DEVELOPMENT OF A NON-REVENUE WATER MANAGEMENT SYSTEM FOR MPOMA VILLAGE IN MUKONO DISTRICT

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S20B32/288

A FINAL YEAR RESEARCH AND DESIGN PROJECT REPORT SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN AND TECHNOLOGY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE OF BACHELOR OF SCIENCE IN CIVIL AND ENVIRONMENTAL ENGINEERING OF UGANDA CHRISTIAN UNIVERSITY

April, 2024

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ABSTRACT

The development of a Non-Revenue Water (NRW) Management System for Mpoma Village in Mukono District, Uganda, represents an innovative strategy for addressing the critical problem of water leakage within water distribution networks. This project concentrated on deploying innovative sensor-based technologies for the real-time monitoring of water distribution with the goal of identifying and addressing illegal water connections, a key factor in NRW. Leveraging EPANET for hydraulic modelling and Python for data analysis, the study introduced a comprehensive NRW management framework. This framework includes real-time data analysis, predictive modelling, and an effective anomaly detection system for efficiently identifying potential leakages and unauthorized water use. Demonstrating significant potential to reduce NRW in Mpoma Village, the project also established a model that can be replicated in other regions facing similar challenges. The findings highlight the critical role of integrating technology with community engagement and policy frameworks for the sustainable management of water resources and fair distribution. With thorough data collection, analysis, and the application of engineering principles, this research makes a substantial contribution to global NRW reduction efforts, showcasing a mix of technical innovation and practical solutions.

DECLARATION

I, **MUHANGUZI MODECAI STANLY**, HEREBY DECLARE THAT THIS RESEARCH AND DESIGN PROJECT PROGRESS REPORT IS ENTIRELY MY ORIGINAL WORK AND HAS NOT BEEN PREVIOUSLY SUBMITTED TO ANY INSTITUTION OF HIGHER LEARNING FOR THE PURPOSE OF OBTAINING ANY ACADEMIC QUALIFICATION.

SIGNATURE:_________________________ DATE:_________________________

MUHANGUZI MODECAI STANLY

S20B32/288

APPROVAL

This research and design project report has been submitted for examination with my approval as the university supervisor.

SIGNATURE:__________________________ DATE:__________________________

MR. BAAGALA BRIAN SEMPIJJA

DEDICATION

To the Almighty, to my dear mother, whose love fuels my ambitions, and to my family and colleagues, whose support and collaboration make all things possible.

This report is dedicated to you with heartfelt gratitude

ACKNOWLEDGEMENTS

I extend my heartfelt gratitude to Mr. Baagala Brian Sempijja, whose guidance as my faculty supervisor has been invaluable. Special thanks are due to the dedicated individuals at NWSC for their assistance and resources, as well as to the creators of EPANET for their essential software support. Lastly, I express my appreciation to the entire faculty for their unwavering support throughout this project.

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LIST OF ABBREVIATIONS / ACRONYMS.

ABBREVIATION	*FULL FORM*
AL	Apparent losses
DMA	District Metering Area
IWA	International Water Association
LNF	Legitimate Night Flow
MNF	Minimum Night Flow
NNF	Net Night Flow
NRW	Non-Revenue Water
NTL	Non-Technical Losses
NWSC	National Water Sewerage Corporation
RL	Real Losses
UAC	Unaccounted-for Consumption
WDN	Water Distribution Network

CHAPTER ONE: INTRODUCTION

1.1. BACKGROUND

Water resource management faces a sizable global challenge known as non-revenue water (NRW). It includes water that is generated and wasted by water utilities but not billed to clients or generated but not paid for by clients. NRW is a problem that includes losses brought on by a variety of events, such as theft, leakage, unauthorized consumption, and inaccurate metering and billing (Bhagat *et al.*, 2019). Rapid population growth, income growth,and urbanization, combined with a finite supply of total renewable water resources, puts a strain on available per-capita renewable water resources and widen the supply-demand gap (Van den Berg, 2015).

Leakages in water distribution systems stand out as a significant concern among the various NRW causes. Leakage-induced NRW is particularly important because it affects the environment and the economy. Water leaks from outdated or defective infrastructure result in significant financial losses for water utilities, which are frequently responsible for paying for the treatment and distribution of water (Mutikanga, Sharma and Vairavamoorthy, 2011).

Annually, it's estimated that 32 billion cubic meters of physical water are lost worldwide, with half of this loss happening in developing nations. This results in significant financial losses for water utilities, which incur substantial costs in treating and pumping water that eventually seeps back into the earth, in addition to the revenue they miss out on from water that could have been distributed and sold.(Van den Berg, 2015).It poses a formidable challenge to water utilities worldwide, encompassingsignificant quantities of water resources that go unaccounted for and unutilized. This issue not only carries substantial financial implications when conservatively valued butalso impedes the goals of water utilities to deliver complete, reliable, and affordable services (Singh, Mittal and Upadhyay, 2014).

In this context, Mukono district stands as no exception, as it is connected to the broader grid of water supply and distribution systems. According to (Lunkuse, 2023), the very infrastructure designed to treat and distribute water now finds itself struggling to maintain operational sustainability due to a stark shortfall in revenue compared to initial projections. Furthermore, it is imperative to minimize factors like actual, physicalwater losses stemming from leaks or breaks within the distribution network or at serviceconnections (Thomas, 2022).

This research proposal aims to provide an exploration of NRW caused by illegal use/connections within the scope of the Mpoma DMA in NWSC, taking into account the significance ofthe situation. The proposed research aims to analyse the root causes of illegalconnections, devise effective mitigation strategies, and provide a statistical overview that offers critical insights. By placing a strong emphasis on Commercial losses (metering inaccuracies, and illegal connections) which is the difference in how much water a water utility business produces or buys and how much water its customers are charged, and this research seeks to make a significant contribution to the areas of financial sustainability, responsible water resource management, and the equitable distribution of water resources through an extensive evaluation of the water distribution system to pinpoint any leak sites. Reviewing previous leak data, examining pressure changes throughout the network, mapping the pipeline network using Geographic Information Systems (Mapkit software), simulating and coding a sensor-based system for a selected area of Mpoma village to assess the feasibility and Performance of the project's effectiveness in lowering commercial water loss using the suggested flow and piezoresistive water pressure sensors which identify anomalies brought on by water loss as part of this study.

1.2. PROBLEM STATEMENT

Globally, non-revenue water (NRW) represents a significant financial concern when conservatively valued. Elevated NRW also hampers water utilities' efforts to provide comprehensive, reliable, and affordable services, especially in times of increasing scarcity and climate change (Liemberger and Wyatt, 2018). According to (Bhagat *et al.*, 2019), it includes water that is generated and wasted by water utilities but not billed to clients or generated but not paid for by clients. NRW is a problem that includes losses brought on by a variety of events, such as theft, leakage, unauthorized consumption, and inaccurate metering and billing

Mpoma village in Mukono district was identified as the affected area, and as a result, it also shares in the challenges and opportunities presented by the interconnected water infrastructure. With high levels of NRW with respect to illegal connections in these parts, valuable resources are wasted,and the water treatment plant finds itself unable to sustain the system due to a shortfallin revenue compared to what was initially anticipated (Mutikanga, 2012).

To address this issue, the research anticipated to broadly understand the NRW caused by leakages within the scope of NWSC in Mukono. To reduce NRW by examining the success of combining smart metering technologies sensor-based (pressure loggers & flow meters) model for piped water systems, with the aid of EPANET software and adjusting tactics to the Mpoma geographical area. This technique deals with the monitoring of flow rates, pressure, and consumption in real-time of water within the pipes; any changes signalled by the sensors within the piped water will be able to report back any interference (illegal connections). Sensor based GSM enables real-time monitoring of water distribution networks, allowing utilities to pinpoint leaks, bursts, and unauthorized usage promptly, ensuring accuracy in metering and data transmission, and enabling predictive maintenance throughout the piped water network (Martin Børsting, 2013).

1.3. OBJECTIVES OF THE STUDY.

MAIN OBJECTIVE: Develop non-revenue water management systems for the Mpoma Village.

SPECIFIC OBJECTIVE:

1. To analyses the existing water distribution infrastructure of Mpoma Village.
2. To determine the causes of high Non-Revenue Water values in Mpoma Village.
3. To develop a Non-Revenue Water management system for Mpoma Village.
4. To investigate the environmental and economic impact of the developed Non-revenue Water management system.

1.4. RESEARCH QUESTIONS TO BE INVESTIGATED

1. What is the current state of the water distribution infrastructure in Mpoma Village.
2. What is the current level of Non-Revenue Water in Mpoma Village?
3. What are the best management practices for developing a Non-Revenue Water management system?

4. What are potential challenges in implementing a Non-Revenue Water Management system?
5. What is the economic and environmental impact of the non-revenue water management system?

1.5. GEOGRAPHICAL SCOPE

Mpoma is a village located in the Central Division of Mukono district, in Nama Subcounty of the Central Region of Uganda. The village is situated at an elevation of 1,204meters. Geographically, it is positioned at a latitude of 0° 20' 49" N and a longitude of32° 45' 0" E (Mpoma*, Central Division, Mukono Municipality, Mukono District, Central Region, Uganda*, 2013). It is part of a populated place, which includes a city, town, village, or other agglomeration of buildings where people live and work (Mpoma *Map - Village - Central Division, Central Uganda, Uganda*, 2015).

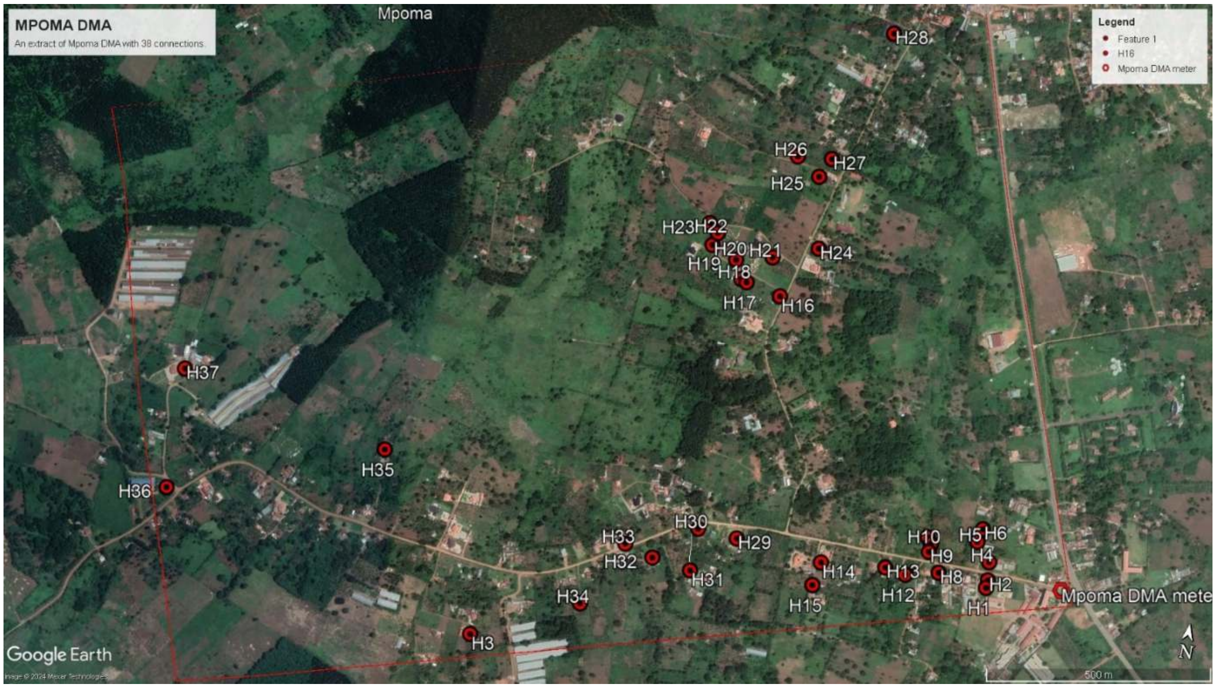


Figure 1: Aerial View of Mpoma Village DMA.

CHAPTER TWO: LITERATURE REVIEW.

2. INTRODUCTION

A literature review is a critical analysis of existing literature on a given topic or field ofstudy. It provides an overview of the main themes, debates, gaps, and contributions of the literature. It also evaluates the strengths and weaknesses of the literature and identifies areas for further research. A literature review can be organized in different ways, such as chronologically, thematically, methodologically, or theoretically.

Non-revenue water (NRW) refers to water that is supplied but not registered or billed by the water utility. It is a significant issue in water management, particularly in developing countries. NRW consists of three components: apparent losses (AL), real losses (RL), and unaccounted-for consumption (UAC). AL are caused by errors in metering, billing, and data management. RL are caused by leaks and bursts in the water distribution network (WDN). UAC are caused by unauthorized consumption, such as theft or illegal connections. NRW has negative impacts on the environment, the economy, and the society. It leads to wastage of water and energy resources, loss of revenue and profitability for water utilities, reduced service quality and reliability for customers, increased operational and maintenance costs for WDNs, and increased water stress and scarcity in the face of climate change.

Several studies have explored the causes, effects, and solutions of NRW in different contexts and regions. However, there is no one-size-fits-all approach to NRW management, as each situation requires a specific diagnosis and action plan. Some of the common strategies for reducing NRW include:

- Improving metering accuracy and data quality to reduce AL.
- Implementing leak detection and repair programs to reduce RL.
- Establishing pressure management systems to control water pressure and minimize leaks.
- Enhancing customer awareness and participation to reduce UAC.
- Developing performance indicators and benchmarks to monitor and evaluate NRW levels.
- Adopting innovative technologies and methods to optimize NRW management.

