Prioritizing Leaks that Matter: Evidence-Based Assessment of Water Loss KPIs

Daniel Kozelj†
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana, Slovenia
daniel.kozelj@fgg.uni-lj.si

Abstract

This study presents a comprehensive assessment of water losses in Slovenian public water supply systems for the period 2014–2024. Key performance indicators derived from the IWA water balance, in particular Non-Revenue Water (NRW%) and the Infrastructure Leakage Index (ILI), have been calculated, segmented and uncertainties added to assess performance at national and system level. The results indicate persistently moderate to high levels of leakage, with 60 systems reporting NRW percentages above 40% and nine large utilities reporting ILI values above 8. The uncertainty analysis showed that 54.5% of systems could change performance classes. The results highlight the critical role of data quality, uncertainty quantification and targeted measures to improve efficiency and resilience.

Keywords

Water supply systems, Water losses, Infrastructure Leakage Index (ILI), Non-Revenue Water (NRW), Uncertainty quantification

1 Introduction

Following the European Citizens' Initiative 'Right2Water' in 2013, the European Commission launched procedures to assess the regulatory fitness and performance (REFIT) of Directive 98/83/EC [1]. This identified a general lack of awareness of water leakage caused by insufficient investment in the maintenance and renewal of water infrastructure [2]. Directive (EU) 2020/2184 on water intended for human consumption (recast) introduced new obligations to carry out an assessment of water losses in public water supply systems (WSS) using the Infrastructure Leakage Index (ILI) assessment method, with the aim of reducing losses to an acceptable level [3]. The public water suppliers must carry out the assessments of water losses in their respective supply areas. Based on these assessments, the Ministry of Natural Resources and Spatial Planning (MNVP) will prepare a consolidated assessment of water losses for the entire territory of the Republic of Slovenia, the results of which must be submitted to the European Commission (EC) by January 12, 2026. Thereafter, the EC will adopt a delegated act by January 12, 2028, in which the acceptable loss threshold will be set. Member states whose losses fall outside the prescribed limits must adopt national action plans to reduce losses by 2030 [3].

The obligations of Directive (EU) 2020/2184 are implemented by the Law on Drinking Water Supply and the Discharge and Treatment of Urban Wastewater (ZOPVOOV) [4], which requires utilities and municipalities to ensure a reduction in water losses, maintain and submit data on volumes/water balance/losses to the state register, prepare four-year drinking water supply programs that include leakage reduction targets, and publish annual reports. The government has yet to set detailed service standards and technical/maintenance measures by law. The executive order implements this by requiring operators to monitor and record losses in the water balance and to develop and implement loss reduction programs, with the infrastructure owner being responsible for financing the necessary investments.

Reliability and security depend on the stability and long-term availability of water resources and the resilience and efficiency of existing infrastructure [5]. The Operational Program for Drinking Water Supply 2022–2027 [6] and ZOPVOOV [4] identify systematic loss reduction as a strategic priority. As each component of the water balance is subject to measurement/estimation errors, the derived KPIs - net water consumption, water/real losses and especially the Infrastructure Leakage Index (ILI) — are inherently uncertain and, if not quantified, can steer operational decisions and large capital investments in the wrong direction. The key finding of Babić et al. [7] is that the uncertainty of the ILI is dominated by the uncertainty of the UARL inputs - in particular the average pressure and the length or number of service connections. Therefore, the most effective mitigation measure is the systematic improvement of data (pressure/flow capture in the DMAs, calibrated models and robust asset inventories) prior to benchmarking. Given the upcoming investments in water supply, municipalities, utilities and the government need to improve the reliability, consistency and accuracy of data.

1.1 Water Resources and Security of Supply

Data from the Statistical Office of the Republic of Slovenia [8] and the Operational Program for Drinking Water Supply 2022–

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2027 [6] show that Slovenia withdraws about 185 million m³ per year for public supply, while water consumption has increased by 10.3%, while household consumption has increased by 4.1% and industrial consumption by 33.6% [8]. For the same observation period from 2014 to 2023, water losses have also increased by 17.1% to a total of 53.7 million m3 per year. Although the national permits for water abstraction offer a potential of about twice the current consumption, we must be concerned about the regional imbalances in the availability of water sources — especially in the south-eastern part of Slovenia, in Slovenske gorice and in the coastal karst region.

In terms of reliability and security, the sparse backup sources pose an additional risk: Only about one-fifth (21%) of WSS have technically adequate, functioning backups, leading to high vulnerability in emergencies (natural disasters, drought, pollution or system failures). This is particularly acute in coastal communities, where the failure of the main source (e.g. Rižana) is often irreplaceable and jeopardizes the stability of the summer supply.

