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Water Loss Analysis at Perumda Air Minum Tirta Lestari Tuban Regency Using the Water Balance Method and Infrastructure Leakage Index

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A B S T R A C T

Perumda Air Minum Tirta Lestari of Tuban Regency provides clean water services but experiences significant water losses. This study evaluated water losses using the Water Balance method and the Infrastructure Leakage Index (ILI). Results showed water losses of 984,739 m^3/year, equivalent to 22.8% of the system input, with 78.6% attributed to physical losses. The calculated ILI of 13.18 places the utility in Category D, indicating excessive leakage and poor distribution efficiency. Water losses also caused an estimated IDR 1.93 billion in annual financial losses. Current leakage management remains largely reactive without District Metered Areas (DMA). Improving pressure management, active leak detection, pipeline rehabilitation, data management, and staff capacity is essential to reduce leakage, improve operational efficiency, and ensure sustainable water supply services

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INTRODUCTION

Non-Revenue Water (NRW) is a major issue for Indonesian PDAMs, reflecting low efficiency in SPAM management and reduced service quality. According to the (World Bank, 2020), over 45 million m^3 of water are lost daily in developing countries, including Indonesia, due to network leakages, meter inaccuracies, and illegal connections, leading to economic losses, reduced investment capacity, and service disruptions. Globally, NRW continues to burden utilities in both developed and developing nations (Liemberger & Wyatt, 2019). Systematic reviews highlight that effective NRW reduction requires integrated infrastructural, technological, and managerial approaches (Farouk et al., 2023). Thus, NRW control has become a key priority to improve PDAM performance in Indonesia (Farley et al., 2008).

Nationally, water loss remains far above government standards. The 2023 Performance Report of Regional Water Utilities shows an average NRW of 33.90% or 1.74 billion m^3 annually, up 0.18% from the previous year, while Permen PUPR No. 27/PRT/M/2016 limits losses to 20%. This indicates that most PDAMs still face major challenges, with losses reaching IDR 9.75 trillion per year (Ministry of PUPR, 2023). Studies further stress that effective NRW reduction requires not only infrastructure rehabilitation but also structured management programs (Thornton et al., 2020).

Perumda Air Minum Tirta Lestari in Tuban Regency also faces high water loss. In 2024, only 253,151 m^3 of 359,360 m^3 produced was billed, leaving 106,209 m^3 (29.56%), well above the national limit. Contributing factors include pipeline leaks in high-iron areas like Bancar, manual flow regulation, and inaccurate meter readings from faulty devices. Similar challenges are reported in other developing countries, where Water Balance and Infrastructure Leakage Index (ILI) are used to better quantify and manage NRW (Mutikanga et al., 2013). The high level of water loss has serious impacts from technical, institutional, and financial perspectives. Technically, pipeline leakages cause a decrease in distribution pressure, thereby affecting service continuity (Romdloni et al., 2021). Institutionally, limited technical competence among field staff and the suboptimal implementation of monitoring systems remain major challenges in Non-Revenue Water control (Dayanti et al., 2022).

Meanwhile, from a financial perspective, water loss directly reduces the revenue of the regional water utility, limits fiscal space for investment, and potentially causes losses amounting to billions of rupiah annually (Mustafidah, 2019). Furthermore, leakages increase environmental risks such as contaminant intrusion into the distribution network and potential infrastructure damage around leakage points (Hazairin et al., 2024). Thus, water loss not only disadvantages the utility economically but also has implications for service quality and infrastructure sustainability (Megarini, 2020).

In addition to domestic challenges, international research highlights the growing importance of data-driven approaches in the management of Non-Revenue Water (NRW). Advanced technologies such as artificial intelligence and deep reinforcement learning have demonstrated significant potential in detecting and predicting leakages (Javed et al., 2025). Comparative studies further emphasize that each method of leakage detection and isolation possesses specific advantages and limitations that must be carefully considered by water utilities (Vrachimis et al., 2022). These insights suggest that Indonesian PDAMs could benefit from the gradual adoption of such technological innovations within their NRW management programs.

