

BINDURA UNIVERSITY OF SCIENCE EDUCATION

A MODEL TOWARDS REDUCING NON-REVENUE WATER (WATER LEAKAGES) THROUGH PREDICTIVE LEAK DETECTION AND PRESSURE MANAGEMENT IN HARARE CITY COUNCIL

BY

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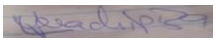
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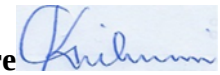
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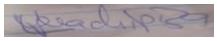
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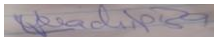
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DECLARATION

I, Luxon Panashe Machipisa Student Reg Number B251099A, do hereby declare that this dissertation is a result of my own investigation and research, except to the extent indicated in the acknowledgments, bibliography, references, and comments included in the body of the report, and that it has not been submitted in part or in full for any other degree to any other university.

STUDENT SIGNATURE **DATE: 20/6/2026**



DEDICATION

I dedicate this work to my family for their unwavering support and patience throughout this academic journey, and to the engineers at Harare City Council who strive daily to manage our precious water resources under challenging conditions.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Dr. V. Basera, for his insightful guidance and technical expertise. Special thanks to the Harare City Council (HCC) Department of Wwater for providing access to the pilot District Metered Areas and hydraulic data. Finally, I thank Bindura University of Science Education for the academic environment that fostered this research.

ABSTRACT

Non-Revenue Water (NRW) has become one of the most significant challenges affecting urban water utilities in developing countries, particularly in Zimbabwe where aging infrastructure, intermittent water supply, and inadequate leak management systems have contributed to substantial water losses. Harare City Council currently experiences NRW levels estimated at approximately 58.6%, resulting in financial losses, reduced service delivery, and increased operational costs. This study sought to develop a model towards reducing non-revenue water through predictive leak detection and pressure management in Harare City Council. The study was guided by five objectives, namely: to determine the relationship between hydraulic transients and pipe burst frequency, assess the effectiveness of Long Short-Term Memory (LSTM) machine learning models in predicting leak locations, establish optimal pressure modulation set-points for leakage reduction, evaluate the financial implications of adopting predictive maintenance systems, and develop an integrated framework for NRW reduction. A mixed-methods research approach was adopted using questionnaires, interviews, and secondary operational data collected from engineers, water technicians, ICT personnel, and operations managers within Harare City Council. Quantitative data were analyzed using the Statistical Package for Social Sciences (SPSS), while qualitative data were analyzed thematically. The findings revealed a strong positive relationship between hydraulic transients and pipe burst frequency, confirming that pressure surges significantly contribute to infrastructure failure within the water distribution network. The study further established that predictive leak detection using LSTM-based models can accurately identify leak patterns and potential failure points before catastrophic pipe bursts occur. Pressure management techniques were found to significantly reduce leakage volumes and infrastructure stress. Financial analysis indicated that implementing an Internet of Things (IoT)-enabled predictive maintenance system could reduce physical water losses by approximately 22%, improve operational efficiency, and generate a return on investment within 14 months. The study concludes that integrating predictive leak detection, real-time monitoring, and automated pressure management provides a sustainable solution for reducing NRW in Harare City Council. The study recommends the phased deployment of IoT pressure sensors, adoption of machine learning-based predictive analytics, establishment of District Metered Areas (DMAs), and implementation of smart pressure regulation systems. A predictive NRW reduction framework was developed to guide utility managers in transitioning from reactive maintenance to proactive and data-driven water loss management strategies.

Keywords: Non-Revenue Water, Predictive Leak Detection, Pressure Management, Internet of Things, Machine Learning, LSTM, Hydraulic Transients, Water Distribution Networks, Harare City Council

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LIST OF ABBREVIATIONS

AC:	Asbestos-Cement
DMA:	District Metered Area
FAVAD:	Fixed and Variable Area Discharge
HCC:	Harare City Council
IWA:	International Water Association
LSTM:	Long Short-Term Memory
NRW:	Non-Revenue Water
WDN:	Water Distribution Network

CHAPTER

INTRODUCTION

In the arid and semi-arid landscapes of Southern Africa, water is not merely a utility but a critical driver of socio-economic stability. Since excessive NRW levels immediately jeopardize the financial sustainability of utilities and the quality of water services, managing NRW is a global economic and environmental necessity (Fluence, 2025). The World Bank and the International Water Association (IWA) stress that emerging markets sometimes suffer losses between 25% and 50%, and in severe circumstances, up to 75%, whereas affluent countries keep losses as low as 5-10% (Fluence, 2025; Proparco, 2025). For Zimbabwean municipalities, the management of this resource is currently reaching a breaking point. The amount of water produced and processed that does not make it to the customer's billing system, known as non-revenue water (NRW), has grown from a technical inefficiency to a national emergency. NRW levels are said to vary between 40% and 60% in large cities like Harare, Bulawayo, and Mutare, which is far higher than the 15% standard that the International Water Association (IWA) recommends (ZIMSTAT, 2023). This chapter gives the study's background, problem statement, research goals, research questions, and research justification very evident. These features aid in reflecting the existing state of affairs at Harare City Council and the necessity of creating a model to reduce non-revenue water through pressure control and predictive leak detection.

1.1 Background of the Study

The management of urban water distribution networks (WDN) in developing sub-Saharan African cities has reached a critical juncture where traditional engineering interventions are no longer sufficient to offset systemic deterioration. The water company is presently caught in a disastrous Resource Loop, according to the Harare City Council (HCC). The difference between the amount of treated water that leaves the Morton Jaffray and Prince Edward Works and the amount that is actually invoiced to customers is anticipated to be 58.6% for Non-Revenue Water (NRW) as of early 2026 (Mafume, 2025).