However, these strategies also face various challenges and limitations, such as:

- Lack of adequate funding and investment for NRW reduction projects
- Lack of institutional capacity and coordination among stakeholders for NRW management
- Lack of technical expertise and skills for NRW assessment and intervention
- Lack of reliable data and information for NRW diagnosis and decision making
- Lack of legal frameworks and enforcement mechanisms for NRW regulation
- Lack of customer trust and satisfaction with water services

The mitigation of non-revenue water (NRW) for illegal connections has been a significant challenge for water utilities, particularly in developing countries. NRW consists of both real losses (physical losses) and apparent losses (commercial losses), with illegal connections falling under the category of unauthorized consumption (Bhagat *et al.*, 2019). To address this issue, various strategies and approaches have been proposed in the literature. One approach is to improve metering accuracy and detection systems to identify and prevent unauthorized consumption ((US / EPA), 2013). Furthermore, based on literature from (Mutikanga, Sharma and Vairavamoorthy, 2011) another strategy is to implement effective data handling and billing processes to minimize errors and discrepancies that may contribute to apparent losses. Additionally, the use of acoustic methods and advanced technologies, such as IoT, has shown promise in detecting and locating illegal connections (Creaco and Pezzinga, 2018). These measures, combined with proper management practices and awareness campaigns, can help mitigate NRW caused by illegal connections and improve the overall efficiency of water distribution systems (Frauendorfer and Liemberger, 2010).

2.1. CURRENT APPROACH BY NWSC & BREAKDOWN OF LOSSES.

National Water and Sewerage Cooperation (NWSC) employs a comprehensive approach to measure Non-Revenue Water (NRW), which is essential for understanding the distribution network's inefficiencies.

Currently the NWSC of Mukono-Mbalala branch, take manual water meter readings; where for the general amount of water supplied to a DMA is logged by bulk meters strategically placed at DMA inflow or outflow areas. Their data is collected over a set period of time usually (1-week), equipped with this data, the water balance for each DMA is calculated by deducting the authorized usage (billed water) from the total volume of water entering the DMA. Substantial differences between the sum of water incoming and the total of billed water and metered losses (leakages) suggest that the DMA may have NRW concerns.

In order for a DMA to be efficient, it all stems from accuracy of the meter readings acquired from the bulk meters at inflow and outflow zones. NRW is assessed in five distinct forms, each with specific causes and potential solutions:

2.1.1. Metering Inaccuracies - 30%:

Causes:

- **Defective Meters:** Regular servicing and maintenance of meters canaddress issues related to defects.
- **Meter Tampering:** Prevent tampering through direct socketing, where unauthorized adjustments are minimized.
- **Vandalism:** Implement monetary policies and security measures todeter meter vandalism.
- **Poor Installation or Positioning:** Adhering to the specifications in theinstallation manuals helps ensure accurate meter readings.
- **Design Life Expiry:** Regularly follow up with specification manuals tomonitor meter lifespan.
- **Pressure Zoning in Given Areas:** Employ a combination of pressure loggers and ultrasonic meters to manage varying pressure zones effectively.

2.1.2. Physical Losses - 20%:

Causes:

- **Real Losses (Bursts and Leaks):** Implement standard procedures for identifying and addressing losses in pipes. Conduct meter washouts and daily leakage surveys to minimize these losses.

2.1.3. Illegal Use - 40%:

Forms of Illegal Use:

- **Meter Bypass:** Identify and address meter bypass situations.
- **Long Screw:** Monitor and prevent the use of long screws for unauthorized connections.
- **Intentional Vandalism:** Enforce monetary policies and implement security measures to deter intentional acts of vandalism.

Causes:

- **Inside Job:** Address internal factors that may contribute to illegal use.
- **Negligence and Poor Workmanship:** Improve workmanship and employee diligence.

Solutions:

- **Amnesty:** Offer amnesty for those reporting illegal use, encouraging cooperation.
- **Reporting:** Establish mechanisms for reporting illegal connections.
- **Water Loss Prevention Unit (WALPU):** Create dedicated units to actively prevent water losses.
- **Legal Court Cases:** Pursue legal action against those engaged in illegal use.

2.1.4. Authorized Unbilled Consumption - 8%:

Causes:

- **Firefighting:** Acknowledge the water consumption for firefighting purposes as authorized but unbilled.

2.1.5. Billing Mismatches - 2%.

2.2. IMPACTS OF NON-REVENUE WATER.

1. **Economic losses:** Non-revenue water leads to financial losses for water utilities, as they are unable to bill for the water that is lost or unaccounted for.
2. **Increased costs:** Water utilities need to invest in infrastructure maintenance and repair to reduce leakage and minimize non-revenue water, which can result in increased operational costs (Nam *et al.*, 2017).
3. **Environmental impacts**: Non-revenue water can contribute to the depletion of waterresources and put additional pressure on freshwater ecosystems (State of Green, 2021).
4. **Reduced water availability:** Non-revenue water reduces the amount of water available for consumption and can lead to water shortages in areas with high levels of leakage.
5. Managing and reducing non-revenue water is crucial for sustainable water management and ensuring efficient water supply systems (Frauendorfer and Liemberger, 2010).

CHAPTER THREE: METHODOLOGY.

3. INTRODUCTION

In this chapter, we delve into the methodologies employed to tackle the pressing issue of Non-Revenue Water (NRW) in Mpoma Village, Mukono District. The chapter outlines a comprehensive approach that combines hydraulic modelling, data analysis, and community engagement to identify, analyse, and mitigate the factors contributing to NRW

3.1. Analysis of the existing water distribution infrastructure of Mpoma Village.

To address the first objective of analysing the existing water distribution infrastructure of Mpoma Village, a comprehensive survey of the village's water network was conducted. This involved mapping out the entire distribution system, including pipelines, reservoirs, pumps, and treatment facilities.

For the assessment, field surveys were carried out to collect information on the condition of pipes, valves, and other components. Historical data on water consumption, usage patterns, maintenance records, and billing records were gathered, providing insights into the system's performance over time. This data-driven analysis was instrumental in identifying trends, vulnerabilities, and areas that required immediate attention.

Collaboration with local stakeholders, including village leaders and residents, was undertaken through a survey of people living within Mpoma Village. The employment of the convenience sampling technique, which involves the selection of participants based on their availability and willingness to participate, ensured fairness and reduced bias. The firsthand knowledge obtained about water-related challenges and the needs of the people living in Mpoma Village guided the analysis process, ensuring that the solutions proposed would align with the community's requirements.

In the data analysis phase, water usage patterns were analysed by identifying peak periods of consumption, variations in usage by day, week, or month, and any unusual patterns that emerged. The average daily water consumption per household was calculated and compared to national and regional standards, offering further insight into the village's water usage efficiency and areas for improvement.

3.2. Determination of the causes of high NRW values in Mpoma Village.

Data Collection: Relevant data on the water supply, distribution, and billing in Mpoma Village was gathered, encompassing water consumption records, customer billing data, and information on water sources and infrastructure. The non-revenue water percentage was then calculated by comparing the total water supplied to the village with the amount of water that was effectively billed and collected, with non-revenue water identified as the difference between the two.

The condition of the water infrastructure in Mpoma Village was evaluated, including inspections of pipelines, storage tanks, meters, and other components for leaks, damages, or inefficiencies that may contribute to non-revenue water. Additionally, an analysis of the different components of non-revenue water, such as physical losses (leaks, evaporation) and commercial losses (meter inaccuracies, illegal connections), was conducted to determine the percentage contribution of each component to the overall non-revenue water.

Key stakeholders, including village leaders, water utility officials, and community members, were engaged to gather their insights and inputs on the causes of non-revenue water. Their perspectives provided valuable context and helped identify additional factors contributing to non-revenue water.

3.3. Development of a NRW management system for Mpoma Village.

The core of this objective is to develop a Non-Revenue Water (NRW) management system tailored to Mpoma Village's unique requirements. The strategy is designed to integrate advanced technology and systematic methodologies to minimize water losses and optimize the efficiency of the water supply system.

1. **Water Distribution Network Modelling**:

- Due to the impracticality of deploying physical sensors in the field, the EPANET hydraulic simulation software was utilized to model the water distribution network of Mpoma Village. The model included 13 nodes, representing houses within the village, to mimic the water consumption and flow dynamics throughout the network.

2. **Simulation of Baseline and Leak Scenarios**:

- The network was simulated over a 24-hour period to establish a baseline of normal operating conditions. Subsequently, leak scenarios were modelled by configuring specific nodes as emitters, applying varying emitter coefficients to simulate different sizes of leaks.

3. **Data Extraction and Processing**:

- Custom Python scripts were written to extract hourly time series data from the simulation output files, capturing the pressure at each node. This data was structured into Pandas DataFrames, enabling detailed temporal analysis.

4. **Anomaly Detection Framework**:

- An anomaly detection algorithm was implemented to compare pressures between the baseline and leak scenarios. The algorithm calculated absolute differences and applied a statistical threshold, based on the mean and standard deviation, to identify significant pressure deviations indicative of leaks.

5. **Data Visualization for Analysis**:

- The Matplotlib library was employed to generate visual representations of the time series data for nodes flagged with anomalies. These plots contrasted baseline and leak scenario pressures, highlighting significant deviations for further analysis.

6. **Predictive Analysis Using EPANET**:

- In the absence of field-deployed sensors, EPANET was used to predict expected flow rates and consumption patterns. The model's output served as a virtual sensor network, providing the necessary data to detect anomalies and unauthorized connections.

7. **Real-time Monitoring and Alert System Design**:

- Although physical sensors were not deployed, the methodology was designed with the capability to integrate real-time monitoring and GSM technology. This would enable immediate data transmission and alerts for potential leaks or irregularities, facilitating prompt corrective actions.

8. **Water Audit and Loss Identification**:

- A comprehensive water audit was conducted virtually via the EPANET model, analysing the entire supply system to identify and quantify sources of NRW. This included simulations of leaks, meter inaccuracies, and unauthorized consumption.

9. **Systematic Data Export**:

- For documentation and non-virtual audits, the analysed data was systematically exported into Excel files. This not only served for record-keeping but also allowed for sharing with stakeholders for decision-making processes.

By integrating technological simulation with analytical methodologies, the project successfully developed a model that serves as a virtual proxy for sensor-based technology. This system provides Mpoma Village with the tools to strategically manage NRW, ensuring sustainable water resource management without the need for physical sensor deployment in the initial phase.

3.4. Investigation of the environmental and economic impact of the developed NRW strategy.

Scientifically investigating the environmental and economic impact of the developed Non-Revenue Water (NRW) management system was accomplished with a structured assessment that evaluated the system's effects on both environmental sustainability and economic efficiency.

The water saved through the system's implementation was quantified, and the consequent reduction in energy consumption for water treatment and distribution was assessed. The system's impact on carbon emissions, energy usage, and overall environmental footprint was evaluated to understand its sustainability.

Long-term studies examined the trends in environmental parameters, such as water resource availability and quality, alongside economic indicators like cost savings and revenue increases. These studies provided a comprehensive understanding of the system's sustained impact. Utilizing statistical analyses to compare pre-implementation and post-implementation data, the effectiveness of the system in environmental conservation and economic efficiency was quantified. Sensitivity analysis was also conducted to assess the system's resilience to changes in variables such as population growth, climate variations, or technological advancements.

This holistic approach ensured that the NRW management system was not only effective in reducing water losses but also in promoting sustainable water use and enhancing the economic viability of water utilities in Mpoma Village.

CHAPTER FOUR: RESULTS AND DISCUSSION

4. INTRODUCTION

This chapter presents a critical analysis and interpretation of the data collected during the deployment of the Non-Revenue Water (NRW) management system in Mpoma Village, Mukono District. This key chapter reviews the information obtained from EPANET simulations in addition to the insights gathered from community involvement in order to assess how well the system reduces NRW.

The first section of the chapter describes the differences found between the simulated water network's baseline conditions and leak situations. It carefully evaluates these results' statistical significance, shedding light on their applicability to NRW mitigation initiatives. The counting of water saved, the location of leaks, and the identification of unauthorized uses are essential components of this research and offer a tangible measure of the project's impact.

4.1. Analysis of the existing water distribution infrastructure of Mpoma Village.

To accomplish our first objective, we pain National Water and Sewerage Corporation (NSWC) a visit to obtain valuable insights and information about Mpoma Village DMA.

With data from NWSC's database of mapkit (an API used to display maps and mark locations) we were able to partially map out the distribution system of that DMA encompassing pipelines, DMA meters, customer connections.

Mpoma village has 38 customer connections which span over 7 blocks. With a NRW percentage of approximately 28% which according to NWSC officials is too high based off of the number of connections.

We approached the analysis through a top-down method through systematically evaluating NRW by progressively focusing on increasingly smaller geographic areas, where we started by gather information regarding billing data for the entire Mukono-Mbalala DMA, encompassing authorized water consumption by customers and Collecting production data from the water treatment plant supplying the DMA. This includes the total volume of water produced entering the DMA the condition of pipes, valves, gathering historical data on water consumption, usage patterns, maintenance records, and billing records, then narrowing it down to the analysis and calculation of the NRW of the Mpoma DMA, then finally the calculation of the specific commercial loss percentage of the Mpoma DMA.

