Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Estimation of the economic level of water losses in water supply systems: a case study in northeastern Brazil

Estimativa do nível econômico de perdas em sistemas de abastecimento de água: um estudo de caso no Nordeste brasileiro

Emannuel Henrique Piancó da Silva Martins[1], *Saulo de Tarso Marques Bezerra*[1], *Isabelle Sales Alves de Sousa*[1], *Gilvandro Barbosa Tito*[2], *Edevaldo Miguel Alves*[1]

ABSTRACT

Reducing water losses is a strategic challenge for water supply systems (WSS), particularly in regions characterized by operational heterogeneity, water scarcity, intermittent supply, and increasing production and distribution costs. Although the Economic Level of Losses (ELL) is widely recognized as a valuable decision-support tool, its application remains limited at regional scales and in systems with diverse structural and economic characteristics. This study proposes and applies a methodological approach to estimate the ELL, considering both real and apparent losses, in WSS with heterogeneous regional characteristics, using the state of Pernambuco, Brazil, as a case study. The methodology combined the Wyatt method with analysis of variance (ANOVA) to evaluate spatial and temporal variations among mesoregions. The results showed that four of the five mesoregions experienced reductions in water loss rates over the study period. However, the observed values generally exceeded the estimated ELL, which ranged from 20.72% to 22.58% at the state level. ANOVA indicated no statistically significant differences among the regional mean values of ELL and IN049; however, pairwise comparisons revealed important contrasts between specific mesoregions, highlighting the need for region-specific management strategies. The findings advance understanding of ELL behavior in WSS with high operational heterogeneity and demonstrate that its application at the regional scale can support more efficient, replicable water loss control policies in other regional contexts.

Keywords: water resources; basic sanitation; operational efficiency; distribution loss index; Wyatt method.

RESUMO

A gestão eficiente das perdas de água é um desafio estratégico para sistemas de abastecimento, especialmente em contextos marcados por heterogeneidade operacional, restrições hídricas, intermitência no fornecimento e custos crescentes de produção e distribuição. Embora o conceito de Nível Econômico de Perdas (NEP) seja amplamente reconhecido como ferramenta de apoio à tomada de decisão, sua aplicação ainda é limitada em escalas regionais e em sistemas com diferentes condições estruturais e econômicas. Este estudo teve como objetivo aplicar uma abordagem metodológica para estimar o NEP, contemplando perdas reais e aparentes, em sistemas de abastecimento de água com características regionais heterogêneas, utilizando o estado de Pernambuco, Brasil, como estudo de caso. A metodologia combinou o método de Wyatt para a quantificação do NEP com análise estatística por meio do teste ANOVA, permitindo avaliar variações espaciais e temporais entre mesorregiões. Os resultados indicaram que quatro das cinco mesorregiões apresentaram redução no índice de perdas ao longo do período analisado, embora os valores observados tenham permanecido, em geral, superiores aos NEP calculados, que variaram entre 20,72% e 22,58% no agregado estadual. A ANOVA não indicou diferenças estatisticamente significativas entre as médias regionais do NEP e do IN049; entretanto, as análises em pares evidenciaram contrastes relevantes entre determinadas mesorregiões, reforçando a importância de estratégias ajustadas às condições locais. O estudo contribui para o avanço da compreensão do comportamento do NEP em sistemas com elevada heterogeneidade operacional e demonstra que sua aplicação em escala regional pode subsidiar políticas de controle de perdas mais eficientes e replicáveis em diferentes contextos.

Palavras-chave: recursos hídricos; saneamento básico; eficiência operacional; índice de perdas na distribuição; método de Wyatt.

[1]Universidade Federal de Pernambuco – Caruaru (PE), Brazil.
[2]Companhia Pernambucana de Saneamento – Caruaru (PE), Brazil.
Corresponding author: Saulo de Tarso Marques Bezerra. Campus do Agreste, Universidade Federal de Pernambuco, Av. Marielle Franco, Km 59, Nova Caruaru, Caruaru, PE, Brasil, CEP 55014-900. E-mail: saulo.tarso@ufpe.br
Received on: 05/21/2025. Accepted on: 07/03/2026.
https://doi.org/10.67790/rbciamb.026.2601

Introduction

Freshwater availability is fundamental to ecosystems, food production, energy generation, industrial activity, and human well-being. However, increasing demand driven by population growth and economic development, combined with the impacts of climate change, has placed growing pressure on global water resources.

In this context of increasing water scarcity, the operation of water supply systems (WSS) plays a fundamental role in urban water management (Stamou et al., 2024). Among the major challenges faced by water utilities is reducing water losses, which account for a significant proportion of the total volume of water abstracted from sources. According to Azevedo and Saurin (2018), high levels of water losses are common in Brazilian systems, reflecting decades of corrective maintenance, aging infrastructure, and limitations in operational management. In the present study, this challenge is examined in the context of the state of Pernambuco, Brazil, whose water supply infrastructure is characterized by marked contrasts between highly urbanized regions and water-scarce areas. Intermittent systems are also widespread throughout the state.

Reducing water losses is a strategic measure that increases water availability, lowers operation, maintenance, and infrastructure expansion costs, and strengthens resilience to water scarcity. The implementation of structured interventions encompassing economic, environmental, and ethical dimensions can substantially improve the efficiency of WSS. Nevertheless, a key question remains for water utility managers: are the investments required to reduce water losses financially justified (Firat et al., 2021; Yilmaz et al., 2023)? Consequently, water utilities must determine the economically optimal level of water loss while accounting for the specific characteristics of their systems.

The Economic Level of Losses (ELL) has emerged as a fundamental concept for efficient water loss management because it represents the point at which the marginal cost of reducing water losses equals the marginal benefit obtained from the recovered water. Therefore, reducing losses below the ELL is not economically justified, as the costs of additional interventions exceed the financial benefits from the recovered water. Estimating the ELL requires consideration of several variables, including water production costs, leak detection and repair costs, water treatment and distribution costs, and electricity costs (Paraschiv et al., 2023; Yilmaz et al., 2023).

The importance of water loss control is widely recognized in the literature, and methodologies for technical and economic assessment have advanced considerably. Nevertheless, a significant gap remains in applying the ELL concept to heterogeneous regional contexts, particularly in systems characterized by operational constraints, intermittent water supply, and high energy costs – conditions common in many regions of developing countries.

Most previous studies have focused on large urban centers or have employed generalized models with limited adaptation to local operating conditions, water tariffs, cost structures, and supply intermittency. Furthermore, relatively few studies explicitly incorporate electricity costs as a critical component in estimating the ELL, despite their particular importance in systems that rely on high pumping heads and long pumping distances, as is the case in several regions of Pernambuco.

Studies addressing the ELL also contribute directly to the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). Effective water loss management is essential to ensuring the sustainable availability of water resources, promoting efficient water use, and supporting equitable access to safe drinking water. Moreover, sound water resource management strengthens institutional capacity and fosters sustainable approaches to the use and conservation of natural resources.

Building on this background, this study proposes and applies a methodological framework for estimating the ELL in heterogeneous WSS, using the state of Pernambuco, Brazil, as a representative case study. This research is expected to advance the application of the ELL concept in systems operating under heterogeneous conditions by providing empirical and analytical evidence that improves the understanding of the relationships among costs, water losses, and operational efficiency. In addition, the findings may support the practical implementation of the proposed methodology in real-world water utility management.

From a scientific perspective, this study contributes by integrating the Wyatt method with regional-scale statistical analysis to investigate the spatial variability of the ELL and its relationship with operational performance indicators. This approach enhances the understanding of how the ELL behaves under heterogeneous operating conditions and broadens the discussion of its applicability across different types of systems.

Literature review

The complete elimination of water losses in WSS is neither technically feasible nor economically justified (Al-Washali et al., 2020). Beyond a certain point, additional efforts to reduce water losses become economically unviable because the cost of intervention exceeds the resulting benefits. Therefore, when a water utility is aware of its ELL, it can establish realistic performance targets and define more effective strategies to achieve them.