1.1.1 Zimbabwean Context: The Harare Water Crisis (2025–2026)

The Harare City Council operates a network characterized by a widening Production-Demand Gap, where Non-Revenue Water (NRW) serves as the primary drain on financial and physical resources. As of April 2026, the HCC reports NRW levels at 58.6% (Mafume, 2025). This means for every 1,000 liters of water treated at Morton Jaffray, approximately 586 liters are lost before reaching the consumer's bill.

1.1.1.1 Production vs. Demand

Current demand for Greater Harare is estimated at 800–1,200 Megalitres per day (ML/d). However, effective production often fluctuates between 350 and 450 ML/d (HCC, 2025). The city reportedly loses approximately US$1.2 million monthly on treatment chemicals for water that is never billed. The 6,400 km network relies on Asbestos-Cement (AC) pipes laid in the 1950s–1970s. These pipes have a 30-year design life, meaning they are over 40 years past their replacement date. The Water Hammer from intermittent supply restoration is the leading cause of new bursts.

1.1.1.2 Why Traditional Engineering Fails

Traditional Find and Fix methods in Harare fail because they do not address the FAVAD (Fixed and Variable Area Discharge) principle. In a brittle network like Harare's, leaks are variable, meaning the hole in the pipe expands when pressure increases. Without the Predictive Leak Detection and Pressure Management outlined in your dissertation, repairing one leak often increases the pressure elsewhere, triggering a new burst in a nearby AC pipe a phenomenon known as the Balloon Effect.

1.1.2 The International Context: The Era of Water 4.0

Cyber-Physical Systems (CPS), also known as Water 4.0, has replaced traditional civil engineering in the management of Water Distribution Networks (WDN) worldwide. In the Global North, Non-Revenue Water (NRW) is no longer viewed as an inevitable operational loss but as a data-driven challenge. Utilities in cities like Singapore and Tokyo have successfully reduced NRW to below 5% by integrating Digital Twins and Predictive Leak Detection (Fluence, 2025; Rajan & Li, 2025).

At an international level, the World Bank estimates that USD 50 billion is lost annually due to NRW. Reducing this by half could provide enough water for 1 billion people (Proparco, 2025). Developed utilities such as in the UK and China are transitioning to Cyber-Physical Systems and Digital Twins. These systems use real-time pressure transducers and LSTM algorithms to predict leaks before they manifest as visible bursts—the exact model proposed in your dissertation (Fluence, 2025; Rajan & Li, 2025).

Nowadays, the global scientific community places a high priority on Active Leakage Control (ALC), processing pressure and acoustic data using Machine Learning (ML) methods, particularly Long Short-Term Memory (LSTM) networks. These systems allow utilities to transition from Run-to-Failure models to Predictive Maintenance, where micro-leaks are identified via Internet of Things (IoT) sensors before they evolve into catastrophic pipe bursts.

The UK operates under a strict regulatory framework (monitored by Ofwat) where water utilities are penalized for failing to meet leakage targets. The Economic Level of Leakage (ELL), which is the threshold at which the cost of further leak reduction surpasses the value of the water saved, was invented in the UK (Thornton et al., 2008). Infrastructure fatigue is a major problem in the USA, especially with cast-iron and asbestos-cement pipes like those in Harare.

The American Water Works Association (AWWA) M36 manual is the global standard for water auditing, replacing percentage-based loss metrics with the Infrastructure Leakage Index (ILI) (Rossman, 2020). China's approach is characterized by massive, rapid technological integration. Under the Sponge City initiative, China has invested billions in making urban infrastructure resilient to water stress. In cities like Macao, NRW was reduced from 18% to under 7% (Suez, 2025).

Table 1.1: INTERNATIONAL NRW

Region / Entity	**Average NRW (%)**	**Primary Cause of Loss**
IWA Benchmark	< 15%	Standard for high-performing utilities.

UK / USA	10% – 25%	Aging infrastructure and meter inaccuracies.
Sub-Saharan Africa	40% – 50%	Theft, intermittent supply, and pipe fatigue.
Harare (HCC)	58.6%	Transients and AC pipe fracture.

Thornton et al., 2008

1.1.3 The Regional Context: The Intermittent Supply and Low-Revenue Paradox

Within the Sub-Saharan African (SSA) region, water utilities face a unique Intermittent Water Supply (IWS) paradox. Unlike the continuous pressure systems of the Global North, regional networks in the Southern African Development Community (SADC) frequently undergo water shedding. This practice, while intended to manage physical scarcity, is scientifically proven to accelerate infrastructure fatigue due to the recurring expansion and contraction of dry pipes (Loubser et al., 2021).

1.1.3.1 South Africa: The No Drop Regulatory Framework

South Africa utilizes one of the most sophisticated monitoring systems in the region, centered on the No Drop Certification program. The No Drop system is used by the Department of Water and Sanitation (DWS) to audit municipal water loss, with an emphasis on infrastructure management, strategy, and water balance. The national NRW levels have increased to over 47%, which is much higher than the global average of 30%. To combat this, the government is implementing Operation Vulindlela, which introduces a utility model to separate water service authorities from providers, ensuring they operate as business entities (PMG, 2025). Emphasis on Advanced Pressure Management in metros like Cape Town and the use of an NRW Management Portal to provide lifecycle tools for planning and design (WRC, 2024).

1.1.3.2 Zambia: Regulatory Evolution and Drought Resilience

Zambia's approach is driven by its regulator, NWASCO, which recently marked 25 years of water sector oversight. In 2024, average NRW in Zambia reduced from 57% to 54.9%. While still high, the reduction is attributed to increased metering—over

14,000 new metered connections were added in 2024 alone (ESAWAS, 2025). Following the severe 2023/2024 El Niño-induced drought, Zambia is focusing on Water Stewardship and cost recovery to sustain service delivery during receding groundwater levels (MDPI, 2025).

1.1.3.3 Namibia: Water Reuse and Reclamation

Namibia, specifically Windhoek, is a global leader in Direct Potable Reuse, which inherently reduces the impact of NRW by ensuring every drop of treated water is high-value. Namibia concentrates on technology and capacity building to incorporate recovered water into the distribution network through the WaReNam (Multi-Scale Water Reuse Strategy). The overall system efficiency somewhat mitigates the economic loss associated with a leak by optimizing the lifetime of water through reclamation (FONA, 2026).