Despite the growing body of research on Non-Revenue Water (NRW), most previous studies have primarily focused on either quantifying water losses using the Water Balance method or evaluating leakage performance through the Infrastructure Leakage Index (ILI), with limited integration of technical, institutional, and financial perspectives into a single assessment. Furthermore, studies on regional water utilities in Indonesia, particularly medium-sized utilities such as Perumda Air Minum Tirta Lestari in Tuban Regency, remain scarce. This study addresses these gaps by combining Water Balance and ILI analyses with an evaluation of institutional capacity, financial impacts, and existing leakage control practices to provide a more comprehensive assessment of water loss management. The findings are expected to offer practical recommendations for reducing physical water losses and improving the operational efficiency and sustainability of water supply services in Tuban Regency.

LITERATURE REVIEW

Non-Revenue Water (NRW)

Non-Revenue Water (NRW) is defined as the difference between the volume of water entering the distribution system and the volume of water that generates revenue through customer billing. According to the International Water Association (IWA), NRW consists of authorized unbilled consumption, apparent losses, and real (physical) losses (Farley et al., 2008). High NRW levels reduce operational efficiency, increase production costs, and limit the financial capacity of water utilities to improve service quality. Therefore, NRW reduction has become one of the primary performance indicators for water utilities worldwide (Liemberger & Wyatt, 2019).

Water Balance and Infrastructure Leakage Index (ILI)

The Water Balance method is widely used to identify and quantify water losses by classifying water volumes into revenue water and non-revenue water components. This method provides a systematic framework for determining the sources of water losses and evaluating distribution system performance (Mutikanga et al., 2013). To assess the efficiency of physical leakage control, the Infrastructure Leakage Index (ILI) is commonly applied. ILI is calculated as the ratio between Current Annual Physical Losses (CAPL) and Minimum Achievable Annual Physical Losses (MAAPL). Lower ILI values indicate more effective leakage management, whereas higher values reflect greater opportunities for infrastructure and operational improvements (Thornton et al., 2020).

Water Loss Control

Effective water loss management requires integrated technical and managerial approaches. Pressure management, active leakage detection, pipeline rehabilitation, and accurate customer meter management are recognized as effective measures for reducing physical losses (Farley et al., 2008). Recent studies also emphasize the importance of technological innovations, such as artificial intelligence and advanced leakage detection techniques, to improve the effectiveness of NRW management and support sustainable water utility operations (Javed et al., 2025; Vrachimis et al., 2022).

METHODOLOGY

This research utilized both primary and secondary data sources. Primary data were collected through direct field observations of the water distribution system, which included evaluating the physical condition of the network, measuring pressure at selected locations, and inspecting service connections and customer meters. These observations were intended to provide an accurate representation of the infrastructure and identify potential sources of water loss in the field.

Secondary data were obtained from Perumda Air Minum Tirta Lestari in Tuban Regency. These included records on water production, distribution volumes, sales figures, the number of active customers, total pipeline length, and average system pressure. The secondary data supported the quantitative analysis required to calculate water loss and offered a comprehensive overview of the current state of the distribution system.

The analytical process involved constructing a water balance in accordance with the International Water Association (IWA) guidelines. This framework facilitated the assessment of the relationship between water produced, water sold, and water lost. From this analysis, the Current Annual Physical Losses (CAPL) were identified, representing the actual volume of physical water losses within the distribution network.

Following the CAPL calculation, the Minimum Achievable Annual Physical Losses (MAAPL) were estimated based on technical parameters such as pipeline length, number of service connections, and average pressure. The MAAPL serves as a benchmark for the lowest tolerable level of physical water loss under existing network conditions and is used to evaluate the efficiency of leakage control efforts.

A comparison between CAPL and MAAPL was then conducted to determine the Infrastructure Leakage Index (ILI), a widely recognized metric in international studies for benchmarking utility performance (Mutikanga et al., 2013). The ILI reflects the effectiveness of leakage management in potable water systems. A high ILI value indicates poor leakage control and the need for corrective actions, whereas a value close to one suggests efficient system management. Through this method, the study aims to provide a detailed assessment of water loss levels and inform strategic recommendations for reducing Non-Revenue Water (NRW) at Perumda Air Minum Tirta Lestari in Tuban Regency.

Beyond the water balance and ILI analysis, international research also highlights the importance of hydraulic modeling in simulating pressure conditions within the distribution system. Calibrating these models with field data enhances the accuracy of leakage assessments and supports informed decision-making by utilities (Boztaş & Fırat, 2024). Additionally, regulating valves play a critical role, as rapid adjustments can significantly influence leakage rates and distort loss estimations if not properly accounted for (Coronado-Hernández et al., 2024).

