Sustainability of Public Water Networks in Romania: Assessment of Failures and Network Expansion

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Abstract

Sustainability in public water infrastructure requires balanced investment, efficient management, and long-term resilience against failure and degradation. This article evaluates the sustainability of public water distribution networks in Romania, based on technical performance indicators from 43 regional operators. The analysis focuses on pipeline failures, distribution network failures, and network length, using hierarchical cluster methods to identify operational differences. Results show notable disparities between operators, with a small number exhibiting high failure rates and infrastructure stress. Most operators fall within a more uniform performance range. These findings underline the importance of differentiated infrastructure strategies and informed investment planning. Such approaches are essential in reducing non-revenue water, improving cost-efficiency, and enhancing service quality. The study contributes to improving decision-making processes for water sector governance, supporting the alignment of technical management practices with sustainability goals and regulatory requirements.

Key words: water distribution networks, technical performance indicators, sustainable infrastructure management, Romania
J.E.L. classification: C10, Q53, R10

1. Introduction

Access to safe and reliable drinking water is a fundamental component of public infrastructure, with direct implications for health, economic productivity, and environmental management. Water distribution networks (WDNs) ensure the conveyance of treated water from sources to end users, but they remain vulnerable to structural degradation, frequent failures, and operational inefficiencies (Serafeim *et al*, 2024, p.16). Despite improvements in materials, installation methods, and monitoring systems, elevated failure rates and substantial volumes of non-revenue water (NRW) persist in many countries, regardless of development level (Moise, 2024, p.208).

Globally, water losses in WDNs may exceed 30% of the input volume, generating increased operational costs, energy consumption, and risks to service continuity and public health (Tariq *et al*, 2021, p.2). In Romania, these issues are compounded by infrastructure heterogeneity, regional disparities, and varied levels of technical capacity among operators. Although major investments and institutional reforms have been implemented, such as regionalization and EU-funded modernization, performance remains inconsistent (Moise, 2024, p.209; Platon *et al*, 2024, p.658). The sector includes 43 regional public operators and numerous smaller providers, with significant differences in network size, age, and frequency of technical failures.

The persistence of failures is influenced by both external (e.g., geotechnical and climatic) and internal (e.g., network age, materials, hydraulic conditions) factors (Ociepa *et al*, 2019, p.2; Serafeim *et al*, 2024, p.11). Limited capacity for timely leak detection and repair contributes to increased water losses and additional energy usage.

From an economic perspective, NRW results in reduced cost recovery and delayed rehabilitation measures due to budgetary constraints. Romanian regulations allow losses of up to 15% in distribution and 5% in transmission systems, with compulsory upgrades when total losses exceed 20%. These thresholds are often surpassed, particularly in older systems. Consequently, the adoption of economic mechanisms such as pricing strategies and full-cost recovery is promoted to ensure financial and operational sustainability (Platon *et al*, 2024, p.659).

In this context, performance analysis of water operators becomes necessary to support informed decision-making and infrastructure prioritization. The present article aims to evaluate the sustainability of Romania's public water networks by analyzing infrastructure performance, focusing on failure rates and network expansion. Using data from 43 regional operators, the study applies cluster analysis to identify structural differences and operational patterns, with the objective of informing investment planning and aligning management strategies with national and European policy frameworks.

2. Literature review

The sustainability of Romania's public water distribution networks is situated at the intersection of infrastructural resilience, institutional adaptation, and economic rationalization. The literature addressing this topic reveals an intricate interplay of technical degradation, governance constraints, and evolving environmental imperatives. Underpinning much of the current discourse is a recognition that infrastructure failures and suboptimal expansion trajectories are symptomatic of deeper systemic inefficiencies, rooted both in the legacy of underinvestment and the fragmented articulation of policy and financial mechanisms. Understanding of these interdependencies allows for more effective identification of intervention points, where targeted policies and infrastructure investments can produce measurable improvements. Moreover, evaluating sustainability must also include the capacity of operators to manage risks, adapt to regulatory change, and ensure service continuity across varied territorial and institutional settings.

