From Invisible Leaks to Measurable Data: A Statistical Analysis of Water Piping Systems: Patterns, Causes, and Predictive Indications in Pulilan, Bulacan

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ABSTRACT

The study emphasizes the overall analysis and understanding of factors that can cause piping leakages, patterns that can arise from said leaks, and ways to identify indicators that can assist in the hazard's occurrence, with the target demographic centered on Pulilan, Bulacan. With the utilization of water distributor documents and records that highlight the Distribution Records, Production, and Rehabilitation History, and Leakage logs covered by the said company. The records indicated that unequal distribution and leakage anomalies were highlighted as the main areas of attention within the study. Ultimately, recommendations such as scheduled pipeline inspections, automated monitoring, swift repair response time, and aging pipeline replacements were mentioned.

Keywords: Water leakages, Unequal Piping Distribution, Piping Workload, Pipe

INTRODUCTION

Within every country, water plays a significant role in human life, whether it is for entertainment, personal hygiene, or simply life in general (Popkin, B. et al., 2010), and the primary source of water comes from a water distribution system. A main downside is the risk of resource deprivation, as well as the continuous production hindrances across the globe (Jun, H. et. al., 2007).

In China, 40% of major causes regarding urban ground collapse are due to underground water piping leaks and demands for reconstruction, which in turn, increases operational costs and time driveway consumption (Wang and Xu, 2022). In addition, microorganisms such as viruses and bacteria could enter through leaks from the piping systems and be part of the water distribution, which could lead to serious health effects on clients and users from the water distributor (Collins R., 2015).

This research aims to **(1)** support and inform engineers, policymakers, and water distribution handlers with the necessary and crucial information centered on early detection techniques, as well as procedures to reduce water leakages, and **(2)** identify causes and factors that can result in pipeline leakages from the main distribution systems.

Statement of the Problem

1. What are the common patterns of water leakage in the pipe system?

2. What are the possible causes of water leakages based on the available data?

3. How do factors such as pipe age, material, and location affect the occurrence of leaks?

Significance of the Study

This research will be beneficial to the following:

To the residents and community, this research helps identify common water leak locations, recognize warning signs early, and support timely repairs in affected areas.

To the local water service providers, this research gives evidence-based data for better maintenance planning and budgeting. Moreover, the research helps reduce non-revenue water and promote efficient leak-detection strategies.

To future researchers, the research establishes baseline data on water leak patterns and serves as a support to develop predictive models and new detection or monitoring approaches.

REVIEW OF RELATED LITERATURE

Relevant Theories

Acoustic Emission Theory (Simpsons, A. and Clough, R., 1981). The theory of acoustic emission discusses the internal areas of physical materials, similar to water pipes, generating elastic waves due to unprecedented scenarios affecting the pipes in terms of deformation, cracking, or any form of changes that generate a negative and physical outcome.

Moreover, the theory of acoustic emission is also applicable in terms of detecting Acoustic Emission (AE) signals, and can be used for pattern recognition and early indicators for pre-leaks in water distribution systems, which will hold a high significance for the research in terms of identifying leakage patterns and predictive indicators at pipelines.

Stress Corrosion Cracking Theory (Warke, W. R., 2002). As the name suggests, it illustrates the corrosion along with the generation of miniature cracks, with the major cause of internal stress in an environment over time. Normally, the theory is present in areas that are either under development or material-focused, such as households.

Similarly, water pipelines are also a great example of the theory, because water pipes can either be made out of Polyvinyl Chloride (PVC) or materials such as stainless steel, aluminum, and other metallic materials, in which both forms of water pipelines can develop high exposure to stress. Knowing this, the theory will hold high value to the research in terms of cause detection within piping systems.

Related Literatures

Based on this research analysis, **"Leak detection in water distribution networks: an introductory overview"** (Zahab and Zayed, 2019), improved analysis and monitoring technologies due to the constant increase in water losses under water distributors and the significance for addressing water pipeline errors, such as lower repair costs and service interruptions, as well as improving the public safety of the clients under the water distribution.