The Slovenian water supply sector is highly fragmented, which undermines economies of scale and integrated management. In 2024, there were 82 public service providers and over 1,114 physical WSS, but only 85 serve more than 5,000 inhabitants [9]. These large WSS serve about 1,701,500 inhabitants (79.9% of the population); the remaining 20.1% rely on smaller, capacity-constrained utilities that often do not meet quality and reliability standards. Fragmentation leads to limited network optimization, higher unit costs, weak long-term planning and limited access to EU/national funding. Small systems (≤5,000 customers) typically lack capital and staff for modernization, increasing vulnerability to crisis. Limited investment and inadequate damage control lead to a disproportionate amount of water loss, further straining resources and increasing environmental and economic pressure on communities[10].

1.2 Water Losses and Condition of Infrastructure

The regulatory framework for dealing with water losses in the Slovenian public water supply is set out in the Ordinance on the Methodology for Determining Prices for Compulsory Municipal Environmental Services [11]. Although it was adopted in 2012, its implementation has been repeatedly postponed, reflecting the complexity of reconciling municipal infrastructure ownership, utility operations and consumer price regulation. The measure is intended to encourage municipalities and operators to actively seek to reduce water losses while preventing all financial burdens from being passed on to end users. For systems serving more than 5,000 inhabitants, the regulation sets the allowable level of losses as a condition for the inclusion of water balancing costs in tariffs [6]. Recognizing that structural improvements take time, the allowable thresholds have been set above the long-term policy target of an Infrastructure Leakage Index (ILI) ≤ 4, but will gradually decrease from ILI 6 (2022–2023) to ILI 5 (2024–2026), reaching ILI 4 in 2027 [6].

Against this regulatory background, the performance data reveal persistent structural inefficiencies. On average, Slovenia's public systems have water losses of 29%, well above the ~20% benchmark generally considered sustainable in EU practice [8]. Larger municipal utilities perform slightly better at ~25%, while smaller and technologically outdated systems reach ~45%, revealing a systemic vulnerability. The national ILI is currently 3.6, which according to the IWA methodology indicates weak operational control and underdeveloped active leak detection, coupled with limited use of advanced optimization and pressure management. Without targeted action, these weaknesses will affect the long-term resilience of the supply and exacerbate vulnerability to climate-induced hydrological stress [5].

The time series indicators [8] further illustrate this dynamic. The total system input volume (SIV) increased by 12.2% between 2014 and 2023, accompanied by growth in billed authorized consumption (BAC), which increased by 12.6% (Figure 1). At the same time, water losses increased by 17%, confirming that improvements in billing have not led to lower leakages [8]. Unbilled authorized consumption (UAC) decreased significantly (−30%), a positive result reflecting better control of administrative and non-income categories [8]. However, the amount of unaccounted for water (NRW) increased by 11.2%, while the percentage of NRW remained essentially unchanged, indicating that absolute losses increased in parallel with system inputs [8].

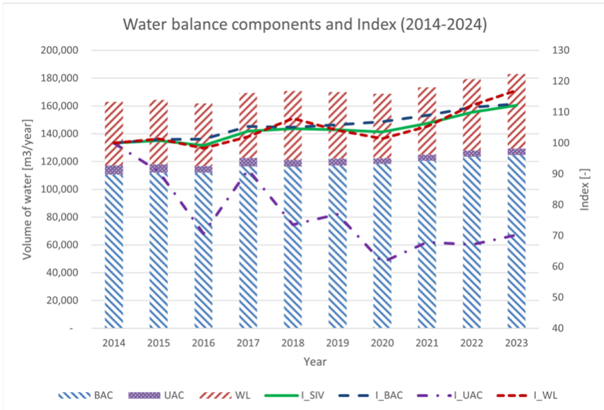

Figure 1: Water balance components from the observed period 2014-2024 [8]

The expansion of the infrastructure is a decisive explanatory factor. The total length of the network has increased by 86% during this period, while the number of connections has risen by 21%. As a result, the connection density fell from an indicated value of 100 in 2014 to 65 in 2023, reflecting the integration of additional, predominantly rural networks with fewer customers per kilometer of pipeline. Such networks are inherently more prone to losses as higher infrastructure costs per unit go hand in hand with lower consumer density, which reduces economies of scale and operational efficiency. The observed increase in water loss (WL), BAC and SIV is therefore closely linked to the inclusion of these less efficient rural systems [8].

To summarize, the Slovenian water supply sector faces a double challenge: regulatory thresholds increasingly demand efficiency improvements, while the ongoing expansion into rural networks with low connection density increases structural vulnerability to losses. Addressing these challenges requires targeted investment in leakage management, systematic pressure optimization and strategies tailored to the specific vulnerabilities of distributed systems. To better understand these dynamics and identify actionable priorities, the following chapter turns from national-level statistics to the detailed IJSVO dataset [9], which enables an assessment of individual systems (WSS_ID) in all relevant categories.