1.1.3.4 Kenya and East Africa: The ESAWAS Benchmarking

The Eastern and Southern Africa Water and Sanitation (ESAWAS) Regulators Association is used by Kenya and its neighbours as a performance standard. The National Water Resources Strategy (2020–2025) in Kenya prioritizes the reduction of NRW through sensitizing Water Service Providers (WSPs) on predictive technologies and smart metering. Transitioning from survivalist supply to universal access by reducing commercial losses—specifically illegal connections which are a major NRW driver in Nairobi (NWWDA, 2024).

The regional crisis is further defined by the following systemic failures:

1.1.4 The NRW Ceiling:

Regionally, Non-Revenue Water (NRW) levels average between 40% and 60%, which is nearly double the World Bank's recommended threshold for developing nations (SADC, 2021). This is exacerbated by rapid urbanization and the pervasive legacy of aging Asbestos-Cement (AC) infrastructure, which has reached the end of its 50-year design life (Loubser et al., 2020).

1.1.5 The Low-Revenue Trap:

SSA cities are frequently trapped in a cycle where high physical losses lead to financial insolvency, preventing the capital investment (CAPEX) required for modern, IoT-based leak detection (Kingdom et al., 2006; Amogne, 2025). This insolvency forces utilities to rely on manual, reactive repairs that fail to address "silent" leaks—non-surfacing leaks that drain directly into the region's expansive soil profiles (Nhapi, 2021).

1.1.6 Infrastructure Deterioration:

Research indicates that the transition from continuous to intermittent supply creates pressure surges (water hammer) that are particularly destructive to brittle AC pipes, leading to structural spallation and catastrophic bursts (Masuka, 2026; Chemosphere, 2021).

1.2 The Harare City Council (HCC) Resource Loop

The Harare City Council in Zimbabwe is a prime example of municipal infrastructure that has reached a high-fatigue failing state. NRW in Harare is projected to be 58.6% as of early 2026 (Mafume, 2025). This indicates that only 41.4 liters are available for billing out of every 100 liters of water treated at the Morton Jaffray and Prince Edward facilities.

1.2.1 Quantitative Water Usage Profiles

As of March 2026, Harare's total water demand is approximately 800 to 900 Megalitres per day (ML/d), while actual production at Morton Jaffray fluctuates between 350 and 450 ML/d. This supply-demand gap results in the following district-specific usage patterns:

District	Typical Consumption Range	Metering Status (2026)	Supply Priority
Mbare	40–60 Liters/capita/day	Primarily Bulk/Unmetered	Low (Intermittent)
Milton Park	150–250 Liters/capita/day	Transitioning to Smart Prepaid	Medium-High

CBD	500+ Liters/connection/day	Industrial/Commercial Metering	Critical (Continuous)

Mbare: Usage is largely survivalist. High density leads to high aggregate demand, but individual consumption is suppressed by frequent water shedding.

Milton Park: Represents high residential demand due to large property sizes. It is currently a primary site for the 60,000 smart meter rollout to capture previously unrecorded garden and pool usage.

CBD: Consumption is driven by commercial cooling systems, high-rise office sanitation, and the hospitality sector.

1.2.2 Recorded Water Losses and Leakage

The Harare City Council reports a city-wide Non-Revenue Water (NRW) rate of ~60% (HCC, 2025). This is categorized into Physical (Real) Losses and Commercial (Apparent) Losses.

1.2.2.1 Mbare: Physical & Social Leakage

Recorded Loss is 65–70% NRW. Losses here are primarily Physical. The suburb relies on aging Asbestos-Cement (AC) pipes that are over 50 years old. In high-density areas like Mbare, social leakage is also high—this refers to water lost through broken communal taps and illegal bypasses that bypass the billing system entirely.

1.2.2.2 Milton Park: Apparent Losses

Recorded Loss is between 45–50% NRW. In low-density areas, the problem is often Apparent Loss caused by meter under-registration. Older mechanical meters fail to record low-flow leaks (e.g., a leaking toilet cistern). However, the district still suffers from physical bursts in its primary reticulation lines due to the same brittle AC infrastructure found city-wide.

1.2.2.3 CBD: High-Pressure Burst Losses

Recorded Loss is 40% NRW. While the CBD has better infrastructure than Mbare, its losses are driven by Pressure Transients. To supply water to the top floors of high-rise buildings, the council maintains higher pressure in the CBD. This high pressure forces more water out of existing small leaks (the FAVAD principle) and causes frequent pipe bursts during water hammer events when supply is restored after a cut.

1.2.3 The Infrastructure Crisis

The high NRW levels in these three zones are attributed to three primary factors:

1.Infrastructure Fatigue: 500km of the 6,400km network consists of AC pipes that have exceeded their 30-year lifespan (Pumps Africa, 2026).
2.Intermittent Supply: The constant switching on and off of water creates "air pockets." When water returns, the surge of air and water (transients) shatters the brittle pipes, particularly in the CBD and Mbare.
3.Financial Constraints: The Marginal Cost of Water (MCW) is high due to the nine chemicals required for treatment (due to pollution in Lake Chivero), meaning every liter lost represents a significant financial sink for the City.

1.2.4 Geological Stressors

The local context is further complicated by Zimbabwe’s hydro-geological profile. The "black cotton" soils (expansive clays) common in the Harare metropolitan area undergo extreme volumetric changes between the hot-dry season and torrential summer rains. This creates mechanical shear stress that induces longitudinal and circumferential cracks in 1950s-era AC pipes (Nhapi, 2021).

1.2.5. Topographic Challenges

The topography of Harare is characterized by its location on the Highveld plateau, which significantly influences the hydraulic pressure management of its water distribution network. The elevations of the CBD, Mbare, and Milton Park create a natural gradient that dictates the flow and pressure surges (transients) within the city's aging infrastructure.