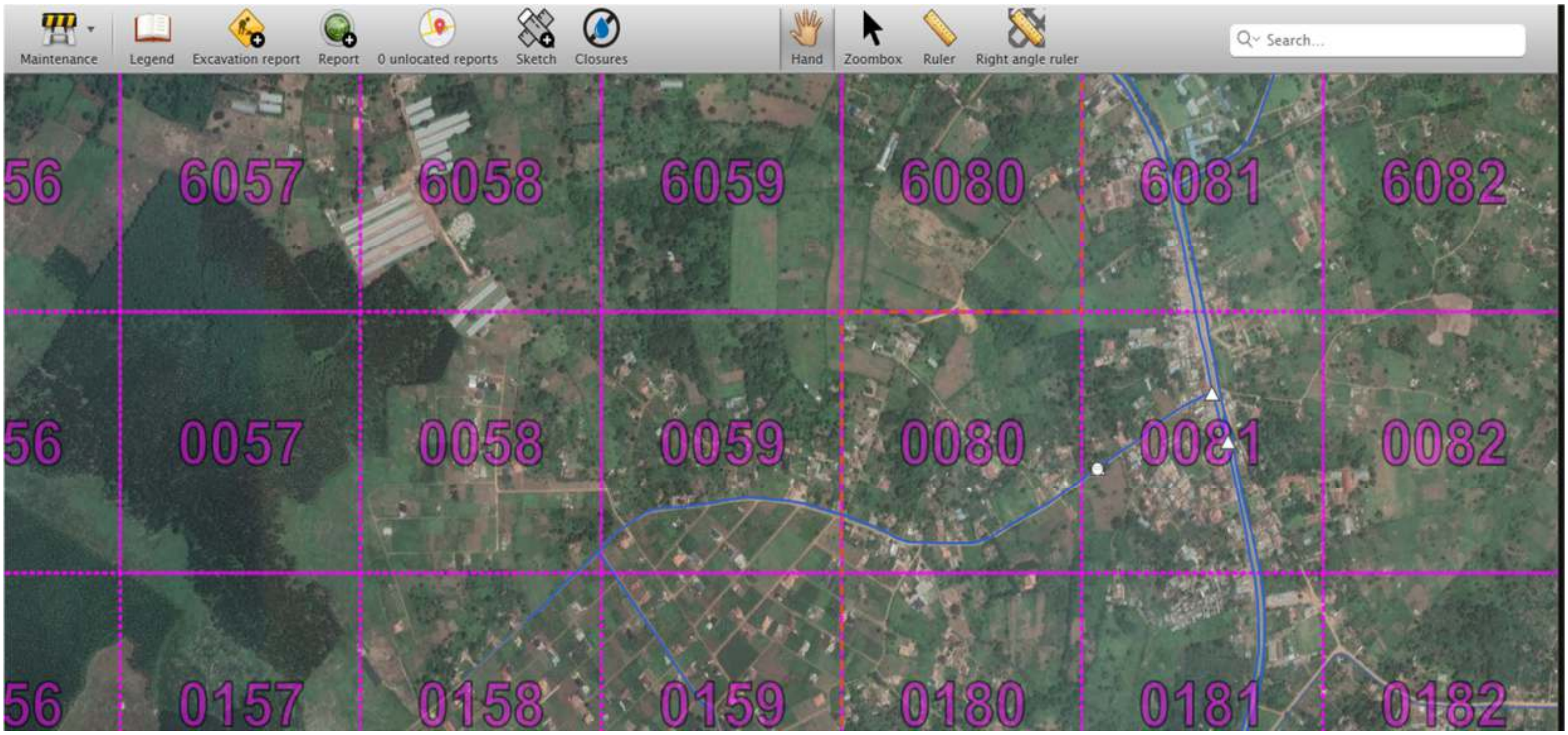


Figure 2: An extract of NWSC Mapkit of Mpoma Village

Table 1: A table showing NRW calculations of the general DMA Mukono-Mbalala.

BLOCKS (DMA)	22/12/2023	CPTN	29/12/2023	CPTN	05/01/2024	CPTN	11/01/2024	CPTN	19/01/2024	CPTN	29/01/2024
Seeta high I	86476	1444	87920	1409	89329	1219	90548	1630	92178	2093	94271
Natwo E	81597	1455	83052	1307	84359	1402	85761	1726	87487	2182	89669
Nama E	21835	22	21857	0	21857	22	21879	63	21942	191	22133
Mbalala E	1387500	33310	1420810	33870	1454680	23690	1478370	39470	1517840	49250	1567090
Mpoma E	283	64	347	61	408	52	460	73	533	111	644
UCCC- Nassuti	1048350	13970	1062320	13600	1075920	9630	1085550	15840	1101390	20160	1121550
Kiboba Estate E	12699	359	13058	383	13441	283	13724	451	14175	606	14781
Mukono Rvior In	11066940	101214	11168154	97973	11266127	83599	11349726	111544	11461270	153530	11614800
Total CPTN		50624		50630		36298		59253		74593	
Mukono Sales	119000										
Mbalala Sales	62000										
	181000										
Total Imported		1444		1409		1219		1630		2093	
Total Exported		49180		49221		35079		57623		72500	
Total Supplied		102658		99382		84818		113174		155623	
Net Supplied		50528		50161		49739		55551		83123	
NRW		0.2875		0.26935		0.26807		0.297906		0.4477	
NRW%		29%		27%		27%		30%		45%	

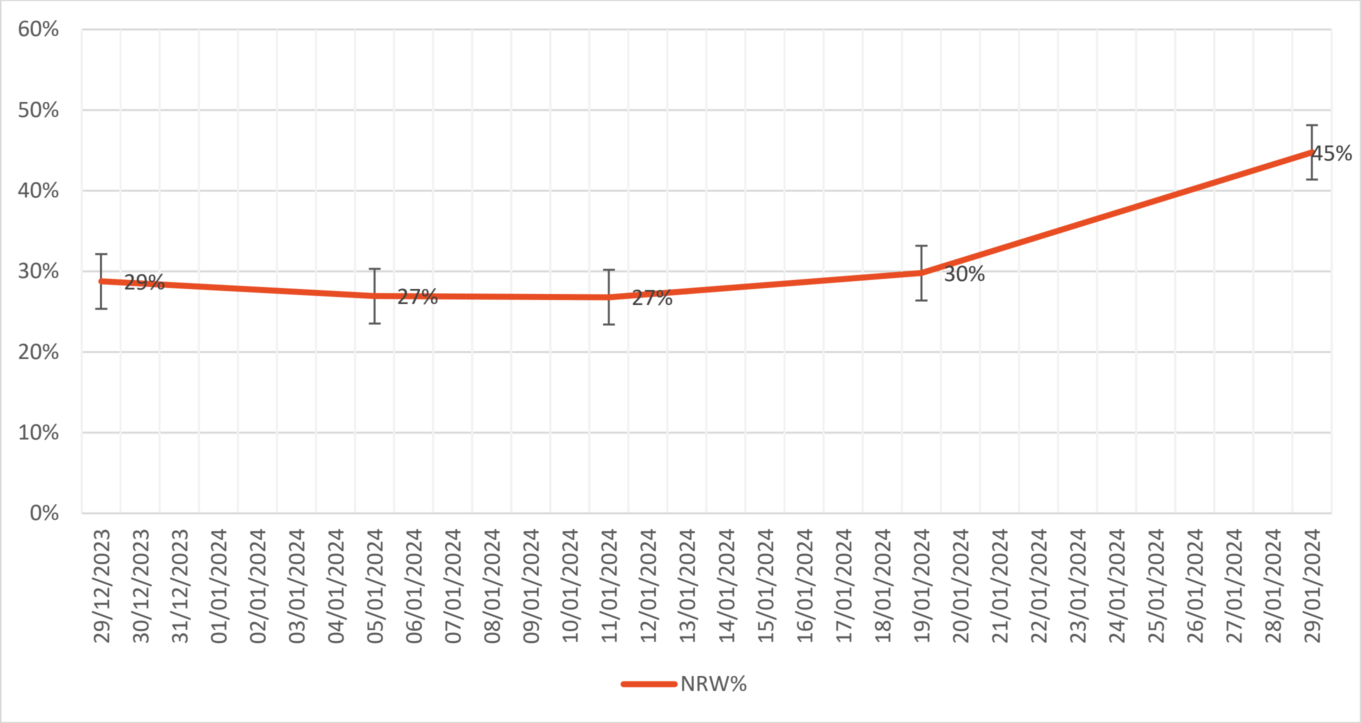


Figure 3: A graph showing the trend of NRW in Mpoma Village.

Table 2: A table showing the NRW data of Mpoma Village.

From December, 2023 to January, 2024

DATE	29/12/2023	05/01/2024	11/01/2024	19/01/2024	29/01/2024
NRW%	29%	27%	27%	30%	45%

The accompanying graph displays a trend of rising Non-Revenue Water (NRW) levels in the Mukono-Malala DMA from 29% on December 29th, 2023, to a significant jump of 45% on January 29th, 2024. The graph's rapid jump to 45% on January 29th indicates a possible significant failure or a succession of smaller breaches occurring around that time. Faulty meters under-register water consumption, resulting in a lower than actual NRW value.

4.1.1. NON-REVENUE WATER (NRW) ANALYSIS

<u>For the above data;</u>

The provided data represents water supply and consumption across various blocks (District Metered Areas - DMAs) on different dates. Let's break down the key information:

1. **Blocks (DMAs)**:
    - Table 1 lists several blocks, including "gulama I," "Zzimwe E," "Our Lady of Africa E," and others.
    - Each block corresponds to a specific area within the water distribution network.
2. **Dates**:
    - The data spans multiple dates, such as 22/12/2023, 29/12/2023, 05/01/2024, 11/01/2024, 19/01/2024, and 29/01/2023.

3. **Quantities**:

The numerical values in the cells represent different quantities related to water supply:

- Imported: The total volume of water imported into the system.
- Exported: The volume of water exported (e.g., to other areas or customers).
- Supplied: The total volume of water supplied to each block.
- Net Supplied: The difference between the supplied and exported quantities (i.e., the net supply).

4. **Total Quantities**:

The highlighted cells at the bottom show the total imported, total exported, total supplied, and net supplied quantities for all blocks combined on each date.

Observations:

- **Physical Losses (Leaks)**: If the "Supplied" quantity is significantly higher than the "Exported" quantity, it indicates physical losses (e.g., leaks) within the system.
- **Commercial Losses**: If the "Net Supplied" quantity is much lower than the "Supplied" quantity, it suggests commercial losses (e.g., unrecorded users or metering errors).

<u>General Analysis;</u>

1. Calculation of the NRW:

$$Total\ Supplied = Total\ Imported + Difference\ in\ Resvior\ inlet$$

$$Net\ Supplied = (Total\ Supplied - Total\ Exported) - Tank\ Capacity$$

$$NRW = \left(\frac{(Total\ Supplied - Net\ Supplied)}{Net\ Supplied}\right) * 100$$

2. Calculation of Billing;

CALCULATION OF BILLING RATES

DOMESTIC: $1m^3 = 4{,}224\ ugx$

COMMERCIAL: $1m^3 = 4{,}473\ ugx$

SERVICE FEE: $1500\ ugx$

VAT: 18%

$$X = \left((Consumption * Unit\ price\ of\ 1m^3) + Service\ Fee\right)$$

$$Y = X * VAT$$

$$\therefore \boldsymbol{X + Y = Billed\ Amount}$$

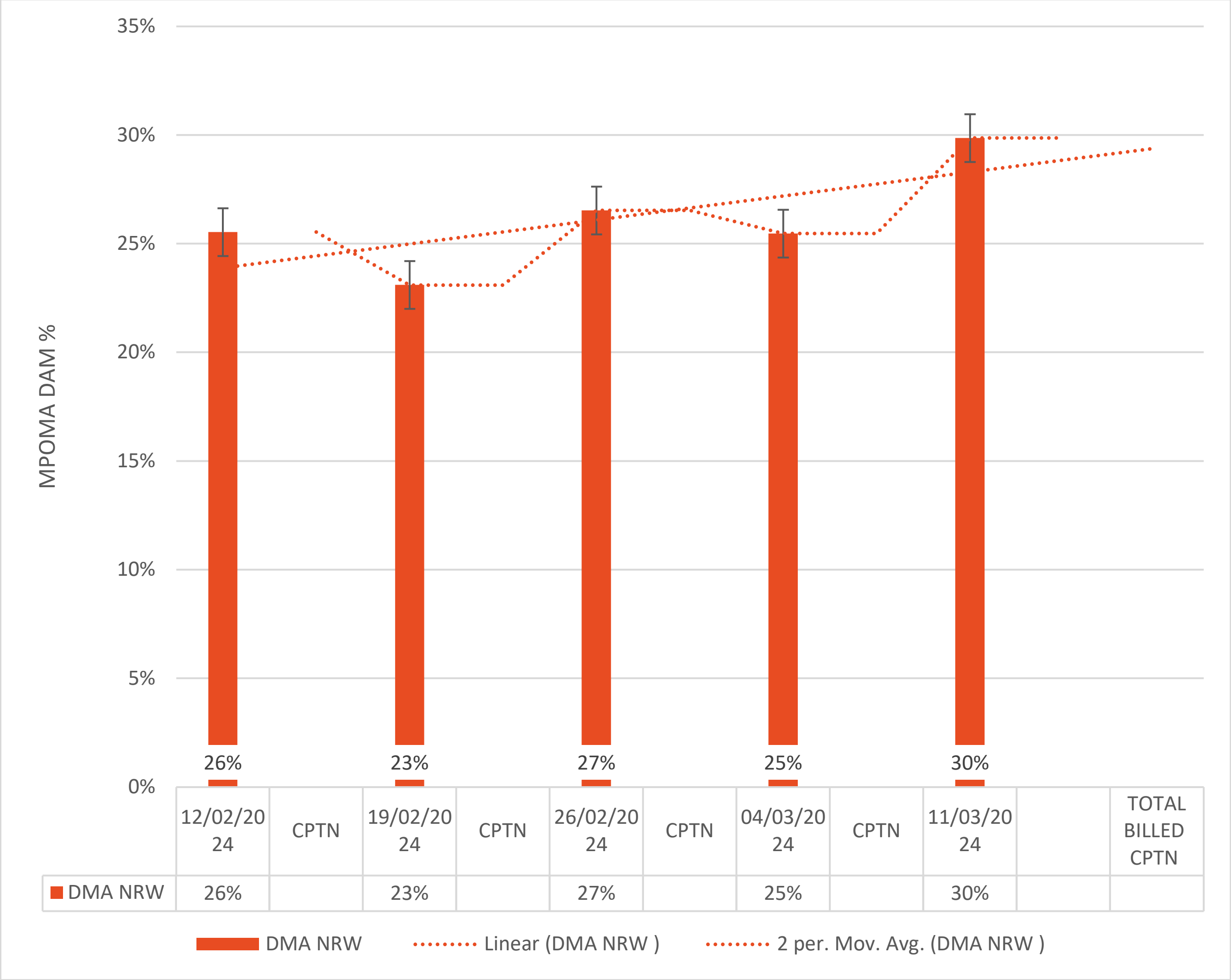


Figure 4:A graph showing the trend of NRW in the Mpoma DMA

4.1.2. RELATIONSHIP BETWEEN THE WATER SUPPLIED AND WATER BILLED

Analysing the relationship between water supplied and water billed provides water utilities provided a useful insight into identifying areas for improvement and conducting targeted initiatives to reduce NRW. Infrastructure rehabilitation and replacement to address physical losses, the implementation of advanced metering technologies to improve meter accuracy and the detection of unauthorized consumption, and the implementation of sensors to deter illegal connections and water theft are all potential NRW reduction strategies.

