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Analysis of regional water operator typologies and its implications for sustainable management

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***Abstract* – This study analyzes the heterogeneity of regional water operators in the context of current challenges regarding the sustainable management of public water supply services. The objective of the research is to identify the operational typologies of operators, based on relevant technical and economic indicators for the year 2024. The methodology used consists of applying the K-means clustering method, complemented by descriptive analysis of cluster centers and variance. The results highlight the existence of three distinct typologies of operators, differentiated mainly by the structure of water sources, the dimension of the infrastructure, the level of losses and the economic performance.**

Keywords – K-means, regional operators, sustainable management.

1. INTRODUCTION

Water supply services are an essential component of public infrastructure, with a fundamental role in ensuring the health of the population, supporting economic activity and protecting the environment. In the context of increasing pressures generated by climate change, accelerated urbanization and budgetary restrictions, the efficient and sustainable management of water resources has become a strategic priority at national and international level. Regional water operators are thus in a position to balance multiple and often competing objectives, such as security of supply, economic efficiency, tariff accessibility and reducing environmental impact.

In many water supply systems, the performance of operators is marked by significant structural differences, determined by factors such as available water sources, the size and condition of the infrastructure, the density of the population served and the regulatory framework [1]. These differences are reflected in variable levels of network losses, operational costs and economic results, highlighting the difficulty of applying uniform management and investment policies [2]. In this context, a thorough understanding of the typologies of water operators becomes necessary, allowing the substantiation of management strategies adapted to the specifics of each case.

The specialized literature increasingly emphasizes the usefulness of multivariate approaches in analyzing the performance of public utility services, especially in the case of sectors characterized by high complexity and multiple interdependencies between technical and economic variables. Clustering methods provide an efficient analytical tool for identifying homogeneous operational profiles, allowing to highlight similarities and differences between operators beyond the simple comparison of individual indicators.

Based on these considerations, the purpose of this study is to identify and analyze the typologies of regional water operators, based on a set of relevant indicators for the year 2024, which reflects technical efficiency, resource structure, economic performance and infrastructure scale. By applying the K-means clustering method, the research aims to highlight distinct operating models and analyze their implications for the sustainable management of water supply services. The study thus aims to contribute to a better understanding of the heterogeneity of the sector and to provide empirical support for the development of differentiated public policies and management strategies, oriented towards increasing efficiency and long-term sustainability.

2. THEORETICAL BACKGROUND

Water supply management is approached in the literature as a complex field, located at the intersection of public utility economics, infrastructure management and environmental policies. Established theoretical models emphasize that the performance of water operators cannot be evaluated in isolation, exclusively based on financial results, but must be analyzed in an integrated framework that includes technical efficiency, resource sustainability, service quality and social equity [3] - [5]. From this perspective, water operators are considered multi-objective entities, whose operation is simultaneously influenced by economic constraints, natural conditions and imperatives of public interest.

A central concept in the analysis of water service performance is the technical efficiency of distribution systems, often associated with the level of water losses in the network. Non-Revenue Water (NRW) is widely used in the literature as a synthetic indicator of operational performance, reflecting physical losses, commercial losses and management deficiencies. High levels of NRW are correlated with outdated infrastructure, lack of investment and low institutional capacity, having a negative impact on financial sustainability and security of water supply. The structure of water sources is another essential element in defining the profile of operators. The distinction between groundwater and surface water use is relevant both from an economic and environmental sustainability perspective [6]. While groundwater is generally associated with lower operational costs and stability of supply, overexploitation can generate significant risks for ecosystems and long-term strategic reserves. Surface water usually involves larger investments in treatment and infrastructure, but allows for supporting high volumes of consumption, being characteristic of systems serving large urban agglomerations [7].

The economic performance of water operators is often assessed in terms of their ability to generate operating surpluses to support infrastructure maintenance and modernization. The operating profit rate for water activity reflects the degree to which revenues obtained from providing the service cover operating costs and allow for reinvestment in the system. However, the literature highlights the existence of tensions between profitability objectives and the social role of water services, especially in the context of tariff regulation and the need to maintain accessibility for the population [5].