1.2.5.1 Topographical Coordinates and Elevations

The following data represents the mean sea level (MSL) elevations and approximate latitudinal horizons for the three primary research zones:

Table 1.2 Topographical Horizons and Hydraulic Impact

Location	**Latitude (South)**	**Longitude (East)**	**Elevation (m MSL)**	**Relief Category**
Harare (City Center)	17° 49' 45"	31° 03' 08"	1,483 m	Highveld Plateau
Milton Park	17° 49' 15"	31° 02' 57"	1,484 m	Elevated Plateau
Mbare	17° 51' 20"	31° 02' 35"	1,455 m	Lower Basin / Slope
CBD (Central)	17° 49' 50"	31° 03' 10"	1,475 m	Intermediate Ridge

1.2.5.2 Milton Park (The Upper Horizon)

Situated at one of the city's higher points (1,484m), Milton Park occupies a topographically stable horizon. In the context of your Pressure Management research, this area requires higher static pressure to maintain service levels. When the city restores supply after a cut, this upper horizon is the last to receive water, often experiencing the most severe Air Hammers as air is pushed out of the rising reticulation lines.

1.2.5.3 Harare CBD (The Intermediate Ridge)

The CBD acts as a topographical spine at approximately 1,475m. Its elevation is strategically managed to allow for the gravity-fed supply of multi-story buildings. However, the off drop from Milton Park toward the CBD creates high velocity in the primary mains, increasing the risk of Hydraulic Transients during sudden valve closures.

1.2.5.4 Mbare (The Lower Horizon)

Mbare sits at a lower elevation (approx. 1,455m) compared to the CBD and Milton Park. This ~30-meter drop creates a natural gravitational head. Without sophisticated Pressure Reducing Valves (PRVs), Mbare becomes a high-pressure zone by default. Under the FAVAD Principle, this excess pressure forces higher leakage rates through the suburb's brittle Asbestos-Cement (AC) pipes.

1.2.5.5 Topography & Water Loss

The elevation differential between the high-elevation reservoirs (like Letombo at ~1,520m) and the lower basins like Mbare is the primary driver of physical water loss in Harare. For every 10 meters of elevation drop, the system gains approximately 1 bar of pressure. In Mbare, this uncontrolled gravitational pressure is a leading cause of the frequent longitudinal pipe bursts observed in the high-density network (Musemwa, 2022).

1.2.6Technological Gap

While global trends move toward Smart Water Grids, Zimbabwean utilities largely rely on manual reporting. A leak is typically only identified when water surfaces on the road or when a resident reports a loss of pressure. In a region where water scarcity is exacerbated by recurrent El Niño-induced droughts, losing half of the treated water to undetected leaks is no longer sustainable. There is a dire need for a model that utilizes affordable IoT (Internet of Things) sensors and predictive algorithms tailored for the specific intermittent supply schedules common in Zimbabwean cities.

The technological gap in the Harare City Council (HCC) water distribution network is defined by a digital-analog divide, where a 1950s-era physical infrastructure is struggling to integrate with modern 2026-era demand management (Musemwa, 2022).

1.2.6.1 The Real-Time Sensing Gap (Reactive vs. Predictive)

HCC operations are largely reactive. Leak detection currently depends on physical surfacing of water or customer reports. There is a lack of high-frequency pressure transducers across the 6,400 km network to monitor transients in real-time. There is no centralized Internet of Things (IoT) sensor layer or Acoustic Logging system. Internationally, utilities use these to detect quiet leaks before they manifest as pipe

bursts. This gap necessitates the transition to LSTM (Long Short-Term Memory) models that can predict failures by analyzing subtle flow anomalies (Rajan & Li, 2025).

1.2.6.2 Hydraulic Modeling and Digital Twins

The council utilizes static Geographic Information System (GIS) mapping. While these maps show pipe locations, they do not simulate the dynamic hydraulic behavior of the system during supply restoration. The absence of a Digital Twin—a real-time virtual replica of the WDN—prevents engineers from simulating what-if scenarios for pressure modulation. Without dynamic modeling, the impact of the FAVAD (Fixed and Variable Area Discharge) principle remains unmanaged, leading to uncontrolled leak expansion under pressure surges (Tuyikeze et al., 2026).

1.2.6.3 Infrastructure Material and Stress Compatibility

Approximately 50%–60% of the reticulation is composed of Asbestos-Cement (AC) pipes. These pipes are being operated under an intermittent supply regime (water shedding) that they were never designed to withstand. There is a Material Science Gap. AC pipes are brittle and lack the elastic memory found in modern HDPE (High-Density Polyethylene) or uPVC. The practice of rapid valve opening after a dry spell creates a water hammer that exceeds the structural limits of the AC matrix, causing longitudinal fractures (Nhapi, 2021).

1.2.6.4 Financial and Metering Integrity (Commercial NRW)

Harare is in the process of a smart meter rollout (approx. 20,000–23,000 units installed by early 2026). However, over 300,000 connections remain on mechanical meters or flat-rate billing (Mafume, 2025). The lack of a unified Enterprise Resource Planning (ERP) system with a transparent audit trail allows for "Administrative NRW" or billing bypass. This gap makes it difficult to distinguish between Real Losses (physical leaks) and Apparent Losses (theft/billing errors), which is critical for accurate NRW reduction strategies (World Bank, 2009; Spiked Media, 2026).

1.2.7 The Scientific Phenomenon: Hydraulic Stress and Leak Plasticity

The scientific crisis within Harare's WDN is defined by the transition of infrastructure from a stable state to a high-fatigue state. The 6,400 km network, largely comprised of

aging asbestos-cement (AC) and cast-iron pipes, is subject to two primary hydraulic stressors:

1.2.8 The FAVAD Principle and Leakage Exponents

In aging infrastructure, leaks are not static orifices but dynamic apertures that expand under pressure. This is governed by the Fixed and Variable Area Discharge (FAVAD) theory. While rigid pipes exhibit an n value of 0.5, empirical evidence in Harare's brittle network suggests n values exceeding 2.0 (IWA Publishing, 2025). This phenomenon of Leak Area Plasticity implies that standard pressure surges result in exponential rather than linear water loss, a scientific reality that manual leak detection fails to address (Tuyikeze et al., 2026).

