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REVIEW ON LEAKAGE DETECTION MODEL OF WATER DISTRIBUTION SYSTEM FOR NON-REVENUE WATER

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Abstract:

Efficient water distribution systems are essential for ensuring global access to clean water, yet the persistent challenge of Non-Revenue Water (NRW) poses a significant threat to the sustainability of water utilities. NRW, comprising losses from leaks, unauthorized consumption, and inaccurate metering, remains a critical concern with economic and environmental implications. The escalating global demand for water highlights the urgency of addressing Non-Revenue Water, with leakage being a substantial contributor to these losses. Leakage models are pivotal tools in understanding and quantifying the factors contributing to water losses. This review consolidates current knowledge on leakage models, offering insights into their applicability in reducing Non-Revenue Water. It aims to guide water engineers, policymakers, and researchers toward effective strategies for minimizing water losses, improving system efficiency, and promoting sustainable water management practices. This paper presents a comprehensive review of leakage models within water distribution systems, focusing on their role in mitigating Non-Revenue Water.

Keywords:

Non-Revenue Water, Water Distribution System, Leakage Model, Sustainable Water Management

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Introduction

Access to clean and sustainable water resources is a critical global concern, and efficient water distribution systems play a critical role in ensuring the availability and accessibility of this valuable resource. However, the challenge of Non-Revenue Water (NRW) remains a significant obstacle to the optimal functioning of water utilities worldwide. NRW encompasses water losses due to leaks, unauthorized consumption, and inaccurate metering, collectively contributing to economic and environmental concerns (Güngör-Demirci et al., 2018; Jabari, 2017).

Water utilities face an ongoing struggle to minimize losses within their distribution networks. Leakage, in particular, represents a substantial component of NRW, impacting the economic viability of water utilities and posing environmental challenges. Leakage models serve as essential tools in understanding, quantifying, and addressing the factors contributing to water losses. As urbanization and population growth accelerate, the need for accurate and efficient leakage models becomes increasingly paramount to sustainably manage water resources (Torkaman, Ahmadi & Aminnejad, 2021; Al-Washali et al., 2020).

Efficient management of water distribution systems requires a deep understanding of factors contributing to NRW. Among these factors, leakage remains a persistent concern, prompting researchers and practitioners to develop and refine models aimed at identifying, quantifying, and mitigating these losses (Torkaman, Ahmadi & Aminnejad, 2021; Al-Washali et al., 2020; Liemberger & Wyatt, 2019). Several methods have been suggested to address the issues caused by leakage, including conventional hydraulic models as well as newer, data-driven and AI-based techniques.

Consequently, recent advancements in sensing technologies and data analytics have led to the development of data-driven leakage models. These models leverage real-time sensor data, historical consumption patterns, and statistical analyses to identify anomalies indicative of leaks. The integration of these approaches has shown promise in enhancing the accuracy of leak detection, allowing for more targeted interventions to reduce NRW (Tabesh, Asadiyami Yekta & Burrows, 2009).

The integration of artificial intelligence (AI) techniques marks a notable leap forward in leakage modeling. Machine learning algorithms, such as neural networks and support vector machines, demonstrate the capacity to learn complex patterns from data, improving the accuracy of leakage predictions. AI-based models not only enhance leak detection capabilities but also offer the potential for predictive maintenance, enabling utilities to proactively address potential issues before they escalate (Şişman & Kizilöz, 2020).

This review aims to consolidate the current state of knowledge regarding leakage models within water distribution systems, focusing on their applicability to reducing Non-Revenue Water. Such insights are crucial for developing targeted strategies to minimize water losses, improve system efficiency, and promote sustainable water management practices.

This paper is organized into sections that explore in-depth into various aspects of leakage modeling, including theoretical foundations, computational methodologies, case studies, and emerging technologies. Each section contributes to the overarching goal of enhancing our

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understanding of leakage models for water distribution systems and their role in mitigating NRW.

