Exploring the Determinants of Operational Performance in the Water Supply Sector: A PCA Analysis of Networks, Meters, Raw Water and Operating Costs

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Abstract

The water sector is essential for sustainable development, but faces complex challenges arising from climate change, accelerated urbanization, and increasingly stringent economic and environmental demands. This study examines the determinants of operational performance in the water sector, using principal component analysis (PCA) to analyze key variables such as distribution networks, meter usage, raw water characteristics, and operational costs. Results highlight that infrastructure modernization, implementation of digital technologies, and use of circular economy principles are essential for sustainability. The analysis also underscores the link between infrastructure investments and water loss reduction, cost optimization, and service improvement. Temporal evolution reflects a transition from major operational difficulties to improved performance, thanks to effective investment strategies. The conclusions provide valuable insights for strategic decision-making and recommend integrated approaches that ensure the balance between economic sustainability, technological efficiency, and social responsibility, thereby contributing to the management of water resources for the benefit of future generations.

Key words: principal component analysis (PCA); wastewater management; performance of water operators
J.E.L. classification: C10, Q53, R10

1. Introduction

Access to safe and affordable drinking water is recognized as a fundamental necessity and a universal right (Brașoveanu, 2023c, p.23), but achieving this goal faces multiple obstacles globally. The water sector is exposed to complex challenges, stemming from the interaction between climate change, population growth, accelerated urbanization and rising costs associated with resources and energy. At the same time, operators in the sector face strict requirements regarding service quality, economic sustainability and operational efficiency, all in the context of an often outdated infrastructure and strict regulation (Sakai, 2024, p.169).

The operational performance of water supply services is a central concern for operators and authorities worldwide, with a significant impact on the quality of life, economy and environment. Water systems, which include water abstraction, treatment, transport and distribution, operate in a dynamic environment, where limited resources must be managed efficiently to meet increasing demand and to avoid losses and risks associated with unequal access to water (Vilanova, Magalhães Filho and Balestieri, 2015, pp.2-3). Given the current trends of integrating economic mechanisms into the sustainable management of water resources, it becomes imperative to analyze the factors that influence the performance of these systems, in order to ensure both sustainability and efficiency (Platon *et al*, 2024, p.658).

This article aims to explore the interdependencies among the determinants of operational performance in the water sector, with a focus on distribution networks, meter use, raw water characteristics and cost management. By identifying the challenges and opportunities associated with these drivers, the paper provides an integrated perspective on how the water sector can respond to current challenges and contribute to sustainability and equity goals.

2. Literature review

The water sector is a critical component for sustainable development, while at the same time a challenge due to climate change, population growth and increasingly stringent regulatory requirements. Efficient management of water resources requires the implementation of sustainable and innovative strategies that integrate both economic and environmental perspectives (Ramos *et al*, 2019, p.2).

Sala-Garrido *et al* (2023, p.121078) emphasize the importance of dynamically evaluating the performance of water operators in terms of service quality and economic sustainability. They suggest that an effective management system should integrate both operational variables and customer satisfaction aspects, such as continuity of supply and loss reduction (Sakai, 2024, p.177).

The operational performance of water services is often assessed through efficiency and sustainability indicators, which reflect the ability of operators to manage resources in an optimal way. Alegre *et al* (2016, pp.52-58) highlight the importance of using standardized metrics, such as water losses, operational cost coverage and service quality, to support informed decision-making.

In Romania, a recent study (Moise 2024, p.209) shows that the regionalization of water operators has had a positive impact on financial and operational efficiency. These reforms have been accompanied by significant investments in infrastructure, supported by European funds (Stan and Cojocaru, 2022a, p.467; Stan and Cojocaru, 2022b, p.181; Stan and Tasențe, 2023, p.172), which have contributed to reducing losses and increasing the quality of services, as well as the adoption of a favorable legislative framework (Brașoveanu 2023a, p.46; 2023b, p.52) that amplifies the positive effects of an efficient management system. At the same time, the analysis carried out by Bakó and Fulop (2017, p.96) highlights that the financial performance of water operators can be improved by consolidating infrastructure and optimizing resources.