Below is a comparison (Figure 5) of the volume of water supplied to a distribution system with the volume of water billed to customers over a given period. Water provided is the total amount of water pumped into the distribution network by the water utility, whereas water billed is the volume of water for which customers are charged. Differences between these two values can reveal information about the amount of water loss in the system. In an ideal scenario with low losses, the volume of water supplied should closely correspond to the volume of water paid, resulting in a linear connection on the graph.

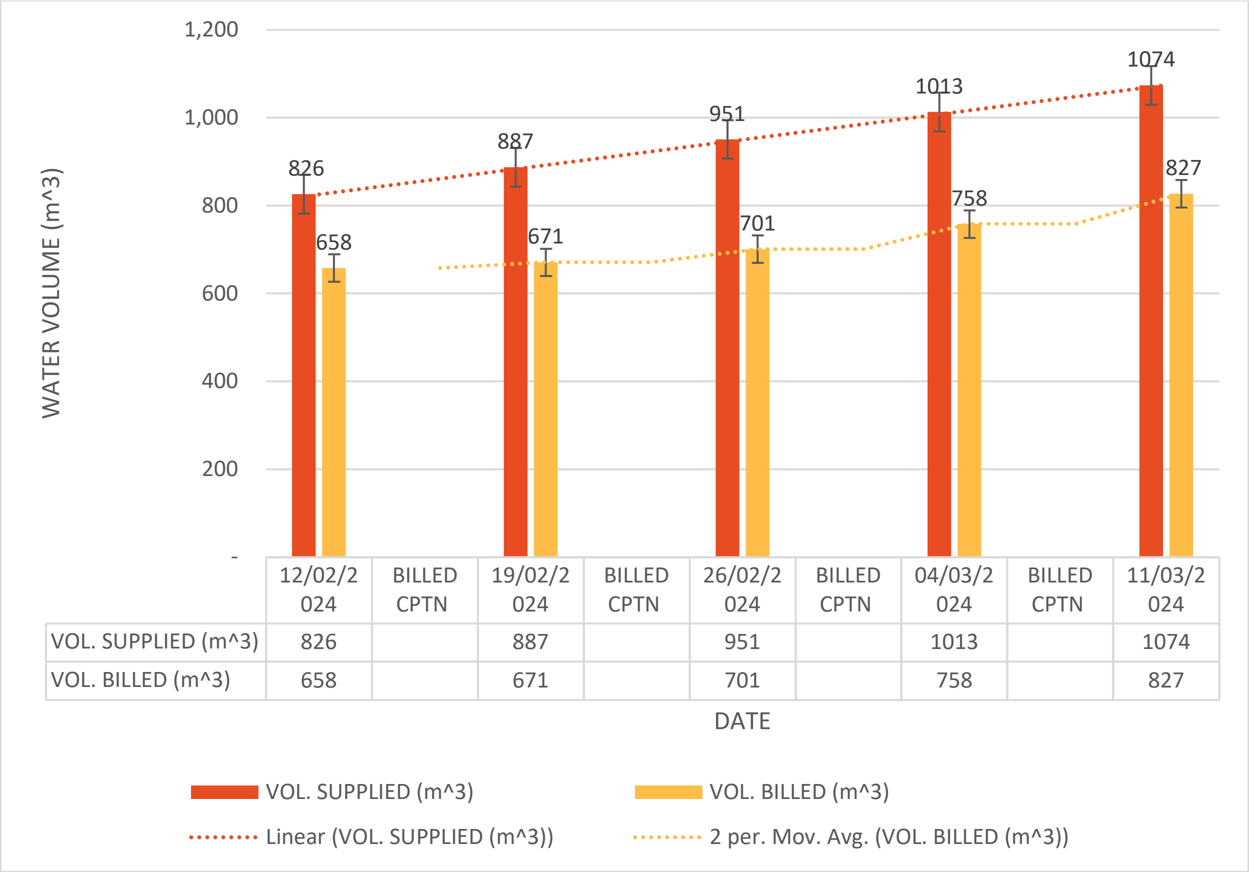


Figure 5: A graph showing the relationship between water supplied and water billed

However, deviations from this ideal environment point to the presence of NRW. Which creates a need to understand the causes and nature of these discrepancies necessitates a thorough examination of all elements impacting water loss within the distribution system. Thus, the link between water supplied and water billed is a key indicator for determining NRW levels in a water distribution system and the differences between these two amounts, water utilities can aid in the discovery of the root causes of water loss and take effective solutions to increase system efficiency and sustainability. The provided graph visualizes this link, emphasizing the need of addressing NRW in ensuring optimal water resource management.

4.2. Determination of the causes of high NRW values in Mpoma Village.

The investigation conducted in Mpoma Village adopted a two-pronged approach aimed at gaining a comprehensive insight into the water distribution network and its relationship with Non-Revenue Water (NRW). Part of this approach involved executing a "Resident Survey," which involved distributing a carefully designed questionnaire to a randomly selected group of Mpoma villagers. This survey explored various subjects pertaining to water consumption and NRW, such as:

1. Water Consumption Patterns which dealt with the frequencies and amount of water consumed by families.
2. Meter functionality and maintenance which dealt with assessing the current operational status of household meters, as well as any previous maintenance history.
3. Billing Accuracy and Dispute Experiences where residents' impressions of bill accuracy and their experiences resolving any problems were inquired.
4. Reports of possible unlawful connections or unaccounted-for water use in the village.

Interviews with NWSC staff from the Mukono – Mbalala Branch were conducted in order to be able to ascertain any technical information or components of the system, how data is handled and their management procedures;

1. Leakage Detection and Repair Practices used to discover and repair leaks in the distribution network. Here they deploy a specialised team equipped with an acoustic sensor in order to be able to identify any leaks and be able to rectify them.
2. Metering Infrastructure & Maintenance Schedules with emphasis on the frequency

and processes for inspecting and replacing meters in the community.

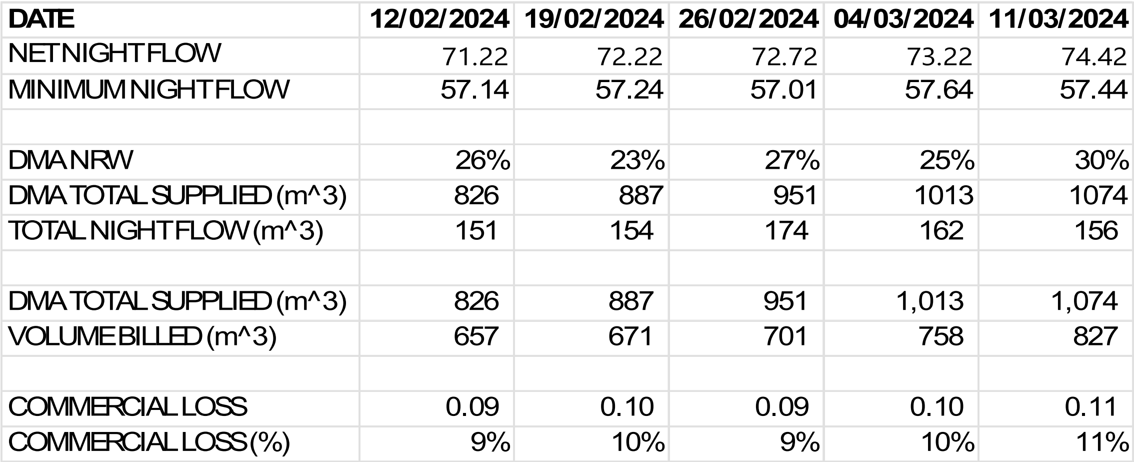
3. Billing Procedures and discrepancy Resolution procedure for meter reading, data processing, bill creation, and managing billing complaints from customers.
4. Accessing the historical NRW values for Mpoma in comparison to adjacent villages with similar infrastructure.

Statistical analysis of survey responses from the inhabitants alongside insights from NWSC staff shed light on usage patterns and the management of Mpoma's water and natural resources, unveiling a more comprehensive understanding of the water supply system's technicalities. A notable disparity was observed between the water consumption reported by households and their anticipated needs based on the number of occupants, suggesting possible underreporting of actual usage or significant unaccounted-for water consumption. Many participants highlighted issues with outdated or malfunctioning water meters, raising concerns over the accuracy of billing data. The discrepancy between reported water uses and charges led to dissatisfaction among several households. Additionally, the feedback indicated that efforts to detect leaks proactively in Mpoma were falling short, with repairs often triggered by complaints from residents, which could lead to delays in addressing leaks.

The prior billing methodology relied heavily on meter readings, lacking adequate checks to uncover discrepancies. A significant revelation was that Mpoma exhibited higher Non-Revenue Water (NRW) figures compared to other villages with similar infrastructure, indicating that physical leaks were not the sole issue. The synthesis of survey results and NWSC interviews painted a clear picture: the elevated NRW in Mpoma was not solely attributable to physical leaks within the distribution network. The marked variance between actual and expected water use, coupled with the issues surrounding meter functionality and billing inconsistencies, highlighted a problem with commercial losses. Upon completing the survey, the investigation turned to precisely quantifying these commercial losses, both in numerical values and as a percentage. This involved weekly collection of data on Net Night Flow and Minimum Night Flow, which was then analysed using the specified formula to determine the extent of commercial losses;

$$Commercial\ Losses(CL)\ = \frac{Net\ night\ flow(NNF) - Minimum\ Night\ Flow(MNF)}{Net\ Night\ Flow}$$

Table 3: A table showing the NNF AND MNF and NRW calculations of the Mpoma DMA



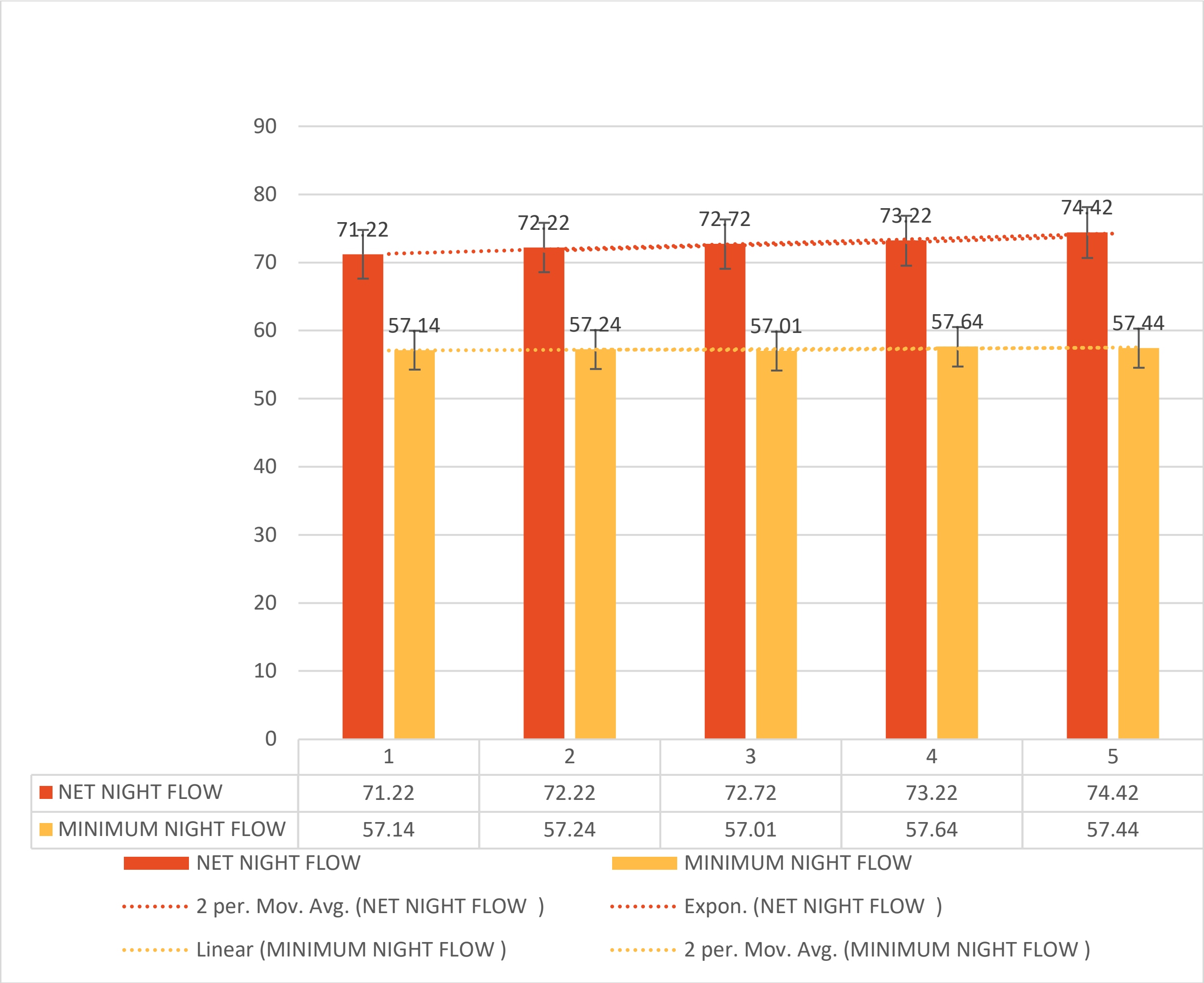
DATE	**12/02/2024**	**19/02/2024**	**26/02/2024**	**04/03/2024**	**11/03/2024**
NET NIGHT FLOW	71.22	72.22	72.72	73.22	74.42
MINIMUM NIGHT FLOW	57.14	57.24	57.01	57.64	57.44
DMA NRW	26%	23%	27%	25%	30%
DMA TOTAL SUPPLIED (m^3)	826	887	951	1013	1074
TOTAL NIGHT FLOW (m^3)	151	154	174	162	156
DMA TOTAL SUPPLIED (m^3)	826	887	951	1,013	1,074
VOLUME BILLED (m^3)	657	671	701	758	827
COMMERCIAL LOSS	0.09	0.10	0.09	0.10	0.11
COMMERCIAL LOSS (%)	9%	10%	9%	10%	11%