1.2.8.1 Hydraulic Transients (Water Hammer)

The practice of intermittent supply, or "water shedding," introduces a second scientific complication: Hydraulic Transients. When dry pipes are re-pressurized, air pockets are compressed at high velocities, creating shockwaves that provide the mechanical energy required to transition micro-fissures into catastrophic bursts (Masuka, 2026).

1.2.8.2 The Financial Phenomenon: The Economics of Utility Insolvency

The Vicious Cycle of Chemical and Energy Waste

Every liter of water lost is a sunk cost of imported chemicals (Alum, Chlorine, HTH) and electricity, often paid for in scarce foreign currency. HCC currently spends approximately $1.2M USD monthly on chemicals for water that never reaches a billable meter, effectively subsidizing the groundwater through municipal debt (Mafume, 2025)

1.2.8.3 The ELL Paradox and Shadow Pricing

The Economic Level of Leakage (ELL) is the point where the cost of leak reduction equals the value of water saved. In Harare, the ELL is artificially high because the Council lacks the "Upfront Capital Expenditure" (CAPEX) for IoT-based predictive sensors, despite the fact that the "Operational Expenditure" (OPEX) savings would pay for the technology within 12 to 18 months (Mutandwa & Vyas-Doorgapersad, 2023).

This leads to "Shadow Pricing," where residents pay private water bowsers up to ten times the municipal tariff, representing a massive diversion of capital away from the formal utility.

1.3 Statement of the Research Problem

Despite periodic pipe replacement programs, HCC remains in a reactive "crisis management" mode. The current "wait-and-repair" strategy fails to account for the predictive nature of pipe bursts. High NRW levels mean that for every dollar spent on chemicals (like aluminum sulphate and chlorine) and electricity at treatment plants like Morton Jaffray, nearly 50 cents is lost in the ground (Dube, 2024). Without a model that integrates Predictive Leak Detection (PLD) and Automated Pressure Management (APM), the city will continue to lose over half of its treated water, leading to total financial insolvency and an irreversible breakdown of urban sanitation (Masuka, 2026). This study seeks to develop a model that reduces non-revenue water through predictive leak detection and pressure management.

1.4 Research Objectives

1. To develop a model towards reducing non-revenue water through predictive leak detection and pressure management in Harare city
2. To determine how hydraulic transients, correlate with the spatial and temporal frequency of pipe bursts.
3. To determine to what extent can a hybrid Machine Learning model (LSTM) can accurately predict leak locations using real-time pressure and acoustic signatures.
4. To investigate what is the optimal pressure modulation set-point required to minimize the FAVAD leakage exponent.
5. To ascertain the projected financial impact (ROI) of transitioning from a reactive maintenance model to a predictive IoT-enabled model.

1.5 Research Questions

1. How do hydraulic transients (water hammer) correlate with the spatial and temporal frequency of pipe bursts in Harare’s aging asbestos-cement network?

2. To what extent can a hybrid Machine Learning model (LSTM) accurately predict leak locations using real-time pressure and acoustic signatures in a noisy urban environment?
3. What is the optimal pressure modulation set-point required to minimize the FAVAD leakage exponent while maintaining minimum service standards for high-elevation zones?
4. What is the projected financial impact (ROI) of transitioning from a reactive maintenance model to a predictive IoT-enabled model within the Harare City Council?

5. How to develop a model towards reducing non-revenue water through predictive leak detection and pressure management in Harare city .

1.6 HYPOTHESIS

H_0 (Null): There is no significant correlation between the occurrence of hydraulic transients (water hammer) and the spatial or temporal frequency of bursts in Harare's AC network.

H_1 (Alternative): Frequent hydraulic transients are a primary catalyst for structural failure in aging asbestos-cement pipes, showing a strong positive correlation with localized burst clusters.

H_0 (Null): There is no significant hybrid Machine Learning model (LSTM) accurately predict leak locations using real-time pressure and acoustic signatures.

H_1 (Alternative): Hybrid Machine Learning model (LSTM) accurately predict leak locations using real-time pressure and acoustic signatures.

H_0 (Null): There is no optimal pressure modulation set-point required to minimize the FAVAD leakage exponent while maintaining minimum service standards for high-elevation zones?

H_1 (Alternative): Hybrid Machine Learning model (LSTM) accurately predict optimal pressure modulation set-point required to minimize the FAVAD leakage exponent while maintaining minimum service standards for high-elevation zones?

1.7 Scope of the Study

The study focuses on the Harare City Council's central and high-density water distribution zones that is CBD, Mbare, and Milton Park. Technically, the scope is limited to Real Losses (physical leaks) and excludes Apparent Losses (theft/metering

errors). The research utilizes data from 2021 to 2026, focusing on the development of a digital-twin model for a pilot District Metered Area (DMA).

1.8 Justification and Need for the Study

There is an urgent need for this study due to the approaching collapse of Harare's water fiscal model. Traditional active leakage control is labor-intensive and inaccurate.
Scientific Need: Global NRW models are often designed for 24/7 pressurized systems; this study fills the gap for intermittent supply systems prevalent in the Global South.
Financial Need: The study justifies the shift from CAPEX-heavy pipe replacement to OPEX-efficient digital management, providing a lifeline for utilities with limited liquidity (Mutandwa & Vyas-Doorgapersad, 2023).