Several authors explore how infrastructural vulnerability undermines water system sustainability. Thus, Aghapoor Khameneh *et al* (2020, p.421) underscore the growing complexity of water distribution networks (WDNs) and the necessity of integrating uncertainty modeling into failure analysis. Their use of fuzzy fault tree analysis (FFTA) is particularly notable, addressing both data scarcity and systemic interdependencies. Tchórzewska-Cieślak *et al* (2023, p.1) reinforce this view, highlighting how factors such as pressure fluctuations, poor hydraulic design, and corrosive soils act cumulatively to accelerate network degradation – issues compounded by insufficient preventive maintenance and a lack of systematic data collection. Moreover, works such as those by Mirea and Aivaz (2016, p.202) and Aivaz (2021a, p.53) emphasize how cost structures and workforce inefficiencies influence long-term infrastructure vulnerabilities.

In the Romanian context, these technical deficiencies intersect with institutional inertia. Moise, Banghiore, and Stan (2024a, p.124) present empirical evidence on the correlation between infrastructure investment levels and performance outcomes in the wastewater sector, illustrating persistent regional disparities despite substantial EU funding allocations. Their findings resonate with those of Banghiore Moise, and Stan (2024, p.101), who argue that the sustainability of sewerage services is intrinsically linked to coherent financial strategies, regulatory compliance, and cost-reflective pricing mechanisms – an interconnection often absent from sectoral reforms. This dynamic also reflects broader governance issues observed in public services, where the strategic integration of human capital and EU funding mechanisms remains inconsistent (Stan and Tasențe, 2023, p.172).

Efforts to modernize water networks have been further hindered by administrative fragmentation and uneven absorption capacity for EU funds. The regionalization of services, while conceptually sound, has yielded mixed results, largely due to poor coordination among local stakeholders and a lack of robust institutional support (Banghiore *et al*, 2024, p.97; Moise *et al*, 2024a, p.120). This fragmentation exacerbates the structural imbalance between urban and rural service areas, impeding equitable access and undermining long-term service viability. Studies such as Rauhut and Humer (2020, pp.2120-2122) document spatial-economic divergences that mirror infrastructural disparities, reflecting broader inefficiencies in development policy coordination. In this regard, sustainable urban planning is increasingly acknowledged as essential for reconciling urban growth with ecological constraints, ultimately enhancing quality of life across communities (Brașoveanu, 2024, p.104).

Against this backdrop, the role of digitalization and advanced monitoring technologies has emerged as a recurrent theme in the literature. Authors such as Hangan *et al* (2022, p.2) and Ismail *et al* (2023, p.71795) emphasize the strategic value of smart metering, remote sensing systems, and artificial intelligence (AI) applications in water treatment, which support pollutant removal through non-linear modeling and improved process control. Although their deployment remains limited in Romania, largely due to capital constraints, the potential for transformative impact is clear. These findings align with international best practices in performance-based asset management, as proposed by Mazumder *et al* (2018, pp.7-11), who advocate for a shift from reactive to predictive maintenance models. The integration of digital innovation into public infrastructure management also remains closely linked to the ability to absorb and strategically allocate EU funds. In this regard, recent analyses reveal that regional disparities in absorption rates and project implementation significantly affect the efficiency and sustainability of funded interventions (Stan and Cojocaru, 2022a, pp.467-468. 2022b, p.180). Although funding mechanisms are available, insufficient institutional coordination, administrative delays, and fragmented planning reduce the transformative potential of digital solutions in sectors such as water infrastructure.

Economic sustainability remains a defining pillar in discussions on infrastructure viability. Aivaz and Avram (2021, p.476), as well as Munteanu, Ionescu-Feleagă, and Ionescu (2024, pp.3-4), underscore the financial fragility of utility operators, particularly in the absence of risk-sharing instruments and diversified funding streams. Circular economy models, explored by Smol, Adam, and Preisner (2020, p.683) and further elaborated by Munteanu *et al* (2025, pp.2-3), offer a pathway toward financial and environmental alignment, yet demand significant upfront investments and regulatory innovation. In this regard, Romania faces the dual challenge of enabling institutional flexibility while managing fiscal prudence. Improved treatment technologies contribute directly to operational sustainability, reducing pollutant loads and enhancing compliance with environmental standards.

Moise, Banghiore, and Stan (2024b, p.62) provide a nuanced statistical portrait of Romanian water operators, applying principal component analysis (PCA) to identify performance clusters and typological disparities. Their research not only confirms the operational heterogeneity of utilities but also illustrates how raw water quality, pipe materials, and energy consumption affect cost-efficiency and service reliability. These variables, while technical in nature, are closely tied to institutional capacity and strategic planning. This complexity also echoes the broader findings of Mirea and Aivaz (2016, p.203) who emphasize risk-based decision models as essential for competitiveness and long-term sustainability in utility management.