The condition of the public water supply networks in the Republic of Slovenia is worrying, as the average age of the pipelines is over forty years, which means that a large part of the network has long exceeded its intended economic and technical lifespan. More specifically, over 35 percent of the pipeline infrastructure is depreciated, technically obsolete and no longer meets the basic standards of reliability and safety required for a modern drinking water supply. Between 2007 and 2012, investments in Slovenia's public water supply amounted to 356.5 million euros, rising to 606.3 million euros in the period 2013–2018 [6]. Despite this upward trend, financial efforts remain insufficient to cope with the scale of infrastructure renewal needs. By the end of 2027, it is estimated that 6,551 km of pipelines will have exceeded their depreciation period, meaning that around €1.311 billion will be needed for replacement [6]. Given the time and budget constraints, the current program envisages an annual refurbishment of only 1.5% of the pipelines (≈380 km), which equates to around 2,280 km nationwide, falling short of the 3% replacement rate deemed necessary to maintain system condition and service reliability [6].

2 Methods

The IJSVO database is the national database for structured reporting on Slovenian public water supply systems [9]. It provides utilities with a harmonized framework for reporting technical, operational and performance data in a way that supports regulatory oversight, sector benchmarking and scientific analysis. The structure of the database is modular: Each table corresponds to a specific aspect of system operation or infrastructure, while together they form a comprehensive database covering water sources, abstraction, treatment, distribution, consumption, losses and household connections. Reporting begins with contextual overview tables that describe system identification, organizational data and general service coverage. The VT series tables then provide increasingly detailed records of operational and physical parameters:

- VT1 and VT2 deal with water sources, abstraction points, and treatment characteristics;
- VT3 and VT3a report on the system's input volumes, billed authorized consumption, apparent and real losses, imports/exports of water, and the number of connections;
- VT4 and VT5 deal with water quality monitoring and compliance;
- VT6 provides an insight into continuity of supply and service coverage, including breakdown by customer category;
- VT7 and VT8 document the physical network, pressure levels, length of connection, and other key infrastructure features.

Together, these data sets make it possible to reconstruct the overall water balance of a system and to quantify performance against technical and political benchmarks. An in-depth analysis will primarily focus on the VT3 and VT8 tables, as they form the analytical backbone for water balance and loss assessment and their data quality directly influences the robustness of derived KPIs, such as water losses, Infrastructure Leakage Index (ILI) and service continuity metrics, while allowing cross-comparison between utilities of different sizes and contexts.

2.1 ETL, Data Cleaning and Quality Control

The extract, transform and load (ETL) process formed the basis of the analytical workflow, in which IJSVO tables VT3, VT3a, VT6 and VT8, covering the period 2014–2024 [9], were batch imported into a unified SQLite database to enable cross-year comparability. The schema harmonization was necessary to compensate for attribute inconsistencies resulting from successive changes to the IJSVO database structure and thus ensure methodological continuity. Subsequent data cleansing, validation and quality control steps involved deduplication, record consolidation and integrity checking of system identifiers to ensure consistency throughout the analysis period. Validation routines included range checks (e.g., non-negativity) and cross-table coherence constraints, such as ensuring SIV ≥ BAC, given the overlap of input components across multiple tables. Missing or conflicting values were resolved via rule-based selection, favoring VT3 as the primary source. For isolated gaps, interpolation to the next year was performed with rate of change controls unless all four consecutive years were missing, thereby maintaining structural consistency of the reconstructed dataset.

2.2 Water loss key performance indicators KPIs

The key performance indicators (KPIs) for water losses are derived from the standardized IWA water balance (Figure 2), which is also anchored in Slovenian regulatory practice. Their quantification is not only based on the components of the balance, but is further refined by integrating variables of the water distribution system such as network length, number and length of house connections and average operating pressure. These enriched indicators provide a consistent framework for benchmarking and are important for supporting management decisions, guiding operational practices such as leak detection and pressure control, and for long-term investment planning to improve the efficiency, resilience and sustainability of water supply systems [10].

All performance indicators used in the regulatory assessment are derived from the standardized IWA water balance to ensure methodological consistency between systems of different sizes. In Slovenia, regulatory requirements are based in particular on the Infrastructure Leakage Index (ILI) and the percentage of non-revenue water (NRW%) [4], [6]. The classification is population-based: water systems serving more than 5,000 inhabitants are assessed using the ILI, which is a more robust, infrastructure-adjusted metric, while systems with less than 5,000 inhabitants are assessed using NRW%, which is a simpler yet practical measure of efficiency suitable for smaller networks with limited data availability and monitoring capacity [4], [6].