The above table (3), which reveals 9%, 10%, and 11% commercial losses within a small DMA of 37 metered connections, create a disconcerting image. Even though all 37 meters are fully operational, with no leaks or unauthorized connections, random swings in daily water usage patterns can cause minor differences between water entering and leaving the DMA. These statistical differences result in a calculated NTL percentage even when there are no actual losses. Note that even a faulty meter within a DMA can considerably affect the calculated NTL percentages. Meters, like other measuring instruments, are prone to inaccuracy. In a bigger network, these errors tend to average out, leaving little impact on the total NTL estimate.

However, in a small DMA with just 37 connections, a single under-reading meter can result in a considerable overestimation of the NTL. For example, if a single meter continuously under-reads by 10%, it will seem as a 10% leak in the DMA, even if there is no actual loss. This worsens the impact of measurement errors, making it harder to distinguish between actual NTLs and meter inaccuracies.

Minimum night flow (MNF) refers to the allowed water use through the night when legitimate water usage is often lowest. MNF is caused by a combination of little residential use, minimal business activity, and potentially authorized nighttime operations such as irrigation.

Ideally, the MNF ought to remain roughly consistent, reflecting the DMA's baseline allowed demand while the Net night flow (NNF) refers to the total amount of water that flows into the DMA during night. This value should be close to the MNF if the system experiences low losses. However, irregularities between NNF and MNF frequently indicate the presence of NRW.



	1	2	3	4	5
🟥 NET NIGHT FLOW	71.22	72.22	72.72	73.22	74.42
🟨 MINIMUM NIGHT FLOW	57.14	57.24	57.01	57.64	57.44

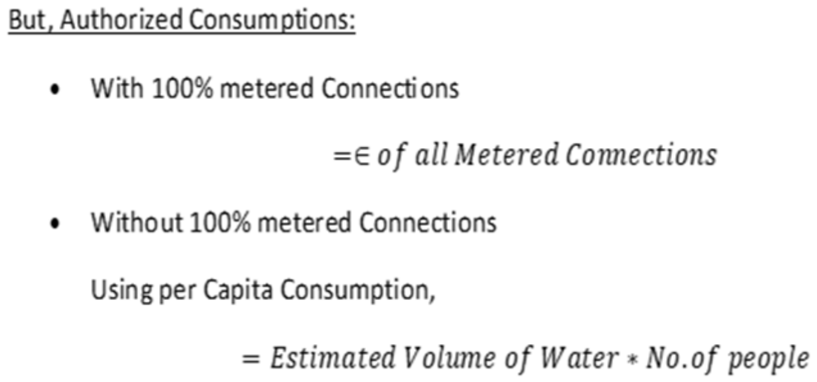
Figure 6: A graph to show the relationship between NNF and MNF.

The above graph (Figure 6) illustrates the connection between net night flow (NNF) and minimum night flow (MNF) which can be helpful for finding non-revenue water (NRW) in a water distribution system and this particular one shows that the NNF regularly exceeds MNF, indicating an issue of NRW in the DMA. This could be credited to a mix of leaks, unauthorized connections, and data handling challenges.

4.2.1. COMPUTATION OF MONETARY IMACTS OF COMMERCIAL NRW

The volume of water supplied to the DMA, which represents the total volume of water entering the DMA from the source, was recorded on a weekly basis. This measurement was gathered via bulk meters located near the DMA's entry site. Additionally, the total amount of water for which consumers are billed, calculated from meter readings at individual customer connections, was also documented. To calculate the volume of Unbilled Water, we subtracted the billed volume from the total volume of water provided to the DMA. This difference reflects the unaccounted-for water in the system, possibly due to commercial losses.

In this scenario, the volume of unbilled water was provided to us by the National Water and Sewage Corporation (NWSC). This data enabled us to estimate the exact monetary loss using NWSC's flat rate billing system. By calculating the typical water usage per client type (residential or commercial) and applying those figures to the unbilled volume, we obtained a projected billed amount. The discrepancy between the projected billed amount and the actual revenue collected represented our monetary loss. Employing the formulas below, we calculated the current revenue, monetary profit and loss, as well as the annual profit and loss.



But, Authorized Consumptions:

- With 100% metered Connections

$$= \in of\ all\ Metered\ Connections$$

- Without 100% metered Connections

  Using per Capita Consumption,

$$= Estimated\ Volume\ of\ Water * No.of\ people$$

$$Peak\ Hour\ Flow\ Rate(PHFR) = No.of\ Connections * Flow\ Rate\ Per\ Connection$$

$$Night\ Time\ Water\ Demand = 15\% * PHFR$$

$$Total\ Night\ Flow(TNF) = Night\ Time\ Water\ Demand * No.of\ Connections$$

$$\text{Current Revenue} = \text{Volume Billed} \times \text{Current billing methods (NWSC)}$$

$$\text{Monetary Loss} = \text{Expected Revenue Volume Supplied} - \text{Revenue From Volume Billed}$$

$$\text{Expected Revenue} = \text{Total Volume Suplied} \times \text{Current billing methods (NWSC)}$$

4.3. Development of a NRW management system for Mpoma Village.

The Mpoma District Metering Area's water network was analysed through simulations conducted with the EPANET hydraulic modelling software. The concept introduced for simulating illegal connections involves representing each unauthorized connection at a single node within the network as an individual data point within the dataset.

4.3.1. SIMULATION OF ILLEGAL CONNECTION AND DATASET PREPARATION.

In a specific instance or data point, a node in a particular section of the network was set as an emitter with a defined emitter coefficient at a certain "simulation time" to mimic a leakage of a specified size. The simulations ran for a 24-hour period from 00:24 to 00:24, with data collection occurring hourly.

For the simulation of non-leak cases, the network was simulated without the presence of an emitter. The emitter coefficient in this context would simulate the leak as if it were a pressure-dependent outflow from the node. This is because an emitter in EPANET behaves similarly to a leak in that the flow rate through the emitter is a function of the square root of the pressure at the node, according to the equation:

$$Q = C\sqrt{P}$$

$Where;$

$Q\ is\ the\ flow\ rate\ from\ the\ emitter\ or\ leak\ (lps)$

$C\ \ is\ the\ emitter\ co-efficient\ (lps)$

$P\ is\ the\ pressure\ at\ the\ node\ (m)$

The emitter coefficient, associated with the node, determines its characteristics. When conducting a leak simulation, the parameter C is adjusted to match the desired size of illegal connections. Lower values of the emitter coefficients are employed to replicate smaller illicit connections. A pressure exponent of 0.2 was utilized as the standard default value.

1. **Data Simulation Setup**:

- The water distribution network model was configured in EPANET with nodes representing houses, specifically 13 houses modelled as nodes (J10-J22). The network simulation ran over a 24-hour period, collecting data every hour.

2. **Data Extraction**:

- A Python function named **extract_epanet_time_series_data** was crafted to parse through the EPANET simulation output files, designed to extract time series data for each node within the network at hourly intervals.
- The pressure data for each node was meticulously extracted and stored in a structured dictionary, keyed by the simulation time.

3. **Dataframe Conversion**:

- Utilizing the **hourly_data_to_df** function, the extracted data was adeptly transformed from a dictionary into a Pandas DataFrame, thereby providing a coherent and analysable tabular format of the time series data.

- This transformation involved numerically sorting node IDs and amalgamating hourly pressure data into a comprehensive DataFrame representing the entire simulation period for all nodes.

4. **Anomaly Detection Implementation**:

- A vital step in the process was implementing a block of code dedicated to calculating the absolute differences between pressures in baseline and leak scenarios at each node, thus enabling anomaly detection.
- A statistical threshold was astutely determined—set as the mean of all absolute differences augmented by twice the standard deviation—to discern any substantial deviations that might signify anomalies.
- Nodes surpassing this threshold in terms of pressure differences were flagged as anomalies, marking them as candidates for potential leaks within the network.

5. **Visualization and Interpretation**:

- The **plot_anomalies** function was created, harnessing the Matplotlib library, to visually represent the discrepancies between baseline and leak scenarios for the nodes flagged with anomalies.
- This visualization not only highlighted the deviations but also aided in comprehensively interpreting complex data, facilitating the identification of potential leak locations.

6. **Leak Location Suggestion**:

- The node exhibiting the maximum deviation in pressure, indicative of a substantial anomaly, was suggested as the potential site of the leak.

- This inference was deduced by pinpointing the index of the maximum value in the DataFrame detailing the pressure differences.

7. **Data Export:**

- In a move to preserve the data derived from the simulations, the DataFrames detailing the baseline and leak scenarios were exported to an Excel file, ensuring the information remained accessible for further analysis and sharing.

Through a meticulous process of simulating, extracting, transforming, analysing, and visualizing data, the project adeptly identified potential problem areas within the water distribution network. The incorporation of scripting for data parsing, leveraging data analysis libraries, and employing statistical methodologies culminated in an effective strategy for tackling non-revenue water by pinpointing leaks and thereby enabling focused remedial actions.

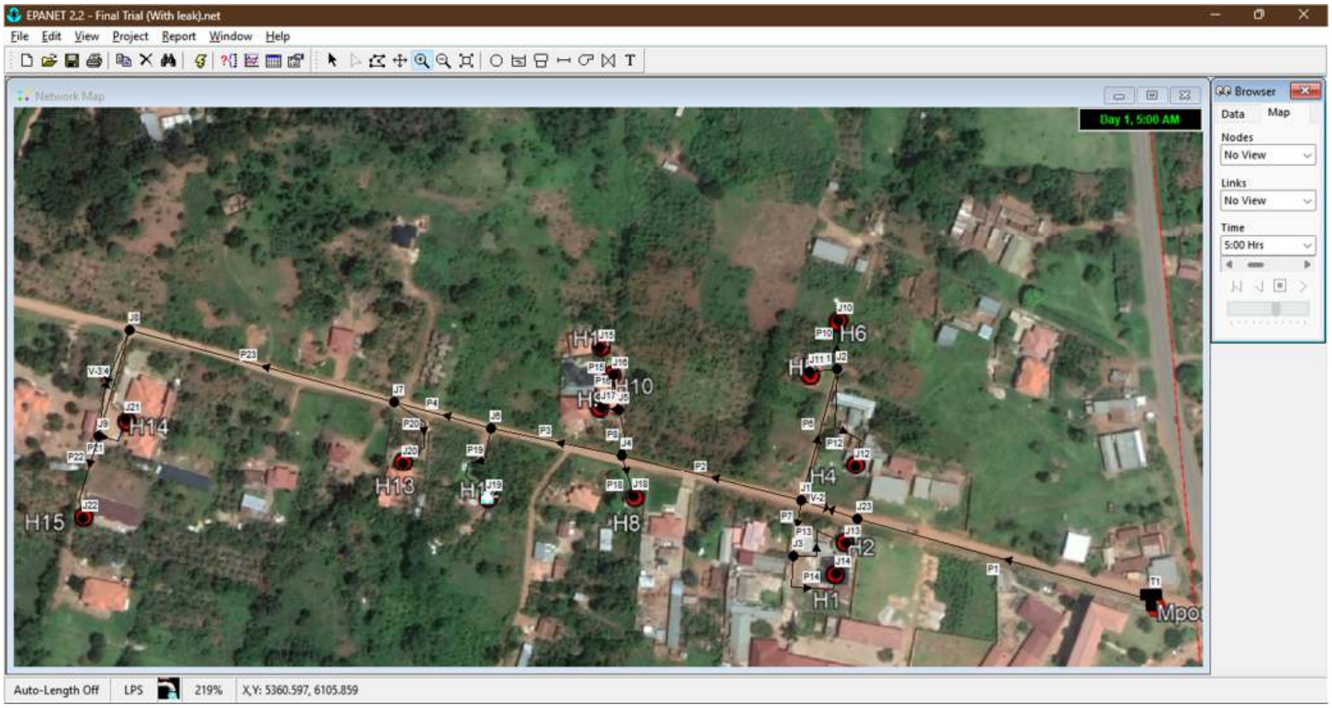


Figure 7: A map snippet of the pilot for Mpoma Village.

```python
import pandas as pd

def extract_epanet_time_series_data(file_path):
    hourly_data = {}  # Dictionary to hold data by hour
    current_hour = None  # Track the current hour being processed

    with open(file_path, 'r') as file:
        for line in file:
            # Identify and set the current hour
            if 'Node Results at' in line:
                # Keep the hour in 'HH:00' format
                current_hour_str = line.split()[3]  # This will be '0:00', '1:00', etc.
                current_hour = current_hour_str  # No conversion to int, keep as 'HH:00' string

                if current_hour not in hourly_data:
                    hourly_data[current_hour] = {}
                continue


            # Extract node pressure data for the current hour
            if current_hour is not None and 'J' in line:  # Assuming node IDs start with 'J'
                parts = line.split()
                if len(parts) >= 4:
                    node_id = parts[0]
                    pressure = float(parts[3])  # Convert pressure to float for numerical analysis

                    if node_id not in hourly_data[current_hour]:
                        hourly_data[current_hour][node_id] = pressure

    return hourly_data