The average water tariff is a central public policy instrument, used to recover costs and guide consumer behavior. In dominant theoretical frameworks, tariffs are considered to be the result of a compromise between the financial sustainability of operators and consumer protection, being strongly influenced by regulations and institutional mechanisms. As a result, tariff differences between operators tend to be smaller than differences in technical efficiency or infrastructure structure [8].

The size and condition of the infrastructure are reflected by indicators such as the total length of water networks and the number of pipe failures, which provide relevant information on the operational complexity and risks associated with the provision of the service. The literature highlights a direct relationship between the expansion of networks, the frequency of failures and the level of investments required to maintain the functionality of the systems, underlining the importance of asset management in the sustainability strategy of operators [9] - [10]. Also, the number of meters installed at household consumers, respectively at economic agents and institutions, is used as a proxy for the size of the serviced area and the degree of maturity of the metering system. Full metering is recognized in the specialized literature as a key factor in reducing commercial losses, improving transparency and optimizing the relationship between the operator and the user [11].

Integrating these variables into a common analytical framework allows water operators to be approached as complex systems, whose performance is determined by multiple interactions between resources, infrastructure, tariff policies and institutional capacity [12]–[14]. From this perspective, the use of multivariate analysis methods, such as clustering, is theoretically justified as a tool for identifying operational typologies and substantiating strategic decisions oriented towards the sustainable management of water supply services.

3. RESEARCH METHODOLOGY

The research adopts a quantitative, exploratory approach, aiming to identify typologies of regional water operators and analyze their implications on the sustainable management of water supply services. The methodological design is based on the use of multivariate analysis techniques, appropriate for studies that aim to highlight latent structures and similarity patterns in complex data sets.

The dataset used in the analysis is composed of technical, economic and operational indicators for the year 2024, reported by regional water operators. The selected variables reflect essential dimensions of water service performance, including the level of non-revenue water, the structure of supply sources, the economic performance of the water activity, the tariff policy, the extent of infrastructure, the condition of the networks and the size of the metered user base. The selection of variables is supported both by the specialized literature and by their relevance for assessing the operational and financial sustainability of the operators.

In order to identify operator typologies, the K-means clustering method was applied, due to its ability to group observations according to multidimensional similarity and to maximize the internal homogeneity of the clusters. Before applying the algorithm, the data were preprocessed to ensure the comparability of the variables, through standardization, considering the significant differences in magnitude between the indicators used. The optimal number of clusters was established based on empirical criteria and the economic interpretability of the results. The analysis of the results was carried out by examining the final centers of the clusters, which provide a synthetic interpretation of the average profile of each identified typology, as well as by analyzing the distances to the centers of the clusters, used to assess the homogeneity and stability of the groups. Analysis of variance (ANOVA) was also used for descriptive purposes, to evaluate the contribution of each variable to the differentiation of the clusters and to identify the indicators with the highest discrimination power. Data processing and analysis were performed using the SPSS statistical package, and the interpretation of the results was carried out in an integrated manner, correlating the statistical conclusions with the theoretical perspective on the sustainable management of water supply services. This methodological approach allows obtaining robust and relevant results for substantiating strategic decisions and public policies oriented towards efficiency and long-term sustainability.

4. RESULTS AND SIGNIFICANCES

The results of the analysis led to the grouping of regional water operators into three clusters, confirming the existence of distinct typologies, with different degrees of homogeneity and variable positionings with respect to the cluster centers. The relatively balanced distribution of operators between clusters 1 and 2, compared to the small size of cluster 3, suggests a dominant structure of the sector, complemented by a small group of atypical operators (Table. 1).