The ELL encompasses both real and apparent losses and consists of the Economic Level of Real Losses (ELRL) and the Economic Level of Apparent Losses (ELAL) (Heryanto et al., 2021; Ociepa-Kubicka et al., 2024). Estimating the ELRL requires detailed knowledge of the distribution network, leakage volumes, and the actual costs associated with leakage management.

Several methods have been developed to estimate the ELL (Wyatt, 2010; Vermersch et al., 2016; Firat et al., 2021). Wyatt (2010) proposed a comprehensive methodology designed for developing countries that requires relatively limited data to estimate water losses. The approach incorporates cost curves for leak repairs, water production, and system expansion to estimate the ELL for real losses, while simplifying the analysis of apparent losses by focusing primarily on customer meter under-registration. Vermersch et al. (2016) developed a methodology that, although it does not provide explicit mathematical formulations, describes a cost–benefit analysis for optimizing customer meter replacement. This approach evaluates meter replacement and labor costs against the additional revenue generated by reducing meter under-registration.

The literature also includes several practical applications of these methodologies in real-world case studies, yielding promising results. Banovec and Domadenik (2018) presented an analysis based on the parallel leakage market concept, in which the marginal cost of supplying water represents the supply side, while the marginal cost of leak repair represents the demand side for mitigating water losses. The methodology was applied to VO-KA Ljubljana, Slovenia's largest public water utility.

Moll (2019) applied the Wyatt (2010) methodology to estimate the economic levels of apparent and real losses in 92 district metered areas (DMAs) located in Curitiba (Paraná, Brazil). To quantify actual water losses and compare them with the estimated ELL values, both real and apparent losses were determined using the International Water Association (IWA) water balance methodology. Heryanto et al. (2021) estimated the ELL using four approaches – the total cost method, the marginal cost method, the cumulative cost-benefit method, and component-based methods – for water utilities in Malang, Indonesia. The authors concluded that the total cost method provides the most accurate estimates, is the easiest to apply, and does not require long historical datasets.

Firat et al. (2021) developed a discrete stochastic optimization model to estimate the ELL for real losses (leakage), obtaining an economic loss level of 11.9%. Similarly, Yilmaz et al. (2023) employed an optimization algorithm to determine the ELL in utilities with different network characteristics, water production capacities, operating costs, and institutional capabilities. The analyzed systems had non-revenue water levels of 57%, 50%, and 37%, respectively. In contrast, their corresponding ELL values were estimated at 29%, 16%, and 23%, demonstrating the strong influence of system-specific characteristics on ELL estimates.

More recently, Haider (2025) proposed an environmental valuation model for real losses to determine the economic level of leakage, focusing on the Qassim region of Saudi Arabia, where water scarcity is severe, and water losses in distribution systems are substantial. Yilmaz et al. (2025) applied the Ant Lion Optimizer (ALO), Mountaineering Team-Based Optimization (MTBO), and Grey Wolf Optimizer (GWO) algorithms to develop optimal management strategies for three WSS. The estimated ELL values ranged from 16.83% to 24.27%.

In the present study, the methodology proposed by Wyatt et al. (2021) was adopted because of its suitability for the Brazilian water sector, its methodological robustness, and the evidence of its successful application in previous studies conducted in Brazil. This methodology provides a modern and reliable framework with a demonstrated ability to represent the operating conditions of Brazilian systems accurately.

Materials and methods

The methodology adopted in this study was designed to enable its replication in different regional contexts, provided that basic operational data are available, such as those reported by national information systems. In addition to estimating the ELL under a specific context, the proposed approach aims to investigate the behavior of this indicator across WSS with different operational characteristics, thereby assessing its consistency and sensitivity at the regional scale. The state of Pernambuco, Brazil, was selected as the case study because of its wide diversity of operating conditions, including densely populated urban systems, areas with intermittent supply, and regions highly dependent on pumping. This diversity makes it a representative setting for applying the proposed methodology.

The study covers the five mesoregions of Pernambuco, as defined by the Brazilian Institute of Geography and Statistics (IBGE): Agreste Pernambucano (Agreste), Mata Pernambucana (Zona da Mata), Sertão Pernambucano (Sertão), São Francisco Pernambucano (São Francisco), and the Recife Metropolitan Region (RMR). The analysis included 178 of the state's 184 municipalities for which data were available in the Brazilian National Sanitation Information System (SNIS) during 2018–2022.

The data extracted directly from the SNIS comprised: (i) annual water consumption; (ii) population served; (iii) average per capita water consumption; (iv) number of service connections; (v) average water tariff; (vi) average network length per service connection; and (vii) average number of inhabitants per service connection. For each variable, annual averages were calculated over the study period to minimize the influence of short-term fluctuations and ensure greater statistical stability and representativeness of the results.

The performance indicators and the ELL were calculated individually for each municipality, allowing local characteristics – such as operating costs, tariff structures, and infrastructure features – to be explicitly incorporated into the analysis. This approach enables a more accurate and context-specific assessment of the economic level of water losses in WSS.

To consolidate the results at the mesoregional level, the performance indicators and ELL values were aggregated using population-weighted averages based on the population served in each municipality. This procedure ensures that the regional indicators appropriately reflect the relative contribution of each municipality, providing a more representative assessment of the water supply conditions within each mesoregion.

Water loss index in distribution

The Water Loss Index in Distribution (IN049), published by the SNIS, is widely used to evaluate the operational performance of Brazilian systems. This indicator measures the proportion of water losses, including both real and apparent losses, relative to the total volume of water produced and distributed.

The IN049 provides a standardized, comparable measure of water losses, enabling the performance of water utilities to be monitored across locations and over time. Furthermore, it serves as an essential tool for identifying operational inefficiencies, supporting water management strategies, and establishing performance targets. Its standardized methodology also facilitates the development of public policies to reduce water losses and improve system efficiency.

Wyatt method

The ELAL and the ELRL were calculated using data weighted by their relative importance, which in this study corresponded to the population served in each municipality. This approach improves the representativeness of the results by accounting for the relative importance of each municipality within the mesoregions analyzed.

The SNIS provides only aggregated data on total water losses, without distinguishing between real (physical) losses and apparent (commercial) losses. To overcome this limitation and enable a more detailed analysis, total water losses were assumed to consist of 60% real losses and 40% apparent losses. This estimate is based on the report "The Challenge of Reducing Non-Revenue Water (NRW) in Developing Countries", prepared by Kingdom et al. (2006) for the World Bank, which analyzed data from more than 900 water utilities in 44 developing countries.

Determination of the economic level of real losses

The annual water production cost and the unit production cost — the latter representing the average cost per unit of water produced, including all operating costs associated with water abstraction, treatment, and distribution — were both determined using Equation 1.

$$C_{PROD} = \frac{(FN011 + FN013) \times \left(\frac{AG028}{AG028 + ES028}\right) \times Qc}{1000 \times (AG006) \times (1 - PR)} \quad (1)$$

where C_{PROD} is the annual water production cost (R$/year); PR is the dimensionless real loss ratio; Qc is the annual volume of water consumed (m^3); FN011 is the annual expenditure on treatment chemicals (R$/year); FN013 is the annual electricity expenditure (R$/year); AG006 is the annual volume of water produced (1,000 m^3/year); AG028 is the total electricity consumption of the water supply system (1,000 kWh/year); and ES028 is the total electricity consumption of the wastewater system (1,000 kWh/year).

The annualized system expansion cost was calculated using Equation 2, and the ratio of installed production capacity to the volume of water consumed (E) was determined using Equation 3.

$$C_{exp} = FRC \times F\exp(1 + r)^{-\frac{\frac{E}{k1} - \frac{1}{1-PR}}{G}} \quad (2)$$

$$E = \frac{U \times Qp}{Qc \times k1} \quad (3)$$

where FRC is the capital recovery factor (%); Fexp is the future expansion cost of the water production system (R$); r is the rate of return (%); G is the annual population growth rate (%); k1 is the maximum-day demand coefficient, for which a value of 1.2 was adopted according to the internal standards of the local water utility; E is the ratio of installed water production capacity to water consumption (–); U is the ratio between installed production capacity and demand (–); and Qp is the annual volume of water produced (1,000 m^3/year).