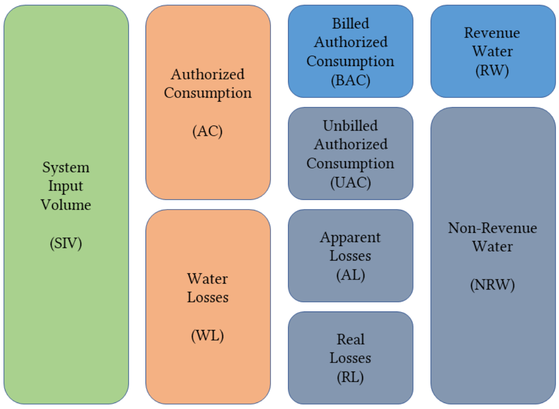

Figure 2: IWA water balance components [12]

The two key metrics used to calculate water losses are [12]:

- Non-Revenue Water (NRW) in percent:

$$NRW = \frac{SIV - BAC}{SIV} * 100 \quad (1)$$

where SIV is the system input volume (m^3/year), and BAC is the billed authorized consumption (m^3/year).

- Infrastructure Leakage Index (ILI):

$$ILI = \frac{CARL}{UARL}, \quad (2)$$

where $CARL = RL$, and

- Unavoidable Current Annual Losses (AURL):

$$UARL = \left(6.57 * L_m + 0.292 * N_C + 9.132 * L_p\right) * P\,, \quad (3)$$

where L_m is the total length of the pipe network (km), N_C is the number of service connections (from the main pipe to the property boundary), L_p is the total length of underground pipes, from property boundary line to the meter (km), and P is the average pressure (m).

The UARL formula is a practical, user-friendly tool for assessing a system-specific lower limit for the annual amount of real losses that would be technically achievable at the current operating pressure, taking into account global "best practice" for the speed and quality of repairs, active leakage control and management of pipelines and facilities when economics are not a constraint (i.e. for systems where water is scarce or has a very high marginal cost). The ILI index is regarded to be less reliable for systems with >5,000 connections, >20 conn/km, and >25 m average pressure [12].

All performance indicators used in this study were derived from the standardized IWA water balance, which provides a consistent basis for benchmarking water supply performance. To enable a comparative assessment, the results for both the Infrastructure Leakage Index (ILI: A1–D) and the percentage of non-revenue water (NRW%) were divided into fixed classes that follow internationally recognized thresholds [2], [13]. In addition, a regulatory size lens was introduced to differentiate between systems serving more than 5,000 customers (urban-like) and those with less than 5,000 customers (rural), while temporal segmentation was performed on an annual basis (2014–2024) for each WSS_ID to ensure both structural comparability and longitudinal analysis.

2.3 Uncertainty quantification of KPIs

The accuracy of water balance components and performance indicators in water distribution systems is limited by the reliability of their input data. Therefore, uncertainty must be systematically quantified and included in all subsequent calculations. In this study, uncertainty at the input data level is treated as first-order information rather than noise, with year-to-year variability assessed per WSS_ID and 95% confidence limits given using t-based intervals (if n > 2) or nonparametric bootstraps otherwise. For proportional KPIs such as NRW% and ILI, closed confidence intervals are derived using the delta method. To capture dispersion effects, Monte Carlo simulation with Latin Hypercube Sampling (10,000 draws, seeded) is applied to empirically based input distributions (Normal, Lognormal, Triangular) that generate KPI distributions from which two-sided 95% intervals are extracted [14]. Results are presented in the form of medians, confidence limits and relative half-widths, while uncertainty indicators facilitate interpretation. Ultimately, accurate water loss estimation requires robust input data, which is ensured by systematic infrastructure inventories, source and water integration, advanced monitoring platforms and satellite-based detection [15].

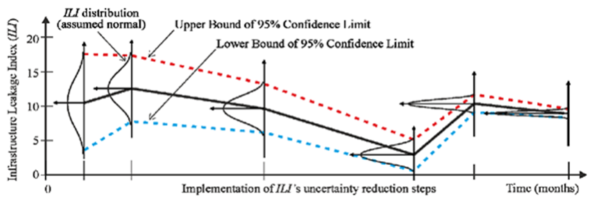

Figure 3: ILI estimations and confidence intervals by reducing uncertainty [7]

By systematically including uncertainties in the assessment of water balance components and performance indicators, the methodology applied ensures that the results obtained are not only statistically robust, but also more meaningful for decision-making [7]. Instead of treating variability as noise, the approach explicitly quantifies confidence limits and thus clarifies the degree of reliability associated with each KPI (Figure 3). This improves the interpretability of water loss assessments as both optimistic and pessimistic bounds are made transparent, allowing for more nuanced comparisons between systems and years. As a result, the results presented in the following section are more meaningful and provide a deeper insight into the extent, distribution and causes of water loss and leakage in Slovenian water supply systems.