RESULT AND DISCUSSION

Water Balance

The water balance method is a fundamental analytical approach used to quantify, assess, and categorize water volumes according to demand types and their distribution within a water supply system. Establishing a water balance is widely recognized as a critical initial step in Non-Revenue Water (NRW) management, as it enables a clearer understanding of the scale of water losses and facilitates the identification of their sources.

To promote consistency in calculation methodologies, the International Water Association (IWA), in collaboration with the World Bank, has developed a conceptual framework and standardized terminology for global application. This standardization has been adopted by numerous national water associations, allowing water balance analyses to be more easily compared and evaluated across different regions and operational contexts.

In practice, preparing a water balance requires sufficiently complete baseline data as input for calculations. The data used are generally collected on an annual basis to align with NRW calculations for the corresponding year. All these data serve as the basis for analysis, ensuring that the resulting water balance reflects the actual conditions of the distribution system. In general, water balance analysis is carried out through six interrelated stages to provide a comprehensive overview of water loss conditions within a service area.

A. System Input Volume

The system input volume represents the total water entering the distribution network of Perumda Air Minum in the Tuban area from all production sources. This data serves as the primary basis for preparing the water balance using the WB-Easycalc software. Through the System Input Volume sheet, data from 13 water sources are entered and processed, as shown in Table 1. The contribution of each source varies, with Tuwiri Wetan 01 providing the largest supply of 539,568 m^3, while Sugihwaras contributes only 15,957 m^3.

Table 1. Water Distribution Volume of Perumda Air Minum Tirta Lestari in Tuban Area, January-July 2025

No	Water Source	Water Volume (m³)
1	Tuwiri Wetan 01	539,568
2	Tuwiri Wetan 02	489,888
3	Tuwiri Wetan 03	445,266
4	Bektiharjo MA	385,407
5	Sugiharjo	131,688
6	Perumnas	122,760
7	Widengan	121,536
8	Sugihwaras	15,957
9	Sleko	54,252
10	Besaran	52,686
11	G.Ombo Pasar Sapi	52,164
12	Karang Indah	98,885
	Total	2,510,057

The processing results indicate that the total system input volume during the period of January to July 2025 reached approximately 2.51 million m^3. This value is then used as a reference in the water balance calculation to determine the magnitude of water losses and their components within the distribution system of Perumda Air Minum in the Tuban area.

B. Billed Consumption Input

Billed metered consumption refers to the volume of water usage recorded through official customer meters of Perumda Air Minum in the Tuban area and included in the billing system. This data is entered into the Billed Metered Consumption sheet in WB-Easycalc and reflects the amount of water billed according to the applicable tariff categories.

As shown in Table 2, the total billed metered consumption reached 1,937,854 m^3. The household category contributed the largest share, accounting for more than 88% of total usage, with Household A at 1,114,025 m^3 and Household B at 599,859 m^3. Meanwhile, the social, institutional, commercial, and industrial sectors contributed relatively small volumes. This indicates that the majority of Perumda Air Minum customers in the Tuban area are households, while large industries likely still rely on alternative water sources.

Table 2. Billed Metered Consumption of Perumda Air Minum Tirta Lestari in Tuban Area, January-July 2025

No	Billed Metered Consumption	
	Description	**Volume (m^3)**
1	General Social	54,260
2	Special Social	26,415
3	Household A	1,114,025
4	Household B	599,859
5	Government Institutions	62,450
6	Small Commercial	23,724
7	Large Commercial	55,355
8	Small Industry	562
9	Large Industry	844
Total		1,937,854

Billed metered consumption is one of the main components in preparing the water balance, which is then compared with the system input volume to determine the amount of water successfully billed to customers and the difference classified as water loss or Non-Revenue Water (NRW).

Unbilled consumption refers to water usage that is not recorded through customer meters but is still included in official billing. In this study, the data entered via the Billed Unmetered Consumption sheet amounted to 245 m^3, categorized under water tanks (Table 3).

Table 3. Billed Unmetered Consumption of Perumda Air Minum Tirta Lestari in Tuban Area, January-July 2025

Billed Unmatered Consumption	
Description	**Water Volume (m^3)**
Water Tank	245
Total	245

Although relatively small, this consumption plays a role in providing water for public facilities, government institutions, social activities, and emergency needs that cannot be served through the distribution pipeline network. Therefore, recording unbilled consumption remains relevant as part of the revenue water component in the water balance.