In addition, the paper advises examining the pressure and flow under the pipelines using the data from existing records. Additionally, the implementation of the varieties of detection systems holds high significance in understanding how the utilization of infrastructure manipulates the occurrences of leakages. Ultimately, the researchers examine the related literature to hold a solid foundation for the analysis of water leaks using statistical methods.

Based on the literature known as "**Decision with Uncertain Information: An Application for Leakage Detection in Water Pipelines**" (Meydani et al., 2022),leakage detection, specifically, in old underground networks for the reason of incomplete data and uncertain error probabilities.

Moreover, the journal centers on the usage of the Bayesian theory for the rehabilitation process and the identification of pipe characteristics and factors that can transition to a leakage risk.

Finally, the literature suggests the use of historical data and inspection results to arrive at the results, which aligns with the research's objective of identifying measurable patterns and predictive indicators in water piping occurrences.

According to this research entitled, **"Beyond Leakage: Non-Revenue Water Loss and Economic Sustainability"** (Santos E., 2024), the concept of Non-Revenue Water (NRW) and the negative impacts on water production companies and the general financial stability worldwide.

According to the literature, NRW percentage commonly increases with the major causes of water operation and production facilities, in both handled by both the private and public sectors of society. Hence, the literature holds high significance to the research as a point of reference within the data analysis.

Based on this literature, **"Application of Software and Hardware-Based Technologies in Leaks and Burst Detection in Water Pipe Networks: A Literature Review"** (Joseph et al., 2023), the usage of modern as well as technical mechanisms and techniques for water leakage anomalies within piping systems, such as the application of deep electronic learning algorithms for the benefit under a software- based approach, which is the analysis of hydraulic signals using statistics, and the hardware-based tools for precision pinpoints during on-site checking.

Hence, the paper perfectly aligns with the major goals of the research, considering the use of data-driven approaches and the implementation of quantitative models that examine pipe characteristics and how these characteristics can influence and produce leak frequencies and negative outcomes.

Based on **"Leakages in Water Distribution Networks: Estimation Methods, Influential Factors, and Mitigation Strategies—A Comprehensive Review"** (Alvisi and Franchini, 2014), the utilization of internal pressure and flow as a key identifier for water leakages in distribution systems. Moreover, the literature explains the consistent patterns that can be obtained with the analysis of operational data derived from the network.

Therefore, the research contributes to the advancement and utilization of existing data to identify leakage patterns and possible predictive indications, which align with the research objectives, with the usage of an estimation approach that promotes the integration of statistical analysis for obtaining information.

Related Studies

According to here in **"Corrosion of pipelines in urban water systems: Current research status and future trends based on bibliometric analysis"** (Zhong, H. et al., 2023), The article focuses on the corrosion of the pipe networks and how corrosion affects major factors of society, such as drinking quality, general urbanization, and an increase in Non-Revenue Water (NRW) percentage.

Furthermore, the research also implied that factors similar to outer stress were focused on in terms of factors to be mitigated or avoided. In terms of the research technique of data gathering and analysis, the research was focused on the usage of records from a specific organization or company, which aligns with the main idea and goals of the research.

As stated here in **"Water Leak Diagnosis in Pressurized Pipelines: A Real Case research"** (Delgado-Aguiñaga, J. A., & Begovich, O., 2017),the occurrences of leaks within pipelines were due to corrosion, construction-related activities, and even factors related to material degradation, acoustic emission, and natural events.

Ultimately, this study will hold a solid usage value throughout the research, since the research utilizes documents and records from certain companies, and the manipulation of mathematical equations for the entire statistical analysis of data to arrive at the expected output.

In accordance with the study **"A Review on Water Leakage Detection Method in the Water Distribution Network"** (Al Qahtani, T et. al., 2020), the main flow from pipelines is commonly stretched and accompanied by jointed sections, in which overusage or high results of workload throughout the internal pipes can damage pipelines located near jointed sections and cause pipe corrosion.

Moreover, this study recommends the use of mathematical methodologies and state observers as a form of predictive indicator for leakage for accurate results; hence, the study aligns with the main objectives of the research for identifying the main predictive indications on water leakages.

As stated in the study, **"Leakage Management and Pipe System Efficiency: Its Influence in the Improvement of the Efficiency Indexes"** (Ávila, C. A., et al, 2020), Water distribution companies hold high relevance to society in the modern era. However, repairs and other distribution errors are inevitable due to factors related to pressure level, internal valve size, and pipe material.