3 Results

The primary sources of information for this analysis are the IJSVO tables VT3 and VT8, with VT3 forming the basis for the water balance for the period 2014–2024 [9]. However, VT3 data is very sparse, particularly in terms of quantifying water losses and dividing them into apparent and actual losses, the availability of which rarely exceeds 50%. Even greater challenges are associated with VT6, where implausible entries-including negative values and unrealistic variations from year to year for the same attribute- are common (Figure 4). In addition, critical infrastructure descriptors such as service connection length and average system pressure are not available until 2021, with coverage stabilizing at 64–70% for connection length and above 85% for pressure. This uneven availability over time and the inconsistency of the core variables highlight the limitations of the dataset. They complicate longitudinal assessments of water loss performance and limit the robustness of regulatory KPIs without the application of imputation, harmonization and strict quality control rules.

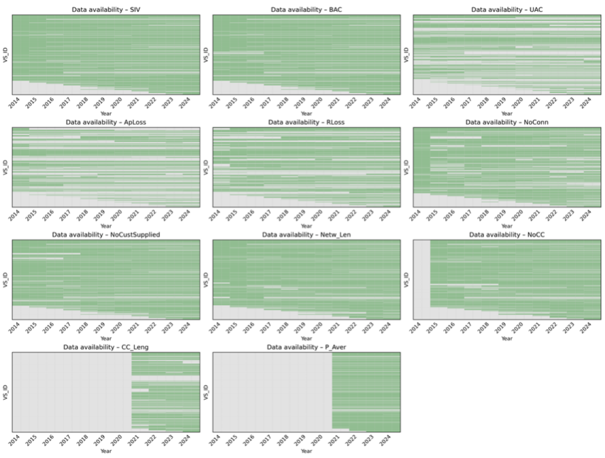

Figure 4: Selected attribute data availability from tables VT3 and VT6 in period 2014-2024 [9]

The spatial distribution of non-revenue water (NRW%) in the Slovenian water supply systems (WSS) shows pronounced regional differences, as shown in Figure 5. A total of 60 WSS have a very high NRW share of more than 40%, 15 of them even more than 70%, which indicates severe inefficiencies. A further 65 WSS fall into the high category (30–40%), while 34 are classified as moderate (25–30%). Conversely, 121 WSS perform relatively well, with NRW between 15–25%, and 81 fall into the excellent category (<15%). Within the latter group, 24 WSS report an NRW value of less than 5%, a value that is considered implausibly low and suggests possible data inconsistencies or reporting errors. For 52 WSS, the NRW% value could not be determined due to incomplete data. Overall, the NRW% map highlights the areas where losses are most critical and underlines the dual challenge posed by excessive real losses in certain networks and the questionable reliability of data in others.

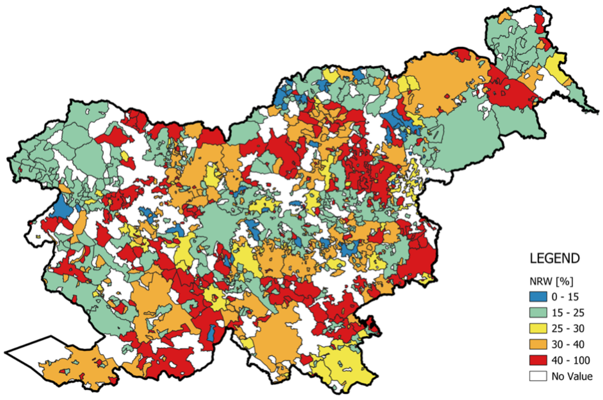

Figure 5: NRW (in %) for 2024

The spatial assessment of the Infrastructure Leakage Index (ILI) provides a clearer picture of leakage intensity in larger water supply systems (WSS) in Slovenia. As shown in Figure 6, only 74 WSS exceed the legal threshold of 5,000 customers supplied, making them eligible for an ILI-based assessment. Of these, 9 WSS fall into the very high loss category (ILI > 8), with the most extreme case reaching an ILI = 28, due to severe structural inefficiencies and persistent leakage. A further 15 WSS fall into the high range (4–8), while the majority, 26 WSS, have a moderate performance with ILI values between 2–4. At the lower end of the scale, 6 WSSs achieved good scores (1.5–2) and 12 WSSs showed excellent performance (≤1.5), which is in line with international best practice. These results highlight the heterogeneity of leakage management, where a significant proportion of larger systems continue to face significant challenges despite regulatory focus and resources. In contrast, only a minority of utilities achieve consistently low levels of leakage.