C. Unbilled Consumption Input

Unbilled metered consumption refers to water usage that is recorded through meters but not billed according to company policy. In this study, data processing showed that there was no unbilled metered consumption in Perumda Air Minum in the Tuban area (0 m^3). This indicates that all metered usage has been included in the billed category or other official categories. This condition reflects the consistency of the company’s policy in minimizing potential Non-Revenue Water from a social policy perspective.

Unbilled unmetered consumption refers to water usage that is neither recorded through meters nor billed, but still needs to be recorded because it is related to operational activities or social services. In this study, the volume of unbilled unmetered consumption was recorded at 18,200 m³ (Table 4).

Table 4. Volume of Unbilled Unmetered Consumption of Perumda Air Minum Tirta Lestari in Tuban Area, January- July 2025

No	**Billed Unmatered Consumption**	
	Description	**Water Volume (m³)**
1	Fire Fighting (Hydrants)	600
2	Flushing/Pipe Cleaning	15,300
3	Pipe Repair	500
4	New Connection	1,200
5	Meter Replacement	600
Total		18,200

The largest contribution comes from flushing or pipe cleaning activities at 15,300 m³, followed by new connections (1,200 m³), fire fighting (600 m³), meter replacement (600 m³), and pipe repair (500 m³). Although this category does not generate revenue, it is important as part of the water balance because it reflects the water needed to support company operations and social services. Accurate recording of this data can be used to evaluate Non-Revenue Water and improve distribution efficiency at Perumda Air Minum in the Tuban area.

D. Unauthorized Consumption

Unauthorized consumption refers to water usage resulting from illegal connections or unauthorized use that is not recorded as official customers. This category is included in Non-Revenue Water (NRW) because the water used is not billed and potentially causes financial losses. In Perumda Air Minum in the Tuban area, unauthorized consumption is divided into two main categories. First, household illegal connections, estimated at 15 connections, account for approximately 3,180 m³ of water usage. Second, non-household illegal connections, consisting of 2 connections, have a total usage of 424 m³. Meanwhile, no cases of meter tampering, bypass, or other forms of fraud among official customers were found.

Table 5. Unauthorized Consumption of Perumda Air Minum Tirta Lestari in Tuban Area, January-July 2025

No	Description	Number of Connections	Consumption (m³)
1	Household Illegal Connections	15	3,180
2	Non-Household Illegal Connections	2	424

Overall, unauthorized consumption in the Tuban area is estimated at 3,604 m³. This value indicates the potential water loss due to illegal connections, highlighting the need for regular monitoring and enforcement measures to reduce commercial losses and improve distribution efficiency.

E. Innaccuracy and Data Handling

Meter inaccuracy and data handling are sources of non- physical water loss. These factors arise from limitations in customer meter accuracy as well as errors in recording, inputting, and processing administrative data.

In this study, calculations were conducted using an average percentage approach for all customers, in line with the computerized recording system already implemented at Perumda Air Minum in the Tuban area. The recorded billed metered consumption amounted to 1,937,854 m³, with an estimated under-registration of 4%, or approximately 80,744 m³. Additionally, meter reading fraud was estimated at 1% (19,577 m³), while administrative data handling errors amounted to approximately 193 m³.

Table 6. Input for Meter Inaccuracy and Data Handling

No	Description	Total (m³)
1	Meter Inaccuracy	80,744
2	Meter Reading Fraud	19,577
3	Data Handling Errors	193
	Total	**100,514**

The results of the analysis using WB-Easycalc indicate that water losses attributed to meter inaccuracies and data handling errors are estimated at 100,514 cubic meters. This finding underscores that, despite the implementation of a computerized recording system, these factors continue to contribute significantly to overall water loss. Consequently, corrective actions are necessary, including regular calibration of water meters, enhancement of meter reading accuracy, improvement of data management practices, and enforcement against fraudulent activities.

F. Calculating the Water Balance

The water balance method is employed to calculate and analyze both physical and apparent water losses within a water supply system. This analysis can be performed using basic software such as Microsoft Excel or dedicated tools like WB- Easycalc.

The water balance analysis for Perumda Air Minum in the Tuban area shows a System Input Volume of 4,321,560 m³/year. From this total, Authorized Consumption was recorded at 3,368,156 m³/year, consisting of Billed Authorized Consumption of 3,336,821 m³/year and Unbilled Authorized Consumption of 31,335 m³/year. Thus, the total water successfully billed to customers (Revenue Water) amounted to 3,336,821 m³/year.