Sanitation projects are generally financed by national or multilateral institutions focused on sustainable development, allowing lower rates of return to be adopted to improve the financial feasibility of investments while accounting for their social benefits and relatively low direct economic returns. In Brazil, the Brazilian Development Bank (BNDES) and other public institutions establish guidelines for expected rates of return, considering the social and environmental impacts of sanitation projects. Depending on financing conditions, project maturity, and social objectives, the expected rate of return for sanitation projects typically ranges from 7% to 12% per year. In the present study, an average rate of return of 9.5% was adopted.

The annual population growth rate (G) for the state of Pernambuco was estimated using the most recent Population Projections for Brazil and its Federation Units published by the IBGE. During the study period, the estimated annual growth rate was approximately 0.5%, indicating moderate population growth compared with other regions of Brazil. This value was obtained by calculating annual growth rates over the study period and then averaging them to represent population growth over the analysis period.

The ratio between installed capacity and demand (U) is defined as the inverse of the demand coverage ratio (GD), which represents the ratio between system demand and installed production capacity. A GD value of 0.9406 was adopted, according to Atlas Brasil (ANA, 2021), for the state of Pernambuco.

The planning horizon for expanding large WSS typically ranges from 30 to 40 years, with capacity expansions implemented in shorter stages of approximately 10 to 15 years. Owing to the limited water availability in the study area, a 25-year planning horizon was adopted, following the recommendation of Wyatt et al. (2021) for the state of Pernambuco.

Since no specific methodology is available for estimating the capital cost of system expansion, Equation 4 was used to calculate Fexp. The cost coefficient (k), representing the investment required to increase water production capacity, was adopted as R$ 27,579 per m^3/day, according to Technical Note No. 492/2010 issued by the National Secretariat for Environmental Sanitation of the Brazilian Ministry of Cities. The economy-of-scale coefficient (b), which reflects the reduction in unit costs as production capacity increases, was set to 0.7023, as reported in the same Technical Note.

$$F\exp = k(Q\exp)^{b} \tag{4}$$

where k is the cost coefficient (R$/$m^3$/day); b is the economy-of-scale coefficient (–); and Qexp is the additional production capacity required (m^3/day).

The production capacity required for future system expansion was estimated using Equation 5, proposed by Wyatt et al. (2021). Unlike the original model developed by Wyatt (2010), which assumed a fixed production capacity, the revised model incorporates the variability of real losses into the estimation of the ELRL. This more dynamic approach reflects the direct influence of real losses on the demand for additional production capacity: the greater the real losses, the greater the additional production capacity required. This methodological improvement makes the model more robust and realistic, thereby enhancing the economic management of water losses. The resilience factor (fr) was set to 1.6, following the recommendation of Wyatt et al. (2021) for northeastern Brazil.

$$Q\exp = z \times \frac{Qc}{1-PR}(1+G) \times fr \times fp \tag{5}$$

The cost of water loss control activities and investments (CPR) was calculated using Equation 6. The water distribution network length (M) was obtained directly from SNIS indicator AG005. Additional variables, including per capita water consumption (indicator IN022) and the average number of inhabitants per service connection, were calculated from indicators AG001 and AG002. Coefficient α represents background losses and reported leaks, whereas coefficient β represents unreported leaks, both expressed in m^3/km/day. Because these coefficients are difficult to determine directly, they were estimated using Equations 7 and 8, which were empirically derived by Wyatt et al. (2021).

$$C_{PR} = \frac{C_{prr} \times M \times \beta}{\left(\frac{c \times p}{1000 \times D}\frac{PR}{1-PR}\right) - \alpha} \tag{6}$$

$$\alpha = 0.1654 \times PRl + 1.4253 \tag{7}$$

$$\beta = 0.5137 \times PRl - 2.3828 \tag{8}$$

where Cprr is the cost of the principal real loss control activities (R$/km); M is the water distribution network length (km); p is the average number of inhabitants per service connection; D is the distribution network length per service connection (km/connection); and PRl is the linear real loss index (m^3/km/day), represented by SNIS indicator IN050.

The total cost of principal real loss control activities equals the sum of leak detection and repair, loss management, and maintenance and rehabilitation of the water distribution network (Table 1). The unit costs were based on estimates reported by Wyatt et al. (2021), derived from the Brazilian National System of Construction Costs and Indices (SINAPI) for the state of Pernambuco. Since the costs presented in the guide were expressed in 2021 monetary values, they were updated to 2024 using the National Construction Cost Index (INCC).

Tables 2–4 summarize the equations and parameter values adopted for estimating the ELRL. The ELRL was determined by minimizing the total cost curve obtained from the sum of the water production cost, system expansion cost, and water loss control program cost curves. At the minimum point of this curve, expenditures associated with real losses still exist but correspond to their economically optimal level, balancing water production and system expansion costs against investments in water loss control. The optimum point was determined using the Solver tool available in Microsoft Excel®.

Determination of the economic level of apparent losses

The linear relationship between annual operating revenue and the dimensionless apparent loss ratio is expressed by Equation 9. The values adopted for technically avoidable and technically unavoidable meter under-registration were 12% and 4%, respectively, based on Brazilian Standard NBR 15538 (ABNT, 2023) and the study by Wyatt et al. (2021). The number of active service connections was obtained directly from SNIS indicator AG002, while the average number of inhabitants per service connection was calculated as the ratio between indicators AG001 and AG002.

Table 1 – Costs of water loss control activities and investments (R$/km).

Cost category	Cost	
Cost category	2021	2024
Leak detection	664.78 R$/km	784.11 R$/km
Leak repair	292.89 R$/km	345.46 R$/km
Loss management	200.00 R$/km	235.90 R$/km
Network maintenance and rehabilitation	884.88 R$/km	1,043.72 R$/km
Total cost of water loss control activities	2,042.55 R$/km	2,409.19 R$/km

Table 2 – Equations and parameter values used to calculate the annual water production cost.

Variable	Equation / Indicator / Value	Source
Annual water production cost (CPROD)	$C_{PROD} = \frac{C_{prod} \times Qc}{(1 - PR)}$	Wyatt et al. (2021)
Unit production cost (Cprod)	$C_{prod} = \frac{(FN011 + FN013)\left(\frac{AG028}{AG028 + ES028}\right) + FN020}{1000 \times (AG006 + AG018)}$	Wyatt et al. (2021)
Annual water consumption (Qc)	AG010	SNIS (2022)

Table 3 – Equations and parameter values used to calculate the annualized system expansion cost.

Variable	Equation / Indicator / Value	Source
Annualized system expansion cost (Cexp)	$C_{exp} = FRC \times Fexp(1+r)^{-\frac{\frac{E}{k1} - \frac{1}{1-PR}}{G}}$	Wyatt et al. (2021)
Annual population growth rate (G)	0.50%	IBGE (2022)
Ratio of installed production capacity to water consumption (E)	$E = \frac{U \times Qp}{Qc \times k1}$	Wyatt et al. (2021)
Ratio between installed capacity and demand (U)	1.0631	ANA (2021)
Annual water production (Qp)	AG006	SNIS (2022)
Maximum-day demand coefficient (k1)	1.2	Local water utility (2022)
Demand coverage ratio (GD)	0.9406	Atlas Brasil (2021)
Capital recovery factor (FRC)	$FRC = \frac{r(1+r)^z}{(1+r)^z - 1}$	Wyatt et al. (2021)
Rate of return (r)	9.5%	This study (2024)
Planning horizon (z)	25 years	Wyatt et al. (2021)
Future expansion cost (Fexp)	$Fexp = k(Qexp)^b$	Wyatt et al. (2021)
Cost coefficient (k)	27,579	Brasil (2011)
Economy-of-scale coefficient (b)	0.7023	Brasil (2011)
Additional production capacity (Qexp)	$Qexp = Zexp \frac{Qc}{1-PR}(1+G) \times fr \times fp$	Wyatt et al. (2021)
Resilience factor (fr)	1.6	Wyatt et al. (2021)
Peak factor (fp)	1.2	Wyatt et al. (2021)

Table 4 – Equations and parameter values used to calculate the annual cost of real loss control activities.