```

Figure 8: A snippet of the code used

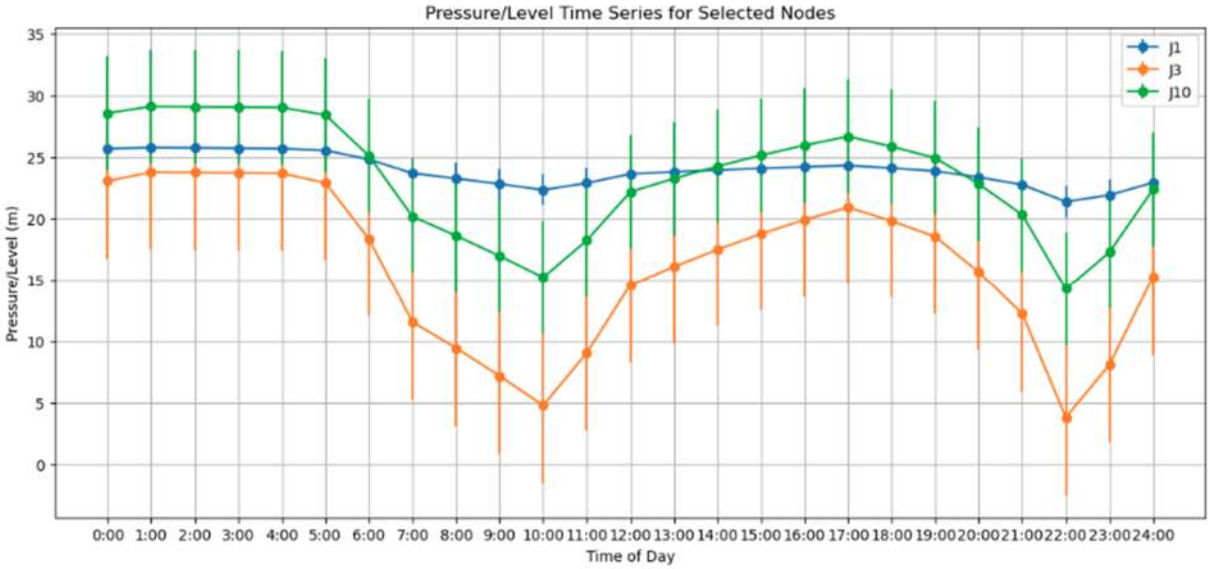


Figure 9: A graph showing pressure at example nodes

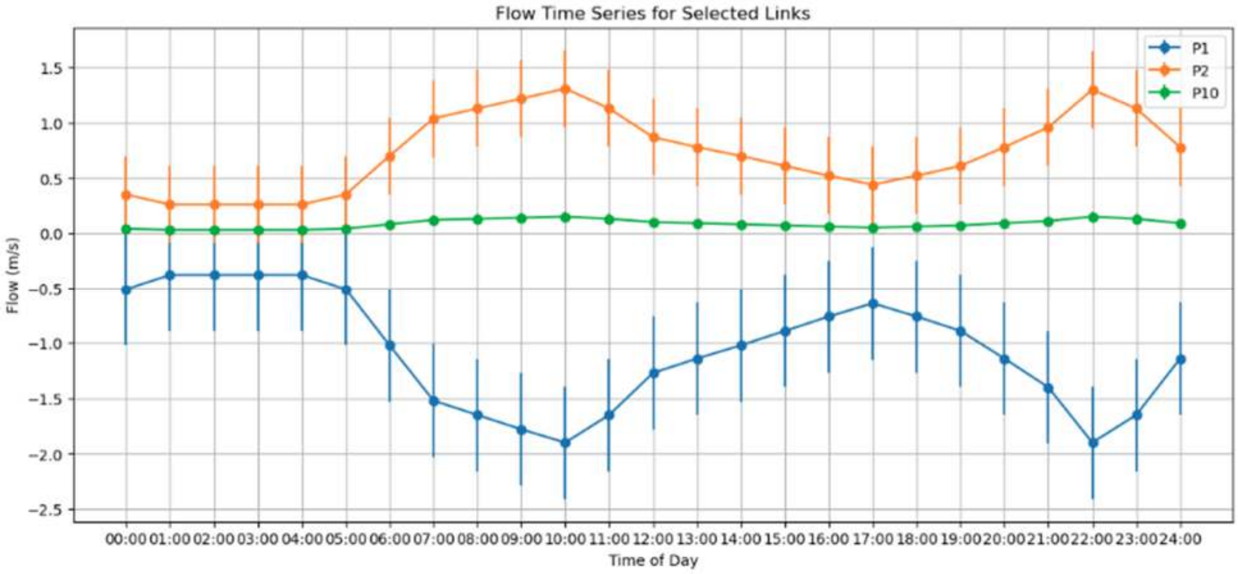
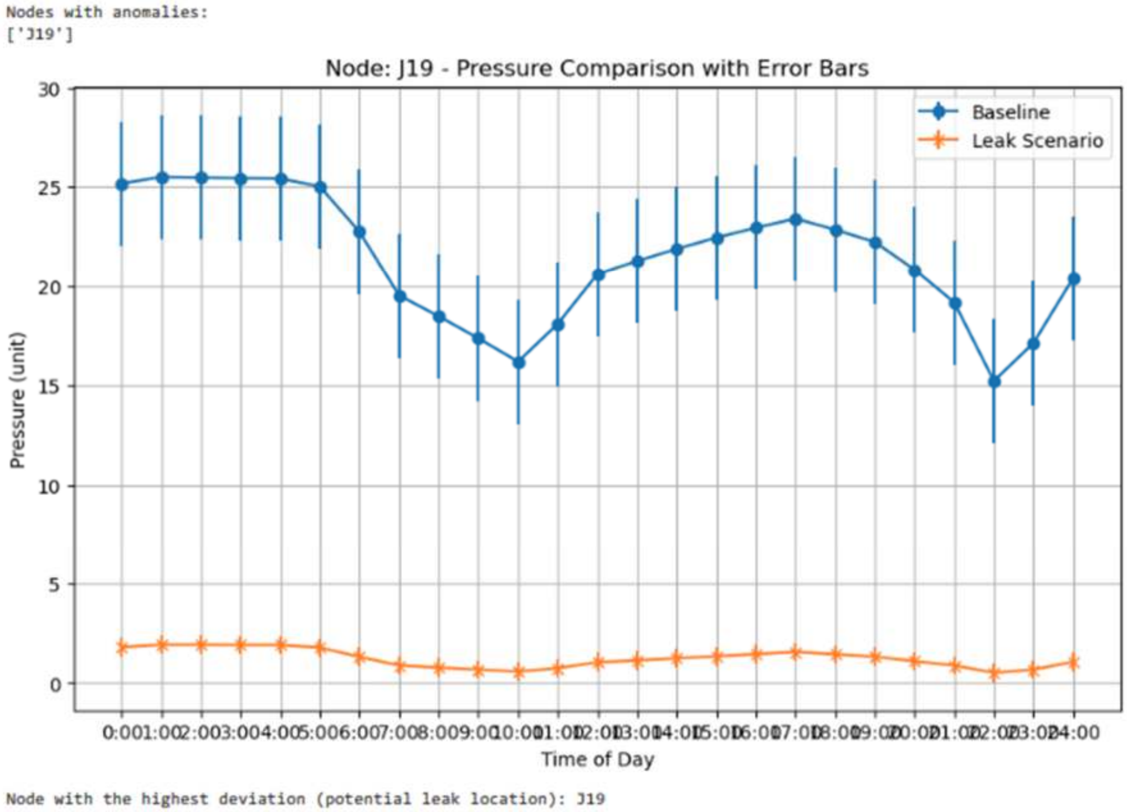


Figure 10: An example graph comparing flow in pipes



```
Nodes with anomalies:
['J19']
```

```
Node with the highest deviation (potential leak location): J19
```

Figure 11: Output by the code after identifying the node with an anomaly.

4.3.2. INTRODUCTION OF A SENSOR BASED NRW MANAGEMENT SYSTEM

NRW management systems aim to monitor, analyse, and minimize non-revenue water, encompassing losses due to leakage, theft, or unauthorized usage. Therefore, before designing such a system, a thorough understanding of the distribution layout is essential (Wang, Zhang and Jia, 2012). Utilizing Mapkit Software—a monitoring and surveying tool employed at NWSC (Mukono)—alongside Epanet software, we successfully generated a schematic representation of the pipe distribution system for the Mpoma DMA.

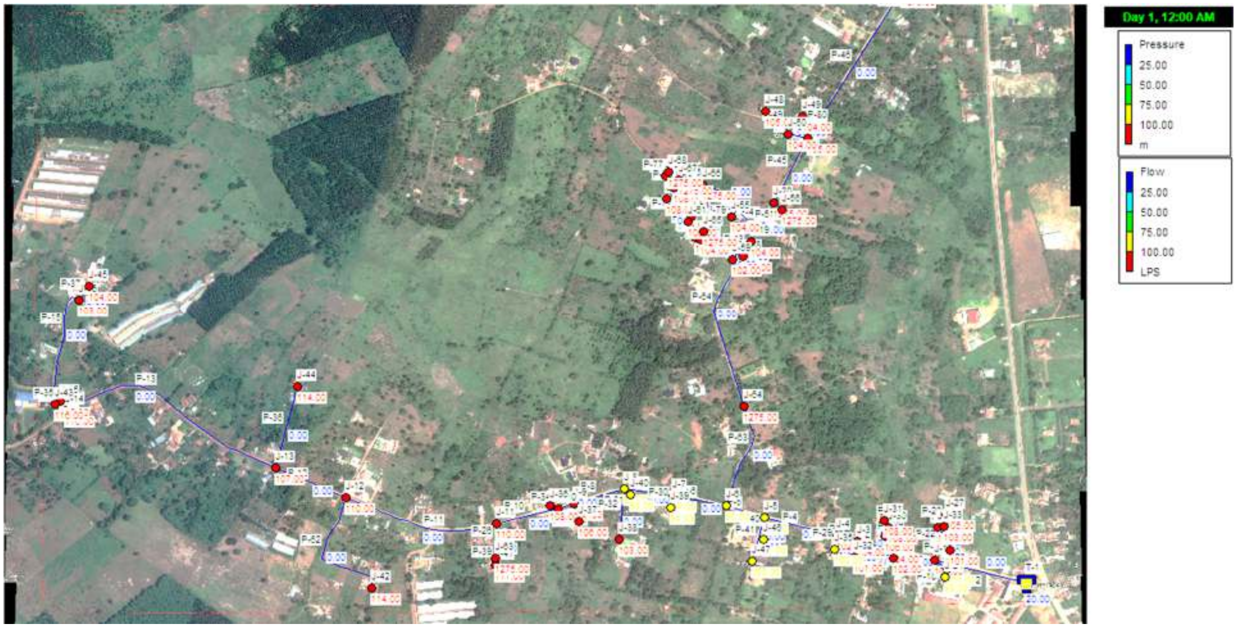


Figure 12: Epanet model of Mpoma

Guided by the schematic provided by Mapkit, the framework for the components of the management system was established. This includes a control centre that will serve as the central hub of the system. It is tasked with collecting data from various sources, including flow meters and Piezoresistive Water Pressure sensors, which are installed throughout the water distribution network. The control centre will then display and monitor the network's performance in real time, allowing for the detection of rapid changes in flow rates or pressure.

The management system will furnish reports and performance data to monitor the effectiveness of NRW reduction efforts and provide insights into the state of the water distribution network. This enables water utilities to make informed decisions regarding maintenance priorities, infrastructure investments, and operational strategies aimed at reducing non-revenue water (Ahmed *et al.*, 2021).

Data Archiving plays a pivotal role in the system, focusing on the systematic storage and management of historical data generated by the network infrastructure. This component allows NWSC to maintain historical data for future study, analysis, and comparison, thereby ensuring data integrity, facilitating analysis and decision-making, ensuring regulatory compliance, and safeguarding against data loss or system failures.

Additionally, a Real-time Monitoring system is integrated, capable of displaying sensor variables and data from monitoring stations as it is collected. This feature enhances the immediacy and relevance of data for operational decision-making.

Complementing these components is Hydraulic and Water Quality Modelling, which employs computational techniques to replicate the behaviour of water distribution networks. This aspect focuses on understanding and optimizing hydraulic performance and water quality within the system by simulating water movement across the network. It considers factors such as pipe size, altitudes, pump characteristics, and demand patterns specific to the DMA. This enables the identification of inefficiencies, such as pressure losses, poor flow rates, and suboptimal pump operation. With this information, NWSC can adjust the system layout, component design, and operational strategies to minimize energy consumption and enhance water delivery efficiency (Ahmed *et al.*, 2021).

