

## Determining Dominant Causes of Non-Revenue Water Using AHP and Priority-Based Control Strategies

Rudolf Simatupang<sup>1\*</sup>, Haiqal Alief Djibran<sup>2</sup>, Eko Adityawan Tumenggung Zees<sup>3</sup>,  
Jamal Darussalam Giu<sup>4</sup>  
Universitas Negeri Gorontalo

**Corresponding Author:** Rudolf Simatupang, [rudolfsimatupang@ung.ac.id](mailto:rudolfsimatupang@ung.ac.id)

---

### ARTICLE INFO

*Keywords:* Non-Revenue Water, Analytical Hierarchy Process, Network Leakage, District Meter Area, Priority-Based Control

*Received :* 28, April

*Revised :* 25, May

*Accepted:* 26, June

©2026 Simatupang, Djibran, Zees, Giu:  
This is an open-access article distributed under the terms of the [Creative Commons Atribusi 4.0 Internasional](https://creativecommons.org/licenses/by/4.0/).



### ABSTRACT

Non-Revenue Water (NRW) is a systemic challenge for Indonesian water utilities. This study aims to identify dominant NRW causal factors and formulate priority-based control strategies using the Analytical Hierarchy Process (AHP) at PERUMDA City X. Data were collected through 42 working days of field observation and single-expert assessment using Saaty's pairwise comparison scale. Four main factors and twelve sub-factors were analyzed. Results show that technical factors were dominant, followed by administrative, operational, and unbilled authorized consumption factors. Network leakage, illegal connections, and pipe age/corrosion contributed 70.71% of total causal priorities. The proposed strategies include DMA implementation, phased pipe replacement, illegal connection legalization, and meter calibration to support integrated NRW reduction.

---

## **INTRODUCTION**

Access to clean water is a fundamental requirement for public health, urban resilience, and sustainable development. In Indonesia, the provision of drinking water services is institutionally supported by regional water utilities, including PERUMDA, which are responsible for ensuring quality, quantity, continuity, and affordability of water supply. However, many utilities still face persistent inefficiencies in distribution systems, particularly through Non-Revenue Water (NRW). NRW refers to water that has been produced and distributed but does not generate revenue because of physical losses, commercial losses, or unbilled authorized consumption. This condition weakens utility performance because it reduces income, increases operational costs, and limits the capacity to expand services.

At the global level, NRW has become an important indicator of water utility efficiency and infrastructure sustainability. WHO and UNICEF (2025) emphasize that safely managed drinking water remains unevenly distributed, making water-loss reduction increasingly important for achieving SDG 6. Santos (2024) explains that NRW affects not only technical performance but also the economic sustainability of water utilities. In developing countries, high NRW is commonly associated with aging pipes, inaccurate metering, weak monitoring systems, and unauthorized consumption. Therefore, reducing NRW is not only a technical agenda but also a strategic requirement for improving financial resilience and service reliability.

The Indonesian water sector faces a similar challenge, as NRW in many PDAM and PERUMDA systems remains above the expected performance threshold. Luthfianto et al. (2025) reported that the average NRW level of Indonesian water utilities reached 33.72% in 2021, exceeding the RPJMN 2020–2024 target of 30%. In the case of PERUMDA City X, internal operational data showed an average NRW of 34.16% in 2025, with a wide inter-installation disparity ranging from 15.53% to 59.51%. This variation indicates that NRW is not caused by a single uniform factor, but by different technical, administrative, and operational conditions across service zones. Such a condition requires a systematic prioritization approach before control strategies can be designed and implemented effectively.

Previous studies have examined NRW from different perspectives, including water balance analysis, leakage control, pipe deterioration, and district-based monitoring. Zafira and Nurhayati (2023) highlighted the relevance of District Meter Area and SCADA-based monitoring for improving NRW control. Nanda et al. (2024) showed that factor prioritization is useful for identifying the most influential causes of NRW in regional water utilities. Shell et al. (2025) found that physical losses remain a major contributor to water loss in Indonesian distribution systems. However, these studies have not fully integrated dominant-factor weighting, causal interpretation, and priority-based control strategies within one structured decision-making framework.

This research gap shows the need for a method that can transform expert judgment into measurable and consistent priorities. The Analytical Hierarchy Process (AHP) is relevant because it allows complex decision problems to be

divided into hierarchical levels of goals, criteria, and sub-criteria. Rozali et al. (2023) note that AHP is useful for ranking decision alternatives through pairwise comparison and consistency testing. In the context of NRW, this method can help utilities determine whether technical, administrative, operational, or unbilled authorized consumption factors should receive greater attention. By applying AHP, decision-making becomes more transparent, structured, and aligned with actual field conditions.

Therefore, this study aims to identify and weight the dominant causal factors of NRW at PERUMDA City X using the Analytical Hierarchy Process. The study also seeks to analyze the relationship among priority factors so that the causes of NRW can be understood as an interconnected system rather than isolated problems. Furthermore, this research formulates priority-based NRW control strategies supported by simulation projections of potential reduction impacts. The contribution of this study lies in combining AHP-based prioritization with practical intervention planning for regional water utilities. The findings are expected to support more targeted, efficient, and evidence-based NRW reduction programs.