Variable	Equation / Indicator / Value	Source
Annual real loss control cost (CPR)	$C_{PR} = \frac{C_{prr} \times M \times \beta}{\left(\frac{c \times p}{1000 \times D} \frac{PR}{1-PR}\right) - \alpha}$	Wyatt et al. (2021)
Distribution network length per service connection (D)	$E = \frac{AG005}{AG021}$	SNIS (2022)
Water distribution network length (M)	AG005	SNIS (2022)
Background loss and reported leakage coefficient (α)	α = 0.1654 × IN050 + 1.4253	Wyatt et al. (2021)
Unreported leakage coefficient (β)	β = 0.5137 × IN050 – 2.3828	Wyatt et al. (2021)
Leak detection cost (Cp)	784.11 R$/km	This study (2024)
Leak repair cost (Cr)	345.46 R$/km	This study (2024)
Loss management cost (Cg)	235.90 R$/km	This study (2024)
Annualized network maintenance and rehabilitation cost (Ccra)	1,043.72 R$/km	This study (2024)

$$R = 0.365 \times T \times N \times C_{cH} \times p \times (1 - Sub_{EV} - Sub_{INEV}) \quad (9)$$

where R is the annual operating revenue as a function of apparent losses (R$); T is the unit water tariff (population-weighted average considering tariffs for connections with sewer service) (R$/m^3); C_{cH} is the average metered per capita water consumption (m^3/person/day), calculated using Equation 10; Sub_{EV} is the technically avoidable meter under-registration (%); and Sub_{INEV} is the technically unavoidable meter under-registration (%).

$$C_{cH} = \frac{\frac{AG010 - AG009}{AG001} \frac{1.000.000}{365}}{(1 - Sub)} \quad (10)$$

The net unit tariff (T) was calculated using Equation 11, where tx represents the conversion factor used to estimate the "net tariff". This factor reflects the actual revenue received by the water utility after taxes and charges levied on operating revenues, accounting for differences among Brazilian states.

$$T = 0.001 \times tx \times \left(\frac{FN002}{AG010} + \frac{FN003}{AG010} \times \frac{AG001}{ES001}\right) \quad (11)$$

where tx is the net tariff conversion factor; AG001 is the population served by the water supply system; AG010 is the annual volume of water consumed (1,000 m^3/year); ES001 is the population served by the sewerage system; FN002 is the direct operating revenue from water services (R$); and FN003 is the direct operating revenue from wastewater services (R$).

The annual cost of meter replacement was calculated using Equation 12. The average meter replacement cost (H) was estimated as a weighted average considering the quantities of the three most common water meter models reported in the SINAPI database (May 2024). The unit costs used to determine the average meter replacement cost are presented in Table 5. The resulting value of H was R$ 111.98.

$$C_h = \frac{H \times N \times s}{2 \times Sub_{EV}} \quad (12)$$

where C_h is the annual cost of meter replacement (R$/year); H is the average meter replacement cost, including labor and materials (R$/meter); and s is the annual deterioration rate of meter accuracy (%/year).

The number of active service connections was obtained from SNIS indicator AG002, while s, representing the annual deterioration rate of water meter measurement accuracy, was assumed to be 1% per year, as proposed by Wyatt et al. (2021).

Finally, the ELAL was determined using Equation 13. It should be emphasized that to accurately estimate the volume of water actually consumed, the IWA Water Balance methodology is the preferred approach. The availability of more reliable input data contributes directly to obtaining more accurate and consistent results. Tables 6–8 summarize the equations, parameters, and adopted values used to estimate the ELAL.

Table 5 – Distribution of average water meter prices in the state of Pernambuco.

SINAPI Code	Description	Proportion	Price
95673	DN 20 (½ in.), 1.5 m^3/h water meter, including supply and installation (AF_11/2016)	90% of water meters	R$ 111.55
95674	DN 20 (½ in.), 3.0 m^3/h water meter, including supply and installation (AF_11/2016)	8% of water meters	R$ 118.46
95675	DN 25 (¾ in.), 5.0 m^3/h water meter, including supply and installation (AF_11/2016)	2% of water meters	R$ 105.40

$$ELAL = \sqrt{\frac{H \times s}{0.73 \times T \times C_{cH} \times p}} \quad (13)$$

Statistical analysis

A statistical analysis was conducted to identify temporal and regional patterns and to provide insights into the operational efficiency of the WSS throughout the study period (2018–2022).

ANOVA, a statistical technique used to compare the means of three or more groups, was applied to evaluate whether statistically significant differences existed among the mesoregions. The interpretation of the ANOVA results was based on the F-statistic and the p-value. A high F-value indicates that the variability between groups is substantially greater than the variability within groups, suggesting meaningful differences among the analyzed means. Furthermore, a p-value below the significance level ($\alpha = 0.05$) indicates that these differences are unlikely to have occurred by chance, suggesting that at least one group has a mean that differs significantly from the others. Together, these metrics provide a robust basis for identifying significant patterns in the results.

Table 6 – Equations and parameters used to calculate the annual operating revenue as a function of apparent losses.

Variable	Equation / Indicator / Value	Source
Annual operating revenue as a function of apparent losses (R)	$R = 0.365 \times T \times N \times C_{cH} \times p \times (1 - Sub_{EV} - Sub_{INEV})$	Wyatt et al. (2021)
Unit tariff (T)	$T = 0{,}001 \times tx \times \left(\frac{FN002}{AG010} + \frac{FN003}{AG010 \frac{ES001}{AG001}} \right)$	Wyatt et al. (2021)
Total number of active service connections (N)	AG002	SNIS (2022)
Average number of inhabitants per service connection (p)	$p = \frac{AG001}{AG002}$	SNIS (2022)
Technically avoidable meter under-registration (SubEV)	12%	Wyatt et al. (2021)
Technically unavoidable meter under-registration (SubINEV)	4%	NBR 15538 (2023)
Average metered per capita water consumption (CcH)	$C_{cH} = \frac{\frac{AG010 - AG009}{AG001} \times \frac{1{,}000{,}000}{365}}{(1 - Sub)}$	Wyatt et al. (2021)

Table 7 – Equations and parameter values used to calculate the annual cost of apparent water loss control due to meter under-registration.

Variable	Equation / Indicator / Value	Source
Annual meter replacement cost (Ch)	$C_h = \frac{H \times N \times s}{2 \times Sub_{EV}}$	Wyatt et al. (2021)
Average meter replacement cost, including labor and materials (H)	R$ 111.98	This study (2024)
Annual deterioration rate of meter accuracy (s)	1%	Wyatt et al. (2021)

Table 8 – Equations and parameters used to estimate the ELAL.

Variable	Equation / Indicator / Value	Source
ELAL	$ELAL = \sqrt{\frac{H \times s}{0.73 \times T \times C_{cH} \times p}}$	Wyatt et al. (2021)

Results and discussion

Distribution water loss index

Overall, a downward trend in the distribution water loss index was observed across all mesoregions throughout the study period, indicating the effectiveness of operational interventions. From an analytical perspective, this trend also reflects the gradual convergence between observed water loss levels and the economically optimal thresholds, a point that has received limited attention in the literature. The year 2022 was particularly noteworthy, with a substantial reduction in the distribution water loss index across four of the five mesoregions, possibly due to infrastructure investments or improvements in operational management. Figure 1 illustrates the evolution of the distribution water loss index (IN049) across the mesoregions of the state of Pernambuco.