Distribution networks play a critical role in operational performance and water losses are a key indicator of efficiency. Hangan *et al* (2022, p.19) and Micu *et al* (2013, p.147) point out that the implementation of advanced technologies such as digital monitoring and smart meters, although involving high upfront costs, is essential to reduce losses, optimize consumption and increase transparency in dealing with consumers. In addition, risk management and the restructuring of operational processes are fundamental elements for increasing the competitiveness of water operators (Stroie *et al*, 2023, p.71; Aivaz *et al*, 2023, p.936). Reducing operating costs, either by upgrading infrastructure or digitizing processes, can ensure better resource allocation and more efficient adaptation to consumer demands. The integration of these strategies allows operators to better respond to market demands, while helping to improve service quality.

The quality of raw water directly influences the complexity of treatment processes and related costs. Mensah-Akutteh *et al* (2022, p.2) emphasize that water sources with high levels of contamination require advanced treatment technologies, which significantly increases operational costs. Bhojwani *et al* (2019, p.2750) analyze the technologies used in water treatment, demonstrating that investing in innovative solutions can reduce long-term costs and improve efficiency.

In this respect, an important factor is the digitalization and transformation of water organizations through the integration of modern technologies. Recent studies highlight that digitization not only supports operational efficiency (Munteanu *et al*, 2023, p.204), but also facilitates transparent interaction with consumers, providing a better understanding of their behavior (Boyle *et al*, 2022, p.6). These transformations are underpinned by circular economy strategies, which emphasize reusing resources and reducing reliance on conventional solutions

(Mbavarira and Grimm, 2021, p.5).

In terms of operational costs, the energy used for pumping and treating water represents a significant part of the total expenses of operators (Bhojwani *et al*, 2019, p.2750). In this context, strategies such as resource recovery and the integration of renewable sources become essential for sustainability. In addition, the integration of circular economy principles in water resource management can lead to the diversification of income sources and the reduction of operational costs (Munteanu *et al*, 2024, p.3).

At the same time, research and innovation funding also plays a key role in improving operational performance. Rus (2018, p.506; 2023, p.1053) emphasizes the importance of collaboration between the private and public sectors to develop sustainable solutions. In this regard, investments in research and development have contributed to the creation of more efficient technologies, adapted to local needs and international standards (Aivaz, 2021, p.9).

In conclusion, to meet the complex and dynamic demands of the water sector, it is essential to adopt practices that integrate advanced technologies, optimize infrastructure and reduce operational costs. By promoting sustainability and efficiency, utilizing renewable resources and circular economy principles, operators can improve service performance and contribute to a more responsible management of water resources, thus balancing economic, social and environmental needs.

3. Research metdodology

This research aimed to explore and analyze the determinants of operational performance in the water sector, using a quantitative approach based on principal component analysis (PCA) (Mirea and Aivaz, 2016a, pp.202-203; Vancea et al, 2021, p.52). The study aimed to reduce the size of the data set and identify the main factors that explain the variation in the data, thus contributing to the understanding of the dynamics of operational performance according to the variables studied. The data used were obtained from administrative and operational sources relevant to the water sector, covering a period of 11 years. The variables analyzed included key indicators such as the percentage of non-revenue water (Op-RO-026), the volume of raw water paid to Apele Române (CI-RO-103a), the volume of raw water imported (A-RO-002a), the length of water networks (C-008), the number of meters installed at household consumers (E-007) and economic agents (E-008), as well as the total operating expenses (G-RO-005). These variables were selected to capture the essential dimensions of operational performance, infrastructure and associated costs.

To explore temporal dynamics, the scores of the main factors were used to generate scatter plots, highlighting changes over the analyzed period. The distribution of years according to the factor scores was analyzed to identify transition and performance stages, reflecting the evolution of the water sector.