From a resilience perspective, the application of complex network theory by Alaggio *et al* (2025, pp.3-5) provides a methodological advancement in identifying critical nodes within WDNs. This analytical approach enables targeted interventions by assessing both the probability and systemic consequences of component failures. Such tools are essential for Romania's utility sector, which operates in a context of chronic underfunding and fragmented governance.

Concurrently, the literature emphasizes the necessity of integrating performance benchmarks and vulnerability assessments into investment planning. Pietrucha-Urbanik (2015, p.138) highlights how failure data, though often underutilized, can serve as a predictive input for renewal prioritization. The absence of centralized databases in Romania significantly constrains this potential, as noted by Tchórzewska-Cieślak *et al* (2023, p.2) and Aivaz (2021b, p.18), who advocate for advanced IT systems to facilitate real-time data collection and analysis.

Institutional development and governance reforms are identified as essential to overcoming structural rigidities. Research by Batrancea *et al* (2021, p.2), Rus (2020, p.44), Stroie *et al* (2023, p.79), and Aivaz and Tofan (2022, p.3) highlights the importance of regulatory stability, capacity-building, and transparent decision-making frameworks. These factors are critical not only for financial solvency but also for social legitimacy, especially in a sector where public trust and affordability remain contentious issues.

Finally, the literature situates Romania’s water infrastructure challenges within the broader European agenda for sustainable development. Smol, Adam, and Preisner (2020, pp.687-689) emphasize that water services must transition from linear to circular models, embedding principles such as resource recovery and demand-side management.

In sum, the reviewed literature converges on a key insight: the sustainability of Romania’s public water networks cannot be achieved through isolated technical upgrades or policy adjustments. Rather, it necessitates a systems-oriented approach that integrates technological innovation, financial instruments, governance reforms, and performance monitoring into a coherent and adaptive framework. The Romanian experience thus serves as both a case study in institutional transformation and a reference point for future research on sustainable infrastructure governance in transitioning economies.

3. Research metdodology

The present analysis was conducted on a sample of 43 major regional operators in the public water supply sector in Romania. The aim of the approach was to identify common patterns and structural differences between these operators, based on relevant technical indicators that reflect both the size of the managed networks and the operational performance in terms of infrastructure. The analysis employed the following indicators: *number of pipeline failures*, *number of failures in transmission mains*, *number of failures in the distribution network*, and the *total length of the distribution network*, measured in kilometers.

To begin with, the data were subjected to a descriptive analysis, designed to highlight the distribution of each indicator. The results indicated a significant dispersion of the values, especially with regard to pipe and distribution network failures. These two indicators presented high levels of positive asymmetry (skewness above 2) and accentuated kurtosis, suggesting the presence of extreme values that influence the mean and internal variability of the data. Thus, before performing cluster analyses, increased attention was required in interpreting the central tendency values, given the highly unbalanced nature of the distributions.

In order to identify patterns of similarity between operators, hierarchical cluster analysis was used, with the method of average linkage (Average Linkage Between Groups), applied based on the standardized Euclidean distance. The result of this analysis was graphically represented by a dendogram, which clearly highlighted the separation of entities into two major clusters. A first, smaller group brought together operators that presented atypical characteristics – especially extreme values of damages and, in some cases, of network size. The second group, much larger, was composed of operators whose values fell within an average range, forming a relatively homogeneous category.

To verify the robustness of the classification achieved, an ANOVA analysis was applied to the four indicators, having as group variable the membership in the cluster. Although the F tests cannot be interpreted in a strictly inferential sense, since the grouping was constructed to maximize differences, the results offer a relevant descriptive perspective. Pipeline failures and distribution network failures were the variables that most clearly differentiated the two groups, with F-statistic values above 180 and extremely low significance levels ($p < .001$). The network length also presented a significant differentiation between clusters, while the number of failures per supply did not contribute significantly to their separation.

Therefore, the adopted methodology allowed the outline of a differentiated profile of regional operators according to the performance of the managed networks, providing an objective framework for analyzing vulnerabilities and intervention needs in the public water sector in Romania. This statistical approach can constitute an important support for the formulation of public policies in the field of water infrastructure, especially with regard to prioritizing investments according to the operational typology of operators.