Meanwhile, Non-Revenue Water (NRW) was recorded at 984,739 m³/year, representing approximately 22.8% of the total system input volume. NRW consists of two major components: commercial losses and physical losses. Commercial losses amounted to 179,259 m³/year, comprising unauthorized consumption of 6,205 m³/year and meter inaccuracies and data handling errors totaling 173,054 m³/year. Meanwhile, physical losses reached 774,145 m³/year, primarily resulting from leakages in transmission and distribution pipelines, as well as household service connections. These findings indicate that physical losses are the dominant contributor to NRW, accounting for approximately 78.6% of total water losses, with pipeline leakage identified as the primary source.

Overall, the results suggest that the existing NRW level remains relatively high and should be reduced to comply with national efficiency targets and international performance benchmarks. Recommended improvement strategies include rehabilitating deteriorated pipelines, implementing active leak detection and repair programs, replacing aging infrastructure, routinely calibrating customer water meters, and strengthening data management systems to improve measurement accuracy. The water balance analysis results are presented in Figure 1.

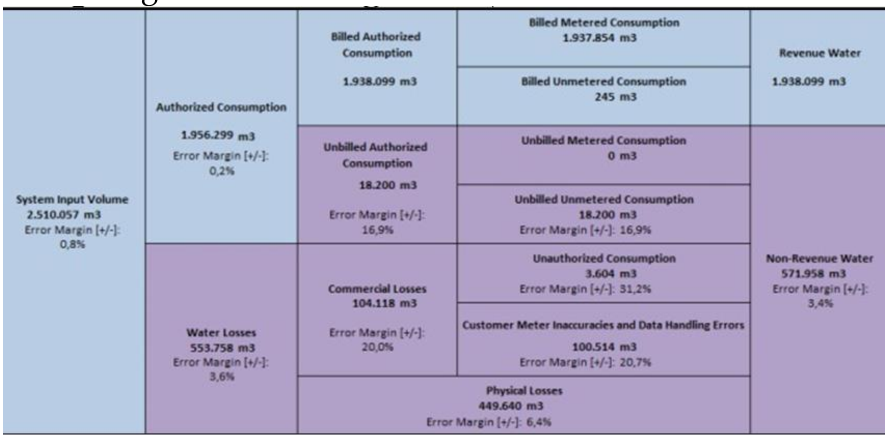

Figure 1. Water Balance of Perumda Air Minum Tirta Lestari in Tuban Area

Infrastructure Leakage Index (ILI)

The Infrastructure Leakage Index (ILI) is a key performance indicator used to evaluate the effectiveness of water distribution systems in managing physical water losses. This index not only quantifies the extent of leakage but also reflects the quality of operational practices in controlling such losses. International comparisons reveal that ILI values in regions such as Europe and the United States are considerably lower than those typically found in developing countries (Kanakoudis et al., 2013).

ILI is determined by calculating the ratio between the Current Annual Physical Losses (CAPL), which represent the actual volume of physical water loss, and the Minimum Achievable Annual Physical Losses (MAAPL), which reflect the lowest feasible loss under optimal management conditions. An ILI value close to one indicates a highly efficient system, while a higher value suggests inefficiencies and highlights opportunities for improvement through measures such as pipeline rehabilitation, leak detection programs, and pressure optimization.

The strength of the ILI lies in its objectivity and its adaptability for comparative analysis across utilities or regions with varying operational contexts. As such, ILI analysis is essential for:

1. Evaluating the effectiveness of physical leakage control strategies.
2. Establishing priorities for infrastructure upgrades and system improvements.

3. Comparing performance over time or between different utilities.
4. Supporting decision-making in infrastructure investment planning.

Minimum Achievable Annual Physical Losses (MAAPL) represent the lowest realistic level of physical water loss that can be achieved if the distribution network is optimally managed, considering the number of household connections, pipe length and material, as well as average operating pressure. This value is often used as an efficiency target by water utilities.

Current Annual Volume of Physical Losses (CAPL) is the actual physical water loss occurring in one year and is calculated based on the water balance, i.e., the difference between the system input volume and the billed volume, minus non-physical losses. MAAPL reflects the ideal condition, whereas CAPL represents the actual condition. The comparison between these two values forms the basis for calculating the Infrastructure Leakage Index (ILI). The smaller the difference between CAPL and MAAPL, the better the network performance. Conversely, if CAPL is significantly higher than MAAPL, it indicates a substantial opportunity for technical and operational improvements.