The median values and standard deviations were calculated for each mesoregion, as presented in Table 9. The mean distribution water loss index ranged from 36.15% in the Agreste mesoregion to 53.96% in the RMR, while Zona da Mata exhibited the second-highest mean value (48.81%). The median values corroborated these findings, indicating that water losses in the RMR and Zona da Mata remained consistently high throughout the study period. In the Agreste mesoregion, the median was 38.10%, reflecting lower water loss than in the other regions. The close agreement between the mean and median values suggests an approximately symmetric distribution of the data, although outliers may be present, particularly in the Sertão mesoregion.

The Sertão and Zona da Mata mesoregions exhibited the highest standard deviations (5.69% and 5.67%, respectively), indicating greater temporal variability in distribution water loss rates throughout the study period. In contrast, the São Francisco mesoregion had the lowest standard deviation (3.63%), with greater consistency among the observed values. This lower variability may be associated with more stable operational policies or a lower frequency of interventions in the water distribution infrastructure.

These findings reflect the specific characteristics of each mesoregion and demonstrate how the ELL responds to different structural, economic, and operational conditions of WSS. Beyond the context analyzed, the observed patterns may also be relevant to other systems characterized by high operational heterogeneity, particularly those

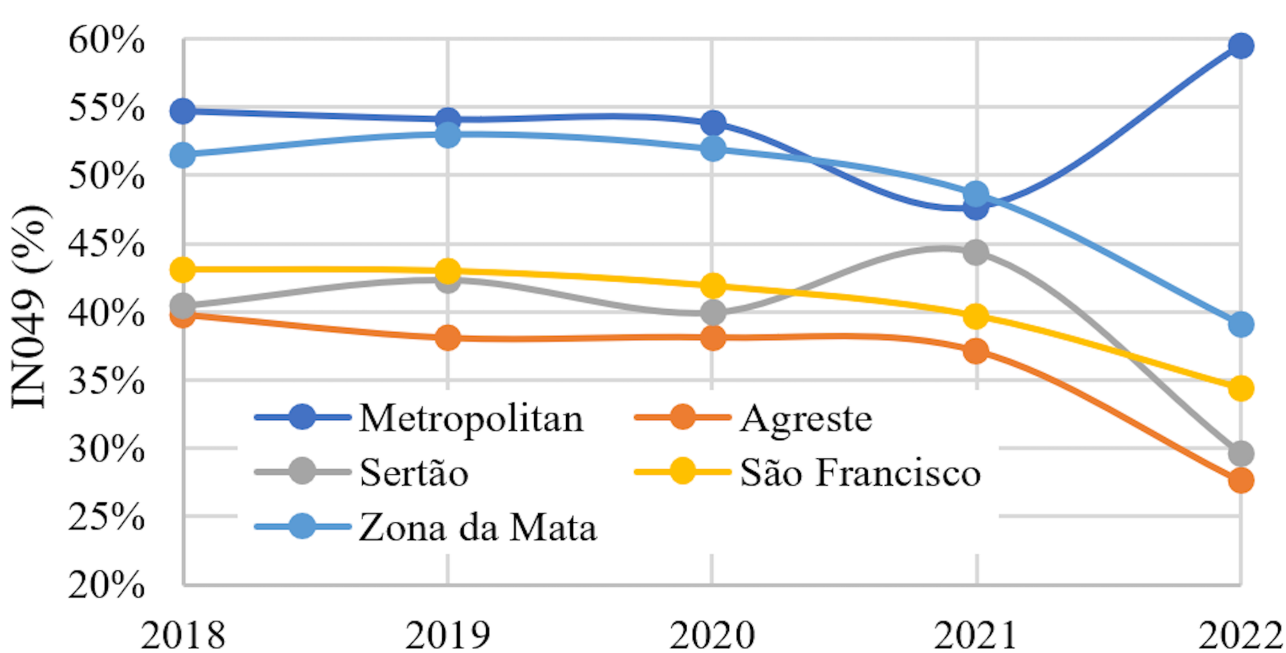

Figure 1 – Distribution water loss index (IN049) in the WSS of the mesoregions of Pernambuco (2018–2022).

Table 9 – Descriptive statistics of the water loss index (IN049) in the WSS of the mesoregions of Pernambuco (2018–2022).

Mesoregion → Statistic↓	RMR	Agreste	Sertão	São Francisco	Zona da Mata
Mean	53.96%	36.15%	39.30%	40.42%	48.81%
Median	54.10%	38.10%	40.40%	41.90%	51.50%
Standard deviation	4.20%	4.88%	5.69%	3.63%	5.67%

affected by variations in urban density, infrastructure constraints, and different levels of operational control.

The RMR exhibited the highest average water loss rate, suggesting a highly stressed WSS, possibly due to high population density and aging infrastructure. In contrast, the Agreste mesoregion presented the lowest average water loss rates, which may be attributed to recent infrastructure interventions or local characteristics, such as lower consumer density in critical areas. Despite relatively similar mean values, the high variability observed in the Sertão and Zona da Mata mesoregions highlights the need for greater stabilization of their distribution systems. Conversely, the São Francisco mesoregion exhibited a more predictable pattern, possibly reflecting more effective operational control or lower exposure to structural vulnerabilities.

These findings are consistent with those reported by Moll (2019), who applied the Wyatt method in Curitiba (Paraná, Brazil) and identified similar regional variations, with lower water loss rates in areas characterized by more effective operational control. Accordingly, the superior performance observed in the Agreste mesoregion, reflected by its lower distribution water loss rates, may be associated with the adoption of more consistent water loss management strategies.

Economic level of losses

The estimated ELL reflects the balance between water loss control costs and the financial benefits achieved through water loss reduction. The analysis of the ELL by mesoregion reveals distinct patterns influenced by operational conditions, management strategies, and local infrastructure characteristics (Figure 2). Overall, the results indicate a gradual increase in the ELL throughout the study period, which may be associated with rising costs of water loss control activities and increasing marginal costs of water recovery.

The results obtained are consistent with those reported by Heryanto et al. (2021), who estimated an ELL of 21.76% for urban WSS in Indonesia using a cost-benefit approach. Similarly, Yilmaz et al. (2023, 2025) reported ELL values ranging from 16.83% to 29%, depending on the optimization methods employed and the characteristics of the water utilities analyzed.

Table 10 presents the average ELL values for the mesoregions of Pernambuco, ranging from 19.24% in the RMR to 24.66% in the

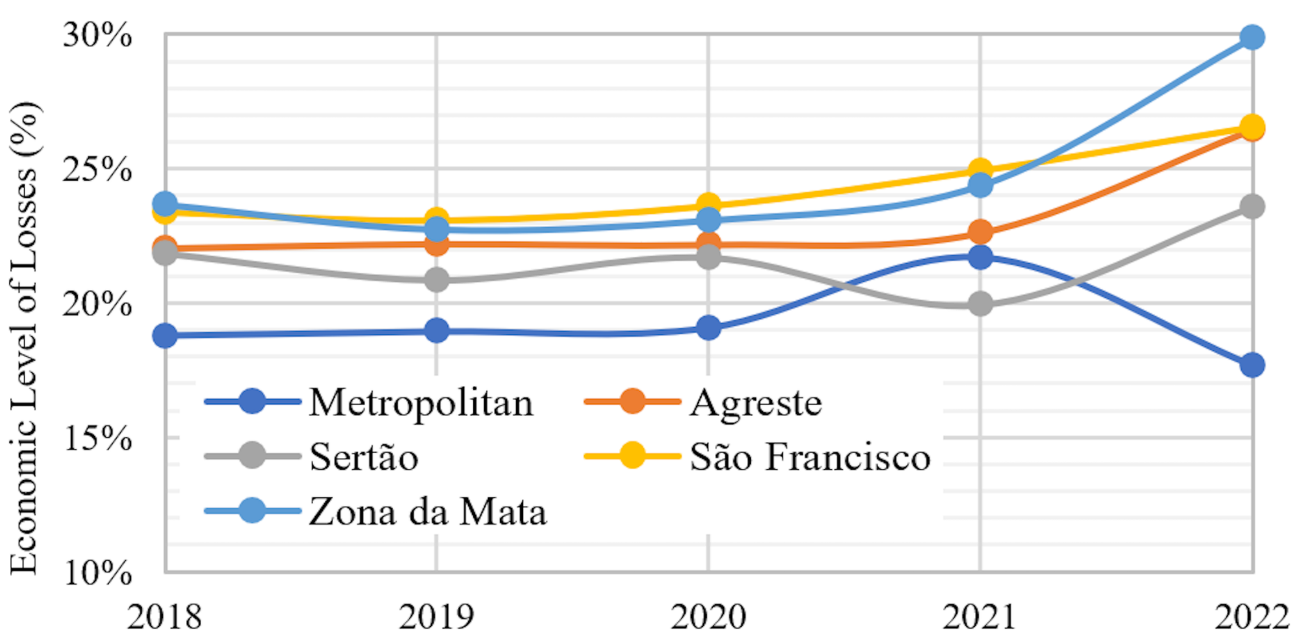

Figure 2 – ELL in the WSS of the mesoregions of Pernambuco.