4. Findings

Table no. 1 provides an overview of the descriptive distribution of the four indicators used in the analysis of the 43 regional operators in the Romanian water sector: pipe failures, distribution network length, supply failures and distribution network failures. Their interpretation allows us to better understand the general characteristics of the dataset and to identify possible asymmetries or extreme values.

Table no. 1 Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Pipeline failures (no.)	43	11	11879	2174.47	2876.403	2.489	.361	5.802	.709
Total length of the distribution network (km)	43	380	3375	1261.95	791.722	1.217	.361	1.290	.709
Failures in transmission mains (no.)	43	0	247	39.12	57.081	2.203	.361	4.792	.709
Failures in the distribution network (no.)	43	11	11739	2135.35	2862.326	2.485	.361	5.768	.709
Valid N (listwise)	*43*								

Source: Authors' work

With regard to *pipeline failures*, the values range between 11 and 11,879, with a mean of approximately 2,174 and a very high standard deviation (2,876), indicating a sharp dispersion of the values. The pronounced positive asymmetry (skewness = 2,489) suggests that most operators have a relatively low number of failures, but there are a few cases with extremely high values that push the mean up. The high kurtosis (5.802) indicates a leptokurtic distribution, i.e. concentrated around the mean, but with thick tails – again, a sign of extreme values.

The *length of the distribution network* varies between 380 and 3,375 km, with an average of approximately 1,262 km and a standard deviation of 792 km, which denotes a significant variability, but more moderate compared to the other indicators. The skewness of 1.217 suggests a slight positive asymmetry – that is, there are a few operators with particularly large networks – and the kurtosis of 1.290 indicates a somewhat flatter than normal distribution, but without pronounced extreme values.

In the case of *failures in transmission mains*, we observe the lowest average (39.12) and a relatively low dispersion (standard deviation of 57.08). However, the extreme values (from 0 to 247) and the skewness of 2.203 still suggest a pronounced asymmetry, i.e. most operators have few breakdowns, but a few have a significantly higher number. The kurtosis of 4.792 reinforces the idea of the presence of isolated cases, with large deviations from the average.

Failures in the distribution network follow an almost identical pattern to pipeline failures, with values between 11 and 11,739, a close mean (2,135), a high standard deviation and high values of skewness (2,485) and kurtosis (5,768). This confirms the presence of operators facing unusually high levels of failures, in a general context in which the majority have much lower values. In conclusion, the distributions of the four indicators are strongly asymmetric, especially those concerning failures. This suggests the existence of significant discrepancies between operators, probably related to the size of the network, the degree of wear of the infrastructure or the operational efficiency. Thus, the subsequent analysis must take into account these characteristics, especially the influence of extreme values, which can affect the interpretations of the mean and the overall variation.

The analysis carried out on the 43 major regional operators with public capital in Romania in the water sector aimed to identify patterns of behavior and technical performance, based on four relevant indicators: pipeline failures, failures in transmission mains, failures in the distribution network, and the total length of the water network. As can be seen in Table no. 2, the application of the clustering method led to the identification of two distinct clusters, suggesting the existence of significant differences between operators in terms of infrastructure and frequency of technical problems.

Table no. 2 Cluster Membership

Case Number	Cluster	Distance	Case Number	Cluster	Distance
1	2	1301.510	23	1	3559.615
2	2	1099.499	24	2	778.539
3	1	4104.671	25	2	432.060
4	2	1918.571	26	2	1191.149
5	2	1131.028	27	2	1611.832
6	2	1187.045	28	2	576.172
7	2	333.500	29	2	369.680
8	2	488.297	30	2	1519.220
9	2	2602.859	31	1	4962.499
10	2	327.272	32	2	713.819
11	2	1085.416	33	2	2699.186
12	2	1541.055	34	2	1104.982
13	1	1711.602	35	2	821.085
14	1	3716.398	36	2	2590.724
15	2	1634.671	37	2	1607.979
16	2	2035.378	38	2	1119.906
17	2	956.306	39	2	1151.404
18	2	1839.043	40	2	668.609
19	2	1129.573	41	2	1108.155
20	2	805.660	42	2	1851.129
21	2	1393.921	43	2	612.900
22	2	358.838	-	-	-

Source: Authors' work

The first cluster brings together a small number of operators, only five in number, who stand out for their atypical behavior in relation to the others. The very large distances from the center of this cluster indicate that these operators face extreme values of one or more of the analyzed indicators. It is possible that they manage very extensive networks or, conversely, operate under very different technical or organizational conditions than the other entities. The frequency of failures could be unusually high, or the managed infrastructure could have particular characteristics, which places them in an area of special interest for the analysis of performance and intervention needs.