## LITERATURE REVIEW

### *Non-Revenue Water and Water Utility Performance*

Non-Revenue Water is a critical indicator of the technical, financial, and managerial performance of water utilities. It represents treated water that enters the distribution system but does not generate revenue because of physical leakage, apparent losses, or unbilled authorized consumption. Recent studies show that high Non-Revenue Water reduces utility income, increases operational expenditure, and weakens the capacity of water companies to reinvest in infrastructure. Naradipta and Slamet (2024) found that Non-Revenue Water in PERUMDA Delta Tirta Sidoarjo reached 31.67% in 2023 and caused substantial annual revenue losses. This finding confirms that Non-Revenue Water should be treated not only as a technical problem, but also as a strategic issue affecting institutional sustainability.

H1: Non-Revenue Water is influenced by technical, administrative, operational, and unbilled authorized consumption factors in regional water utilities.

### *Technical Loss Theory*

Technical losses are generally associated with physical water losses caused by pipe leakage, pipe bursts, corrosion, unstable pressure, and aging infrastructure. In water distribution networks, deteriorated pipes tend to increase leakage frequency because structural weakness reduces pipe resistance to internal and external pressure. Wibowo and Slamet (2024) explain that pressure management is essential in controlling physical leakage because higher pipe pressure can increase the amount of water lost through existing leaks. Spedaletti et al. (2022) also demonstrated that monitoring water flow through the District Metered Area approach can help identify water losses more accurately and support energy efficiency. Therefore, technical factors are theoretically expected to become the most dominant causes of Non-Revenue Water when distribution infrastructure is old, poorly monitored, or hydraulically unstable.

H2: Technical factors have the highest priority weight among the main causes of Non-Revenue Water.

### ***Administrative Loss and Apparent Loss Theory***

Administrative losses are closely related to apparent losses, which occur when water is consumed but not accurately recorded or billed. These losses may arise from illegal connections, customer meter inaccuracies, incorrect meter reading, weak billing systems, or incomplete customer databases. Prastiwi, Masduqi, and Sundoro (2024) found that passive Standard Operating Procedure implementation may limit the effectiveness of Non-Revenue Water control because corrective actions are often taken only after public complaints are received. Netshitanini et al. (2023) further showed that meter under-registration can create significant onsite water losses because actual consumption is higher than recorded consumption. In this study context, illegal connections and damaged meters are therefore expected to be important contributors to Non-Revenue Water because they directly reduce billable water volume.

H3: Administrative factors, particularly illegal connections and meter problems, significantly contribute to apparent losses in Non-Revenue Water.

### ***Operational Control and District Metered Area Theory***

Operational control determines how quickly water utilities detect, localize, and respond to losses within the distribution network. District Metered Area is widely recognized as a practical operational approach because it divides a distribution system into smaller zones that can be monitored through inlet flow measurement, pressure analysis, and minimum night flow evaluation. Mahardini and Tangahu (2023) reported that water loss in District Metered Area Kalipuro 5 decreased after applying monitoring, pressure management, repair, and active leakage control. Puspa et al. (2025) also emphasized that District Metered Area optimization requires hydraulic modeling, logger installation, Supervisory Control and Data Acquisition integration, asset security, and updated geographic information system data. These studies support the argument that the absence of District Metered Area can delay leakage detection and make Non-Revenue Water control less efficient.

H4: The absence of District Metered Area weakens operational control and increases the difficulty of reducing Non-Revenue Water.

### ***Analytical Hierarchy Process Theory***

The Analytical Hierarchy Process is a multi-criteria decision-making method used to structure complex problems into goals, criteria, and sub-criteria. This method is appropriate for infrastructure management because it converts expert judgment into measurable priority weights through pairwise comparisons. Macchiaroli et al. (2023) applied the Analytical Hierarchy Process to rank water infrastructure investments based on sustainable intervention priorities. Their study confirms that the method can support transparent decision-making when utilities must choose among several competing technical and managerial needs. In Non-Revenue Water management, the Analytical

Hierarchy Process is useful because it helps determine which causal factors should be addressed first under limited resources.

H5: The Analytical Hierarchy Process provides a consistent decision-making framework for ranking dominant Non-Revenue Water causal factors.

### *Priority-Based Decision Framework for Integrated NRW Control*

The importance of this study lies in its effort to connect factor identification, priority weighting, and control strategy formulation into one integrated decision framework. Many previous studies have focused on water balance, Infrastructure Leakage Index, pressure management, or District Metered Area evaluation, but fewer studies have combined these technical insights with structured priority analysis. Fathani et al. (2025) showed that water balance and performance indicators are useful for formulating Non-Revenue Water reduction strategies, but such approaches still require prioritization when several causes appear simultaneously. Vaquet et al. (2024) argued that leakage detection in water distribution networks is complex because leakage behavior is dynamic and difficult to identify, especially for small leaks. Therefore, an Analytical Hierarchy Process-based framework is important because it helps water utilities transform complex field problems into ranked priorities and practical intervention strategies.

H6: Priority-based control strategies derived from Analytical Hierarchy Process results can support more targeted and integrated Non-Revenue Water reduction.

To visualize the relationships among the identified causal factors of Non-Revenue Water (NRW) and the proposed priority-based interventions, a conceptual framework was developed. The framework integrates the four main factors—Operational, Technical, Administrative, and Unbilled Authorized Consumption—into a structured model using the Analytical Hierarchy Process (AHP) methodology. Each factor, along with its respective sub-factors, influences the overall NRW level as observed in PERUMDA City X. The framework also depicts how AHP transforms expert judgments into quantitative priority weights, highlighting dominant factors such as Network Leakage, Illegal Connections, and Pipe Age/Corrosion. Finally, the model connects the weighted factors to targeted control strategies, illustrating the expected impact on NRW reduction.