Related Work

Water distribution systems play a crucial role in supplying clean and safe water to communities. However, the challenge of NRW, which encompasses both physical and commercial losses in water distribution, poses a significant issue for utilities and municipalities. This related work assesses existing leakage models designed to mitigate NRW in water distribution system from previous research effort (Güngör-Demirci et al., 2018).

Liemberger and Wyatt (2019) employed a method for quantifying worldwide NRW levels, revealing that the presently estimated volume is considerably greater than earlier assessments. Wyatt's analysis, conducted in collaboration with the Inter-American Development Bank (IDB), suggested that out of 28 countries, 26 have the potential for implementing projects aimed at significantly reducing NRW in their respective utilities. These projects, with a payback period of less than 10 years, could yield various advantages, including reduced operating costs, increased revenues, enhanced water resource efficiency, and expanded water supply. Importantly, these benefits come at a considerably lower cost compared to establishing new water production facilities.

See and Ma (2018) conducted a review of NRW, focusing on assessing the total factor productivity of the Malaysian water services sector. The evaluation aimed to measure the efficiency of a water utility in converting its resources (inputs) into tangible outcomes. The inputs encompassed the resources essential for executing water production activities, while the outputs, including delivered water, the count of connections, and water losses in distribution, represented the immediate results of the water production process. Finding shows that the Malaysian water services industry is becoming slightly less efficient at turning its resources into services with a declining TFP of 0.72 percent per year caused by technology regression. Ensuring the success of water market reforms relies heavily on the regulators' ability to facilitate equitable and robust competition.

Then, Güngör-Demirci et al., (2018) conducted a review on NRW in California, USA. Their analysis identifies that the network length, connection density and net operating revenue per cubic meter of water sold found to be negatively correlated with NRW. This means that as the mentioned factors increase, the NRW decreases. Also, for the number of leaks, there was a positive relationship identified between the number of leaks and NRW. This indicates that an increase in the number of leaks leads to an increase in NRW.

Van den Berg (2014) examined NRW by employing cross-sectional data derived from utilities across 68 countries. In his study, Van den Berg (2014) concluded that factors such as population density per kilometre of network, the type of distribution network, and the length of the network are significant drivers of NRW. These factors are largely determined by urbanization and settlement patterns in the areas served by the utility, indicating that broader socio-economic and geographical contexts play a crucial role in NRW levels. The study also finds that low opportunity costs associated with water losses adversely affect efforts to reduce NRW. This suggest that when the perceived or actual costs of losing water are low, there is less incentive for the utility to invest in reducing water losses. Also, the research underscores the importance of the environmental context, or country-specific factors, in influencing NRW

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levels. This implies that the effectiveness of NRW reduction strategies may vary significantly based on the country's specific environmental, regulatory, and socio-economic conditions. Hence, to design an effective NRW reduction program requires a thorough understanding of the main drivers of NRW.

González-Gómez et al. (2011) conducted an analysis of NRW to explore the implementation of measures aimed at successfully reducing NRW levels. To mitigate apparent losses, a company would need to enhance its payment collection management, directing additional funds towards controlling unauthorized consumption and addressing metering inaccuracies. The endeavour to curb unauthorized consumption also incurs a political cost, particularly when a substantial portion of illegal connections is identified in marginalized districts within large cities, necessitating measures to bill even the most disadvantaged sectors. Considering water costs and the efficient management of scarce resources, minimizing losses becomes imperative. However, water utilities often lack adequate incentives to undertake necessary actions for NRW reduction, with some instances attributed to direct benefits derived from illegal.