Furthermore, the research proposes the usage of existing leak records and specific scientific analysis to further trace and determine areas prone to leakage, the main source of the leakage, and the main indicator before the occurrence of a piping error. Hence, the study aligns with the main objectives of the research and will hold high significance throughout the research.

According to the article entitled **"Analysis and ranking of corrosion causes for water pipelines: a critical review"** (Hussein Farh, H. et al, 2023), corrosion produces significant impacts on water networks in terms of technological and socio-economic aspects. In addition, location, pipeline-centered, and operative aspects were the main focus of what the main contributors to said corrosion from the pipelines were.

Additionally, the article recommended the utilization of an infometric approach, which is the usage of web articles to analyze and gather quantitative data, as well as the usage of a methodical approach, which indicates the usage of past and present records for obtaining an accurate output. Consequently, the article provides an alignment with the overall goals of the research.
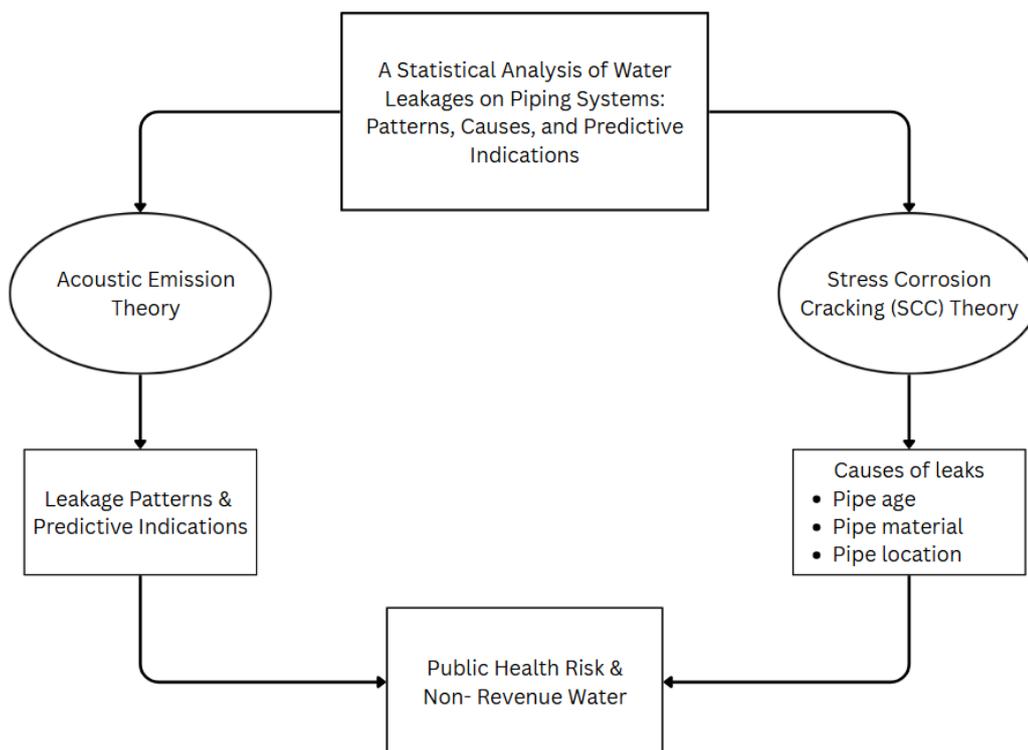
Theoretical Framework

Figure 2.1 Theoretical Framework on factors that influence Public Health and NRW

Figure 2.1 displays the theoretical frameworks that are under the viewpoints of two (2) theories: Acoustic Emission (AE) Theory, which tackles the leakage patterns and the main indicators for the said leakage in water pipelines, and the Stress Corrosion Cracking (SCC) Theory that highlights the major causes that can result in a water leak in pipelines. Ultimately, both perspectives are used to detect the notable elements that can manipulate public health risk, and the non-revenue water percentage.