A. Pipeline Network Data

Perumda Air Minum Tirta Lestari operates an extensive pipeline infrastructure that includes transmission, distribution, and service pipelines. The total length of transmission and distribution pipelines is recorded at 114.212 kilometers, comprising 30.289 kilometers of transmission lines and 83.923 kilometers of distribution lines. In addition, the utility maintains 83,863 service connections that link the distribution network directly to customers.

The availability of this infrastructure demonstrates the system's capacity to deliver piped water services across the Tuban region in a relatively uniform manner. Both the total pipeline length and the number of service connections are critical technical parameters used in analytical assessments, particularly in the calculation of the Minimum Achievable Annual Physical Losses (MAAPL) and the Infrastructure Leakage Index (ILI). Detailed information regarding the pipeline network of Perumda Air Minum Tirta Lestari is presented in Table 7.

Table 7. Pipeline Network of Perumda Air Minum Tirta Lestari, Tuban Area

No.	Description	Length (km)	Description	Length (km)
1	Transmission Pipes	30.289	Services Pipes	83,863
2	Distribution Pipes	83.923		
	Total	114.212	Total	83,863

B. Pressure Data

The availability of this infrastructure demonstrates the system's capacity to deliver piped water services across the Tuban region in a relatively uniform manner. Both the total pipeline length and the number of service connections are critical technical parameters used in analytical assessments, particularly in the calculation of the Minimum Achievable Annual Physical Losses (MAAPL) and the Infrastructure Leakage Index (ILI). Detailed information regarding the pipeline.

Table 8. Pressure Data of Perumda Air Minum Tirta Lestari, Tuban Area

No.	Area	Number of Connections	Average Pressure (m)
1	Wil 1,01 - 1,15	4,362	8.056
2	Wil 1,16 - 2,05	835	11.1152
3	Wil 2,06 - 3,03	925	4.8948
4	Wil 3,04 - 4,14	5,100	12.6448
5	Wil 4,15 - 5,06	3,671	13.4606
6	Wi~~l 5,07 - 6,02~~	~~701~~	10.1337
	Total	15,594	10.89875723

C. Calculating MAAPL (Minimum Achievable Annual Physical Losses)

The MAAPL is calculated using the following formula (L/day):

$$MAAPL\ (L/day) = [18 \times Lm + (0{,}8 \times Nc + 25 \times Lp) \times P]$$

Where:

Lm = length of mains (km)

Nc = number of customer connections (units) Lp = length of service pipes (km)

P = average network pressure (m)

Thus,

$$MAAPL\ (L/day) = [18 \times Lm + (0{,}8 \times Nc + 25 \times Lp) \times P]$$

$$= [18 \times 114{,}212 + (0{,}8 \times 15.594 + 25 \times 83{,}863) \times 10{,}898$$

$$= 160.870\ l/day$$

D. Calculating CAPL (Currenyt Annual Volume of Physical Looses)

CAPL (m^3/year) = Physical Water Loss

= 774.145 m^3/year

E. Calculating ILI (Infrastructure Leakage Index)

The ILI is calculated by comparing the CAPL and MAAPL values:

ILI = $CAPL/MAPL$

= 774.145 / 58.717,55

= 13,1842

The calculation results show that the Minimum Achievable Annual Physical Losses (MAAPL) of the Perumda Air Minum Tirta Lestari Tuban network is 58,717.55 m^3/year, while the Current Annual Physical Losses (CAPL) are 774,145 m^3/year. The comparison yields an Infrastructure Leakage Index (ILI) of 13.18, indicating that the level of physical losses remains high. Similar high values are also reported in other developing countries, highlighting the urgent need for advanced leakage management (Liemberger & Wyatt, 2019).

Technical Performance category		ILI	Physical Losses[litres/connection/day] (When the system is pressured) at an average of				
			10m	20m	30m	40m	50m
Developed countries	A	1-2		<50	<75	<100	<125
	B	2-4		50-100	75-150	100-200	125-250
	C	4-8		100-200	150-300	200-400	250-500
	D	>8		>200	>300	>400	>500
Developing countries	A	1-2	<50	<100	<150	<200	<250
	B	2-4	50-100	100-200	150-300	200-400	250-500
	C	4-8	100-200	200-400	300-600	400-800	500-1000
	D	>8	>200	>400	>600	>800	>1000