Table. 1 Cluster Structure

Case Number	Operator	Cluster	Distance	Case Number	Operator	Cluster	Distance
1	1	1	5836105.778	22	23	3	6724227.198
2	2	2	9316888.128	23	24	2	5697253.254
3	3	1	5017246.757	24	25	1	1958156.089
4	4	3	11010750.538	25	26	1	9766868.240
5	5	2	3213749.007	26	27	1	8228933.923
6	6	1	3697744.481	27	28	1	17035218.180
7	7	1	12780471.668	28	29	2	7299622.329
8	8	1	4955223.934	29	30	2	2770164.050
9	9	3	9534937.971	30	31	2	3754408.243
10	10	2	2410972.854	31	32	2	614233.288
11	11	1	8127429.239	32	33	1	6957908.241
12	12	1	3927345.778	33	34	2	16182902.421
13	15	2	5762738.051	34	35	2	4033623.141
14	16	2	2137536.222	35	36	3	6918727.497
15	17	2	10624541.891	36	37	1	6699189.179
16	18	1	7862000.530	37	38	2	7811412.749
17	19	2	7807581.021	38	39	1	1349638.413
18	20	2	7358481.113	39	40	1	4190909.826
19	21	1	7202898.944	40	41	1	8220108.263
20	21	1	4816243.532	41	42	2	11532801.500
21	22	1	4091620.711	42	43	2	3002803.284

Source: authors' processing with SPSS software

Cluster 1 brings together a significant number of operators and presents a satisfactory overall homogeneity, although the existence of large distances for some cases indicates internal variations determined by differences in infrastructure, water sources or the level of losses. This suggests that, despite a common profile, operating strategies and technical efficiency can vary considerably, with effects on economic performance.

Cluster 2 includes a comparable number of operators, but is characterized by a higher internal heterogeneity, reflected by the different dispersion of distances from the centroid. This aspect indicates the presence of operators in transition between distinct management models. Cluster 3 is distinguished by a small number of cases and extreme operational and economic profiles, highlighting the need for differentiated policies, adapted to the particularities of each operator typology.

The final centers of the clusters obtained by the K-means method provide a synthetic picture of the average profile of each typology of regional water operators, highlighting clear differences in resource use, economic performance and infrastructure management (Table. 2). The centroid values confirm the existence of distinct operating models, with direct implications for the efficiency and sustainability of services.

Table. 2 Cluster structure

	Cluster		
	1	**2**	**3**
NRW (Non-Revenue Water) (%)	51.97	47.11	58.54
Groundwater (m^3/an)	2224638.33	12827913.54	19135208.03
Surface water (m^3/an)	15326888.42	2741981.53	33834329.73
Operating profit rate for water activity (%)	8.19	6.19	12.56
Average water rate (Lei/m^3)	7.22	7.11	7.25
Total length of water networks (km)	1303.17	1316.08	2440.48
Pipeline failures (no.)	1092	1608	5382
Meters for household consumers (no.)	51397	52786	81584
Meters at consumers, economic agents and institutions (no.)	3804	3613	6492

Source: authors' processing with SPSS software

Cluster 1 is characterized by high water levels that do not generate revenue, indicating significant losses or monitoring deficiencies. Operators in this group rely predominantly on surface water sources and serve large urban areas, with complex infrastructures and a high frequency of failures. Although profitability is positive, its level remains modest, affected by losses and high maintenance costs, while the tariff remains around the average, reflecting a fragile balance between financial sustainability and affordability.

Cluster 2 is characterized by a lower level of NRW, indicating a more efficient network management and better control of losses, supported by the predominant use of groundwater and relatively controlled operational costs. However, the lowest operating profit rate suggests that technical efficiency is not sufficient to achieve superior economic performance. The high number of failures, concomitant with a low NRW, indicates the existence of operational interventions that limit effective losses. The tariff policy remains comparable to that of the other clusters. Cluster 3 defines an extreme typology, characterized by the highest level of NRW, very large volumes of treated water and an extensive infrastructure, associated with a high number of failures. Despite these characteristics, the cluster records the highest operating profit rate, explained by economies of scale and a large consumer base. The average tariff is slightly higher, but profitability is mainly determined by the scale of operations, not by the tariff policy.

The analysis of variance associated with clustering using the K-means method, ANOVA, highlights the differential contribution of each indicator in the delimitation of the typologies of regional water operators (Table. 3). The values of the F statistic, reported at the corresponding significance levels, confirm that the variables included in the analysis play a distinct role in separating the clusters, even if, as methodologically specified, these tests have a descriptive character and cannot be interpreted as classic inferential tests regarding the equality of means.