Conceptual Framework

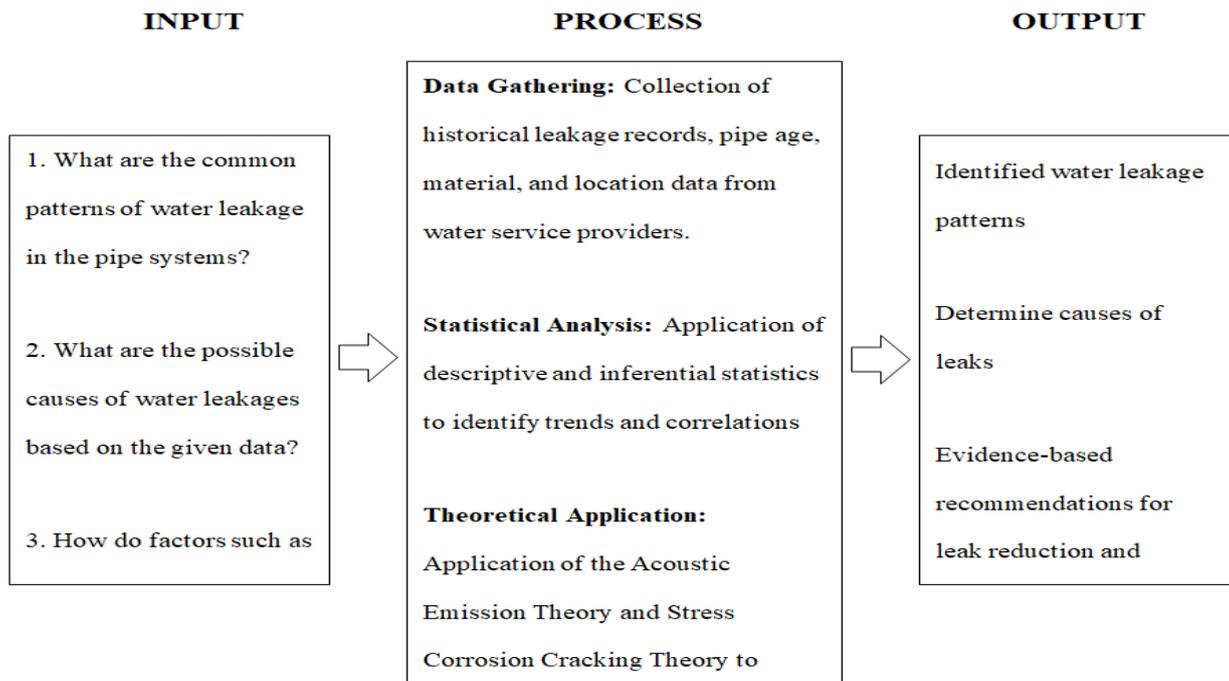| INPUT	PROCESS	OUTPUT
1. What are the common patterns of water leakage in the pipe systems?	**Data Gathering:** Collection of historical leakage records, pipe age, material, and location data from water service providers.	Identified water leakage patterns
2. What are the possible causes of water leakages based on the given data?	**Statistical Analysis:** Application of descriptive and inferential statistics to identify trends and correlations	Determine causes of leaks
3. How do factors such as	**Theoretical Application:** Application of the Acoustic Emission Theory and Stress Corrosion Cracking Theory to	Evidence-based recommendations for leak reduction and

Figure 2.2 Conceptual Framework of the Input, Process, and Output of the Study

The figure illustrated above showcases a conceptual framework for the study, alongside utilizing an Input-Process-Output (IPO) structure. To further expand, the input portion of the framework highlights the overall data necessary, such as the common patterns, possible causes of leaks in water distribution systems, and the factors that contribute to the predicament. Moreover, the process part of the framework includes the overall procedures within the data gathering process and the step-by-step methods of encoding the gathered data. Finally, the output portion illustrates the elements and factors that are expected after the data gathering and analysis procedure.

Research Objectives

- To be able to identify the patterns in water leakage within piping systems.

- To recognize the possible causes of water leakages based on available data.

- To determine if factors such as pipe age, material, and location affect the occurrence of leaks.

METHODS

The type of method utilized in this research is a quantitative descriptive research design. Moreover, the following approaches were used in the research:

- **Research Approach:** Quantitative research for the statistical analysis of data gathered centered on the cause and pattern factors, as well as the main indicators for leaks.

