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Integration of investments, infrastructure, and treatment performance in wastewater services: An analysis at the level of regional operators in Romania

George Banghiore [1*], Octavia Moise [2], Mari-Isabella Stan[3]

1* National Institute for Economic Research "Costin C. Kirițescu" (corresponding author, e-mail: george.banghiore@gmail.com)
2 National Institute for Economic Research "Costin C. Kirițescu" (e-mail: moctavia2005@yahoo.com)
3 Ovidius University of Constanta (e-mail: stanisabella@yahoo.com)

Abstract **– The accelerated modernization of water and wastewater services in Romania imposes an integrated evaluation of the efficiency of regional operators within a complex technical and economic context. The purpose of this study is to analyze the integration of investments, infrastructure and treatment performance in wastewater services at the level of 2024, using a set of investment, operational, energy and environmental indicators. The method used is the Principal Component Analysis, applied to eight relevant indicators. The method employed is Principal Component Analysis, applied to eight relevant indicators. The results reveal a highly integrated performance structure, dominated by a major operational component, indicating the maturation of infrastructures and a strong correlation between investments, capacity, and treatment efficiency.**

Keywords – operational performance, wastewater services, principal component analysis.

1. INTRODUCTION

Water and wastewater services are an essential component of the technical and utility infrastructure, playing a decisive role in ensuring public health, environmental protection, and the sustainable development of communities. In Romania, the modernization of these services has experienced a significant acceleration in the last two decades, especially as a result of the process of compliance with European directives on urban wastewater management. This context has generated substantial investments in sewage networks and treatment plants, leading to a profound restructuring of the way regional operators operate.

Despite this investment effort, the assessment of performance and efficiency in wastewater services remains a methodological challenge, given the structural complexity of the systems and the interdependencies between the infrastructural dimension, operational capacity and economic sustainability. In this regard, an integrated approach is needed that allows the simultaneous capture of the main components of the functioning of regional

operators and the identification of the relationships between them in a coherent analytical framework.

The purpose of this study is to outline an efficiency profile of the water and wastewater services provided by regional operators in Romania for the year 2024, using a multivariate statistical approach. The analysis aims to identify the latent structures of operational performance, to highlight the degree of integration among investments, infrastructure, and treatment processes, and to provide an analytical basis for interpreting the differences observed among operators within a context of wastewater system maturation.

To achieve this objective, the study uses a set of relevant quantitative indicators for characterizing the wastewater collection and treatment activity, collected from the 43 regional operators in Romania. The investment dimension is captured by the total investments made (INV) and by the total length of the rehabilitated, replaced or extended sewage network (TL), reflecting the effort to modernize and extend the infrastructure. The economic component is represented by the total revenue from wastewater services (VE) and the average tariff charged for the collection of one cubic meter of wastewater, excluding VAT (TM), indicators that express financial sustainability and the tariff policies applied. The social and operational dimension is analyzed by the total number of inhabitants connected to the sewage services (LOC), a variable that reflects the service area and the pressure exerted on the systems, as well as by the volume of treated wastewater (AUE), which expresses the intensity of the treatment activity. Technological and environmental performance is evaluated through the energy consumption related to the treatment activity (CE) and through the average daily amount of CBO5 removed at the level of each operator (CBO5), indicators that capture the efficiency of biological processes and the energy effort associated with achieving quality standards.

By integrating these indicators into a unified analytical framework, the study provides a comprehensive perspective on the efficiency of water and wastewater services in Romania and contributes to a better understanding of how infrastructure, investments, and operations correlate in a complex technical system.

2. THEORETICAL BACKGROUND

The efficiency of water and wastewater services is recognized in the specialized literature as a profoundly multidimensional concept, situated at the intersection of infrastructural performance, operational capacity, and the financial sustainability of service providers. The efficient functioning of sewerage systems cannot be evaluated through a single indicator, as technological processes, physical infrastructure, and economic mechanisms are characterized by strong and dynamic interdependencies. In this sense, performance analysis requires an integrated approach capable of simultaneously capturing the technical, economic, social, and environmental dimensions of public utility operators' activities [1], [2].