Figure 2. Matrix of Physical Water Loss Calculation
Source: (Harahap et al., 2023)

Category Description:

- Category A – Water loss is minimal and highly efficient. Further reduction is not cost-effective unless under special conditions such as limited water resources or conservation policies. Any intervention should be preceded by a cost-benefit analysis.
- Category B – Water loss is moderate and can be reduced through measures like pressure control, active leakage detection, and improved pipeline maintenance. These actions typically yield positive results with reasonable investment.
- Category C – Water loss is high but may be tolerated if water resources are abundant and tariffs are low. However, it poses risks to service sustainability. Detailed analysis and targeted interventions, such as pipe replacement and enhanced monitoring, are needed.
- Category D – Water loss is excessive and reflects severe inefficiency. It negatively impacts economic, technical, and environmental aspects. Immediate and comprehensive action is required, including infrastructure upgrades, advanced leak detection, better operational management, and public engagement.

The comparison between the Current Annual Physical Losses (CAPL) and the Minimum Achievable Annual Physical Losses (MAAPL) yields an Infrastructure Leakage Index (ILI) of 13.18. Referring to the physical water loss calculation matrix and considering the average system pressure of 10.90 meters (see Figure 2), this ILI value places Perumda Air Minum Tirta Lestari within Category D for developing countries, which corresponds to ILI values greater than 8 and physical losses exceeding 200 liters per connection per day.

To reduce water losses and improve system performance, the following strategic measures are recommended

1. Pressure management, particularly in zones where pressure exceeds 12 meters, to minimize stress on the pipeline infrastructure.
2. Active leakage detection, utilizing advanced monitoring technologies for early identification and response.
3. Rehabilitation of aging or frequently leaking pipelines, to enhance structural reliability and reduce recurring losses.
4. Improvement of data recording and maintenance systems, ensuring

accurate monitoring and timely corrective actions.

Implementing these measures is expected to lower the ILI value toward Category B (ILI 2–4) or ideally Category A (ILI 1–2), thereby enhancing operational efficiency and supporting the long-term sustainability of water supply services in Tuban Regency.

Losses Due to Water Leakage

Water loss experienced by water supply companies is one of the main factors affecting operational efficiency and financial sustainability. In the context of the Tuban Regional Water Utility (PDAM), water losses not only reduce the effective distribution volume but also directly impact potential revenue and increase production costs. Therefore, calculating the financial losses due to water loss is essential to provide a clear picture of the magnitude of its impact.

Based on an average water selling tariff of IDR 3,488 per m^3 and an average production/distribution cost of IDR 1,200 per m^3, the total losses experienced by PDAM Tuban can be estimated. Non-physical water losses, arising from customer meter inaccuracies and illegal connections, result in lost potential revenue for the company, with losses estimated at approximately IDR 935,237,440 per year. Meanwhile, physical water losses due to leakage in the distribution network lead to increased production and distribution costs, with losses around IDR 997,969,200 per year.

Overall, the total losses incurred by PDAM Tuban due to water loss can reach IDR 1,933,206,640 per year. This figure indicates that both physical and non-physical water losses have a significant impact on the company's performance. Therefore, controlling water losses should be a top priority, through improvements in customer metering and monitoring systems as well as infrastructure rehabilitation to reduce leakage rates. These strategic measures are expected not only to reduce financial losses but also to enhance the effectiveness of clean water service delivery to the community.

Institutional Structure and Human Resource Management

Perumda Air Minum Tirta Lestari in Tuban City is a water supply institution fully responsible for the management, distribution, and sustainability of water services. Currently, the utility employs 100 staff members to serve 15,594 household connections (HC). The staff-to-customer ratio reaches 6 employees per 1,000 HCs, in accordance with BPPSPAM standards (6–8 employees per 1,000 HCs), indicating that the institutional performance can be categorized as efficient. Nevertheless, the distribution of workload across divisions still requires attention to ensure balanced service delivery.

Regarding human resource development, approximately 22% of staff have participated in training programs, which is considered good as it exceeds the minimum standard of 20%. However, training opportunities are not yet evenly distributed, so efforts are needed to ensure that all employees possess balanced competencies, particularly in technical areas such as Non-Revenue Water (NRW) management, distribution management, customer service, and the utilization of information technology. Workload analysis is also important, referring to Ministry of State Apparatus and Bureaucratic Reform Regulation (Permen PAN-RB) No. 1 of 2020, given that the Technical Division covers a wide scope ranging from production, transmission, distribution, to monitoring.