Lastly, the system will incorporate a Reports, Alarm, and Charts component, providing detailed summaries and analyses, issuing alerts for anomalies detected based on predetermined thresholds or conditions, and offering visual representations of data through graphs and charts. This component is designed to support various aspects of the NRW management system within the specified DMA, facilitating a comprehensive and accessible view of the network's performance and issues.

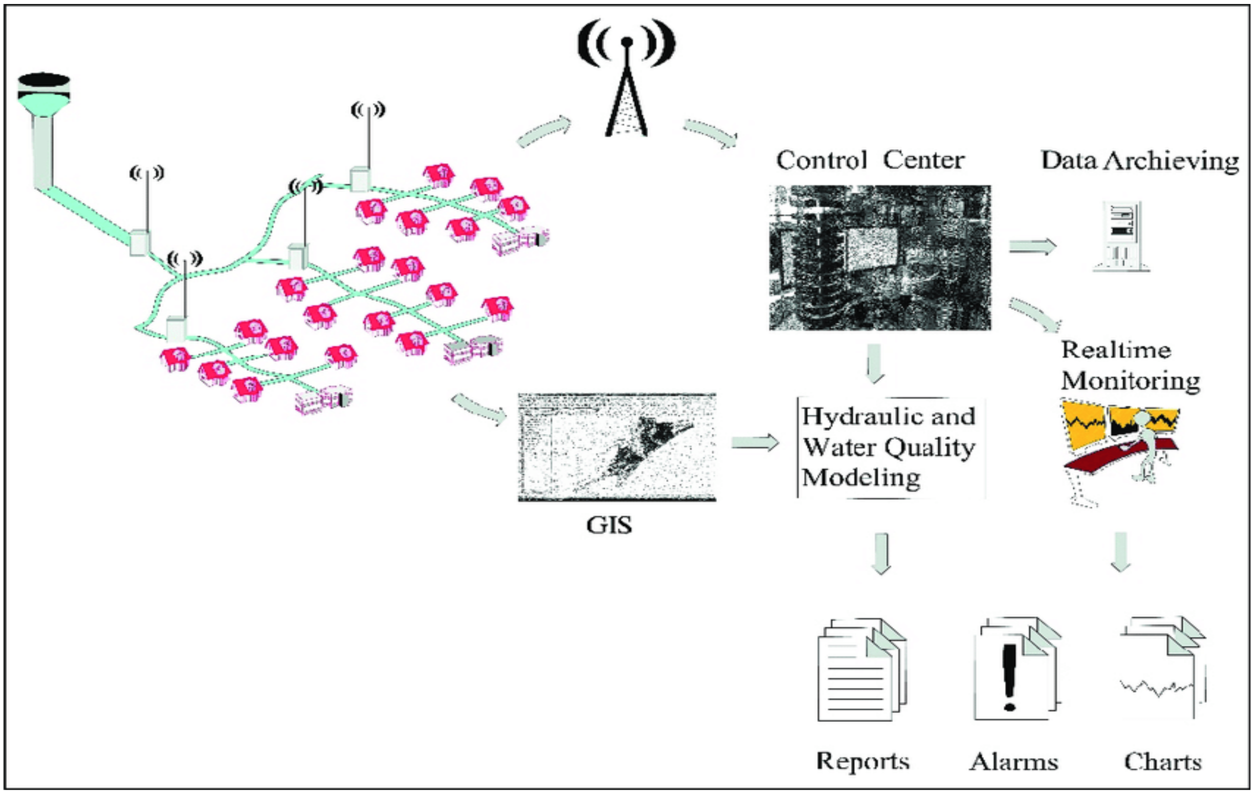


Figure 13: A Schematic representation of the introduced NRW management system

FLOW SENSORS

Flow sensors, strategically positioned throughout the network, continuously monitor water flow at various points. This real-time data enables the identification of anomalies, facilitating an efficient approach to pinpoint leaks, even in buried or hard-to-reach locations (Casillas *et al.*, 2013). This results in direct financial gains for water utilities, as more water becomes billable. Thus, minimizing NRW leads to a more accurate reflection of actual water consumption, allowing utilities to generate revenue from all the water that is delivered.

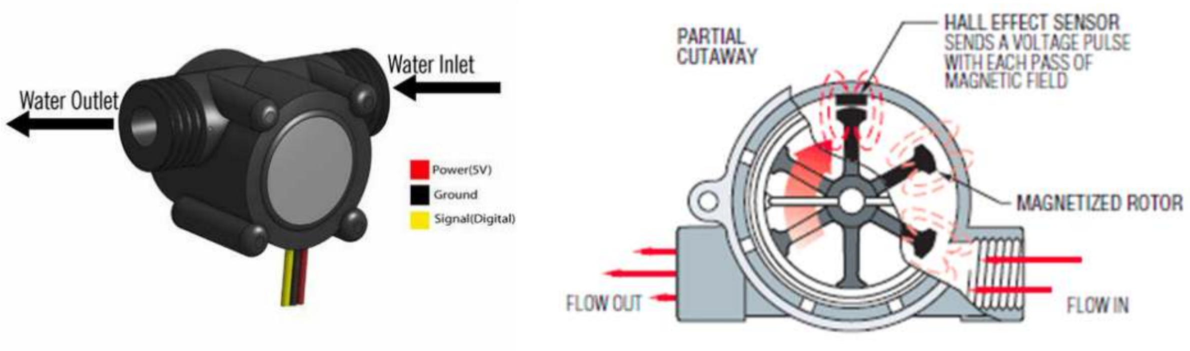


Figure 14: Image showing a flow sensor and it's working principle.

Strategically placing multiple flow sensors throughout the network facilitates targeted repair efforts, thereby minimizing excavation and service disruptions. Unlike traditional methods that might necessitate isolating larger sections of the network and leading to wider customer impacts, flow sensors provide a continuous data stream on water flow patterns. This enables the analysis of field data to understand consumption patterns, identify areas of excessive water use, and potentially detect unauthorized connections. Consequently, this proactive approach yields cost savings over time. By reducing NRW, flow sensors also ensure that more water is available for legitimate use, which is especially critical in areas where even small losses can significantly impact resources (Farouk, Rahman and Romali, 2023a). Optimal sensor locations often include the points where significant changes in flow rates are likely to occur, such as the transitions from high to low elevation, bends in the piping network where flow dynamics can be altered, and proximal to customer service connections where unauthorized usage is most likely to be detected.

PIEZO-RESISTIVE WATER PRESSURE SENSORS:

Piezo-resistors are pressure-sensitive devices that translate mechanical stress into a measurable electrical signal. Within a water distribution network, the installation of these sensors at key points allows for the capture of real-time data on water pressure fluctuations. These fluctuations are more than mere statistical noise; they can be symptomatic of underlying issues within the system. Over time, these seemingly insignificant losses accumulate, potentially accounting for a substantial volume of NRW. By detecting these variations in pressure, utilities can prioritize maintenance activities and infrastructure upgrades, addressing these vulnerabilities before they escalate into more severe leaks or breaks. Identifying and mitigating such inefficiencies is crucial for water conservation and the economic sustainability of water utilities.

A network of strategically placed piezo-resistors will enable the creation of a comprehensive pressure map for the entire Mpoma distribution system. This map will provide valuable insights into pressure variations across different zones within the network. Sudden or sustained pressure drops at specific locations can be clearly indicated. By analysing the pressure data in conjunction with flow sensor data, utilities can pinpoint the locations of leaks or unauthorized water discharges with greater accuracy, which minimizes water loss and potential damage to infrastructure. Furthermore, utilities can identify areas within the network that are experiencing frequent or excessive pressure variations, pinpointing zones that are susceptible to background losses.

4.3.3. SYSTEMATIC WORKFLOW OF THE MANAGEMENT SYSTEM

Flow and piezoresistive water pressure sensors will be strategically placed at key points along the pipe network. These locations include the beginnings of the main supply lines from reservoirs, at both the inlet and outlet points of designated District Metered Areas (DMAs)—which are subdivisions of the entire network—pressure reducing valves, and branch connections (especially those feeding high-demand areas or critical facilities). The aim is to collect timely data at intervals of 2 hours on water flow and its velocity, pressure, and viscosity. Due to the requirement for more frequent measurements, which in turn require greater storage capacities, the frequency of data collection will start at 2-hour intervals and gradually decrease as storage capacities increase

The collected data is subsequently sent to a central computer system, ideally situated at the branches of the National Water and Sewage Corporation. In addition, to mitigate concerns regarding bias and data tampering, this information is also dispatched in parallel to a principal data collection centre situated away from the branch locations (Raei *et al.*, 2018).

A given computer system, such as a Distribution Management System (DMS) or a Hydraulic Modelling System (HMS), will process and analyse the data. It can identify potential leaks or other issues by collecting sensor data at a predetermined frequency (every 2 hours). The data then undergoes initial processing to ensure accuracy, filtering out acceptable errors and anomalies, such as calibration errors, environmental conditions, cross-sensitivity, and electromagnetic interference from nearby equipment emitting signals (Yang and Wang, 2023).

The data is then stored in a database for historical analysis and trend monitoring, and it is used to take steps to address the NRW problem, such as repairing leaks and identifying illegal activities like unauthorized meter replacements. The analysed data can be visualized on a map or dashboard, displaying live flow rates and pressure readings, unusual flow patterns or pressure drops, predicted water demand based on historical data and weather patterns, and results from hydraulic modelling that simulates different scenarios (e.g., valve closures, pipe bursts) to optimize network performance (Farouk, Rahman and Romali, 2023b).

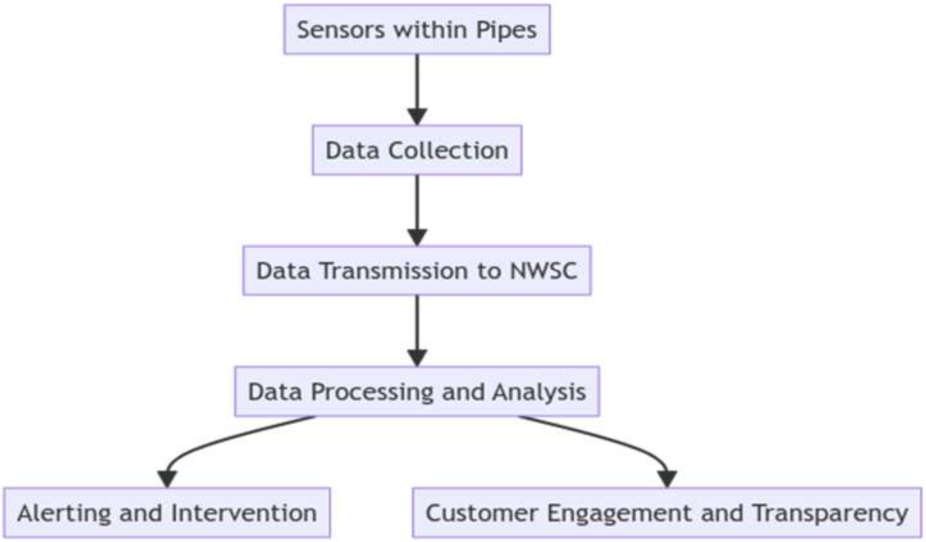


Figure 15: A flow-chart showing how the management system should operate.

4.4. Investigation of the environmental and economic impact of the developed NRW strategy.

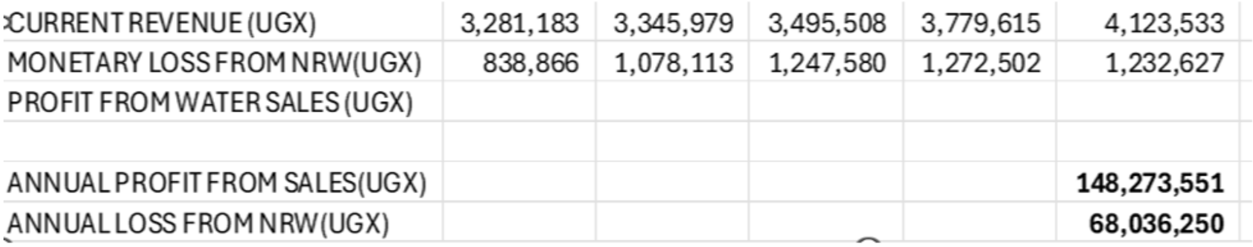
4.4.1. COST BENEFIT AND ECONOMIC ANALYSIS

The existing NRW level in the Mpoma DMA was determined through a water audit, which often combines techniques such as meter balance, leak detection surveys, and pressure measurement. The audit results provide a baseline NRW percentage, essential for assessing the potential water savings achieved by the new management system. This assessment includes the costs of purchasing and installing components of the NRW management system, such as flow and piezoresistive sensors, receivers, control centres, real-time monitoring systems, and data management software. Operational expenditures were also considered, encompassing staff expenditures for data analysis, leak repair crews, and maintenance of the NRW management system.

Current market value prices for the required materials and labour were researched by obtaining quotations from multiple vendors for the NRW management system components, and a cost table was created, as will be shown below.

When the Total Annual Benefit outweighs the Total Annual Cost, the analysis indicates a positive outcome. In the case of the Mpoma DMA, with a projected annual saving of approximately 18 million UGX from the 68 million UGX annual loss, the cost-benefit analysis suggests that implementing the NRW management system is financially viable for NWSC.

Table 4: A table showing Cost analysis of the current NWSC system (none).