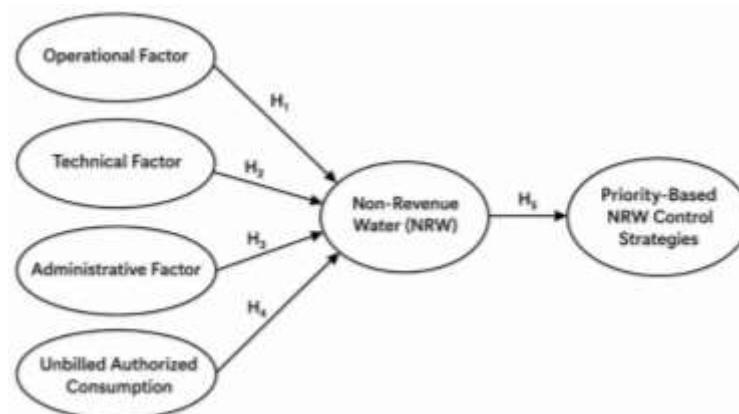


Figure 1. Conceptual Framework

## **METHODOLOGY**

### ***Research Design and Location***

This study employed a quantitative descriptive approach to identify and prioritize the dominant factors contributing to Non-Revenue Water (NRW) at PERUMDA City X. The design was selected because the study aimed to transform expert judgment and field-based findings into measurable priority weights using the Analytical Hierarchy Process (AHP). Primary data were collected through field observations conducted over 42 working days across seven Water Treatment Plants from January 19 to March 20, 2026. In addition, in-depth interviews and AHP questionnaires were administered to the Technical and Development Manager, who was selected as the key expert due to institutional authority, technical competence, and direct responsibility for distribution network management. Secondary data were obtained from the official 2025 NRW report, operational data from each installation, and infrastructure profile documents of PERUMDA City X.

### ***Population, Sample, and Sampling Technique***

The population of this study consisted of the water distribution system, operational units, and managerial decision-makers involved in NRW control at PERUMDA City X. The observed technical population included seven Water Treatment Plants representing different service zones and NRW characteristics. The respondent sample consisted of one key expert selected using purposive sampling, a non-probability sampling technique commonly applied when the research requires specialized knowledge and decision-making authority. This sampling technique was considered appropriate because AHP relies on informed expert judgment rather than large respondent numbers. The selected expert represented the managerial and technical perspective needed to assess pairwise comparisons among NRW causal factors.

### ***Data Collection Techniques and Instruments***

Data were collected using field observation, semi-structured interviews, AHP questionnaires, and documentation review. Field observation was used to identify operational conditions, distribution network characteristics, and service-zone differences across the seven installations. Semi-structured interviews were conducted to validate the relevance of the identified factors and sub-factors. The AHP questionnaire was designed using Saaty's pairwise comparison scale, ranging from equal importance to extreme importance, to compare main factors and sub-factors systematically. Documentation review was conducted using the 2025 NRW report, installation operational records, and infrastructure profile documents to support and triangulate the primary data.

### ***Identification of Factors and Sub-Factors***

The causal factors of NRW were identified through triangulation of literature review, field observation, and expert judgment. The literature review was based on the water balance concept, NRW component classification, and recent studies on leakage control, pressure management, metering accuracy, and District Metered Area implementation. The final framework consisted of four main factors and twelve sub-factors, as shown in Table 1. The four main factors

were Operational, Technical, Administrative, and Unbilled Authorized Consumption. Each factor consisted of three sub-factors that represented the most relevant NRW causes in the study context.

Table 1. Main Factors and Sub-Factors of Non-Revenue Water

Code	Main Factor	Sub-Factors
A	Operational	A1: Inadequate network monitoring; A2: Absence of District Metered Area; A3: Insufficient maintenance
B	Technical	B1: Unstable water pressure; B2: Network leakage; B3: Pipe age/corrosion
C	Administrative	C1: Illegal connections; C2: Meter reading errors; C3: Damaged water meters
D	Unbilled Authorized Consumption	D1: Operational requirements; D2: Public facilities; D3: Network flushing

### *Research Procedure*

The research was carried out in several sequential stages. First, preliminary identification was conducted by reviewing NRW literature, official utility documents, and operational data from PERUMDA City X. Second, field observations were conducted for 42 working days to understand the actual conditions of the seven Water Treatment Plants and their distribution networks. Third, the main factors and sub-factors were validated through expert interviews and then structured into an AHP hierarchy. Fourth, pairwise comparison data were collected using the AHP questionnaire and processed to obtain local and global priority weights. Finally, the priority results were interpreted to formulate control strategies and simulate the potential reduction of NRW under integrated implementation.

### *Validity, Reliability, and Consistency Testing*

Instrument validity was ensured through content validation by aligning questionnaire items with NRW theory, water balance components, field observations, and expert confirmation. The reliability of the AHP judgment was assessed using the Consistency Ratio (CR), which measures the logical consistency of pairwise comparison responses. A pairwise comparison matrix was considered acceptable when the CR value was equal to or below 0.10. If the CR value exceeded 0.10, the comparison matrix would be reviewed and revised to improve judgment consistency. This consistency test ensured that the resulting priority weights were logically reliable and suitable for decision-making.