Table. 3 Analysis of variance associated with clustering using the K-means method

	Cluster		Error		F	Sig.
	Mean Square	df	Mean Square	df		
NRW (Non-Revenue Water) (%)	12645.209	2	168.438	1920	75.073	<.001
Groundwater (m^3/an)	38286916260673176.000	2	26184340079416.914	1920	1462.207	.000
Surface water (m^3/an)	91781607681629888.000	2	33524407876151.920	1920	2737.755	.000
Operating profit rate for water activity (%)	3622.087	2	99.132	1920	36.538	<.001
Average water rate (Lei/m^3)	3.003	2	.822	1920	3.654	.026
Total length of water networks (km)	127878668.321	2	629220.085	1920	203.234	<.001
Pipeline failures (no.)	1699382473.022	2	4308160.714	1920	394.457	<.001
Meters for household consumers (no.)	87654049320.463	2	754163469.409	1920	116.227	<.001
Meters at consumers, economic agents and institutions (no.)	776401720.822	2	2704733.623	1920	287.053	<.001

Source: authors' processing with SPSS software

The indicators relating to the volumes of water used, from underground and surface sources, record the highest values of the F statistic, highlighting a high capacity to discriminate between clusters. This result highlights the essential role of the structure of supply sources in configuring the typologies of operators, reflecting differences in geographical context, resource availability and exploitation strategies. Similarly, the number of failures and the length of water networks present high F values, indicating the importance of the size and condition of the infrastructure in differentiating operational profiles. Non-revenue water (NRW) stands out as an indicator with significant explanatory power, suggesting a close correlation between the level of losses and the typology of the operator. The differences between the clusters reflect both the technical efficiency of the networks and the institutional monitoring capacity. At the same time, the operating profit rate contributes significantly to the separation of the clusters, indicating a clear link between the economic performance and the technical characteristics of the operators.

Indicators regarding the number of meters confirm the role of the size of the user base in defining typologies and increasing the complexity of service management.

In contrast, the average water tariff has a low discriminatory power, suggesting a relative homogeneity of tariff policies, influenced more by the regulatory framework than by the specificities of the operators. Overall, the ANOVA analysis confirms the robustness of the clusters and reveals that the differences between operators are mainly determined by structural and operational factors, supporting the usefulness of the cluster approach in the analysis of sustainable management of water supply services.

5. CONCLUSIONS

The analysis of the typologies of regional water operators carried out using the K-means method highlights the structural and operational complexity of the water supply services sector, confirming that its performance and sustainability are the result of the interaction between technical, economic and institutional factors. The results obtained demonstrate that operators cannot be treated as a homogeneous group, as differences in the water sources used, the size of the infrastructure, the level of network losses and economic performance outline distinct operating models.

The insights provided by the final cluster centers and variance analysis highlight the determining role of the operational dimension and infrastructure structure in defining the profile of each operator, while tariff policies appear as a relatively uniform element at sectoral level, with a limited capacity to differentiate management strategies. This finding suggests that economic efficiency and the capacity to adapt to sustainability challenges do not depend primarily on the level of water prices, but on the way in which resources are managed, losses are controlled, and infrastructure is maintained and modernized [9].

In a holistic approach, the results indicate that large operators can benefit from economies of scale that support profitability, even under conditions of high losses, while more technically efficient operators do not always achieve superior economic performance [12], [15]. This tension between technical efficiency and economic efficiency highlights the need for flexible and differentiated public policies, which take into account the specifics of each typology and avoid standardized solutions.

Overall, the study confirms the usefulness of multivariate analysis methods in underpinning strategic decisions in the water services sector and provides a pertinent analytical framework for guiding investments and regulations towards real sustainability objectives. By identifying operational typologies and the main differentiating factors, the research contributes to a better understanding of the internal dynamics of the sector and opens the prospect of more efficient interventions, adapted not only to the economic constraints, but also to the technical and institutional realities of each regional water operator.

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