The methodology used has demonstrated that principal component analysis is an effective tool for identifying determinants in the water sector (Mirea and Aivaz, 2016b, p.192). It provided a solid basis for interpreting operational performance and highlighted the importance of temporal evolution and the interaction between infrastructure, operational losses and costs. Despite its limitations, the results provide valuable insights for strategic decision-making and for guiding future policies in the water sector.

4. Findings

Table 1 provides an overview of the main statistical indicators used to analyze operational performance in the water sector. The analysis shows that the percentage of non-revenue water, with an average of 48.73%, represents a significant challenge for the sector, indicating significant losses that could be caused by factors such as physical losses, theft or inefficiencies in network management. The variability of this indicator, with a standard deviation of 5.66%, suggests a relatively high consistency of this problem across the regions analyzed.

Table no. 1 Statistical description of the main statistical indicators used to analyze operational performance in the water sector

	Mean	Std. Deviation	Analysis N
Op-RO-026	48.73	5.66	11
CI-RO-103a	79138788.81	6052466.60	11
A-RO-002a	1289585.81	1844540.71	11
C-008	3812.45	253.15	11
E-007	125020.18	17433.76	11
E-008	10886.091	2680.8621	11
G-RO-005	166532365.636	38578660.5150	11

Source: Authors' work

The volume of raw water paid to Apele Române averages 79.14 million cubic meters per year, which highlights a significant dependence on domestic raw water resources. This value is relatively stable, as indicated by the standard deviation of 6.05 million cubic meters. In contrast, the volume of imported raw water, although significantly lower, with an average of 1.29 million cubic meters per year, shows a much greater variation between years or regions, which may reflect fluctuations in the availability of domestic resources or the need for supply from external sources.

The water distribution network is extensive, with an average length of 3812.45 km. This appears to be relatively evenly distributed, as suggested by the standard deviation of 253.15 km, indicating that the water networks are similarly adapted to the needs of the different regions analyzed. Regarding consumption monitoring, the average number of meters installed at household consumers is 125,020, reflecting a considerable effort to accurately measure consumption. However, a standard deviation of 17,433 meters indicates significant differences between regions, probably caused by different levels of infrastructure development. In the economic agents and institutions sector, the average number of meters is much lower, at only 10,886, suggesting a lower coverage compared to the household sector. The variation in this indicator is however notable, with a standard deviation of 2,680, which may reflect differences in the density of economic agents or institutions in different regions.

The total operating costs of water sector activities are considerable, averaging 166.53 million lei per year. The standard deviation of 38.57 million lei suggests moderate variations between regions, which can be influenced by factors such as network size, operational efficiency and local tariffs. This high value of expenses, correlated with high non-revenue water losses, underlines the need for effective strategies to reduce costs and improve operational performance.

The analysis suggests that the water sector faces significant challenges, both in terms of efficient resource management and cost optimization. Reducing water losses and expanding metering infrastructure are priority directions to improve the sustainability and operational performance of this essential sector.

Table 2 of the correlation matrix provides essential information about the statistical relationships between the variables analyzed in the water sector, highlighting the strength and direction of the links between them. Interpretation of the correlation coefficients allows the identification of possible direct and indirect links that influence operational performance and resource use.

The results show that the percentage of non-revenue water (Op-RO-026) is strongly positively correlated with the volume of raw water paid to Apele Române (CI-RO-103a), with a coefficient of 0.859. This relationship suggests that as the amount of raw water purchased increases, there is also an increase in water losses, indicating inefficiencies in the distribution system or in consumption measurement. In contrast, non-revenue water has a moderate negative correlation with the total length of water networks (C-008) and with the number of meters installed for both household consumers (E-007) and economic agents (E-008). These negative correlations suggest that a better developed infrastructure and more efficient measurements can contribute to reducing water losses.

Imported raw water (A-RO-002a) shows significant positive correlations with the length of water networks (C-008), the number of meters (E-007 and E-008) and total operating expenses (G-RO-005). These relationships indicate that raw water import may be associated with a well-developed infrastructure and higher operating costs, which could reflect the complexity of operations in regions requiring water imports.