### *Data Analysis Technique*

The data analysis was conducted using the Analytical Hierarchy Process. The analysis followed nine stages: developing a three-level hierarchy, constructing pairwise comparison matrices, normalizing each matrix, calculating eigenvectors, computing the maximum eigenvalue, calculating the Consistency Index, calculating the Consistency Ratio, validating consistency based on the CR

threshold, and calculating global weights by multiplying the main factor weights with local sub-factor weights. Microsoft Excel was used to organize field data, perform matrix calculations, and present the ranking results. The final priority weights were used to identify dominant NRW causal factors and to formulate priority-based control strategies. The projected NRW reduction was estimated by combining the global weight of each targeted sub-factor with intervention effectiveness values derived from comparable empirical studies.

***Simulation of Projected NRW Reduction***

The simulation was conducted to estimate the potential reduction of NRW after implementing the proposed control strategies. The projection was calculated based on two components: the proportion of each target sub-factor’s global weight and the typical effectiveness range of similar interventions reported in previous studies. The simulation focused on percentage-point reduction rather than monetary investment value. This approach was selected because the study aimed to provide a strategic estimate of intervention impact before detailed financial planning. The projected results were then used to support the formulation of priority-based NRW control strategies for PERUMDA City X.

**RESEARCH RESULTS**

***NRW Profile at PERUMDA City X***

The official Non-Revenue Water (NRW) data for PERUMDA City X in 2025 are presented in Table 2. The data show that the average NRW level reached 34.16%, indicating that more than one-third of distributed water did not generate revenue. The highest NRW was recorded at Bulotadaa I with 59.51%, while the lowest was found at Duingingi with 15.53%. This wide range confirms that NRW conditions differed substantially among installations. These findings support H1, which states that NRW is influenced by a combination of operational, technical, administrative, and unbilled authorized consumption factors across service zones.

Table 2. NRW Data for PERUMDA City X, 2025

	<b>No Installation (WTP) Flow (L/s)</b>	<b>Population Served</b>	<b>NRW (%)</b>
1	Kabila Tanggilingo 320	51,440	33.23
2	Botu I (2×20 Lps) 50	9,744	20.09
3	Botu II (150 Lps) 160	14,264	44.37
4	Bulotadaa I 25	9,500	59.51 *
5	Bulotadaa II 60	17,096	45.70
6	Pilolodaa 15	5,648	20.68
7	Duingingi 25	14,368	15.53 *
	<b>Average 655</b>	<b>122,060</b>	<b>34.16</b>

\*Highest and lowest NRW values.

The numerical pattern in Table 2 indicates that NRW is not evenly distributed across the service system. Bulotadaa I, with 59.51% NRW, represents

the most critical zone and requires immediate technical and administrative intervention. Duingingi, with 15.53% NRW, shows that lower NRW levels are achievable within the same utility system when infrastructure and operational conditions are more favorable. The difference between the highest and lowest values suggests that localized causes, rather than a single general cause, explain NRW variation. Therefore, H1 is accepted because the results demonstrate that multiple causal dimensions affect NRW differently across installations.

**Priority Weighting of Main Factors**

The main factor weighting using the Analytical Hierarchy Process (AHP) is presented in Table 3. The Technical Factor obtained the highest priority weight of 0.558, making it the most dominant factor in NRW causation. The Administrative Factor ranked second with a weight of 0.263, followed by the Operational Factor with 0.122. Unbilled Authorized Consumption ranked lowest with a weight of 0.057. The Consistency Ratio of 0.0654 is below the acceptable threshold of 0.10, indicating that the expert judgment was consistent and reliable.

Table 3. Main Factor Priority Weights (CR = 0.0654)

Factor	A (Operational)	B (Technical)	C (Administrative)	D (Unbilled Authorized Consumption)	Weight	Rank
A (Operational)	1	1/5	1/3	3	0.122	3
B (Technical)	5	1	3	7	0.558	1
C (Administrative)	3	1/3	1	5	0.263	2
D (Unbilled Authorized Consumption)	1/3	1/7	1/5	1	0.057	4

$\lambda_{max} = 4.180$ ; CI = 0.0589; RI = 0.90; CR = 0.0654.

The values in Table 3 show that technical problems contribute more than half of the total priority weight. This result confirms H2, which states that technical factors have the highest priority weight among the main causes of NRW. The relatively high administrative weight of 0.263 also supports H3, because illegal connections, meter problems, and recording errors remain relevant sources of apparent losses. The operational factor, although ranked third, still has strategic importance because network monitoring and District Metered Area implementation influence the speed of leakage detection. The low weight of Unbilled Authorized Consumption indicates that this factor exists but is not the primary driver of NRW in PERUMDA City X.