Zona da Mata mesoregion. This variation reflects the distinct economic and operational characteristics of each region. The RMR, which exhibited the lowest average ELL, suggests that water loss control costs are relatively low compared with the economic value of the water losses. This result may be associated with a more consolidated infrastructure and targeted investments in reducing both apparent and real water losses.

The median values, which are close to the corresponding means across all mesoregions, indicate a relatively symmetric distribution of ELL values, suggesting that management strategies have been consistently implemented, though not equally effective across all regional contexts. The standard deviation provides additional insights into the variability of the ELL estimates. The São Francisco mesoregion exhibited the lowest standard deviation (1.43%), indicating greater stability in ELL estimates over the study period, possibly due to more standardized water-loss management practices. In contrast, the Zona da Mata mesoregion had the highest standard deviation (2.71%), reflecting greater variability, which may be associated with fluctuations in investment levels or differences in the effectiveness of water-loss control interventions. Overall, the relatively low standard deviation values indicate limited temporal variation in the estimated ELL.

These findings highlight the need for region-specific management strategies that account for the operational and economic characteristics of each mesoregion. While the RMR may benefit from maintaining and consolidating its current water loss control strategies, the Zona da Mata mesoregion requires more detailed analyses to identify the underlying causes of its high variability and elevated ELL values.

Figure 3 presents boxplots of ELL values for Pernambuco municipalities in each year, illustrating their variability and temporal evolution throughout the study period. Between 2018 and 2022, the average ELL showed a slight upward trend, increasing from 22.87% in 2018 to 26.15% in 2022. This increase was accompanied by a wider interquartile range (Q3–Q1), indicating greater variability in ELL values among municipalities. Such an increase suggests that the cost of achieving the economic equilibrium between water losses and loss control has risen over time, possibly due to sector-specific inflation and the increasing complexity of water distribution networks.

The greater dispersion observed in 2021 and 2022 indicates that the economic, structural, and operational conditions became increasingly heterogeneous among municipalities. Although outliers were identified in all years, they were particularly frequent during the last two years of the study period. Municipalities with high ELL values may be facing challenges such as aging infrastructure, dispersed service areas, administrative constraints, or elevated operating costs. Conversely, municipalities with low ELL values may reflect investments in innovative technologies, lower network density, or more effective water loss management strategies. These cases should be analyzed individually to identify local factors, such as frequent leakage events, obsolete distribution networks, or highly dispersed service areas.

The analysis of water loss indicators across the mesoregions, considering a 5% economic threshold, revealed that only two of the 25 annual observations fell within the estimated ELL for the corresponding year. One of these cases occurred in the Agreste mesoregion in 2022, with an ELL of 26.46%. This result suggests that, in that particular year and region, the water utility achieved an appropriate balance between water loss control costs and the associated economic benefits, thereby maximizing the system's economic efficiency. Barbosa (2021) evaluated 627 municipalities in the state of São Paulo (Brazil) and found that, according to the methodology proposed by Arregui et al. (2018), 66.66% of the municipalities presented an ELL lower than the current apparent water losses. Using the methodology proposed by Wyatt et al. (2021), 69.69% of the municipalities exhibited an ELL lower than the current apparent losses, while 77.55% presented an ELL below the current real water losses.

The results obtained in the present study indicate that systems with greater structural and operational limitations tend to exhibit larger deviations from the estimated ELL, demonstrating that reducing physical losses alone may not be sufficient to ensure economic efficiency. Figure 4 presents the annual average values of the ELL and the IN049 for the state of Pernambuco. A distinct temporal pattern was observed between the two indicators. While the ELL increased from 20.72% in 2018 to 22.58% in 2022, the IN049 decreased from 48.43% to 44.01% during the same period. This behavior indicates that reductions in water loss rates do not necessarily correspond to proportional progress toward the economically optimal level. The increase in the ELL may be associated with higher marginal costs of water loss control and increasing operational complexity. In contrast, the reduction in IN049 suggests improvements in operational practices aimed at mitigating real water losses.

Moll (2019), applying the methodology proposed by Wyatt (2010) to the Integrated Water Supply System of Curitiba (Paraná, Brazil) and its Metropolitan Region, estimated an ELL of 44%, considerably higher than the values obtained for Pernambuco. The study also demonstrated that investments in water loss control could generate economic savings of up to four times the investment cost in certain pressure management zones.

Despite the isolated case observed in the Agreste mesoregion in 2022, the overall results indicate that the actions implemented in the remaining mesoregions and in previous years were generally insufficient to achieve economically efficient system operation. Water supply infrastructure continues to face significant structural and operational challenges, including deficiencies in preventive maintenance and limited investment in monitoring and water-loss control technologies. Although reductions in IN049 were observed, these improvements appear to have been insufficient to bring water loss rates closer to the economically optimal level.

Table 10 – Descriptive statistics of the ELL in the mesoregions of Pernambuco (2018–2022).

Mesoregion → Statistic↓	RMR	Agreste	Sertão	São Francisco	Zona da Mata
Mean	19.24%	22.59%	21.95%	24.30%	24.66%
Median	18.94%	22.03%	21.70%	23.61%	23.67%
Standard deviation	1.49%	1.62%	2.07%	1.43%	2.71%

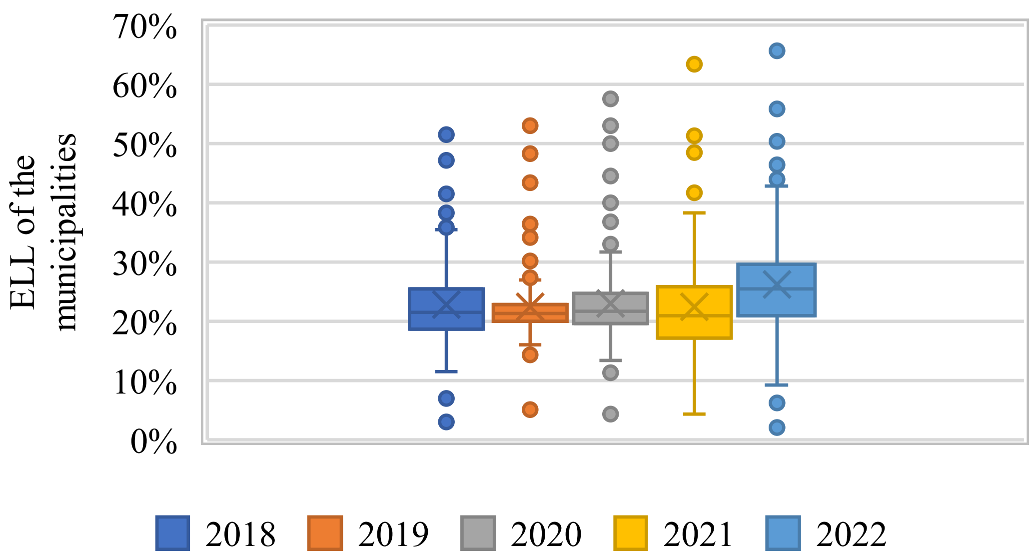

Figure 3 – Boxplot of the ELL with outliers for the WSS of municipalities in Pernambuco (2018–2022).