The length of water networks (C-008) has very strong positive correlations with the number of meters for households and economic agents, with coefficients of 0.967 and 0.893, respectively. This relationship emphasizes that in regions where the distribution network is extensive, there is also a better developed infrastructure for consumption metering. At the same time, network length is strongly positively correlated with operating costs, suggesting that managing larger networks implies higher operating costs.

The number of meters for household consumers (E-007) and economic agents (E-008) show significant positive correlations with each other, suggesting a uniform approach in the installation of meters for the different categories of consumers. Both variables are also positively associated with operating expenditure, indicating that consumption metering requires additional financial investment.

Table no. 2 Statistical relationships between the variables analyzed

		Op-RO-026	**CI-RO-103a**	**A-RO-002a**	**C-008**	**E-007**	**E-008**	**G-RO-005**
Correlation	Op-RO-026	1.000	.859	.208	-.347	-.333	-.181	-.498
	CI-RO-103a	.859	1.000	.194	-.105	-.132	-.005	-.171
	A-RO-002a	.208	.194	1.000	.617	.624	.773	.508
	C-008	-.347	-.105	.617	1.000	.967	.893	.876
	E-007	-.333	-.132	.624	.967	1.000	.843	.844
	E-008	-.181	-.005	.773	.893	.843	1.000	.745
	G-RO-005	-.498	-.171	.508	.876	.844	.745	1.000
Sig. (1-tailed)	Op-RO-026		<.001	.270	.148	.159	.297	.060
	CI-RO-103a	.000		.284	.379	.349	.494	.308
	A-RO-002a	.270	.284		.021	.020	.003	.055
	C-008	.148	.379	.021		.000	.000	.000
	E-007	.159	.349	.020	.000		.001	.001
	E-008	.297	.494	.003	.000	.001		.004
	G-RO-005	.060	.308	.055	.000	.001	.004	
a. Determinant = 3.300E-5								

Source: Authors' work

Operating expenditures (G-RO-005) have significant positive correlations with most indicators, except non-revenue water, where the relationship is moderately negative (-0.498). This could signal that regions that invest more in operations are able to reduce the proportion of water losses.

The statistical significances associated with the correlation coefficients show that most of the identified relationships are statistically significant, with probability values below the 0.05 threshold for the strongest correlations. This analysis suggests that operational performance and resource utilization in the water sector are influenced by complex interactions between infrastructure, metering and operational costs. Reducing water losses and optimizing expenditures could be achieved by improving infrastructure and monitoring systems.

Table 3 provides insight into the contribution of each factor (principal component) in explaining the total variance in the dataset. The analysis identified seven principal components, but only the first two have eigenvalues greater than 1, suggesting that these are the significant components according to Kaiser's criterion. The remaining components have eigenvalues below 1 and do not make a significant contribution to the total variance.

The first principal component has an eigenvalue of 4.221 and explains 60.301% of the total variance in the data. This indicates that most of the information in the original variables can be concentrated in this component, making it the most important in the analysis. The second principal component has an eigenvalue of 1.979 and explains an additional 28.265% of the total variance. Together, the first two components accumulate 88.566% of the total variance, which means that almost 89% of the original information is preserved by using these two components.

This shows that the dataset size can be significantly reduced without losing essential information. The analysis suggests that the first two principal components are sufficient to summarize the major variation in the data. This result supports the effectiveness of PCA analysis in reducing the size of the data and identifying the main factors influencing the analyzed variables.