**Local Weighting of Sub-Factors**

Table 4 presents the local weights of sub-factors within each main factor group. Within the Operational Factor, the absence of District Metered Area obtained the highest local weight of 0.633. Within the Technical Factor, network leakage ranked highest with a local weight of 0.643. Within the Administrative Factor, illegal connections became the dominant sub-factor with a local weight of

0.724. Within Unbilled Authorized Consumption, public facilities obtained the highest local weight of 0.633.

Table 4. Local Weights of Sub-Factors

Factor Group	Code	Sub-Factor	Local Weight	CR
Operational (0.122)	A1	Inadequate network monitoring	0.260	0.0477
	A2	Absence of District Metered Area *	0.633	
	A3	Insufficient maintenance	0.106	
Technical (0.558)	B1	Unstable water pressure	0.074	0.0834
	B2	Network leakage *	0.643	
	B3	Pipe age/corrosion	0.283	
Administrative (0.263)	C1	Illegal connections *	0.724	0.0961
	C2	Meter reading errors	0.083	
	C3	Damaged water meters	0.193	
Unbilled Authorized Consumption (0.057)	D1	Operational requirements	0.106	0.0477
	D2	Public facilities *	0.633	
	D3	Network flushing	0.260	

\*Highest local priority within each factor group.

The local weight results show the most urgent sub-factor within each category. The absence of District Metered Area supports H4 because it weakens operational control and makes leakage localization more difficult. Network leakage strongly supports H2 because it represents the most important technical sub-factor contributing to real losses. Illegal connections support H3 because they directly reduce billable consumption and increase apparent losses. All Consistency Ratio values are below 0.10, indicating that the pairwise comparison results for each sub-factor group are acceptable for further interpretation.

**Global Weighting and Ranking of NRW Sub-Factors**

The global ranking of all twelve sub-factors is presented in Table 5. Global weight was calculated by multiplying the main factor weight by the local weight of each sub-factor. The highest global weight was obtained by network leakage with 35.88%. Illegal connections ranked second with 19.04%, while pipe age/corrosion ranked third with 15.79%. Together, these three sub-factors contributed 70.71% of total NRW causal priorities.

Table 5. Global Weight and Ranking of NRW Sub-Factors

Rank	Code	Sub-Factor	Main Factor Weight	Local Weight	Global Weight (%)
1	B2	Network leakage *	0.558	0.643	35.88
2	C1	Illegal connections *	0.263	0.724	19.04
3	B3	Pipe age/corrosion	0.558	0.283	15.79

Rank	Code	Sub-Factor	Main Factor Weight	Local Weight	Global Weight (%)
4	A2	Absence of District Metered Area	0.122	0.633	7.72
5	C3	Damaged water meters	0.263	0.193	5.08
6	B1	Unstable water pressure	0.558	0.074	4.13
7	D2	Public facilities *	0.057	0.633	3.61
8	A1	Inadequate network monitoring	0.122	0.260	3.17
9	C2	Meter reading errors	0.263	0.083	2.18
10	D3	Network flushing	0.057	0.260	1.48
11	A3	Insufficient maintenance	0.122	0.106	1.29
12	D1	Operational requirements	0.057	0.106	0.60
<b>Total</b>					<b>100.00</b>

\*Highest priority sub-factors within selected factor groups.

The values in Table 5 provide the strongest evidence for determining intervention priorities. Network leakage alone accounts for 35.88%, making it the most critical sub-factor and confirming H2. Illegal connections account for 19.04%, confirming H3 that administrative losses have a substantial role in NRW. Pipe age/corrosion contributes 15.79%, showing that infrastructure deterioration reinforces technical losses. Since the top three sub-factors contribute 70.71%, H6 is accepted because priority-based control strategies should focus first on the most dominant causes rather than treating all factors equally.

#### *Causal Relationship Among Dominant Factors*

The ranking results indicate that the dominant causes of NRW form an interconnected causal pattern. Pipe age/corrosion weakens the physical condition of the distribution network and increases the probability of leakage. Network leakage then reduces pressure stability and may create additional hydraulic stress within the system. Illegal connections intensify this condition because unmeasured consumption can disturb pressure balance and increase water losses in affected zones. This causal interaction supports H6, which states that priority-based control strategies are needed because NRW is driven by interrelated factors rather than isolated causes.

The absence of District Metered Area also plays an important role in the causal structure. Without District Metered Area zoning, leakage cannot be localized quickly and accurately. This condition causes leakage duration to become longer and increases the volume of water lost before repair actions are taken. The same limitation also affects the detection of illegal connections because utilities lack reliable zone-level monitoring. Therefore, H4 is also supported because the absence of District Metered Area weakens operational control and reduces the effectiveness of NRW management.

**Priority-Based NRW Control Strategies**

The recommended priority-based NRW control strategies are presented in Table 6. The strategies were developed based on the global ranking of the most influential sub-factors. Network leakage became the first priority because it had the highest global weight. Illegal connections became the second priority because they represented the largest administrative loss component. Pipe age/corrosion, the absence of District Metered Area, and damaged water meters were also included because they significantly affect NRW reduction effectiveness.

Table 6. Priority-Based NRW Control Strategies

Rank	Sub-Factor (Global Weight)	Implementation Horizon	Strategic Program
1	Network leakage (35.88%) *	Short-Medium term	Establishment of a rapid response team; procurement of acoustic leak detectors; phased District Metered Area implementation starting from high-NRW zones; Pressure Reducing Valve installation in high-pressure zones; night-flow-based leakage audit
2	Illegal connections (19.04%) *	Short term	Quarterly inspections in high-risk zones; legalization program for illegal connections; installation of zonal master meters; regulatory enforcement; public education on the impact of illegal connections
3	Pipe age/corrosion (15.79%)	Medium-Long term	Development of a Geographic Information System-based pipe age and material database; phased pipe replacement based on risk scoring; use of High-Density Polyethylene or unplasticized Polyvinyl Chloride replacement pipes; trenchless rehabilitation for main pipelines
4	Absence of District Metered Area (7.72%)	Medium term	District Metered Area zoning design; inlet flow meter installation in each zone; integration of Supervisory Control and Data Acquisition or Internet of Things monitoring; staff training for minimum night flow analysis
5	Damaged water meters (5.08%)	Short term	Audit of meters older than five years; periodic calibration; replacement using Automatic Meter Reading meters; establishment of a maximum meter service-life policy

\*Highest strategic priorities based on global weight ranking.