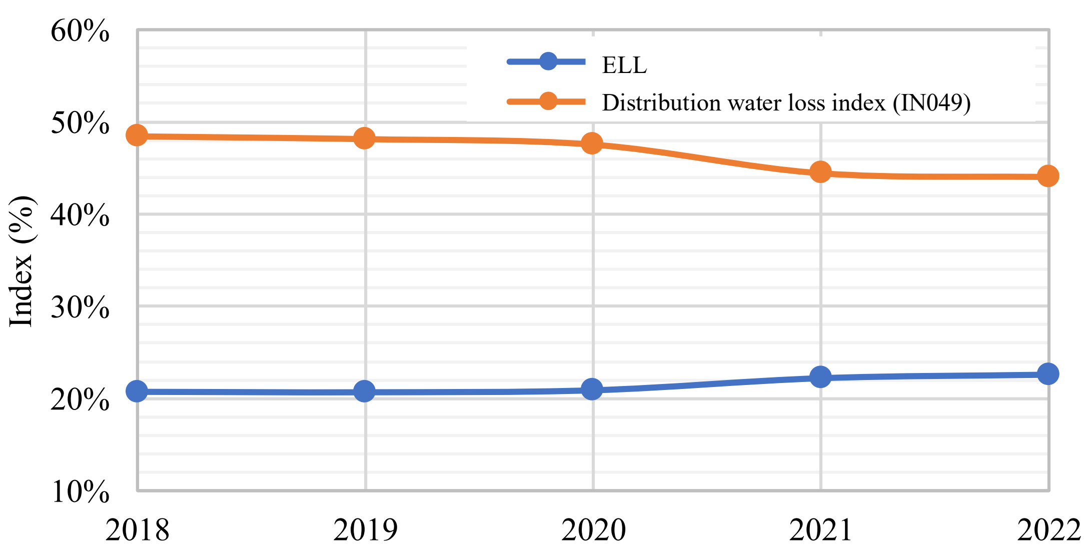

Figure 4 – Distribution water loss index (IN049) and ELL for the state of Pernambuco (2018–2022).

Although this study was conducted using data from the state of Pernambuco, the proposed methodological framework can be applied to other regional contexts, provided appropriate adaptations are made to account for differences in tariff structures, operating costs, water availability, and supply intermittency. Consequently, this study contributes not only to understanding the local context but also to advancing the application of the ELL concept to WSS with different levels of development and operational complexity.

The findings provide further insights into ELL behavior in systems characterized by high operational heterogeneity. They demonstrate that the economic efficiency of these systems depends not only on reducing physical water losses but also on the interaction among technical, economic, and operational factors. This evidence highlights the need for integrated approaches to water loss assessment that simultaneously consider operational performance, cost structure, and infrastructure characteristics – an aspect that remains insufficiently explored in applied studies on the ELL.

Statistical analysis

ANOVA was performed to assess whether the observed variations in ELL and IN049 across Pernambuco's mesoregions and over the study period were statistically significant. ANOVA was used to identify differences among the groups analyzed in terms of the operational performance of water utilities.

Table 11 presents the ANOVA results for the ELL. The calculated F-value (1.4256) was lower than the critical F-value (2.8661), and the p-value (0.2619) exceeded the significance level of 0.05. These results indicate insufficient statistical evidence to reject the null hypothesis that ELL mean values are equal across the mesoregions. Therefore, although apparent differences in values were observed across the mesoregions, these differences were not sufficiently large to be considered statistically significant. This finding suggests a relatively homogeneous ELL across the regions, which may be explained by: (i) similarities in the operational management practices of the water utility, which follows centralized management guidelines; (ii) infrastructure systems exhibiting comparable levels of operational efficiency; and (iii) relatively uniform water loss control costs, including materials and labor, throughout the state.

The ANOVA results for the IN049 are presented in Table 12. The calculated F-value (0.8302) was again lower than the critical F-value (2.8660), while the p-value (0.5216) exceeded the significance level of 0.05. Therefore, there is also insufficient evidence to reject the null hypothesis that the mean IN049 values are equal across the mesoregions. Although apparent temporal and regional variations were observed in the distribution water loss index, the results indicate that most of the variability occurred within the groups – that is, among municipalities within each mesoregion – rather than between mesoregions. This finding may be explained by:

- Centralized and homogeneous management: The water utility may be implementing similar operational policies across all regions, resulting in relatively uniform water loss levels among the mesoregions.

- Influence of local characteristics: Differences in distribution network characteristics and water consumption patterns within each mesoregion may increase internal variability, thereby reducing the detectability of differences between regions.

- Common structural constraints: All mesoregions face similar challenges, including water scarcity, aging infrastructure, and limited adoption of advanced monitoring and water loss control technologies.

Overall, the ANOVA results indicate a relatively uniform pattern in the overall performance indicators (ELL and IN049) across the mesoregions, although statistically significant differences were identified in selected pairwise comparisons. These findings suggest that, while the utility's statewide management policies have contributed to improved system performance over time, local factors continue to play an important role in explaining regional differences in water loss levels.

Table 13 presents the results of the pairwise statistical comparisons of the ELL among the mesoregions. Statistically significant differences were identified in two comparisons:

- Agreste vs. Sertão ($p = 0.0113$): The significant difference reflects the distinct structural and climatic conditions of these regions, with the Sertão facing greater challenges associated with water scarcity and more limited infrastructure.

- Zona da Mata vs. São Francisco ($p = 0.0148$): This difference may be attributed to the higher population density and greater operational complexity of WSS in the Zona da Mata compared with the more stable and predictable systems in the São Francisco mesoregion.

These findings reinforce the importance of adopting a hybrid management approach that combines centralized strategies to improve overall system performance with targeted local interventions designed to address regional specificities. Continued monitoring policies, together with investments in infrastructure and technology, are essential for sustaining the observed improvements and reducing regional disparities. Wyatt et al. (2021) similarly reported that regional variations in the ELL are commonly observed.

Table 11 – ANOVA results for the ELL across the mesoregions of Pernambuco.

Source of variation	SS	gl	MS	F	p-value	F critical
Between groups	0.0037	4	0.0009	1.4256	0.2619	2.8661
Within groups	0.0131	20	0.0007			
Total	0.0168	24				

Table 12 – ANOVA results for the Distribution Water Loss Index across the mesoregions of Pernambuco.

Source of variation	SS	gl	MS	F	p-value	F critical
Between groups	0.0223	4	0.0055	0.8302	0.5216	2.8660
Within groups	0.1345	20	0.0067			
Total	0.1568	24				

Table 13 – Pairwise ANOVA results for the ELL among the mesoregions of Pernambuco.

Comparison	F	p-value
Agreste – RMR	0.135	0.962
Agreste – São Francisco	2.611	0.160
Agreste – Sertão	10.745	0.011
Agreste – Zona da Mata	3.362	0.108
RMR – São Francisco	0.127	0.966
RMR – Sertão	0.092	0.981
RMR – Zona da Mata	0.156	0.952
Sertão – São Francisco	1.401	0.354
Sertão – Zona da Mata	2.390	0.183
Zona da Mata – São Francisco	9.495	0.015

Conclusions

The results demonstrated that the reduction in water loss rates observed across several mesoregions of Pernambuco was insufficient to bring the WSS closer to their respective ELLs. This finding indicates that operational efficiency depends not only on reducing water losses but also on the balance among loss-control costs, infrastructure characteristics, and system operating conditions.

The statistical analysis revealed a relatively homogeneous pattern of water loss indicators at the regional scale. However, statistically significant differences identified in selected pairwise comparisons among mesoregions highlight the influence of local factors on ELL behavior. These findings suggest that the operational, structural, and economic characteristics of systems may affect the economic equilibrium of water losses in different ways, even when the systems are managed under the same institutional framework.