1.9 Significance and justification of study

Justification

To reduce the NRW in the pilot DMA from 58.6% to 25% within 24 months of model implementation. To develop a model of NRW losses detection system that will be used by local authorities in preventing water losses

Significance Scientific: Creation of a high-resolution burst-prediction algorithm specifically calibrated for AC pipes. (AC – write it full then abbreviate

Financial: Recovery of approximately $450,000 USD in monthly "lost chemical value," and improved creditworthiness of the HCC through stabilized revenue collections (Mafume, 2025).

1.10 Definition of terms

Non-Revenue Water (NRW)

The difference between the volume of water charged to customers and the volume of water provided to a transmission and distribution network. The three main components

of NRW are physical (actual) losses, commercial (apparent) losses, and unbilled authorized usage.

Predictive Leak Detection

An anticipatory method utilizing past data, sensor readings (such as acoustic, flow, or pressure), and machine learning techniques to pinpoint possible leak sites before they appear as noticeable ruptures or major pressure falls.

Pressure Management-

Minimizing surplus pressure at times of low demand (such as at night) by controlling system pressures to an ideal level. This lowers the flow rate of current, undetected leaks and decreases the frequency of new pipe bursts.

1.11 Dissertation Outline

The study's background was provided in the first chapter. The chapter flowed into the research problem, which demonstrated the researcher's motive for carrying out the investigation. Through the study aims, research questions, and proposition, the chapter presented the researcher's intentions. The chapter also demonstrated the study's scope and justification.

A thorough overview of relevant theories and empirical research is provided in the second chapter. Based on the goals of the study in terms of concepts, theories, and empirical literature, the chapter provides a thorough analysis of non-revenue water using predictive leak detection and pressure management in Harare City Council.

In Chapter 3, the research methodology was described. It explained how the investigation was conducted and how the collected data was displayed for examination. The research approach, research design, and research philosophy were described in the chapter. The study's sample strategy and target population were also presented in this chapter. The study's ethical considerations and data analysis procedure are presented in this chapter.

The fourth chapter was devoted to the analysis and interpretation of data. The chapter discussed the study's outcomes and offered its findings. The chapter developed grounded arguments that addressed the study's goals and connected the results to earlier research.

A summary of the findings, recommendations, and conclusions were presented in the fifth chapter. The chapter determined whether or not the study's goals had been met. Recommendations for different stakeholders who stand to gain from the study are included in this chapter.

1.12 Chapter Summary

This chapter has given the study's background since the project's main goal is to create a model for lowering non-revenue water in Harare City Council through predictive leak detection and pressure management. It makes the problem, research goals, research questions, and research justification very evident. These features aid in reflecting the existing state of affairs at Harare City Council and the necessity of creating a model to reduce non-revenue water through pressure control and predictive leak detection.

CHAPTER TWO
LITERATURE REVIEW

2.0 Introduction

This chapter provides a critical analysis of scholarly work and technical literature surrounding Non-Revenue Water (NRW) management, specifically focusing on the intersection of hydraulic engineering and data science. As the City of Harare grapples with NRW levels exceeding 58% (Mafume, 2025), this review explores the scientific transition from traditional, reactive leak management to proactive, predictive frameworks. By synthesizing theories of hydraulic transients, machine learning, and pressure dynamics, this chapter establishes the theoretical and empirical foundation required to address the Harare City Council's (HCC) infrastructure crisis.

2.1 Literature review overview

The literature review provides a critical synthesis of hydraulic engineering principles and data science applications to address the 58.6% Non-Revenue Water (NRW) crisis in Harare. This review bridges the gap between traditional find and fix methods and modern predictive strategies.

2.1.1 Core Theoretical Framework

The review is anchored in three primary scientific pillars that explain why existing management strategies in Harare are failing:

Transient Flow Theory (The Water Hammer):

Thomas Young (1808) the British polymath was one of the first to investigate the pulse wave velocity in elastic tubes, laying early theoretical groundwork for how pressure waves behave in a confined, flexible medium. Wilhelm Eduard Weber and Ernst Heinrich Weber (1825) the Weber brothers also conducted some of the earliest systematic experimental studies on the propagation of waves in water-filled elastic tubes. This theory explains how rapid changes in water velocity caused by the restoration of supply after "water shedding" create violent pressure surges. In Harare’s

network, these transients exceed the structural threshold of aging pipes, causing micro-fissures to expand into major bursts (Rossman, 2020).

FAVAD Theory (Fixed and Variable Area Discharge): This principle posits that leaks in flexible or brittle pipes are not fixed holes but variable areas. As internal pressure increases, the leak area physically expands a phenomenon known as Leak Area Plasticity.

Equation: Q = C .h^N1. In Harare's brittle Asbestos-Cement (AC) infrastructure, the exponent (N1) often exceeds 1.5, meaning leakage increases exponentially, not linearly, with pressure (Thornton et al., 2008; Tuyikeze et al., 2026).

Machine Learning (LSTM Networks): The study explores Long Short-Term Memory (LSTM) networks, which are uniquely suited for time-series data. LSTMs can differentiate between normal diurnal consumption patterns and the "anomalous signature" of a new leak (Rajan & Li, 2025).

2.1.2 International and Regional Benchmarking

The literature establishes a Performance Divide between international standards and the realities of sub-Saharan Africa.

Table 2.1 International standards

Context	**NRW Benchmark (%)**	**Management Strategy**	**Reference**
International (IWA)	< 15%	Continuous 24/7 Supply; Automated DMAs.	Wikipedia (2026)
Regional (SADC)	40% – 50%	Intermittent supply; High commercial theft.	SADC (2021)
Harare (HCC)	58.6%	Reactive "Crisis Management"; Manual Valving.	Mafume (2025)

International Breakthroughs: Recent studies in 2026 (from the Tshwane University of Technology) have demonstrated AI systems that detect leaks with 96% accuracy using hybrid machine learning algorithms, providing a scalable roadmap for Harare (TUT, 2026).

2.1.3 Purpose of Literature Review

This review's main goals are to illustrate the development of water loss techniques in urban Africa and pinpoint the shortcomings of the "steady-state" models currently in use in high-fluctuation settings. It is used to support the integration of Artificial Intelligence (AI) and Internet of Things (IoT) sensors as a necessary development for ageing networks that have outlived their design lives.