Table 6 shows that the proposed strategies directly follow the AHP priority ranking. The first strategy focuses on network leakage because this sub-factor has the greatest potential to reduce NRW. The second strategy addresses illegal connections because the analysis shows that apparent losses are highly relevant in PERUMDA City X. The third and fourth strategies strengthen long-

term system reliability through pipe replacement and District Metered Area development. These findings support H5 and H6 because AHP results provide a consistent and practical basis for designing targeted NRW control strategies.

***Simulated NRW Reduction Projection***

The projected reduction of NRW after implementing the proposed strategies is presented in Table 7. The simulation was based on the global weight of each target sub-factor and the estimated effectiveness of similar interventions. District Metered Area implementation combined with active leakage detection produced the largest projected reduction, ranging from 6.1 to 7.8 percentage points. Illegal connection enforcement and legalization were projected to reduce NRW by 2.6 to 3.8 percentage points. Phased pipe replacement was projected to reduce NRW by 2.7 to 3.7 percentage points.

Table 7. Projected NRW Reduction per Program

<b>Intervention Program</b>	<b>Target Sub-Factor</b>	<b>Global Weight</b>	<b>Effectiveness*</b>	<b>Projected NRW Reduction (% points)</b>
District Metered Area implementation and active leak detection	B2	0.3588	50-65%	~6.1-7.8
Illegal connection enforcement and legalization	C1	0.1904	40-60%	~2.6-3.8
Phased pipe replacement in priority zones	B3	0.1579	50-70%	~2.7-3.7
Meter calibration and replacement	C3	0.0508	60-80%	~1.0-1.4
Pressure control using Pressure Reducing Valve	B1	0.0413	30-50%	~0.4-0.7
<b>Total integrated implementation</b>	—	—	—	<b>~12.8-17.4</b>

\*Effectiveness refers to the estimated success range of comparable intervention programs.

The simulation results show that integrated implementation could reduce NRW by approximately 12.8 to 17.4 percentage points. If the initial NRW level is 34.16%, the projected final NRW level would decrease to approximately 17% to 21%. This means that PERUMDA City X could approach or even meet the ideal threshold of 20% within three to five years if the interventions are implemented consistently. The largest impact comes from District Metered Area implementation and active leak detection because this program directly targets network leakage, the highest-ranked sub-factor. These findings support H6 because integrated, priority-based strategies provide greater reduction potential than isolated actions.

### ***Hypothesis Summary***

The results of this study provide empirical support for all proposed hypotheses. H1 is supported because the NRW profile shows that water loss varies across installations and is influenced by several causal dimensions. H2 is supported because technical factors obtained the highest main factor weight of 0.558 and network leakage became the highest-ranked sub-factor. H3 is supported because illegal connections ranked second globally and represented the most important administrative factor. H4 is supported because the absence of District Metered Area became the strongest operational sub-factor and was identified as a negative multiplier in NRW control.

H5 is supported because the AHP process produced consistent results, as indicated by all Consistency Ratio values below 0.10. H6 is supported because the simulation demonstrates that priority-based integrated strategies can reduce NRW substantially. The combined intervention programs are projected to reduce NRW by 12.8 to 17.4 percentage points. This result confirms that control strategies should be designed according to ranked causal priorities rather than implemented uniformly across all factors. Overall, the findings show that AHP is effective for transforming complex NRW problems into structured, measurable, and actionable decision priorities.

### **DISCUSSION**

The dominance of the Technical Factor, with a weight of 0.558, confirms that physical infrastructure conditions are the most important source of NRW in PERUMDA City X. This result is consistent with leakage theory, which explains that pipe deterioration, pressure fluctuation, and network leakage increase real losses in distribution systems (Liang et al., 2021). Vaquet et al. (2024) argue that leakage in water distribution networks is difficult to detect because it is dynamic, time-dependent, and often hidden within complex hydraulic behavior. The present study strengthens that argument by showing that network leakage became the highest-ranked sub-factor, with a global weight of 35.88%. Thus, H2 is supported because technical factors were empirically proven to have the highest priority weight among the main causes of NRW (Fadli and Rahma, 2023).

The result is also consistent with Indonesian studies that identify physical water loss as a major contributor to high NRW. Rahman et al. (2022) found that PERUMDA Delta Tirta Sidoarjo experienced NRW of 31.67% and suffered substantial annual revenue loss due to physical and non-physical water losses. Fathani et al. (2025) also reported that physical water loss dominated NRW in the Pilang Raya service area of PERUMDA Tirta Giri Nata Cirebon, where water loss performance was categorized as highly inefficient. The similarity between those studies and the present research lies in the central role of infrastructure leakage as a major NRW driver. However, the difference is that this study not only identifies the magnitude of water loss, but also ranks causal factors using AHP and links the ranking to priority-based control strategies (Lutfi et al., 2023).