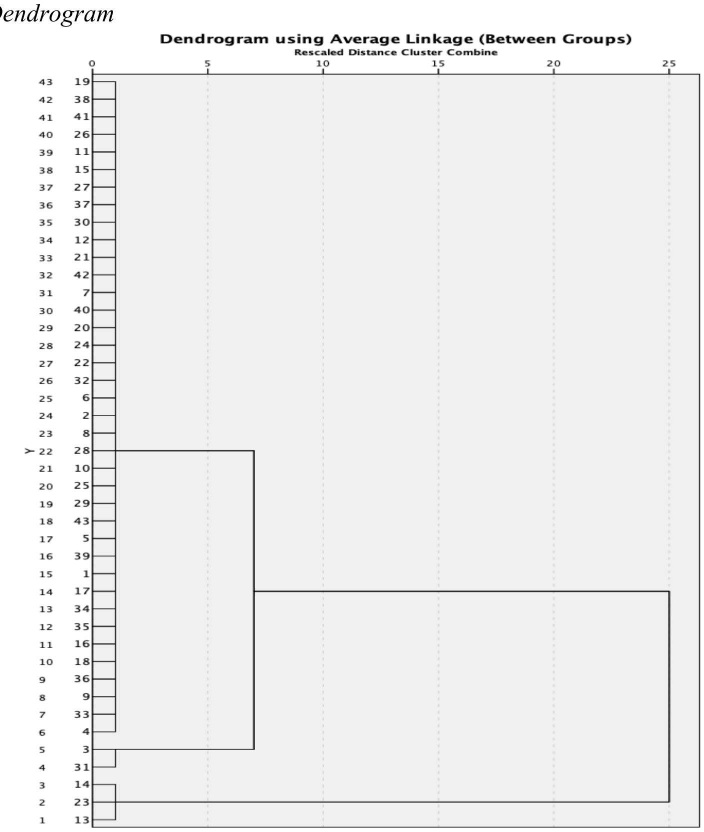
The second cluster, considerably larger, includes the majority of the operators in the sample. These operators appear to share common characteristics, with moderate variation across the analyzed indicators, suggesting a certain level of functional and structural homogeneity. This grouping may be regarded as representative of the average profile of a water operator in Romania and can serve as a reference point for evaluating overall performance within the sector.

Therefore, the result of this analysis highlights the existence of significant structural differences between operators, which may reflect not only the particularities of the network and the territory served, but also different levels of development, investment or efficiency in infrastructure management. The identification of these two distinct groups provides a useful basis for investment prioritization, the formulation of targeted intervention policies, and the promotion of performance standards adapted to on-the-ground realities.

The dendrogram in Figure no. 1, generated by the Average Linkage method, highlights how the 43 regional water operators with public capital in Romania were grouped according to their similarity based on the analyzed indicators (pipeline failures, transmission main failures, distribution network failures, and total water network length). This dendrogram indicates that there are two main groups of operators. The first group is very compact and homogeneous, including the vast majority of cases, which are linked to each other at very small distances on the similarity scale.

This close clustering suggests that most operators are significantly similar to each other from the perspective of the analyzed technical characteristics. They most likely have a common technical and operational profile, in terms of the number of failures and the length of the network managed.

Figure no. 1. Dendrogram



Source: Authors' work

In contrast, in the lower part of the dendogram, a small group of operators can be observed that clearly stands out from the rest, joining the rest of the structures at a much greater distance. Cases 13, 23, 14, 3 and 4 are those that appear in this isolated area. These entities can be considered atypical from the point of view of the indicator values, and their differentiation at a low level of similarity indicates that they exhibit extreme or significantly different features. These could be operators with particularly large or small networks, or with a frequency of failures considerably different from the average.

Thus, the dendrogram confirms the existence of two clear patterns of operation within the analyzed operators: a homogeneous, majority mass, and a restricted group with a distinct profile. This structure supports the idea of the existence of a dual typology in the public water sector in Romania, with important implications for investment policy and prioritization of interventions.