The results also demonstrated that ELL behavior varies with operational conditions and the marginal costs associated with water loss control. Reductions in water loss rates do not necessarily lead to a proportional convergence toward the economically optimal level, emphasizing the importance of integrated analyses that simultaneously consider operational performance, cost structure, and infrastructure characteristics.

Although the state of Pernambuco was used as a case study, the proposed methodological framework can be applied to different regional contexts, particularly in systems characterized by high operational heterogeneity, intermittent water supply, and elevated energy costs. In this regard, the findings contribute to a broader understanding of the application of the ELL concept in real-world systems, demonstrating that interactions among technical, economic, and structural factors strongly influence this indicator's behavior.

From a scientific perspective, this study advances the discussion on the application of the ELL in heterogeneous regional contexts. It provides relevant evidence for the development of more adaptive and context-specific approaches to water loss assessment across WSS. Furthermore, the findings provide an analytical foundation for future studies aimed at integrating operational performance indicators, water loss control costs, and economic efficiency.

Authors' Contributions: Martins, E.H.P.S.: Conceptualization, Data curation, Formal Analysis, acquisition, Investigation, Methodology, Software, Validation, Writing – original draft. Bezerra, S.T.M.: Conceptualization, Funding, Acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing. Sousa, I.S.A.: Data curation, Formal Analysis, Acquisition, Investigation, Validation. Tito, G.B.: Data curation, Formal Analysis, Acquisition, Investigation. Alves, E.M.: Conceptualization, Formal Analysis, Investigation, Supervision.

Conflicts of interest: the authors declare no conflicts of interest.

Funding: This work was supported by the National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq) (Brazil) (grant number 420012/2021-4 and 308202/2022-8).

Declaration on the use of generative artificial intelligence: During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to review and improve the overall writing quality. After using this tool, the authors reviewed and edited the content as necessary and take full responsibility for the content of the published article.

References

Associação Brasileira de Normas Técnicas (ABNT), 2023. NBR 15538. Medidores de água potável – Ensaios para avaliação de eficiência. 1-18.

Al-Washali, T.; Sharma, S.; Lupoja, R.; Fadhl, A.N.; Haidera, M.; Kennedy, M., 2020. Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply. Resources, Conservation and Recycling, v. 152, 104515. https://doi.org/10.1016/j.resconrec.2019.104515.

Agência Nacional de Águas e Saneamento Básico (ANA), 2021. Atlas Águas: segurança hídrica do abastecimento urbano. Brasília, DF: ANA. (Accessed June 01, 2026) at: https://www.ana.gov.br/atlasaguas.

Arregui, F.J.; Cobacho, R.; Soriano, J.; Jimenez-Redal, R., 2018. Calculation proposal for the economic level of apparent losses (ELAL) in a water supply system. Water, v. 10 (12), 1809. https://doi.org/10.3390/w10121809.

Azevedo, B.B.; Saurin, T.A., 2018. Losses in water distribution systems: a complexity theory perspective. Water Resources Management, v. 32, 2919-2936. https://doi.org/10.1007/s11269-018-1976-7.

Banovec, P.; Domadenik, P., 2018. Defining economic level of losses in shadow: identification of parameters and optimization framework. Proceedings, v. 2, 599. https://doi.org/10.3390/proceedings2110599.

Barbosa, J.L.A., 2021. Avaliação de metodologias de nível econômico de perdas. Dissertação (Mestrado), Universidade Federal de Mato Grosso do Sul, Campo Grande.

Brasil. Ministério das Cidades. Secretaria Nacional de Saneamento Ambiental, 2011. Indicadores de custos de referência e de eficiência técnica para análise técnica de engenharia de infraestrutura de saneamento nas modalidades abastecimento de água e esgotamento sanitário. Brasília, DF: Ministério das Cidades, 2011. Nota Técnica SNSA n.º 492/2010.

Firat, M.; Yilmaz, S.; Ateş, A.; Özdemir, Ö., 2021. Determination of economic leakage level with optimization algorithm in water distribution systems. Water Economics and Policy, v. 7 (3), 2150014. https://doi.org/10.1142/S2382624X21500144.

Haider, H., 2025. Environmental valuation for appraising the economic level of leakage in arid environments: a case of Qassim, Saudi Arabia. In: Sefelnasr, A., Sherif, M., Singh, V.P. (eds) Water Resources Management and Sustainability. Water Science and Technology Library, v. 114. Springer, Cham. https://doi.org/10.1007/978-3-031-80520-2_28.

Heryanto, T.; Sharma, S.K.; Daniel, D.; Kennedy, M., 2021. Estimating the economic level of water losses (ELWL) in the water distribution system of the city of Malang, Indonesia. Sustainability, v. 13, 6604. https://doi.org/10.3390/su13126604.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2022. Censo Demográfico 2022: população e domicílios – resultados do universo. Rio de Janeiro: IBGE. https://censo2022.ibge.gov.br/panorama/.

Kingdom, B.; Liemberger, R.; Marin, P., 2006. The challenge of reducing non-revenue water (NRW) in developing countries. How the private sector can help: a look at performance-based service contracting. The World Bank Group, 52p.

Moll, A.C.B., 2019. Nível econômico de perdas em sistemas de abastecimento de água por distrito de medição e controle. Dissertação (Mestrado), Universidade Federal do Paraná, Curitiba.

Ociepa-Kubicka, A.; Deska, I.; Ociepa, E., 2024. Issues in implementation of EU regulations in terms of evaluation of water losses: towards energy efficiency optimization in water supply systems. Energies, v. 17 (3), 633. https://doi.org/10.3390/en17030633.

Paraschiv, S.; Paraschiv, L.S.; Serban, A., 2023. An overview of energy intensity of drinking water production and wastewater treatment. Energy Reports, v. 9 (Suppl. S11), 118-123. https://doi.org/10.1016/j.egyr.2023.08.074.

Sistema Nacional de Informações sobre Saneamento (SNIS), 2022. Diagnóstico Temático Serviços de Água e Esgoto – Visão Geral, ano de referência 2022. Brasília, DF: Ministério das Cidades. https://www.gov.br/cidades/pt-br/acesso-a-informacao/acoes-e-programas/saneamento/snis/produtos-do-snis/diagnosticos/DIAGNOSTICO_TEMATICO_VISAO_GERAL_AE_SNIS_2023.pdf.

Stamou, A.; Mitsopoulos, G.; Koutroulis, A., 2024. Proposed methodology for climate change adaptation of water infrastructures in the Mediterranean Region. Environmental Processes, v. 11 (1), 12. https://doi.org/10.1007/s40710-024-00691-w

Vermersch, M.; Carteado, F.; Rizzo, A.; Johnson, E.; Arregui, F.; Lambert, A., 2016. Guidance notes on apparent losses and water loss reduction planning. LeaksSuit Library, UK, 1-77.

Wyatt, A., 2010. Non-revenue water: Financial model for optimal management in developing countries. Rti Press.

Wyatt, A.; Ferreira, R.C.; Depexe, M.D.; Finger, F.; Manzi, D.; Mendes, R.; Schuch, K., 2021. Perdas de água – Guia para determinar o nível econômico e metas progressivas de controle para municípios, reguladores e prestadores de serviço.

Yilmaz, S.; Ates, A.; Firat, M.; Özdemir, Ö.; Cinal, H., 2023. Determination of economic loss levels in water distribution systems with different network conditions by a district stochastic optimization algorithm. Water Supply, v. 23, 1349-1361. https://doi.org/10.2166/ws.2023.047.

Yilmaz, S.; Ateş, A.; Firat, M.; Cinal, H., 2025. Defining the most appropriate water network management plan with different optimization algorithms for sustainable water management. Water Resources Management, v. 39, 5673-5694. https://doi.org/10.1007/s11269-025-04221-7