Table 1: Summary Of Previous Work On Water Leak Detection

Author	Paper	Summary of Previous Work
Liemberger and Wyatt (2019)	Quantifying the global non-revenue water problem	• Presently estimated volume is greater than earlier assessment.
See and Ma (2018)	Does non-revenue water affect Malaysia's water services industry productivity?	• The evaluation aimed to measure the efficiency of a water utility in converting its resources (inputs) into tangible outcomes.
Güngör-Demirci et al., (2018)	Determinants of non-revenue water for a water utility in California	• Identifies factors of network length, connection density and net operating revenue per cubic meter of water sold to be negatively correlated with NRW while positive relationship between number of leaks and NRW. • Reveal a result of varying degrees of correlation depending on the available data
Van den Berg (2014)	The drivers of non-revenue water: how effective are non-revenue water reduction programs?	• Examined NRW by employing cross-sectional data derived from utilities across 69 countries. • Highlighting factors of influence of urbanization and settlement patterns, opportunity of water losses and country fixed effects for an effective NRW reduction program.
González-Gómez et al. (2011)	Why is non-revenue water so high in so many cities?	• Explore the implementation of measures aimed at successfully reducing NRW levels. • To mitigate apparent losses, a company would need to enhance its payment collection management, directing additional funds towards controlling

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	unauthorized consumption and addressing metering inaccuracies.

Non-Revenue Water

NRW is defined as "the difference between the volume water distributed by the system and the volume that is billed to customers" (Liemberger & Wyatt, 2019. Many nations worldwide are facing the challenging issue of NRW (Jabari, 2017; Murugan & Chandran, 2019). Substantial water losses have resulted in increased expenditures on operational and maintenance activities to ensure uninterrupted water supply to the population.). A high level of NRW could indicate a significant loss of water before it gets to the people who use it, which can lead to more financial losses.

International Water Association (IWA) separated NRW into two components, which then broken down into further elements from the major components (Murugan & Chandran, 2019). The major components include physical (real) losses and commercial (apparent) losses, while minor component is characterized as unbilled authorized consumption (Lambert, 2002).

Real losses represent the tangible water losses caused by leaks from distribution components or overflow storage tanks. Poor operations and maintenance, lack of active leak control, and the deterioration of underground assets are typical causes of leakages and overflows (Jones et al., 2021). The underground assets are components of an underground network such as water drainage systems or sewage. Commercial losses, or interchangeably known as apparent losses, include watering inaccuracy constitutes a large portion of commercial losses (Criminisi et al., 2009). Moreover, unbilled authorized consumption pertains to lawful water usage that is neither unrecorded on metered. This includes water consumed for firefighting, flushing of pipes and sewers, street cleaning, protection, and supplying subsidized water as per government policies.

Physical losses are influenced by factors such as aging or substandard pipelines, insufficient corrosion protection, valves that are not well-maintained, defects in materials, improper installation, overly high-water pressure, water hammer, soil movement resulting from drought or freezing conditions, excessive loads, and vibrations caused by road traffic (Jones et al., 2021). Beyond reservoir overflow and losses, one factor often highlighted were the effect of aged and corroded underground assets and their contribution to NRW rates. Jones et al. (2021) reported six types of pipes used in Malaysia. The main piping system is made up of mild steel pipe asbestos-cement pipes, polyethylene pipes, un-plasticized polyvinylchloride and ductile iron pipes. Lai et al., (2017) also reported that pipe leakage or bust pipes as one of the major water issues.

Similarly, for commercial losses, inaccurate metering and illegal tapping into the water distribution network affect the performance of the water services industry in terms of revenue collection and water management (See & Ma, 2018; Lai et al., 2020, Frauendorfer & Liemberger, 2010). Additionally, inaccurate metering may be caused by meter reader errors, slow-running meters, meter tampering, broken meters, or illegal connections. Administrative error data entry errors, and loss of records for billing purposes may also contribute to the typical losses in a WDS (Muhammetoglu et al., 2018).

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Another main contributing factors to NRW challenges are driven by low awareness among the public of the severity of the NRW issue and considering such a case to be the sole responsibility of the water authority (Lai, Chan & Roy, 2017). Additionally, the lack of cohesive government policy on water security and finance further constraints and dampens the movement towards implementing NRW reduction programs (Lai et al., 2020).