Within wastewater infrastructures, investments play a decisive role in medium and long-term performance, influencing both the capacity to expand services and the efficiency of collection and treatment processes. Studies focused on the economics of infrastructures highlight that the modernization of sewerage networks, the rehabilitation of existing pipelines and the expansion of treatment capacities lead to simultaneous improvements in system reliability and environmental outcomes, especially in regions characterized by increased demographic and climatic pressures [3], [4]. From an economic perspective,

operating revenues reflect not only the size of the operators' activity, but also the degree of utilization of the existing infrastructure, being frequently used as a proxy for the operational intensity and financial sustainability of wastewater services [5], [6].

The social dimension of efficiency is closely linked to the level of population connection to sewage systems [7], an indicator that expresses both the degree of access to essential public services and the level of pressure exerted on collection and treatment infrastructures. The expansion of the service area is systematically associated with an increase in the volumes of wastewater collected and treated, but also with an increase in energy consumption, especially in the case of centralized systems serving large urban agglomerations. The literature highlights the fact that this dynamic amplifies the need for integrated management of infrastructure and resources, in order to maintain a balance between accessibility, performance and operational costs [2], [3], [8].

From an infrastructure perspective, the length of rehabilitated, replaced or expanded sewer networks is a key indicator of the investment effort aimed at increasing reliability and reducing operational losses [9]. The technical literature emphasizes that modernized infrastructures allow for more efficient flow management, reduced infiltration and better adaptation to variations in hydraulic and pollutant loads. These aspects are becoming increasingly relevant in the context of climate change, which intensifies flow variability and generates additional demands on the operating capacities of sewer systems [3], [4].

Beyond the technical and operational dimensions, the literature highlights the determining role of the institutional framework, financing mechanisms and development strategies in influencing the performance of public services. The structure of financing, whether public or private, affects the capacity of operators to support investments, to innovate and to integrate sustainability objectives into current activity [10]. Also, the orientation of research, development and innovation policies towards sustainability is associated with an increase in the resilience of infrastructures and a more efficient use of available resources [11].

At the organizational level, studies on performance in various economic fields underline that integrating economic objectives with social and environmental ones leads to superior long-term results. Analyses conducted in the context of sustainable development indicate the importance of an integrated approach to performance, a perspective that is also particularly relevant for water and sewage operators, whose investment decisions have a direct impact on the communities they serve [12]. In addition, research on the synergy between digitalization, allocations for research and development and business development shows that these elements can support increased operational efficiency and the ability of organizations to adapt to structural changes [13].

The energy consumption afferent wastewater treatment constitutes a critical component of operational efficiency, reflecting both the volume of wastewater treated and the complexity of the biological and mechanical processes used. Numerous studies show that treatment performance is closely correlated with the level of organic load managed, frequently expressed by the amount of CBO5 removed, which makes that the technological efficiency of wastewater treatment plants cannot be dissociated from the energy effort required to achieve the quality standards imposed by environmental regulations [1], [4].

In this conceptual framework, the volume of treated wastewater and the amount of pollutants removed become central indicators of the environmental performance of operators, reflecting the capacity of systems to transform pollutant pressure into a compliant and efficient public service. Correlating these indicators with the size of the infrastructure and economic parameters allows for an integrated picture of efficiency,

which goes beyond fragmentary assessments and captures the functioning of the system as a whole [2].

For the analysis of complex interrelated systems, the literature recommends the use of multivariate statistical methods, capable of identifying latent structures and common factors of performance. Principal Component Analysis is frequently applied in studies of public utility infrastructures, as it allows for the reduction of the dimensionality of data sets and the highlighting of the dominant dimensions of operational efficiency. Through this method, the efficiency of water and wastewater services can be interpreted as the result of integrated and synergistic processes, rather than as the sum of independently analyzed indicators [2], [6].

3. RESULTS AND THEIR SIGNIFICANCE

Applying Principal Component Analysis to indicators characterizing regional wastewater operators in Romania for the year 2024 reveals a coherent and well-integrated performance structure.

The correlation matrix highlights a dense and well-articulated relational structure between most of the analyzed indicators, suggesting the existence of a mature operational system, in which financial, technical and environmental performances are deeply interconnected (Table 1). The strong relationships observed between variables associated with the volume of activity indicate that the functioning of regional operators is dominated by scale effects, in which the expansion of services and the increase in infrastructural capacity simultaneously generate increases in energy consumption, treated volumes and treatment results.