- **Participants:** A purposive sampling of 40 records was obtained from the water distributor company.

- **Data Collection Instrument:** Data Analysis focuses on collecting water company documents to ensure results are correct. The documents include Incident Logs, Maintenance Reports, and Assessment Records related to the clients served by the water distribution company.

- **Validation:** The engineering professionals reviewed and validated the content analysis instrument. This process ensured it was accurate, relevant, and met the research objectives.

- **Data Processing and Analysis:** The overall analysis used a descriptive method, which involved frequency counts, percentages, and means to derive the designated results from the data gathered.

Research Instruments

The section of the research highlights the main methods and instruments used during the data gathering process.

Considering the research focuses on factors such as the identification of causes, patterns, and predictive indications under water distribution systems, the research instrument utilized was a content analysis checklist, which highlights the predetermined categories such as leak type, pipe age, pipe material, identified leak causes, and leak severity, as well as the conversion of relevant information from the documents into the form of quantitative data used for statistical analysis.

Data Gathering Procedure

Throughout the research, the main procedure during the data gathering was to present a request letter or Letter of Consent (LOC) that centers on requesting documents from the said company in relation to the data necessary for arriving at the result of the research. Upon approval from the company, the researchers coordinated with the said company for gathering necessary data, which includes incident logs, maintenance records, and assessment records related to the water piping systems. Ultimately, a total of 40 records were obtained, selected, and validated based on relevance to the research.

Ethical Considerations

To further strengthen the confidentiality of the data gathered, the said company's official name shall not be disclosed throughout the research. Moreover, each branch or client covered by this company will be classified into clusters throughout the analysis of data.

RESULTS AND DISCUSSION

SoTP 1: What are the common patterns of water leakage in the pipe system?

Table 4.1 Water Distribution Records and NRW Percentage from Pulilan, Bulacan

Cluster No.	Production	Total Consumption	
1	164,967.00	132,643	
2	133,598.00	107,632	
3	122,860.92	116,110	
4	124,428.96	95,684	**NRW = 18%**

The table above presents the overall water production and total consumption per cluster in Pulilan, Bulacan, highlighting an overall Non-Revenue Water (NRW) percentage of 18%. NRW represents the variance based on the size of water produced as well as the quantity recorded as consumed**.** Cluster 1 had the highest production at 164,967.00 with corresponding consumption of 132,643. Meanwhile, Cluster 4 recorded a production of 124,428.96 and the lowest consumption at 95,684, resulting in the highest NRW percentage of 23.1%, which

relates to the effects of corrosion under the study of Zhong, H et al. (2023), named "Corrosion of pipelines in urban water systems: Current research status and future trends based on bibliometric analysis" that directly illustrates the usage increase of water consumption is directly proportional to pipe corrosion which results into an increase of NRW percentage and also correlates to the article of Santos, E. (2024) known as the "Beyond Leakage: Non-Revenue Water Loss and Economic Sustainability" that depicts the consumption of water from both private and public sectors highly increase the percentage of NRW. Moreover, data from Cluster 4 exhibits discrepancies between production and consumption as compared to Cluster 3, where its values are closer to each other, specifically 122,860.92 in production, while 116,110 in consumption, indicating relatively lower water loss. The variances of data interpret an unequal production value in each cluster.