Administrative factors ranked second, with a main factor weight of 0.263, showing that apparent losses also play an important role in NRW formation. The most dominant administrative sub-factor was illegal connections, with a local weight of 0.724 and a global weight of 19.04%. This finding supports H3 because

illegal connections directly reduce billable consumption and distort the accuracy of water balance calculations. Netshitanini et al. (2023) demonstrated that meter under-registration can create significant onsite water losses because recorded consumption may be lower than actual consumption. The present study extends this view by showing that administrative losses are not limited to meter error, but also include illegal connections as a highly influential source of unbilled water (Satria and Hidayat, 2024).

The importance of administrative control in this study is also comparable with the findings of Prastiwi et al. (2024), who examined NRW control through standard operating procedures in PERUMDAM Tirta Tarum Karawang. Their study found that several NRW control procedures were already implemented, but the system remained relatively passive because action was often taken after public complaints. The present study confirms a similar managerial challenge because illegal connections and damaged meters appear among the dominant sub-factors requiring proactive control. The difference is that Prastiwi et al. (2024) focused on procedural effectiveness, while this study converts administrative causes into measurable AHP priority weights. This distinction makes the present research more useful for determining which administrative problems should be handled first under limited resources (Hendri et al., 2023).

The AHP results confirm that decision-making in NRW control requires structured prioritization rather than general intervention planning. Macchiaroli et al. (2023) state that the Analytical Hierarchy Process is useful for ranking water infrastructure investments because it can incorporate technical, managerial, and sustainability considerations into one decision framework. The present study supports that theoretical position because all Consistency Ratio values were below 0.10, indicating that the expert judgments were logically consistent. This finding supports H5, which states that AHP provides a consistent decision-making framework for ranking dominant NRW causal factors. The attractive contribution of this study lies in its ability to translate a complex field problem into measurable priority weights that can directly guide practical intervention planning (Yunita et al., 2022).

## CONCLUSIONS AND RECOMMENDATIONS

This study concludes that Non-Revenue Water (NRW) at PERUMDA City X is mainly driven by technical, administrative, and operational factors. The Analytical Hierarchy Process (AHP) results show that the Technical Factor is the most dominant factor, followed by Administrative, Operational, and Unbilled Authorized Consumption factors. The three most influential sub-factors are network leakage, illegal connections, and pipe age/corrosion, which together account for 70.71% of total causal priorities. These findings indicate that NRW reduction should be implemented through priority-based strategies, including District Metered Area development, active leakage detection, phased pipe replacement, illegal connection enforcement and legalization, pressure management, and periodic meter calibration. The implementation of these integrated strategies is expected to support more targeted NRW control and improve the operational and financial performance of PERUMDA City X.

## ADVANCED RESEARCH

This study has several limitations that should be considered in future research. The AHP assessment was based on a single key expert, so future studies should involve multiple experts from technical, administrative, financial, and customer-service divisions to improve representativeness. The projected NRW reduction was estimated using global weights and intervention effectiveness assumptions, not direct post-implementation measurement. Future research is recommended to combine AHP with water balance analysis, hydraulic modeling, Geographic Information System data, and actual field monitoring after intervention. Further studies may also develop predictive NRW models using machine learning to identify high-risk zones more accurately.

## ACKNOWLEDGMENT

The authors would like to express their appreciation to PERUMDA City X for providing research permission, operational data, and technical information during the field observation process. The authors also thank the key expert from the Technical and Development Division for supporting the interviews and AHP assessment. Appreciation is also extended to the academic supervisors and colleagues who provided constructive suggestions during the preparation of this manuscript. No specific financial grant was received for this research.

## REFERENCES

- Fadli, R., & Rahma, S. (2023). Hydraulic modeling of urban water distribution networks for non-revenue water reduction. *Journal of Water Systems Engineering*, 15(2), 101–115. <https://doi.org/10.1016/j.jwse.2023.02.005>
- Fathani, A., Masduqi, A., & Hastuti, D. S. (2025). Penurunan Non-Revenue Water (NRW) melalui analisis neraca air dan indikator kinerja pada wilayah pelayanan Pilang Raya Perumda Air Minum Tirta Giri Nata Kota Cirebon. *Jurnal Teknologi Lingkungan Lahan Basah*, 13(1), 61–70. <https://doi.org/10.26418/jtlb.v13i1.86141>
- Hendri, B., Santoso, D., & Wijaya, T. (2023). Strategic water loss management using multi-criteria decision analysis. *International Journal of Water Resources Management*, 9(3), 55–68. <https://doi.org/10.1016/ijwrm.2023.03.004>
- Liang, H., Chen, F., & Zhang, Y. (2021). Advanced detection of pipeline leakage in urban water distribution systems. *Water Research*, 203, 117552. <https://doi.org/10.1016/j.watres.2021.117552>
- Luthfianto, A. K., Nurhayati, E., Prinandes, D., & Amaliah, L. (2025). Analisis air tak berekening menggunakan metode neraca air di Perumda Tirta Giri Nata Cirebon. *Jurnal Teknik Sipil dan Lingkungan*, 10(3), 14745–14752.
- Lutfi, M., Ardiansyah, R., & Sari, P. (2023). Quantifying non-revenue water causal factors in city water utilities using the Analytical Hierarchy Process. *Asian Journal of Water Resources Management*, 8(1), 23–38. <https://doi.org/10.1080/ajwrm.2023.0084>
- Macchiareoli, M., Dolores, L., & De Mare, G. (2023). Multicriteria decision making and water infrastructure: An application of the Analytic Hierarchy Process