The results of the ANOVA analysis (Table no. 3) applied in the context of the classification of the 43 regional operators in the Romanian water sector provide relevant information about the differences between clusters in terms of the analyzed indicators. Although the F-tests cannot be considered rigorous from an inferential point of view – since the clustering was constructed precisely to maximize the differences between groups – they are useful for describing the consistency of the differences observed between clusters.

The most pronounced differences between the two clusters occur in the case of distribution network failures and pipeline failures. The extremely high F-values for these two indicators (183.35, 184.37, respectively) and the very low statistical significance level ($p < .001$) suggest that these variables contribute most to the differentiation between the two groups of operators. In other words, the frequency of distribution network and pipeline failures are essential factors in shaping the distinct profile of each cluster, probably reflecting different levels of wear, maintenance or modernization of the water infrastructure.

The length of the distribution network also makes a significant contribution to the differentiation of the clusters, with an F-score of 33.71 and a p-value still below the significance threshold (.001). This indicates that the size of the operated infrastructure also plays an important role in shaping the operational profiles, suggesting that operators with larger networks may have distinct characteristics in terms of technical issues and how they are managed. Conversely, the indicator related to failures in transmission mains does not significantly contribute to the differentiation between clusters (F = 1.71, p = 0.199). This result shows that, regardless of the group they belong to, the operators present relatively close values in terms of the number of failures in this component of the network, which suggests a uniformity or reduced variability between regions for this specific indicator.

Table no. 3 ANOVA Analysis

	Cluster		**Error**			
	Mean Square	df	Mean Square	df	F	Sig.
Pipeline failures (no.)	283989360.529	1	1548924.589	41	183.346	<.001
Total length of the distribution network (km)	11880172.559	1	352351.144	41	33.717	<.001
Failures in transmission mains (no.)	5466.645	1	3204.336	41	1.706	.199
Failures in the distribution network (no.)	281502864.899	1	1526815.436	41	184.373	<.001

The F tests should be used only for descriptive purposes because the clusters have been chosen to maximize the differences among cases in different clusters. The observed significance levels are not corrected for this and thus cannot be interpreted as tests of the hypothesis that the cluster means are equal.

Source: Authors' work

To conclude, the results clearly confirm that the differences between clusters are primarily supported by the recorded values for pipeline failures, distribution network failures, and the length of the operated network, while failures in transmission mains appear to have a limited influence on the grouping of operators into distinct clusters. These findings may prove valuable for developing differentiated intervention and support strategies for regional operators, based on the structural vulnerabilities identified.

5. Conclusions

The analysis of Romania’s public water distribution networks confirms the existence of structural disparities among regional operators, reflected in significantly different rates of technical failures and network dimensions. The identification of two distinct clusters of operators indicates that the sector does not operate uniformly, and therefore, infrastructure policies must be differentiated and evidence-based. A small number of operators face very high failure frequencies and manage extensive or atypical networks, while the majority present more moderate values and relatively stable performance profiles.

These findings suggest that water infrastructure performance in Romania is influenced not only by technical factors but also by institutional capacity and resource allocation. High failure rates in some networks are likely the result of both physical degradation and insufficient planning or maintenance. The variability of the analyzed indicators, especially the strong asymmetry in failure-related data, highlights the need for prioritization in investment strategies, focusing on those operators most affected by operational inefficiencies.

The results also show that indicators such as pipeline and distribution failures, as well as network length, are useful for classifying operator performance and can support the formulation of targeted interventions. By contrast, failures in transmission mains showed lower differentiation capacity, suggesting more homogeneous performance in this area. The analytical method used provides a functional basis for comparing operators and supports the development of differentiated technical and financial responses at regional level.

Improving network sustainability will require better integration of performance data into infrastructure planning. This includes systematic use of statistical tools to monitor trends, identify risk patterns, and align rehabilitation programs with objective technical criteria. In addition, the implementation of preventive maintenance systems and digital monitoring technologies can reduce losses and extend the service life of infrastructure.

In conclusion, the sustainability of public water networks in Romania depends on the capacity to address technical imbalances, allocate investments based on performance evidence, and support institutional development. A uniform policy approach is insufficient in the face of operational diversity across regions. Future strategies should promote clearer performance benchmarks, prioritize support for underperforming operators, and encourage the use of operational data in infrastructure management. These steps are necessary to ensure the reliability, efficiency, and long-term viability of the public water sector.

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