Table. 1 Correlation Matrix

	(INV)	(VE)	(TM)	(LOC)	(TL)	(CE)	(AUE)	(CBO5)
(INV)	1.000	0.764	0.348	0.634	0.616	0.643	0.587	0.628
(VE)	0.764	1.000	0.102	0.939	0.604	0.923	0.911	0.886
(TM)	0.348	0.102	1.000	-0.104	0.142	0.021	-0.104	0.005
(LOC)	0.634	0.939	-0.104	1.000	0.531	0.909	0.925	0.826
(TL)	0.616	0.604	0.142	0.531	1.000	0.561	0.561	0.632
(CE)	0.643	0.923	0.021	0.909	0.561	1.000	0.915	0.899
(AUE)	0.587	0.911	-0.104	0.925	0.561	0.915	1.000	0.879
(CBO5)	0.628	0.886	0.005	0.826	0.632	0.899	0.879	1.000

The very close relationship between wastewater revenues and the number of connected residents reflects an operating model in which the size of the service area is the main determinant of economic performance. This association suggests that revenues are generated predominantly by expanding the user base, rather than through tariff adjustments or marginal cost efficiencies. The strong correlations of revenues with energy consumption, volume of treated water and amount of CBO5 removed indicate that financial performance is directly dependent on the intensity of technological processes, confirming the energy and technologically intensive nature of sewage services.

The number of connected inhabitants, in turn, shows strong relationships with almost all major operational indicators, suggesting that the expansion of services generates systemic pressure on the entire operational chain, from collection and transport to treatment

and pollution load management. The strong correlation between this indicator and the volume of treated wastewater reflects a relatively high efficiency of the collection systems, while the association with energy consumption indicates that increasing the service area inevitably implies a significant increase in energy effort.

Investments occupy a strategic position in this relational structure, being consistently correlated with both the economic and technical dimensions of the operators' activity. The relatively high relationships between investments, operating revenues and the number of connected inhabitants suggest that the funds allocated to infrastructure are directed predominantly towards large operators or areas with high demand for services. At the same time, the association of investments with energy consumption, the volume of treated water and the amount of CBO5 removed indicates that infrastructural modernization is closely linked to increasing treatment capacities and intensifying biological activity, not just to passive replacements or rehabilitations.

The infrastructural dimension, reflected by the length of the rehabilitated, replaced or extended sewer network, shows moderate but consistent correlations with most operational indicators. This configuration suggests that the modernized networks contribute to increasing the collection and transport capacity, but their effects are mediated by the size of the service area and the general level of the operator's activity. The visible relationship between the infrastructure and the amount of pollutants removed indicates that the rehabilitation of networks can indirectly contribute to increasing the efficiency of the treatment processes, by reducing losses, infiltrations and uncontrolled loads.

The very strong correlations between energy consumption, volume of treated wastewater and amount of CBO5 removed outline a clear technological dimension of performance, dominated by the intensity of biological and mechanical processes. These relationships indicate that treatment efficiency cannot be separated from the energy effort required to achieve quality standards, suggesting the existence of a structural balance between environmental performance and associated operational costs.

In contrast to this densely interconnected structure, the average tariff for wastewater collection appears as a relatively isolated element, with weak or even negative correlations with most indicators. This separation suggests that tariff policy does not directly reflect the operational dimension or technological effort of operators, being influenced rather by administrative regulations, social constraints or public policy decisions. The absence of a significant link between tariff and investment or energy consumption indicates a structural dissociation between the real costs of the service and financial recovery mechanisms.

Overall, the correlation matrix indicates a performance of regional operators characterized by a strongly integrated operational core, in which the infrastructural dimension, the operating activity and the environmental results evolve in a stable interdependent relationship. This structure reflects the maturation of the sector and suggests an increased capacity for systemic management of sewerage services, while the isolation of the tariff dimension highlights the persistence of imbalances between the technical logic of the infrastructures and the economic regulatory mechanisms.

The very good suitability of the data set for the application of PCA is confirmed by the high values of the *commonalities*, most of the variables being explained in substantial proportion by the first factorial components (Table 2). Major financial and operational indicators, such as operating revenues, connected population, energy consumption and volume of treated water, present extraction values above 0.90, which indicates that their variations are generated by common factors and not by independent fluctuations. This finding reflects a homogenization of the operational behavior of regional operators and a convergence of infrastructure management practices.