Other studies highlighted that effective water management is crucial in reducing NRW losses (Jabari, 2017; Murugan & Chandran, 2019). Nonetheless, achieving consistent reduction in NRW losses presents a challenge in numerous countries, given the technical intricacies and complexities involve in managing NRW. Particularly Malaysia, the issue of NRW remains a challenge (Jones et al., 2021). In Malaysia, the water market has experienced significant water loss levels, ranging from 35 percent to 45 percent of the overall water supply over the past decade (See & Ma, 2018).

Water Distribution System

The water distribution system, a critical component of urban infrastructure, is a complex network designed to ensure the reliable and efficient supply of clean and safe drinking water to communities. This intricate system encompasses a series of well-coordinated processes, from needs assessment and meticulous planning to hydraulic modeling, construction, and ongoing management (Nova, 2023). The success of water distribution systems relies on the careful selection of materials, adherence to regulatory compliance, and the integration of smart technologies for real-time monitoring and control. Efficient water treatment facilities play a crucial role in maintaining water quality, while strategies for energy efficiency, sustainability, and community engagement contribute to the overall resilience and effectiveness of the system (Dwivedi et al., 2023; Dias, Besner & Prevost, 2017). As an essential lifeline for communities, water distribution systems continue to evolve, incorporating technological advancements and sustainable practices to meet the challenges of a growing and dynamic urban landscape.

The escalating demand for water in developing countries has underscored the crucial role of water supply systems. This surge in demand can be attributed to factors such as urbanization, industrialization, improved living standards, and economic growth (De Marchis et al., 2014). Nevertheless, the available water sources are declining both in quantity and capacity (Yussof & Ho, 2022). Over the past two decades, there has been a growing imperative to improve the efficiency of water supply systems.

Countries struggling with substantial water losses highlight the significance of closely monitoring their water distribution systems. This may involve initiatives such as upgrading existing water infrastructure to mitigate physical losses (See & Ma, 2018). In urban environments, it becomes crucial to regularly inspect distribution pipelines for potential contaminants like microbial growth, internal pipe corrosion, and other deposits. These contaminants have adverse effects on both water quality and flow efficiency, causing pressure loss and increased friction (Shamir, Asce & Solomons, 2008). However, the primary drawback stems from the occurrence of leaks in underground pipes, which stands as a major contributor to the wastage of limited water resources (Al Qahtani et al., 2020).

Implementing water distribution systems is a multifaceted process that demands careful planning, engineering precision, and strategic management. The initial phase involves a thorough needs assessment and planning, where the community's water requirements are

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evaluated, and potential sources of water supply are identified. This planning stage also encompasses regulatory compliance and obtaining necessary permits to ensure adherence to legal frameworks (Hassani, Mehdy & Shahdany, 2021). Once the planning phase is complete, the hydraulic modeling and design stage come into play, utilizing advanced software to optimize the layout, sizing, and configuration of pipes, pumps, and other infrastructure. Material selection is crucial during the construction phase, considering factors like water quality and durability (Mcdonald et al., 2014).

Leak Detection

Several leak detection and location methods have been utilized by researchers, posing a challenge in consolidating them into a unified classification (Torkaman, Ahmadi & Aminnejad, 2021). Presently, the predominant focus of leak detection technology is on water distribution and pipeline networks (Yussof & Ho, 2022) with no reference to the issue or presence of non-revenue water (NRW).

Moubayed et al. (2021) have categorized leak detection methods into two primary types: hardware-based and software-based. Hardware-based methods encompass closed-circuit television (CCTV), Acoustic Emission, Infrared Thermography, RFI sensor, Leak Noise Correlators (LNC), and Tracer Gas Technique (TGT). On the other hand, software-based methods include Negative Pressure Wave (NPW), Computational Fluid Dynamics (CFD), and Fuzzy Method (Yusoff & Ho, 2022; Al Qahtani et al., 2020).