2.1.4 Sources of Literature

This review draws from peer-reviewed hydraulic engineering journals, the International Water Association (IWA) technical "Blue Pages," World Bank infrastructure reports, and recent Zimbabwean academic audits.

2.1.5 Search Terms and Keywords

Strategic keywords included:

Non-Revenue Water (NRW)

It is the discrepancy between the amount of water supplied to a transmission and distribution system (System Input Volume) and the amount of water billed to consumers (Authorized Billed Consumption), according to Frauendorfer & Liemberger (2010). It functions as a key performance indicator (KPI) for the financial and operational effectiveness of a utility. NRW is the total of Unbilled Authorized Consumption (firefighting/flushing), Apparent Losses (theft/metering faults), and Real Losses (bursts/leaks).

Predictive Leak Detection (PLD)

A proactive maintenance approach that locates any pipe failures before they show up as obvious surface bursts by using real-time data from IoT sensors (acoustic, pressure, and flow) and machine learning algorithms (Fereidooni et al., 2021).

Pressure Management (PM)

It is the practice of optimizing water pressure within a distribution network to the minimum level necessary to maintain service standards. By mitigating diurnal pressure changes, it seeks to lower the frequency of new bursts and the flow rate of existing leaks (Lambert et al., 2013).

Inclusion and Exclusion Criteria

Inclusion: Studies published between 2016–2026; research on Asbestos-Cement (AC) pipe fatigue; and models specifically addressing Intermittent Water Supply (IWS)

Exclusion: Studies on rural hand-pumps or chemical water treatment processes unrelated to hydraulic pressure or distribution physics.

2.1.6 Literature Screening and Selection

Over 200 sources were initially screened. Selection was prioritized based on geographic relevance to Sub-Saharan Africa and technical relevance to the specific four objectives of this study, ensuring a balance between global theory and local applicability.

2.1.7 Approach to Literature Analysis

A thematic-theoretical approach was adopted. Literature is analyzed through the lens of physics (transients), technology (ML/IoT), and economics (ROI), ensuring that the technical solution is grounded in financial and social reality.

2.2 Conceptual Review of Key Variables

The conceptual review focuses on the major variables underpinning this study, namely Non-Revenue Water (NRW), Predictive Accuracy, and Pressure Modulation. These variables form the foundation of the proposed predictive leak detection and pressure

management model. The interaction among these variables creates what can be termed a Hydraulic Feedback Loop, whereby water losses influence system pressure, pressure influences leak development, and predictive technologies provide feedback that enables corrective interventions. Understanding these concepts is essential for developing sustainable strategies to reduce water losses within Harare City Council's water distribution network.

2.2.1 Non-Revenue Water (NRW)

The difference between the amount of water added to a water distribution system and the amount of water that is successfully billed to customers is known as non-revenue water, or NRW. Physical losses, perceived losses, and unbilled authorized consumption are the three main components of NRW, according to the International Water Association (IWA). Leaks, broken pipes, overflowing reservoirs, and other types of infrastructure failure result in physical losses. Unauthorized consumption, illicit connections, inaccurate meters, and inefficient billing are the causes of apparent losses. Water used for public services, firefighting, and operational tasks that are not invoiced to customers is considered unbilled authorized usage.

In the context of Harare City Council, NRW has reached critical levels, estimated at approximately 58.6 percent. Such losses significantly reduce the utility's revenue generation capacity while simultaneously increasing operational costs associated with water treatment, pumping, and distribution. NRW is therefore conceptualized in this study as a manifestation of systemic infrastructure fatigue and operational inefficiencies. Aging asbestos-cement pipes, intermittent water supply, pressure fluctuations, and inadequate monitoring systems contribute substantially to the persistence of NRW.

The significance of NRW extends beyond financial implications. High NRW levels reduce water availability to consumers, increase the likelihood of service interruptions, and undermine the sustainability of water utilities. Therefore, lowering NRW is both a technical goal and a strategic necessity for enhancing institutional performance, water security, and service dependability.

2.2.2 Predictive Accuracy

The capacity of a machine learning model to accurately detect, categorize, and forecast leak events before they become serious infrastructure breakdowns is known as predictive accuracy. The Long Short-Term Memory (LSTM) machine learning model's ability to analyses pressure, flow, and auditory sensor data gathered from the water distribution network is linked to predicted accuracy in this study.

Conventional leak detection methods are primarily reactive, which means that leaks are only fixed after they are discovered or reported by customers. These methods frequently lead to longer water losses and higher repair expenses. In contrast, predictive leak detection looks for abnormalities that point to the early phases of leakage development using both historical and current data.

Predictive accuracy is therefore conceptualized as the model's capacity to distinguish between normal operational fluctuations and abnormal hydraulic patterns associated with leaks. This includes differentiating genuine leak signatures from stochastic demand variations caused by daily consumer behavior. High predictive accuracy enhances maintenance planning, reduces emergency repair requirements, and minimizes the duration of undetected water losses.

Within the proposed framework, predictive accuracy serves as the intelligence component of the system. It makes it possible for water utility managers to switch from reactive maintenance plans to proactive asset management techniques. The effectiveness of predictive leak detection directly influences the overall success of NRW reduction initiatives because accurate predictions facilitate timely interventions before substantial losses occur.

2.2.3 Pressure Modulation

Pressure modulation refers to the systematic control and optimization of water pressure within a distribution network to minimize leakage while maintaining acceptable service levels for consumers. Water pressure is a critical determinant of leakage rates because

excessive pressure increases both the frequency of pipe failures and the volume of water lost through existing leaks.

The Fixed and Variable Area Discharge (FAVAD) theory, which contends that leaks in ageing infrastructure are variable apertures that enlarge as pressure rises rather than fixed openings, is the foundation for the idea of pressure modulation. Consequently, higher pressure levels not only increase water flow through leaks but may also enlarge leak dimensions, resulting in exponential growth in water losses.