NRW control is still integrated within the core functions of the Production, Transmission, and Distribution sections, without a dedicated team. Tasks include leak detection, customer meter inspection, complaint handling, and distribution recording. However, the limited training and the absence of District Meter Area (DMA) implementation make NRW control conventional and less than optimal. Therefore, institutional strengthening through equitable training, enhanced technical capacity, and improved workload management is essential to ensure the effectiveness of distribution management and the sustainability of water services.

Active Leakage Control Program

Until now, leakage control efforts at Perumda Air Minum Tirta Lestari Tuban, as well as in most regional water utilities (PDAMs) in Indonesia, have tended to be reactive. Repairs are usually carried out only after reports from customers or findings from field staff. This approach is suboptimal because the risk of water loss remains high and recurring losses continue. Therefore, a proactive, planned, and continuous leakage control strategy is required. Similar studies in Mediterranean countries demonstrate that active leakage control provides measurable reductions in NRW (Rizzo & Cilia, 2022).

Active leakage control involves the integration of all technical and non-technical resources to systematically detect, record, analyze, and repair leaks. Although results are not immediate, this approach has been proven to be more effective in reducing physical water losses.

In general, active leakage control can be carried out through three stages:

1. Visible Leakage Control: This stage focuses on repairing leaks that can be directly observed, such as burst pipes, leaking joints, or surface water overflow. The method is simple and relatively inexpensive but requires rapid response procedures and good team coordination. Information is obtained from customer reports, meter readings, and routine inspections. Field response speed is a key factor in success.
2. Invisible Leakage Control: Leaks that are underground or not directly visible require special technology, such as acoustic leak detectors or flow tests (step tests). This stage is conducted routinely to accurately map leak locations so that repairs are more targeted and effective.
3. Comprehensive Leakage Control through District Metered Areas (DMA): The advanced stage involves dividing the distribution network into smaller zones (DMAs) with master meters at strategic points. Each meter records the volume of water entering a specific zone, allowing more detailed monitoring of water losses, even on a daily basis. Analysis of

minimum night flows (00:00–04:00) can indicate new leaks. DMA systems have been proven effective in detecting and controlling leaks continuously.

Although DMA implementation requires an initial investment for meters and monitoring systems, the long-term benefits are significant. In addition to reducing physical losses, the system supports operational efficiency, network rehabilitation planning, and future infrastructure investments. Consistent implementation of active leakage control is expected to reduce the Infrastructure Leakage Index (ILI) to a better category (B or even A). Positive impacts include improved technical efficiency, service sustainability, resource conservation, and increased public confidence in the quality of drinking water.

CONCLUSIONS AND RECOMMENDATIONS

Based on the water balance analysis, Perumda Air Minum Tirta Lestari in Tuban Regency experienced a water loss of 984,739 m^3/year or approximately 22.8% of the total system input during the period of January–July 2025. This value still exceeds the national efficiency benchmark of 20%. The largest component of the loss comes from physical losses, accounting for 78.6% of the total, while the remainder consists of commercial losses resulting from unauthorized consumption, meter inaccuracies, and administrative errors.

The calculation of the Infrastructure Leakage Index (ILI) shows a value of 13.18, placing the network condition in category D for developing countries. This indicates a high level of physical leakage and inefficient management of the distribution network. In addition, water losses have a significant financial impact, estimated at approximately IDR 1.93 billion per year, comprising losses from both physical and commercial sources.

From an institutional perspective, the employee-to- customer ratio meets BPPSPAM standards; however, water loss control is still conducted reactively, without a dedicated team or the implementation of District Metered Areas (DMA). These limitations result in suboptimal leak detection and reduce the effectiveness of NRW control.

To improve efficiency and service sustainability, a more active and continuous leakage control strategy is required. International best practices emphasize pressure management, DMA implementation, and technical capacity development (Thornton et al., 2020). Measures that can be implemented include pressure management in high-pressure zones, active leak detection using supporting technologies, rehabilitation of old pipeline networks, strengthening of data recording systems, and enhancement of human resource capacity through technical training. With consistent implementation of these measures, the ILI value is expected to decrease to category B or even A, thereby improving operational efficiency, reducing financial losses, and ensuring the sustainability of drinking water services in Tuban Regency.

ADVANCED RESEARCH

Each study has limitations; thus, you can describe it here and briefly provide suggestions for further research.

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