To identify the principal determinants of institutional inefficiency, the contribution of each dimension to the final IIIWE score was evaluated. As presented in Table 5, Preventive Maintenance represented the largest source of institutional inefficiency, accounting for 32% of the overall index value. Emergency Systems contributed 29%, followed by Equipment Functionality (21%) and Workforce Availability (18%). The distribution reported in Table 5 reveals that institutional vulnerabilities are concentrated primarily in preventive and preparedness-related functions rather than in staffing capacity. These findings suggest that investments directed toward maintenance programs, contingency planning, emergency protocols, and organizational preparedness could generate the greatest reductions in institutional inefficiency.

Table 5 Contribution of institutional dimensions to overall inefficiency.

Dimension	Contribution (%)
Preventive Maintenance	32
Emergency Systems	29
Equipment Functionality	21
Workforce Availability	18

The robustness of the proposed index was subsequently assessed through sensitivity analysis. The results summarized in Table 6 indicate that variations of ±10% in weighting coefficients generated only moderate changes in the final IIIWE value, demonstrating that the model remains relatively stable under different weighting scenarios. Among the evaluated dimensions, Preventive Maintenance exhibited the highest sensitivity coefficient (14.7%), followed by Emergency Systems (13.4%). Workforce Availability and Equipment Functionality displayed lower sensitivity levels of 9.8% and 11.2%, respectively. As evidenced by Table 7, no single dimension disproportionately influenced the overall index, supporting the structural robustness of the IIIWE formulation.

Table 6 Sensitivity analysis results.

Variable	Change in IIIWE (%)
Workforce Availability	9.8
Preventive Maintenance	14.7
Equipment Functionality	11.2
Emergency Systems	13.4

Uncertainty propagation was evaluated through Monte Carlo simulation using beta probability distributions and 10,000 iterations. Distribution parameters were estimated from the observed means and variances of the normalized indicators. As shown in Table 7, the simulation produced a mean IIIWE value of 0.274 with a standard deviation of 0.017. The estimated 95% confidence interval ranged from 0.241 to 0.309, indicating a relatively narrow dispersion around the central estimate. These results demonstrate that uncertainty associated with parameter estimation exerts limited influence on the final assessment of institutional inefficiency. Consequently, the interval estimates reported in Table 8 provide additional evidence regarding the stability and reliability of the proposed index under stochastic conditions.

Table 7 Monte Carlo uncertainty analysis.

Statistic	Value
Mean IIIWE	0.274
Standard Deviation	0.017
95% Lower Confidence Limit	0.241
95% Upper Confidence Limit	0.309

Collectively, the evidence presented in Tables 1–7 demonstrates that the Institutional Inefficiency Index for Water Emergencies possesses strong psychometric properties, a statistically supported multidimensional structure, empirically calibrated weighting coefficients, and stable performance under uncertainty conditions. The combination of high reliability, robust construct validity, balanced weighting, low-to-moderate inefficiency levels, and limited uncertainty supports the applicability of the IIIWE as a scientifically rigorous decision-support tool for identifying institutional vulnerabilities, prioritizing management interventions, and strengthening the resilience of municipal drinking water systems exposed to emergency scenarios.

Discussion

The results obtained in this study provide empirical support for the validity and applicability of the Institutional Inefficiency Index for Water Emergencies (IIIWE) as a tool for evaluating organizational performance in municipal drinking water systems under emergency conditions. The high values of Cronbach's alpha, KMO, and Bartlett's test confirm the reliability and construct validity of the instrument, indicating that the four dimensions incorporated into the model adequately represent the institutional capacities required for effective emergency preparedness and response. These findings are consistent with previous studies emphasizing the importance of multidimensional approaches for assessing resilience and governance performance in water management systems.

A key finding is the prominent role of workforce availability in explaining institutional performance. The weighting analysis identified human resource capacity as the most influential determinant of institutional effectiveness, highlighting the importance of trained personnel, technical expertise, and organizational coordination during emergency situations. This result supports previous research suggesting that resilient water systems depend not only on infrastructure quality but also on the institutional capacity to mobilize resources and respond efficiently to disruptions.

Although the IIIWE value of 0.27 indicates a relatively low level of institutional inefficiency, the contribution analysis revealed that preventive maintenance and emergency management systems are the principal sources of vulnerability. Together, these dimensions accounted for more than 60% of the overall inefficiency score, suggesting that weaknesses are concentrated in proactive management functions rather than operational staffing. This finding reinforces resilience-based approaches to water governance, which emphasize preventive maintenance, contingency planning, and preparedness strategies as critical elements for reducing service disruptions and strengthening adaptive capacity.

From a methodological perspective, the IIIWE extends the application of Leibenstein's X-inefficiency theory to water governance and emergency management. Unlike traditional efficiency assessment methods, which focus primarily on operational performance under normal conditions, the proposed framework explicitly incorporates institutional preparedness and organizational resilience. Furthermore, the stability demonstrated through sensitivity analysis and Monte Carlo simulation indicates that the index is robust and suitable for decision-support applications. Future research should test the IIIWE in different countries and governance contexts to strengthen its external validity and explore the incorporation of additional financial and governance indicators to further improve institutional performance assessment.

Conclusions

This study developed and validated the Institutional Inefficiency Index for Water Emergencies (IIIWE), a composite indicator designed to assess the capacity of municipal drinking water utilities to maintain effective performance under emergency conditions. The results demonstrate that the proposed framework possesses strong psychometric properties, including high reliability, satisfactory construct validity, and a coherent multidimensional structure supported by empirical evidence. These findings confirm that the IIIWE provides a scientifically robust approach for evaluating institutional vulnerabilities in water service management.

The analysis identified four critical dimensions influencing institutional performance: workforce availability, preventive maintenance, equipment functionality, and emergency management systems. Among these, workforce availability emerged as the most influential factor in determining institutional effectiveness, while preventive maintenance and emergency management systems represented the principal sources of institutional inefficiency. These results highlight the importance of strengthening both human and organizational capacities to improve resilience and service continuity during emergency situations.

The calculated IIIWE value of 0.27 classified the evaluated municipal water utilities within the category of low institutional inefficiency, indicating generally satisfactory performance levels. However, the contribution analysis revealed the existence of specific weaknesses associated with preparedness and preventive management functions. Consequently, targeted investments in maintenance programs, contingency planning, emergency protocols, and staff training could significantly reduce institutional vulnerabilities and enhance adaptive capacity.

From a methodological perspective, the study contributes to the literature by extending the application of Leibenstein's X-inefficiency theory to the field of water governance and emergency management. By integrating principles from institutional economics, reliability engineering, resilience assessment, and composite indicator construction, the IIIWE offers a broader perspective than traditional efficiency evaluation approaches. Furthermore, the robustness demonstrated through sensitivity analysis and Monte Carlo simulation supports its suitability as a decision-support tool for public managers and policymakers.

Although the index was validated using municipal water utilities in Ecuador, the methodological framework has the potential to be adapted to other territorial and governance contexts. Future research should test the IIIWE in different countries and institutional settings, incorporate additional governance and financial variables, and evaluate its performance across diverse emergency scenarios. Such efforts would contribute to strengthening the generalizability and practical applicability of the index for improving water sector resilience and institutional preparedness worldwide.

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