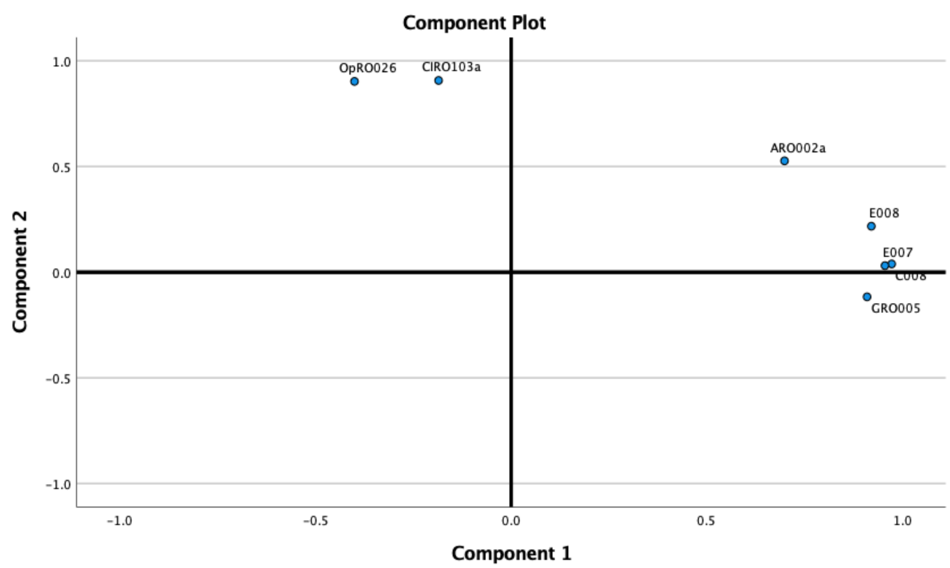
Table no. 3 Contribution of each factor (principal component) in explaining the total variation in the dataset

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	4.221	60.301	60.301	4.221	60.301	60.301
2	1.979	28.265	88.566	1.979	28.265	88.566
3	.443	6.333	94.899			
4	.186	2.664	97.563			
5	.132	1.888	99.451			
6	.022	.313	99.764			
7	.017	.236	100.000			
Extraction Method: Principal Component Analysis.						

Source: Authors' work

Figure no. 1 provides a two-dimensional representation of the variables analyzed in terms of the first two principal components identified in the PCA analysis. These principal components explain the majority of the variation in the data, and the positioning of the variables on the Component 1 and Component 2 axes reflects their relationships with these principal factors.

Figure no. 1. Two-dimensional representation of the analyzed variables in terms of the first two components