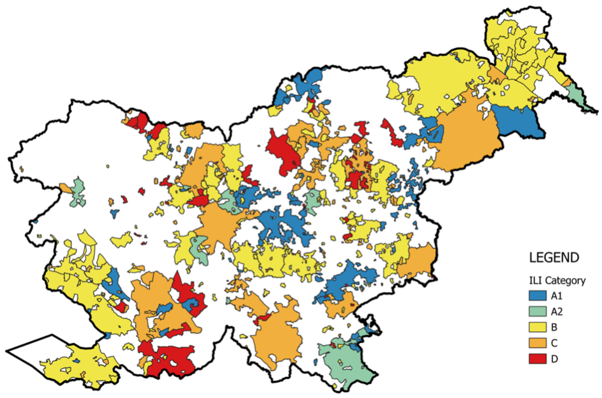

Figure 6: ILI for 2024

Comparing the ILI-based classification with the corresponding percentage of non-revenue water (NRW%) for the same group of larger WSS provides further insights into the alignment of the indicators. The results show that 27 WSS fall into the very high category with an NRW of over 40%, while 26 fall into the high category (30–40%). Thirteen WSS are classified as moderate (25–30%), 17 fall into the good category (15–25%) and only 3 systems achieve an excellent level (<15%), with the lowest NRW at 8.4%.

These values suggest that NRW% provides a more realistic and consistent representation of water loss for larger utilities, particularly because such utilities are typically managed by organizations with greater staff capacity, technical expertise and monitoring resources [12]. This underlines the importance of considering ILI and NRW% together: While the ILI captures the structural efficiency of the infrastructure, NRW% provides a more intuitive measure, and their joint interpretation strengthens the robustness of leakage assessments in large systems [7].

The inclusion of the uncertainty analysis in the KPI classification shows that the assignments to the categories are often less stable than the mean values alone would suggest. For the Infrastructure Leakage Index (ILI), more than half of the systems assessed (54.5%) have at least a 95% confidence limit that falls into a different performance band than their mean. This suggests that class membership is sensitive to the variability of inputs and the rankings should therefore be interpreted with caution. In practice, a system classified as “moderate" can plausibly fall into either the “good" or “high" category within its confidence limits. This highlights the need for regulators and operators to consider uncertainty ranges when using banded KPIs for benchmarking or compliance purposes.

Table 1: Switch of ILI class based on high / low confidence interval

Switch ILI class	No. of WSS	Example
Any	48 (54.5%)	B → A2 or B → C
to better ILI	33 (37.5%)	B → A2
to worse ILI	24 (27.3%)	B → C

A closer examination of Table 1 shows the directionality of the uncertainty effects and shows that 37.5% of the systems could fall into a better category at the lower 95% confidence limit, while 27.3% could move into a worse category at the upper limit. These proportions highlight that while there is optimism in some cases, the potential for underestimation of losses is significant and should not be overlooked. Consequently, median values and band classifications should be considered together with their confidence intervals, as together they define the robustness of the assessment of system performance. The results underline the importance of integrating uncertainty indicators into reporting to ensure that both operators and policy makers recognize the probabilistic nature of KPI-based assessments [10].

4 Analysis and Discussion

The analysis of Slovenian water supply systems confirms that national leakage remains a structural challenge, with the corrected Infrastructure Leakage Index (ILI) serving as a key benchmark. The national median and confidence intervals show that while a proportion of systems achieve excellent or good performance (A1–A2), a significant proportion remain in the problematic C and D ranges, indicating chronic inefficiency. These patterns anchor the broader story: despite targeted initiatives to reduce leakage, structural losses persist and are often concentrated in larger, more complex networks. Analysis over time from 2014–2024 shows mixed progress: Billed authorized consumption has improved and unbilled consumption has decreased, but water losses have increased by 17%. The annual shifts in band shares highlight the stagnation in structural efficiency, with non-accidental omissions and inconsistencies in reporting complicating interpretation. The robustness of these conclusions is further strengthened by the quantification of uncertainty. It shows that more than half of the systems could change bandwidths within the confidence intervals, underlining the importance of probabilistic rather than deterministic performance assessments.

At the same time, the representativeness of the data set and the regulatory split between large (≥5,000 customers) and small systems (<5,000 customers) shape the scope of the conclusions. While the larger systems - which account for nearly 80% of the population and the majority of national system input volume - are reliably assessed using the ILI, smaller systems remain dependent on NRW%, a less precise indicator that is prone to billing apportionment errors. This distinction is crucial for national compliance with EU Directive 2020/2184 and highlights the need for greater investment, monitoring and methodological adjustments to ensure fair comparability between scales.