While the researcher did not quantify for hydraulic pressure or mechanical stress in this research, imbalance in water distribution efficiency indicates certain clusters experience greater operational strain. Although not stated in the table, this can be observed with the high percentage of NRW in cluster 4. Building on this, as discussed under SCC Theory, constant tensile stress combined with environmental factors, such as in the case of the results——- accelerates the degradation of a structure eventually resulting in its failure. The researcher concluded that the 18% NRW total is concentrated in specific areas, which likely reflects differences in pipe quality and system performance.
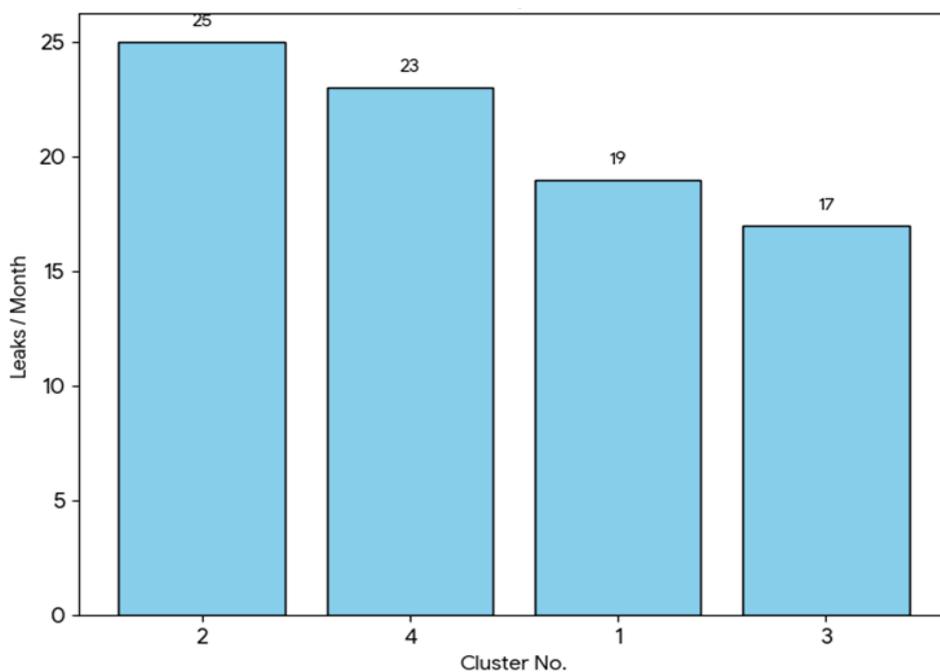

Figure 4.2 Summary of monthly leakage reports of clusters in Pulilan, Bulacan.

The figure above explains the monthly leakage report in Pullian, Bulacan. Each bar represents an individual cluster with a corresponding value, which refers to the frequency of clusters experiencing leakages in a single month. Based on the graph, clusters 2 and 4 are described to gain more frequent incidents with 25 and 23 leaks per month, respectively, compared to cluster 1, having 19 leaks per month, and cluster 3, with over 17 leaks on a monthly basis. The researcher would like to provide that cluster 1 serves four districts, cluster 2 serves three districts, and clusters 3 and 4 both consist of six districts. Knowing these, when the number of districts per cluster is considered, cluster 2 exhibits the highest number of leaks per district, indicating more frequent leakage incidents relative to its size. The findings indicate that leakage incidents are more concentrated in specific areas.

Overall, the results from table 4. 1 and Figure 4.2 stated that a leakage pattern is more concentrated in specific clusters. This suggests that some sections of the water distribution network in Pulilan, Bulacan, are commonly prone to stress-related degradation, which significantly contributes to recurring leakage patterns within the network.

SoTP 2: What are the possible causes of water leakages based on the available data?

Table 4.3 Distribution of Water Leakage by Reason, Frequency, and Indicator

Reason Category	Clusters Involved	Frequency (f)	Percentage (%)	Primary Detection Indicator
High Water Usage	1 & 2	44	52.38%	Reporting / Meter Checking
High Temperature Area	3 & 4	40	47.62%	Reporting / Meter Checking
TOTAL		84	100%	

Table 4.3 provides the distribution of reported water leakage incidents according to identified reasons, frequency, and detection indicators across four (4) clusters. As shown in the table, the causes of water leakage incidents in Pulilan, Bulacan are divided between (1) operational-related issues in high-usage zones which involved Clusters 1 and 2 with a percentage of 52.38% (f = 44) of total reported leaks and (2) environmental-related stressors in high-temperature areas involving Clusters 3 and 4, which represents the 47.62% (f = 40) of the total leakage incidents. The high frequency of leaks in Clusters 1 and 2 highlights the effect of operational demand across water distribution. Moreover, this implies that areas with higher water usage experience continuous internal flow and pressure variations within the pipeline system, which eventually weaken the pipeline's structural integrity. This result supports the discussion of Acoustic Emission Theory, which states that when a pipeline is under constant pressure, the formation of small cracks releases elastic waves. These waves serve as an indicator of the progressive degradation, where minor internal stresses are accumulating slowly, and then will eventually transition to the actual formation of a leak in the water distribution system. In contrast, Clusters 3 and 4 are categorized as high-temperature areas and account for 47.62% of leakage incidents. While slightly lower in frequency than operational causes, Cluster 4 can be calculated in Table 4.1 to have the highest NRW percentage (23.1%), implying that while usage accounts for more leak occurrences, temperature intensifies water loss severity.