CURRENT REVENUE (UGX)	3,281,183	3,345,979	3,495,508	3,779,615	4,123,533
MONETARY LOSS FROM NRW(UGX)	838,866	1,078,113	1,247,580	1,272,502	1,232,627
PROFIT FROM WATER SALES (UGX)					
ANNUAL PROFIT FROM SALES(UGX)					**148,273,551**
ANNUAL LOSS FROM NRW(UGX)					**68,036,250**

Table 5: A table showing the cost estimates for the project.

DEVICE/ACTIVITY	DURABILITY (Yrs.)	UNIT COST (UGX)	QTY	COST (UGX)	MAINTANCE COST(UGX)	TOTAL (UGX)
Piezoresistive Sensors	8	2,150,000	2	4,300,000	500,000	4,800,000
Flow Sensors	8	1,160,000	2	2,320,000	405,000	2,725,000

DEVICE/ACTIVITY	DURABILITY (Yrs.)	UNIT COST (UGX)	QTY	COST (UGX)	MAINTANCE COST(UGX)	TOTAL (UGX)
Receivers	7	500,000	1	500,000	190,000	690,000
Control Centre and Archive	10	1,650,000	1	1,650,000	300,000	1,950,000
Real Time Monitoring system	12	2,000,000	1	2,000,000	300,000	2,300,000
Hydraulic Simulations	12	500,000	1	500,000	100,000	600,000
Operational Staff	3 yr. (contracts)	1,000,000	5	5,000,000	150,000 (allowance)	5,150,000
					Total	**18,215,000**

The cost-benefit analysis provides NWSC with a framework for determining the financial sustainability of deploying the NRW management system in the Mpoma DMA. Based on current market value pricing and predicted water savings, the analysis suggests that the system could potentially generate annual savings of around 18 million UGX from the 68 million UGX annual loss. However, the accuracy of this study relies on robust data and a comprehensive understanding of all costs and benefits involved.

CHAPTER FIVE: LIMITATIONS, RECCOMENDATION & CONCLUSION

5. INTRODUCTION

In this chapter, we look at the limitations encountered during the course of our research, provide insightful recommendations for future research, and draw meaningful conclusions based on our findings. While our investigation has shed light on various aspects of developing a Non-Revenue Water (NRW) Management System for Mpoma Village, it is crucial to acknowledge the limitations that have influenced our study outcomes and to propose pathways for further exploration.

5.1. LIMITATIONS;

During this research, the initial focus on commercial losses overlooked the potentially significant impact of physical losses due to leakage, underscoring the necessity for a comprehensive approach that addresses both aspects to maximize water conservation efforts. Consequently, without an in-depth examination of physical losses, achieving a holistic approach to managing NRW would be incomplete.

Furthermore, the study encountered challenges in leak detection within small DMAs, where traditional methods, such as acoustic correlators, proved less effective in networks with only 37 connections.

A notable obstacle identified during the research was a lack of resources. Mpoma Village, similar to many rural areas, faced a shortage of financial, human, and technological resources. This scarcity of resources hindered the procurement of essential equipment, technology, and expertise necessary for a thorough study and the implementation of a robust NRW management system.

Moreover, having access to accurate and reliable data is crucial for informed decision-making and effective planning. Yet, limited data availability emerged as a significant barrier during the research project. The success of surveys and calculations hinged on the precision of both obtained and historical data, which was either inaccessible due to security concerns or had been lost (e.g., historical meter data).

5.2. RECOMMENDATIONS;

Scientific evidence underscores the significance of community engagement and capacity-building in enhancing Non-Revenue Water (NRW) management efforts. When local communities are involved in participatory initiatives, it fosters a sense of ownership and empowerment, which is vital for ensuring the sustainability of adopted policies over the long term. This engagement can be achieved through educational workshops, training programs, and awareness campaigns that inform community members about the importance of natural resource conservation and waste reduction (Tsitsifli *et al.*, 2017). Projects that support sustainable livelihoods, such as eco-tourism and agroforestry, can also incentivize community participation in NRW management, cultivating a culture of environmental stewardship .

Moreover, a robust policy framework, grounded in evidence-based decision-making, is indispensable for the successful deployment of an NRW management system. Scientific guidelines advocate for the establishment of comprehensive legislation and regulatory norms to govern resource exploitation and deter illegal (Mutikanga, Sharma and Vairavamoorthy, 2011). Policy instruments, including economic incentives, market-based approaches, and enforcement mechanisms, can motivate stakeholders to adhere to environmental standards and embrace sustainable practices. By harmonizing policy actions with scientific insights, Mpoma Village can cultivate an enabling environment for effective natural resource and waste management (Kingdom *et al.*, 2006).

The actualization of a Natural Resources and Waste Management system in Mpoma

Village, Mukono, necessitates adherence to scientific recommendations and principles. By integrating scientific knowledge with technological advancements, community engagement, and sound regulatory frameworks, Mpoma Village can develop a comprehensive and sustainable strategy for natural resource management that is both environmentally sound and economically beneficial (Frauendorfer and Liemberger, 2010).

5.3. CONCLUSION;

The implementation of an NRW management system in Mpoma Village, Mukono, holds significant potential for advancing resource recovery and the efficient redirection of national funds. An in-depth analysis of relevant literature underscores the importance of maintaining acceptable NRW levels and the role of management systems in conserving water resources and fostering sustainable development. The research project adopted a mixed-methods approach, encompassing field observations, data collection, and the proposed deployment of sensors. Flow and piezoresistive sensors were recommended for installation throughout Mpoma Village's water distribution network to monitor flow rates, detect illegal connections, and identify faulty meters. Data was systematically collected over a designated time period, and advanced statistical analysis techniques were employed to interpret the results.

The research findings, coupled with simulations of the management system, indicate a substantial reduction in NRW—particularly a decrease in commercial losses from 9% to 3% within six months of implementing the system equipped with flow and piezoresistive sensors. By accurately monitoring water flow rates and identifying leaks in real-time, the system facilitates prompt intervention and repairs, curtailing water losses.

Statistical analysis of the collected data reveals a marked decline in NRW levels, contributing to enhanced water conservation and financial savings for the community. Furthermore, the adoption of this NRW management system promises to augment the overall efficiency and reliability of Mpoma Village's water supply network. The system promotes sustainable water management practices and ensures the fair distribution of water resources by rectifying issues such as faulty meters and unauthorized water use (Vishe, 2019). The implementation of a non-revenue water management system in Mpoma Village, Mukono, utilizing flow and piezoresistive sensors, represents a scientifically robust and effective solution to rural water management challenges. The findings from this research demonstrate that the system can reduce NRW commercial losses from 9% to an acceptable 3%, thereby promoting water conservation and enhancing the reliability of the water delivery network.

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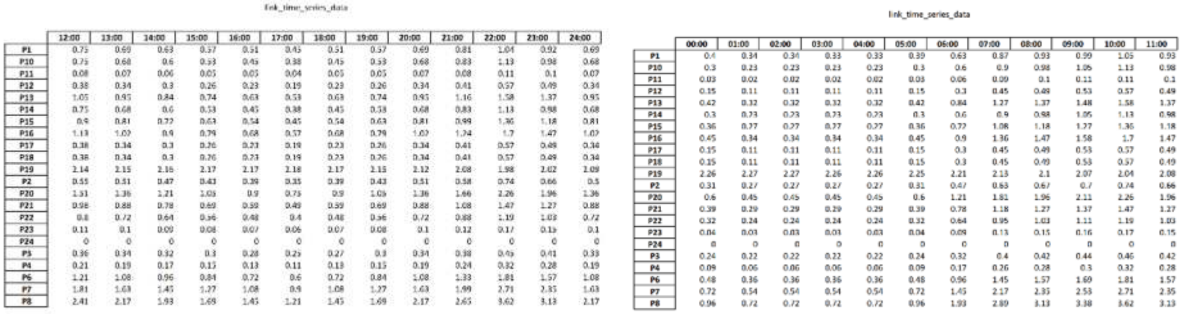
APPENDICES

Figure 16: NWSC officials collecting DMA readings

Figure 17: Students taking meter readings. (L) Readings for Mpoma DMA. (R)



link_time_series_data

	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
P1	0.75	0.69	0.63	0.57	0.51	0.45	0.51	0.57	0.69	0.81	1.04	0.92	0.69
P10	0.75	0.68	0.6	0.53	0.45	0.38	0.45	0.53	0.68	0.83	1.13	0.98	0.68
P11	0.08	0.07	0.06	0.05	0.05	0.04	0.05	0.05	0.07	0.08	0.11	0.1	0.07
P12	0.38	0.34	0.3	0.26	0.23	0.19	0.23	0.26	0.34	0.41	0.57	0.49	0.34
P13	1.05	0.95	0.84	0.74	0.63	0.53	0.63	0.74	0.95	1.16	1.58	1.37	0.95
P14	0.75	0.68	0.6	0.53	0.45	0.38	0.45	0.53	0.68	0.83	1.13	0.98	0.68
P15	0.9	0.81	0.72	0.63	0.54	0.45	0.54	0.63	0.81	0.99	1.36	1.18	0.81
P16	1.13	1.02	0.9	0.79	0.68	0.57	0.68	0.79	1.02	1.24	1.7	1.47	1.02
P17	0.38	0.34	0.3	0.26	0.23	0.19	0.23	0.26	0.34	0.41	0.57	0.49	0.34
P18	0.38	0.34	0.3	0.26	0.23	0.19	0.23	0.26	0.34	0.41	0.57	0.49	0.34
P19	2.14	2.15	2.16	2.17	2.17	2.18	2.17	2.15	2.12	2.08	1.98	2.02	2.09
P2	0.55	0.51	0.47	0.43	0.39	0.35	0.39	0.43	0.51	0.58	0.74	0.66	0.5
P20	1.51	1.36	1.21	1.06	0.9	0.75	0.9	1.06	1.36	1.66	2.26	1.96	1.36
P21	0.98	0.88	0.78	0.69	0.59	0.49	0.59	0.69	0.88	1.08	1.47	1.27	0.88
P22	0.8	0.72	0.64	0.56	0.48	0.4	0.48	0.56	0.72	0.88	1.19	1.03	0.72
P23	0.11	0.1	0.09	0.08	0.07	0.06	0.07	0.08	0.1	0.12	0.17	0.15	0.1
P24	0	0	0	0	0	0	0	0	0	0	0	0	0
P3	0.36	0.34	0.32	0.3	0.28	0.25	0.27	0.3	0.34	0.38	0.45	0.41	0.33
P4	0.21	0.19	0.17	0.15	0.13	0.11	0.13	0.15	0.19	0.24	0.32	0.28	0.19
P6	1.21	1.08	0.96	0.84	0.72	0.6	0.72	0.84	1.08	1.33	1.81	1.57	1.08
P7	1.81	1.63	1.45	1.27	1.08	0.9	1.08	1.27	1.63	1.99	2.71	2.35	1.63
P8	2.41	2.17	1.93	1.69	1.45	1.21	1.45	1.69	2.17	2.65	3.62	3.13	2.17

link_time_series_data

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
P1	0.4	0.34	0.34	0.33	0.33	0.39	0.63	0.87	0.93	0.99	1.05	0.93
P10	0.3	0.23	0.23	0.23	0.23	0.3	0.6	0.9	0.98	1.05	1.13	0.98
P11	0.03	0.02	0.02	0.02	0.02	0.03	0.06	0.09	0.1	0.11	0.11	0.1
P12	0.15	0.11	0.11	0.11	0.11	0.15	0.3	0.45	0.49	0.53	0.57	0.49
P13	0.42	0.32	0.32	0.32	0.32	0.42	0.84	1.27	1.37	1.48	1.58	1.37
P14	0.3	0.23	0.23	0.23	0.23	0.3	0.6	0.9	0.98	1.05	1.13	0.98
P15	0.36	0.27	0.27	0.27	0.27	0.36	0.72	1.08	1.18	1.27	1.36	1.18
P16	0.45	0.34	0.34	0.34	0.34	0.45	0.9	1.36	1.47	1.58	1.7	1.47
P17	0.15	0.11	0.11	0.11	0.11	0.15	0.3	0.45	0.49	0.53	0.57	0.49
P18	0.15	0.11	0.11	0.11	0.11	0.15	0.3	0.45	0.49	0.53	0.57	0.49
P19	2.26	2.27	2.27	2.26	2.26	2.25	2.21	2.13	2.1	2.07	2.04	2.08
P2	0.31	0.27	0.27	0.27	0.27	0.31	0.47	0.63	0.67	0.7	0.74	0.66
P20	0.6	0.45	0.45	0.45	0.45	0.6	1.21	1.81	1.96	2.11	2.26	1.96
P21	0.39	0.29	0.29	0.29	0.29	0.39	0.78	1.18	1.27	1.37	1.47	1.27
P22	0.32	0.24	0.24	0.24	0.24	0.32	0.64	0.95	1.03	1.11	1.19	1.03
P23	0.04	0.03	0.03	0.03	0.03	0.04	0.09	0.13	0.15	0.16	0.17	0.15
P24	0	0	0	0	0	0	0	0	0	0	0	0
P3	0.24	0.22	0.22	0.22	0.22	0.24	0.32	0.4	0.42	0.44	0.46	0.42
P4	0.09	0.06	0.06	0.06	0.06	0.09	0.17	0.26	0.28	0.3	0.32	0.28
P6	0.48	0.36	0.36	0.36	0.36	0.48	0.96	1.45	1.57	1.69	1.81	1.57
P7	0.72	0.54	0.54	0.54	0.54	0.72	1.45	2.17	2.35	2.53	2.71	2.35
P8	0.96	0.72	0.72	0.72	0.72	0.96	1.93	2.89	3.13	3.38	3.62	3.13

Figure 18: Snippet of the clean ordered data after extraction from the Epanet report.

Figure 19: Images showing some of the customer meters.