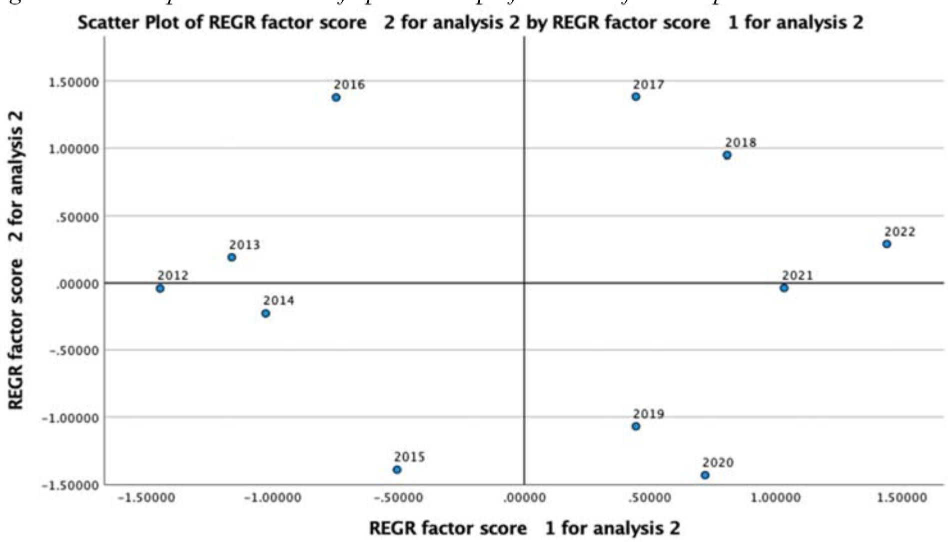
Source: Authors' work

Op-RO-026 and **CI-RO-103a** are very close on the Component 2 axis, suggesting a strong relationship between them and a common influence of this component. This indicates that non-revenue water losses and raw water paid to Apele Române are correlated factors, jointly influencing operational performance. **A-RO-002a** (imported raw water) is positioned further along the Component 1 axis, showing a distinct relationship with other factors representative for this component. Its more isolated positioning suggests a specific influence on the variation in the data. **E-007**, **E-008** and **C-008**, representing the measurement infrastructure and water network, are very close together on Component 1, showing a close relationship between them. This closeness indicates that these variables contribute similarly to explaining the variation in Component 1, reflecting the importance of infrastructure in overall system performance. **G-RO-005** (operating costs) is also positioned close to the infrastructure variables (E-007, E-008 and C-008), indicating a link between operating costs and infrastructure development.

Therefore, the graph suggests that there are two major groups of variables: the first, represented by Op-RO-026 and CI-RO-103a, indicates losses and purchases of raw water, and the second, consisting of E-007, E-008, C-008 and G-RO-005, indicates the link between infrastructure and operational costs. A-RO-002a stands out as a variable with a unique contribution, but less correlated with the other groups. These relationships provide a solid basis for identifying the main factors influencing operational performance in the water sector.

Figure no. 2 illustrates a clear temporal evolution in the operational performance of the water sector, suggesting a significant transformation over the years analyzed. The positioning of the years 2012-2015 in the lower left indicates a period characterized by major difficulties. During this phase, the sector likely faced high water losses that were not generating revenue, lack of adequate infrastructure, and high operating costs that were not supported by efficient performance. These problems could be the result of lack of investment or less efficient management.

Figure no. 2. Temporal evolution of operational performance of water operators



Source: Authors' work

The following years, from 2016-2020, are distributed in an intermediate area of the graph, suggesting a transition phase. This period is characterized by the implementation of the first improvement measures, such as investments in infrastructure and modernization, which have started to gradually reduce losses and optimize operating costs. The effects of these measures seem to have been visible in the steady progress of the sector, although the overall performance had not yet reached an optimal level.

In the upper right part of the graph, the years 2021 and 2022 mark a stage of significantly improved performance. This positioning indicates positive results, supported by better developed infrastructure, increased operational efficiency and a significant reduction in water losses. This progress is likely the result of better-founded policies, consistent investments and the use of modern technologies. The clear separation between the early years, which highlight a problematic state, and the recent years, which reflect high performance, suggests a gradual and systematic transformation of the sector.

This evolution indicates that the water sector has undergone a process of continuous adaptation and improvement, highlighting the benefits of modernization and efficiency strategies implemented over time. The changes reflected in the graph are the result of a concerted effort to overcome initial challenges and ensure more efficient management of resources and costs.

5. Conclusions

In conclusion, the water sector is a vital component of sustainable development, and success in this area depends on the integration of advanced technologies, cost optimization and the adoption of sustainable strategies. Efficient resource management involves not only modernizing infrastructure, but also implementing proactive measures such as reducing leakage, using energy efficiently and applying circular economy principles to minimize waste and maximize resource reuse. Operational performance, defined by reducing water losses, expanding metering infrastructure and improving customer relationships, thus becomes a key indicator of the sustainability of this essential sector.

The results of the analysis highlight the close relationship between operating expenditure and infrastructure development, revealing the importance of well-structured investment policies, supported by European funds, which have facilitated an increase in the quality of services and a reduction in resource vulnerabilities. The study shows that determinants factors, such as the length of the distribution network and the number of meters, significantly influence the operational efficiency and sustainability of the system, being supported by digitization and the use of smart technologies to monitor consumption and improve performance.

Furthermore, PCA analysis and correlation matrix confirm that most of the data variation can be explained by a few principal components, providing a solid basis for strategic decisions. The performance evolution graph indicates a clear transition from major difficulties to improved performance, reflecting the positive effects of investments and strategies implemented over time. Reducing losses, diversifying revenue sources and implementing digital solutions remain critical priorities to ensure efficient management of water resources and to respond to current challenges, thus contributing to the well-being of future generations and the balance between economic, social and environmental requirements.

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