This data shows consistency with Stress Corrosion Cracking (SCC) Theory, as this theory states that elevated temperature can accelerate Stress Corrosion Cracking in susceptible materials under sustained tensile stress and corrosive environments, contributing to pipe leaks, as well as the study from Al Qahtani, T et al. (2020) entitled "A Review on Water Leakage Detection Method in the Water Distribution Network" wherein high stress levels or in this case high usage of water can damage sections from piping systems, developing leakages.

The table also provides the indicators involved in determining water leakages in the water distribution network of Pulilan, Bulacan. A total of 100% of leakage assessments across all clusters rely solely on "manual reporting or pressure gauge checking".

This finding indicates that the current detection pattern presented in the table is a contributing factor for Non-Revenue Water. Also, it signifies the lack of proactive technology, such as hardware-based technologies for detecting leaks. This aligns with Joseph et al. (2023) in their article entitled, "Application of Software and Hardware-Based Technologies in Leaks and Burst Detection in Water Pipe Networks: A Literature Review". The author of the article describes hardware-based technological interventions as important tools for mitigating system bursts and maintaining pressure stability in water distribution networks.

SoTP 3: How do factors such as pipe age, material, and location affect the occurrence of leaks?

Table 4.4 Repair and Rehabilitation History of Pumping Stations in Pulilan, Bulacan

Year	Count of Pumping Stations	Summary of Repair and Rehabilitation Activities
2022	4	Upgrade of pumps, motor reconditioning, cleaning, and addition of PVC

		components
2023	2	Installation of new pumps and motors; motor reconditioning
2024	3	GI to PVC riser pipe replacement; installation of new pumps and motors
2025	4	Brushing and bailing; motor upgrades (20HP to 30HP); pump reconditioning
2026	1	Capacity upgrades (SP80-8), P-board upgrades, and comprehensive pump testing

The table above presents the documented repair and rehabilitation activities conducted between 2022 and 2026 across the pumping stations of Pulilan, Bulacan. The table shows that the highest number of interventions was recorded in 2022 and 2025, with a total of 4 pumping stations subjected to necessary repair and rehabilitation measures in each of these years involving pump reconditioning, well cleaning, and upgrading motors from 20HP to 30HP. These upgrades indicate an intention of increasing system capacity. In addition, the results align with the discussion in the article of Joseph et al's (2023) referenced in this research, which indicated the age and materials of a pipe as well as its mechanical performance influences the frequency of the failure of a system. Meanwhile, records for 2023 and 2024 have 2 and 3 intervention respectively, indicating a moderate level of maintenance compared to the busiest years.

Additionally, the current year 2026 recorded the lowest number of interventions, with only one pumping station requiring upgrades, focused on performance over repair. Activities like capacity upgrades (SP80-8), p-board upgrades, and comprehensive pump testing were observed during the early months of the same year.

As presented in the table, data on 2024 show a significant technical shift, specifically the Galvanized Iron(GI) was replaced with Polyvinyl Chloride (PVC) pipes, along with the installation of new pumps and motors. PVC is more resistant to corrosion and structural degradation than metallic GI pipes, suggesting that using PVC is a preventive strategy that can significantly improve the long-term reliability of the network. The replacement of GI with PVC suggests that pipe material was identified as a concern within the system.

These findings reflects the discussion of Alvisi & Franchini (2014) in their journal entitled, "Leakages in Water Distribution Networks: Estimation Methods, Influential Factors, and Mitigation Strategies—A Comprehensive Review," in which the authors signifies pipe material to be among many factors influencing leakage occurrence in a water distribution networks.

Overall, the (5) five-year record shows that repair frequency is influenced by infrastructure condition, material upgrades, and mechanical improvements.