Yusoff and Ho (2022) employ a smart building application that combines both hardware and software-based leak detection methods to monitor and manage water leakage issues. Table 2 presents a summary of key performance aspects of sensing technology in water leak detection as reported by Yusoff & Ho (2022).

Table 2: Key Performance Sensing Technology In Water Leak Detection

Methods	**Performances**			
	LC	EI	HA	FT
Closed Circuit Television (CCTV)	X	X	/	X
Acoustic Emission	X	/	/	/
Ground Penetration Radar	X	/		
Fiber Optics	X	/	X	/
Infrared Thermography	/	/	X	/
RFID Tags Sensor	/	/	X	/
Leak Noise Correlation (LNC)	X	X	/	X
Tracer Gas Technique (TGT)	X	X	/	X
Pig-Mounted Acoustic (PMA)	X	X	/	X
Negative Pressure Waves (NPW)	/	/	X	/
Computational Fluid Dynamics (CFD)	/	X	/	/
Fuzzy Method	X	X	/	/

Note: LC = Low Cost, EI = Easy Installation,
HA= High Accuracy, FT = Fast Response Time.
X = Advantages, / = Disadvantages

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Vitan et al. (2022) investigated model-based and data-driven strategies for leak detection and location in Water Distribution Systems (WDS). Model-based approaches encompass sensitivity matrix-based methods, mixed model-based/data-driven approaches, optimization techniques, calibration approaches, and error-domain model falsification. In contrast, data-driven approaches include feature set classification methods, prediction-classification methods, statistical methods, and unsupervised clustering methods.

It is observed that model-based approaches are effective in detecting and locating leaks, but they necessitate calibrated hydraulic models and optimized sensor placement. On the other hand, data-driven methods do not require an in-depth understanding of the WDS, as they involve statistical or signal processing analyses of acquired data. However, these methods demand a substantial amount of data and are susceptible to issues such as missing data, unusual sensor readings, communication problems, and unwanted background noise (Gupta et al., 2020).

The adoption of district metered areas (DMA) presents notable benefits, including pressure control, network management, monitoring and detection of leaks, ensuring water quality, and effective management (AL-Washali, Sharma & Kennedy, 2016). The use of Artificial Neural Networks (ANNs) and Multiple Linear Regression (MLR) as predictive techniques for estimating the NRW ratio. The particular formulas applied for prediction can vary depending on the factors taken into account and the characteristics of the study area.

The evaluation of NRW seeks to quantify losses within a specific water system, yet it does not pinpoint the exact locations of these losses (Güngör-Demirci et al., 2018). This is due to the extensive nature of public water pipe systems, spanning thousands of kilometres and consisting of numerous interconnected pipe sections and joints (Murugan & Chandran., 2019).

Conclusion

This paper provided a comprehensive overview of leakage models applied to water distribution systems, with a specific focus on mitigating non-revenue water (NRW). The exploration of diverse valuable insights in NRW management.

The significance of leak detection methods, which include both hardware-based and software-based approaches, has been underscored by the incorporation of various technologies and tools available for efficient NRW assessment.

As water demand continues to rise amidst diminishing water sources, the insights gathered from this review emphasize the urgency of refining and implementing leakage models. By continuously advancing our understanding and application, it can make significant strides in minimizing non-revenue water, fostering sustainable water management practices, and ensuring the prudent use of water resources in the face of evolving global challenges. This review serves as a valuable resource in leak detection, water distribution system and NRW system. For future work, the study anticipated to explore the leakage detection for NRW that integrate in technologies with IoT, machine learning, and real time analytic system.

Limitation

This research on NRW and the leakage detection models in water distribution system is still in the initial stages. A global review was conducted to understand and identify the leakage detection model used in previous studies. Going forward, this research aims to thoroughly explore NRW issues in Malaysia, pinpoint critical areas experiencing high levels of NRW, and investigate suitable leakage detection models to address these challenges.

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