Table. 2 Communalities

	Initial	Extraction
Total investments	1.000	0.787
Total revenues from wastewater exploitation	1.000	0.951
Average tariff per m3 of collected wastewater (excluding VAT)	1.000	0.889
Residents connected to sewerage services (cumulated across all localities)	1.000	0.918
Total length of sewerage network rehabilitated, replaced, or extended	1.000	0.556
Energy consumption for treatment activity	1.000	0.912
Treated wastewater	1.000	0.929
Average daily amount of CBO5 removed at the operator level	1.000	0.870
Extraction Method: Principal Component Analysis.		

The structure of the explained variance confirms the existence of a dominant factorial axis, which concentrates almost 70% of the total variability and can be interpreted as the dimension of integrated operational capacity (Table 3). This component aggregates, in a coherent manner, investments, revenues, service expansion, energy effort and treatment performance, illustrating the operation of operators within a unitary systemic framework. The second component, contributing approximately 15% of the variance, captures a distinct dimension, mainly associated with tariff policies, suggesting that the tariff applied evolves relatively independently of the size of the network and the intensity of operational activity.

Table. 3 Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.569	69.608	69.608	5.569	69.608	69.608
2	1.244	15.548	85.156	1.244	15.548	85.156
3	0.552	6.901	92.057			
4	0.316	3.948	96.006			
5	0.155	1.943	97.948			
6	0.074	0.923	98.871			
7	0.064	0.805	99.676			
8	0.026	0.324	100.000			
Extraction Method: Principal Component Analysis						

The significance of these results is major for understanding the recent evolution of the water and wastewater sector in Romania. The dominance of a single main component reflects the transition from a fragmented model, characteristic of previous stages, to a mature and well-articulated model, in which investments, infrastructure and operational performance operate in a stable balance. This structure suggests an increased capacity of operators to simultaneously manage service expansion, technological requirements and environmental pressures, outlining solid premises for increasing the resilience of wastewater infrastructures in the face of future challenges.

4. CONCLUSIONS

The analysis provides an integrated perspective on how water and wastewater services in Romania have evolved towards a more mature and coherent operational model, in which infrastructure, investments and technological processes operate in a stable interdependence relationship. The results obtained through the Principal Components Analysis indicate that the performance of regional operators is no longer determined by isolated factors, but reflects the functioning of a complex system, characterized by synergies between the investment dimension, operational capacity and environmental results.

From a technical perspective, the strong integration between the volume of treated wastewater, energy consumption and the level of organic load removed suggests that modernized infrastructures allow for a more efficient management of hydraulic and pollutant pressures. This convergence indicates the existence of consolidated technological processes, capable of meeting the requirements of compliance with quality standards and providing a relatively uniform performance across the operators analyzed. At the same time, the central role of investments confirms that the infrastructural interventions of recent years have generated structural effects, not just punctual improvements.

From an operational and managerial point of view, the results emphasize a clear alignment between the expansion of services, reflected in the increase in the number of connected inhabitants, and the intensification of operating activity. This correlation suggests an increased capacity of operators to simultaneously manage the expansion of networks and the increase in volumes handled, without compromising the overall performance of the system. The separation of the tariff dimension from the main axis of performance also indicates the existence of distinct decision-making mechanisms, influenced mainly by regulations and public policies, rather than by the technical structure of the operators.

From an economic and sustainability perspective, the integration of operating revenues with technical and energy indicators reflects a higher degree of financial balance of services, suggesting that modernized infrastructures generate sufficient operational volumes to support operating costs. This relationship becomes essential in a context marked by rising energy prices and the need to internalize the costs associated with environmental protection, highlighting the role of efficiency as a determinant of the long-term viability of public services.

Beyond the strictly sectoral dimension, the findings of this study highlight the holistic nature of water and wastewater services efficiency, which cannot be assessed piecemeal, but only through a systemic approach. The strong correlations identified between infrastructure, investment, energy and treatment performance indicate that adaptation to external pressures, such as climate change or increasing demand for services, depends on the system's ability to function as an integrated whole.

Overall, the results suggest that regional operators in Romania are on a favorable trajectory of structural consolidation, but maintaining this trend requires continuity of investments, optimization of energy processes and coherent coordination between tariff policies and operational efficiency objectives. The holistic approach proposed in this study provides a relevant analytical framework for substantiating strategic decisions and for guiding future infrastructure interventions towards sustainable and resilient performance.

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