As only system-level data are available, the research could not provide a geographic analysis hence, the research could not formally analyze how location influences leakage frequency.

SUMMARY OF FINDINGS

The research examined the occurrences of water leakage incidents within selected water distribution systems in Bulacan by analyzing documented operational records from a local water service provider. The researcher examined forty records and was analyzed using a validated content analysis checklist. The analysis, with the application of descriptive statistical techniques, focused on identifying patterns of water leakages and examining whether factors such as materials and age of a pipe and location were associated with the recorded incidents.

The research provides significant findings regarding the measurable patterns related to water leakage within the water distribution network. First, there is a recorded overall level of 18% NRW across four clusters. The data indicates multiple clusters within the service area experienced measurable levels of non-revenue water.

Second, a total of 84 leakage incidents were recorded on a monthly basis. The presence of incidents per month indicates that the distribution network faces constant operational concerns without interval indications.

Third, over half of the documented leaks (52.38%) occurred in areas categorized as having high water consumption. These areas represent locations within the distribution network where recorded water usage levels are noticeably higher. The findings indicate that leakage incidents are also influenced by consumption levels.

Fourth, a significant finding of 47.62 % of the total leak logs is associated with areas characterized by higher temperature conditions. This signifies an insight that elevated temperature may be a contributing factor in leakage incidents.

Fifth, a recurring pattern of pipe replacements, material upgrades, and system conditioning were observed as major interventions during the 5 years period, concerning the structural integrity of a water distribution network.

Lastly, a lack of proactive approach is observed within a five-year period in which 100% of documented water leakage incidents were only detected by meter checking or reporting with no indicated variation between the two and without provided use of automated monitoring systems or sensor-based detection technologies as primary detection indicator. This implies that the time for necessary interventions is expanded as incidents were not automatically detected and this contributes to the significant level of Non-Revenue Water and service disruptions in a water distribution network.

CONCLUSION

The study highlights an in-depth analysis of water networks as well as the major factors that can develop leakages and increase the NRW rate, identifiable patterns that can happen throughout the production of said pipeline errors, and the main predictive indications used specifically focused on the municipality and province of Pulilan, Bulacan.

The datasets indicated a pattern in leakage predicaments wherein the number of districts connected per cluster is directly proportional to the high occurrences of leakage within the interconnection of pipelines.

In addition, the analysis states that the overall usage load or consumption from main distributors significantly contributes to leakage errors due to tensile stress forming resulting in pipe corrosion and, in turn, developing cracks and leaks as well as an increase in the percentage of NRW being produced.

Finally, findings from documents reveal that the materials used to create pipelines display a major factor for the occurrences of leakage considering the major shift from Galvanized Iron (GI) from the year 2024 to Polyvinyl Chloride (PVC) pipes, making 2026 the year with the least hindrances.

RECOMMENDATION

With reference to the conclusion of the study and the datasets gathered from this study, recommendations from the researchers are as follows:

1. The implementation of an orderly and scheduled inspection of pipelines to determine weaknesses and reasons for recurring leaks.

2. Utilization of sensor-based systems to enable automated detection of leaks within piping systems.

3. Implementing step-by-step procedures for reporting and rapid repair is recommended to optimize system response times and minimize cumulative water losses.

4. Strategic evaluation and replacement of aging or deteriorating pipelines to reduce vulnerability to recurring pipeline errors.

5. Future studies may consider the evaluation of predictive modeling and innovative monitoring systems to guide evidence-based infrastructure decisions

Data Availability Statement

The dataset used in this study consists of operational maintenance records obtained from a selected water service provider in Pulilan, Bulacan. These records, which track system performance and infrastructure conditions, were provided exclusively for research purposes. Due to the sensitive nature of the information and the terms under which it was shared, the full dataset remains confidential. The confidentiality of these records is maintained to prevent the unauthorized exposure of critical municipal infrastructure details.

Although the full dataset remains confidential, the manuscript includes statistical summaries and analytical procedures used in this study to ensure transparency of the research process. Researchers interested in reviewing it for legitimate academic purposes are encouraged to contact the corresponding author. Access is not guaranteed and is subject to a review process involving both the water service provider and any applicable institutional requirements.

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