Building on the results at the national level, spatial concentration patterns indicate persistent hotspots of water loss, where ILI values in areas C and D and rural NRW% values indicate regions that require coordinated action. These areas often overlap with zones that have high FLAG rates, highlighting data and operational vulnerabilities that need to be addressed simultaneously. A Pareto analysis of current annual real losses (CARL), weighted by system input volume, shows that a small group of systems in the top decile contribute disproportionately to national losses, suggesting that targeted improvements could deliver the greatest absolute savings. However, the analysis of the band stability with uncertainty factor shows that many systems are close to the thresholds, underlining the need for cautious interpretation. Finally, the categorization into operational typologies- such as urban high-pressure systems with high losses compared to rural networks with long networks - allows measures to be adapted to structural and contextual conditions rather than applying a one-size-fits-all solution.

In order to understand why water loss occur unevenly in different systems, the structural and operational causes must be investigated. Correlation analyzes indicate that higher average pressure (P) is consistently associated with higher losses, while lower customer density (connections per kilometer) and longer length of supply lines also correlate with poorer performance, supporting the known hydraulic and plant-related mechanisms. The source mix appears to be less influential, but can modulate the results in groundwater-fed systems compared to spring-fed systems. Comparisons between the metrics show broad agreement between the ILI and operational indicators, although there are cases where the denominators differ or data quality issues are suspected. Importantly, ILI comparability becomes weaker in systems with atypical density or pressure profiles, emphasizing the need for contextual interpretation rather than universal ranking. Preliminary machine learning readiness checks show stable predictive signals across folds, with pressure, density and link length repeatedly emerging as explanatory variables, confirming their suitability for factor analysis and hypothesis-driven exploration in future modeling work.

The Slovenian regulation on water supply and loss reduction obliges utilities to prepare water balance analyzes and to implement structured measures to reduce leakages. The results of this study show that national water losses are still high. 60 utilities exceed 40% NRW and nine major systems have ILI scores above 8, highlighting the urgent need for a coordinated national approach. To address these challenges, measures need to be systematized into a comprehensive program that prioritizes both data reliability and operational efficiency and enables utilities to translate analytical findings into actionable plans [15], [16].

Table 2: Measures of a national for water loss reduction program [16]

Responsibility	No.	Measure
Municipal / utility level	I	Measures for improving WSS data
	II	Measures for optimizing WSS
	III	Measures for dividing WSS into DMA zones
	IV	Measures for pressure control and management in the WSS
	V	Measures for active leakage control
	VI	Measures for addressing apparent losses
	VII	Measures for pipeline planning and replacement
	VIII	Measures for institutional strengthening
	IX	Measures for analysis and reporting
National level	X	Technical (external) assistance to water utilities for implementing measures
	XI	Costs of the national body for loss reduction

The first group of measures in Table 2 focuses on improving system data, including asset records, breakdown history, consumption patterns and operating parameters, which are consolidated on a GIS platform. This step is essential as nearly half of utilities still report gaps or inconsistencies in water balance components and coverage of apparent and actual losses in VT3 data rarely exceeds 50%. Building on the improved knowledge of the system, further measures include hydraulic optimization, including pressure management and segmentation of the system into DMA and PMA zones [17]. Such steps are crucial in Slovenia as the average system pressure is more than 40 m and the connection density varies greatly, increasing the risk of structural loss [10].

Other measures include the active control of leaks through specialized detection, the reduction of obvious losses through the targeted replacement of meters and the prioritization of pipeline rehabilitation, especially in networks where over 35% of the infrastructure is already depreciated. Equally important is institutional strengthening to ensure that utilities have the organizational capacity and trained staff to implement the measures sustainably. Complementary steps such as regular analyzes, reports and external technical support will strengthen national efforts [16]. Finally, the establishment of a benchmarking system with indicators, supported by a central database, will enable systematic monitoring of progress and ensure accountability. This structured program reflects the evidence base of current losses in Slovenia and provides a way to achieve regulatory thresholds while improving operational resilience.

5 Conclusions

Slovenia's public water supply systems continue to struggle with significant leakage problems, with national water losses averaging well above sustainable EU benchmarks. The analysis confirmed that 60 utilities report NRW values of more than 40% and nine larger systems record ILI values of more than 8, placing them among the most problematic categories. Data availability and quality remain decisive factors in interpreting these results, as gaps in the VT3 and VT6 tables limit the accuracy of loss quantification. Nonetheless, the integration of harmonized ETL processes, rule-based imputation and uncertainty quantification enables the creation of a credible national overview. The combined use of ILI and NRW, represented by spatial mapping and stratified by system size, provides a robust framework for benchmarking. Importantly, the uncertainty analysis shows that 54.5% of systems can change class within confidence limits, highlighting the need for a probabilistic interpretation rather than a deterministic classification. These results show both the scale of the problem and the methodological tools that are now available to address it.