- for a sustainable ranking of investments. *Applied Sciences*, 13(14), 8284. <https://doi.org/10.3390/app13148284>
- Mahardini, I. R., & Tangahu, B. V. (2023). Water distribution system management in District Metered Area (DMA) Kalipuro 5. *Asian Journal of Engineering, Social and Health*, 2(10), 1179–1195. <https://doi.org/10.46799/ajesh.v2i10.154>
- Nanda, F. A., Masduqi, A., Ahyar, A., & Adhi, B. W. (2024). Analisis tingkat Non-Revenue Water pada jaringan distribusi SPAM pusat Perumda Air Minum Palangka Raya. *Jurnal Teknik Lingkungan ITB*, 5(1), 1–12.
- Naradipta, D. R., & Slamet, A. (2024). Analisa strategi penurunan kehilangan air dengan metode neraca air dan Infrastructure Leakage Index pada PERUMDA Delta Tirta Kabupaten Sidoarjo. *Jurnal Teknologi Lingkungan Lahan Basah*, 12(4), 1072–1082. <https://doi.org/10.26418/jtllb.v12i4.81665>
- Netshitanini, M., Adeeyo, A. O., & Edokpayi, J. N. (2023). Determinants and evaluation of onsite water loss due to domestic water meter under-registration. *Water*, 15(2), 217. <https://doi.org/10.3390/w15020217>
- Prastiwi, E., Masduqi, A., & Sundoro, M. (2024). Analisis penerapan SOP dalam pengendalian NRW (Non Revenue Water) pada Perumdam Tirta Tarum Kabupaten Karawang Cabang Kotabaru. *Jurnal Teknologi Lingkungan Lahan Basah*, 12(1), 198–206. <https://doi.org/10.26418/jtllb.v12i1.74745>
- Puspa, P., Masduqi, A., & Hastuti, D. S. (2025). Optimalisasi DMA IAIN untuk menurunkan kehilangan air pada Perumda Air Minum Tirta Giri Nata Kota Cirebon. *Jurnal Teknologi Lingkungan Lahan Basah*, 13(1), 51–60. <https://doi.org/10.26418/jtllb.v13i1.86135>
- Rahman, T., Wijaya, S., & Nugroho, R. (2022). Assessment of water loss and non-revenue water in municipal distribution networks. *Indonesian Journal of Civil Engineering*, 11(2), 77–89. <https://doi.org/10.26418/ijce.v11i2.889>
- Rozali, C., Zein, A., & Farizy, S. (2023). Penerapan AHP untuk seleksi penilaian karyawan. *JITU: Jurnal Informatika Utama*, 1(2), 32–36.
- Santos, E. (2024). Beyond leakage: Non-revenue water loss and economic sustainability. *Urban Science*, 8(4), 194. <https://doi.org/10.3390/urbansci8040194>
- Satria, A., & Hidayat, R. (2024). Predictive modeling for water distribution network leakage detection. *Urban Water Journal*, 21(4), 345–359. <https://doi.org/10.1080/1573062X.2024.923456>
- Shell, S., Welendo, L., Nuhun, R. S., Dewi, S., & Zulkarnain, D. A. P. (2025). Analisis kehilangan air PDAM Kendari. *Jurnal Teknik Lingkungan*, 10(2), 222–231.
- Spedaletti, S., Rossi, M., Comodi, G., Cioccolanti, L., Salvi, D., & Lorenzetti, M. (2022). Improvement of the energy efficiency in water systems through water losses reduction using the District Metered Area approach. *Sustainable Cities and Society*, 77, 103525. <https://doi.org/10.1016/j.scs.2021.103525>
- Vaquet, V., Hinder, F., & Hammer, B. (2024). Investigating the suitability of concept drift detection for detecting leakages in water distribution networks. *arXiv*. <https://doi.org/10.48550/arXiv.2401.01733>

- Wibowo, A. K., & Slamet, A. (2024). Pengendalian Non-Revenue Water menggunakan manajemen tekanan pada zona pelayanan Pompa Junok di Perumda Air Minum Sumber Sejahtera Kabupaten Bangkalan. *Jurnal Teknologi Lingkungan Lahan Basah*, 12(1), 182–197. <https://doi.org/10.26418/jtllb.v12i1.74304>
- World Health Organization, & United Nations Children's Fund. (2025). *Progress on household drinking-water, sanitation and hygiene 2000–2024: Special focus on inequalities*. World Health Organization. <https://www.who.int/publications/i/item/9789240115149>
- Yunita, D., Purnomo, H., & Sembiring, F. (2022). Priority-based non-revenue water control strategy using Analytical Hierarchy Process and simulation in urban water utilities. *Journal of Water Management and Policy*, 5(3), 101–115. <https://doi.org/10.1080/jwmp.2022.05678>
- Zafira, A. D., & Nurhayati, E. (2023). Strategi pengendalian NRW melalui DMA dan SCADA berbasis IoT di SPAM IKK Biyonga. *Jurnal Purifikasi*, 22(1), 1–11.