Strengthening the national data system is the first and most important measure in the Slovenian strategy to reduce water losses. Improved reporting, coupled with advanced monitoring and analysis, will enable more realistic assessments of ILI and NRW and thus provide the basis for effective planning. Technical measures such as pressure management, active leakage control and pipeline rehabilitation need to be pursued in parallel, supported by institutional capacity building and benchmarking systems. Together, these measures will not only ensure compliance with EU Directive 2020/2184, but also improve the efficiency, resilience and long-term sustainability of Slovenia's water supply.

References

[1] Council of the European Union, *Directive 98/83/EC of the Council of 3 November 1998 on the quality of water intended for human consumption*, vol. L 330. 1998, pp. 32–54.

[2] European Court of Auditors, "Implementing the Drinking Water Directive: Water Quality and Access to it Improved in the EU; Commission needs to better support Member States," Luxembourg, Special Report No. 12/2017, May 2017.

[3] European Union, *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast).* 2020. [Online]. Available: http://data.europa.eu/eli/dir/2020/2184/oj

[4] Official Gazette of the Republic of Slovenia, *Zakon o oskrbi s pitno vodo ter odvajanju in čiščenju komunalne odpadne vode*. 2025, pp. 2117–2134. [Online]. Available: https://pisrs.si/pregledPredpisa?id=ZAKO9092

[5] [5] European Commission, "European Water Resilience Strategy (COM(2025) 280 final)," European Commission, Brussels. [Online]. Available: https://environment.ec.europa.eu/publications/european-water-resilience-strategy_en

[6] Ministry of Environment and Spatial Planning, *Operational Program for Drinking Water Supply for the Period 2022–2027*. 2022, p. 102. [Online]. Available: https://www.gov.si/assets/ministrstva/MOP/Dokumenti/Voda/Pitna_voda/op_oskrba_pitna_voda_2022_2027.docx

[7] B. Babić, M. Stanić, D. Prodanović, B. Džodanović, and A. Đukić, "Reducing Uncertainty of Infrastructure Leakage Index – A Case Study," *Procedia Engineering*, vol. 89, pp. 1577–1584, 2014, doi: 10.1016/j.proeng.2014.11.459.

[8] SURS, "SiStat Database - Public Water Supply," Public Dataset, Statistical Office of the Republic of Slovenia. Accessed: May 15, 2018. [Online]. Available: https://pxweb.stat.si/SiStat/en

[9] MNVP, "Information System of Public Environmental Protection Services = Informacijski sistem za spremljanje gospodarskih javnih služb varstva okolja (IJSVO)," Ministry of Natural Resources and Spatial Planning, Ljubljana, Slovenia, 2025. Accessed: July 15, 2025. [Online]. Available: https://ipi.eprostor.gov.si/jgp/data

[10] A. Ociepa-Kubicka, I. Deska, and E. Ociepa, "Issues in Implementation of EU Regulations in Terms of Evaluation of Water Losses: Towards Energy Efficiency Optimization in Water Supply Systems," *Energies*, vol. 17, no. 3, p. 633, Jan. 2024, doi: 10.3390/en17030633.

[11] Official Gazette of the Republic of Slovenia, *Ordinance on the Methodology for Determining Prices for Compulsory Municipal Environmental Services*, vol. 87/2012.

[12] H. Alegre, "Performance Indicators for Water Supply Services - Second Edition," *wio*, vol. 12, May 2013, doi: 10.2166/9781780405292.

[13] WAREG, "An Analysis of Water Efficiency KPIs in WAREG Member Countries," 2017. [Online]. Available: https://www.wareg.org/documents/an-analysis-of-water-efficiency-kpis-in-wareg-member-countries/

[14] J. C. Helton and F. J. Davis, "Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems," *Reliability Engineering & System Safety*, vol. 81, no. 1, pp. 23–69, July 2003, doi: 10.1016/S0951-8320(03)00058-9.

[15] A. V. Serafeim, N. Th. Fourniotis, R. Deidda, G. Kokosalakis, and A. Langousis, "Leakages in Water Distribution Networks: Estimation Methods, Influential Factors, and Mitigation Strategies—A Comprehensive Review," *Water*, vol. 16, no. 11, p. 1534, May 2024, doi: 10.3390/w16111534.

[16] World Bank, "National Water Loss Reduction Action Plan," Washington DC, US, TF073805, Nov. 2023.

[17] D. Kozelj and D. A. Fernández, "Predicting Water Distribution Pipe Failures Using Machine Learning and Cross-Infrastructure Data," *Acta hydrotechnica*, pp. 53–64, June 2025, doi: 10.15292/acta.hydro.2025.05.