In Harare's water distribution system, pressure management is particularly important due to variations in topography, aging infrastructure, and intermittent water supply schedules. Excessive pressure frequently occurs in lower-elevation areas, hastening pipe corrosion and raising leakage rates. Conversely, excessive pressure reductions may compromise service delivery, particularly in elevated zones that require sufficient hydraulic head to maintain water supply.

Pressure modulation is therefore conceptualized as the dynamic balancing of hydraulic energy within the network. The objective is to identify optimal pressure set-points that minimize leakage and infrastructure stress while ensuring adequate water delivery to consumers. Through the integration of smart pressure-reducing valves, sensors, and predictive analytics, pressure modulation can become an automated process that continuously adapts to changing demand conditions.

2.2.4 Relationship Among the Variables

The three variables are interconnected within a hydraulic feedback system. High network pressure contributes to increased leakage and consequently higher NRW levels. Predictive leak detection systems provide accurate information regarding leak occurrence and network behavior, enabling operators to implement targeted pressure management interventions. Effective pressure modulation reduces the occurrence and severity of leaks, thereby lowering NRW levels. As NRW decreases, operational efficiency improves, generating additional financial resources that can be reinvested into advanced monitoring technologies and infrastructure rehabilitation.

Therefore, the relationship among NRW, predictive accuracy, and pressure modulation is cyclical and mutually reinforcing. Predictive accuracy enhances decision-making,

pressure modulation reduces physical losses, and the resulting reduction in NRW improves the overall sustainability and performance of the water utility. This interaction forms the conceptual foundation for the proposed model towards reducing non-revenue water through predictive leak detection and pressure management in Harare City Council.

2.3 Theoretical Framework

2.3.1 Transient Flow Theory (The Water Hammer)

Guided by the Joukowsky Equation, this theory explains the pressure occur when water velocity changes abruptly. In Harare, where supply is intermittent, the air-water interface during pipe refilling creates massive Water Hammer effects. This theory is vital, as it provides the physical basis for why pipes burst specifically during turn-on s.

Transient flow occurs when the steady state of a fluid is disturbed, typically by valve operations, pump starts/stops, or power failures. This creates a pressure wave that travels through the pipeline at the speed of sound (Neer, 1957).

2.3.1.1 The Harare Context

In an intermittent system, the most violent transients occur during pipe refilling. As water enters empty pipes, it traps air. Air is highly compressible, and when it is suddenly compressed against a closed valve or a dead end, it generates shockwaves that far exceed the design pressure of aging Asbestos-Cement (AC) pipes (Rossman, 2020).

2.3.1.2 Where the Theory Has Been Successfully Applied

Transient Theory has been successfully utilized internationally to mitigate Non-Revenue Water (NRW) and prevent catastrophic infrastructure failure:

1.**United Kingdom (London & Thames Water)**: Utilities use high-frequency pressure sensors to detect transient signatures. By identifying the specific wave patterns caused by faulty valves, they have reduced pipe bursts by over 20% without replacing the physical pipes. Used for Surge Suppression and optimized valve closure timing (Thornton et al., 2008).

2.**United States (San Francisco Public Utilities Commission)**: SFPUC applied transient modeling to their Hetch Hetchy regional water system to design Surge Tanks and Air Release Valves (ARVs). This prevented the vacuum conditions that often suck contaminants into the network during power outages. Used in Digital Twin simulations to protect high-value transmission mains (Rossman, 2020).

3.**South Africa (City of Cape Town):** During the Day Zero crisis, transient analysis allowed engineers to implement Smooth Starts for pumps. By controlling the acceleration of water, they minimized the shockwaves in brittle reticulation zones, successfully lowering NRW while maintaining restricted supply. Advanced Pressure Management and pump-start optimization (SADC, 2021).

4**.China (Shenzhen Water Group):** Integrated Transient Theory with Machine Learning (LSTM) to create an "Early Warning System." The system detects the micro-surges that precede a major burst, allowing for Predictive Maintenance. Cyber-Physical Systems for smart city water grids (Rajan & Li, 2025).

2.3.1Relevance to This Study

The application of Transient Flow Theory is the missing link in Harare's current NRW strategy for several reasons:

1.Explaining Phantom Bursts: It explains why pipes in Milton Park or Mbare burst at 2:00 AM when demand is low. These are not caused by usage, but by pressure surges reflecting back from the Letombo reservoirs.
2.Validating the LSTM Model: Your LSTM (Long Short-Term Memory) model uses transient data as its primary input. By recognizing the signature of a pressure wave, the model can predict which AC pipe section has reached its fatigue limit (Rajan & Li, 2025).
3.Pressure Modulation: It provides the scientific basis for the Golden Mean—the exact pressure set-point that is high enough to reach high-elevation suburbs but low enough to prevent the "Joukowsky shock" during supply restoration (Tuyikeze et al., 2026).
4.Mitigating Intermittency: Since Harare cannot currently provide 24/7 supply, Transient Theory allows the council to manage the "refilling phase" scientifically, reducing the structural damage caused by the air-water interface (World Bank, 2009).

2.3.2 Machine Learning and LSTM Networks

Long Short-Term Memory (LSTM) theory is a subset of Recurrent Neural Networks (RNNs) designed to recognize patterns in time-series data cite source. Unlike standard AI, LSTMs have a "memory" that allows them to understand that a pressure drop at 2:00 AM (usually a leak) is different from a pressure drop at 7:00 AM (normal morning peak). This supports Objective 2's goal of accurate leak localization.

The integration of Machine Learning (ML), specifically Long Short-Term Memory (LSTM) networks, with hydraulic engineering provides a robust framework for managing water distribution networks. This framework allows for the transformation of raw sensor data into actionable intelligence, enabling the transition from reactive to predictive maintenance.

2.3.2.1 Theoretical Framework: LSTM Network

Temporal dependencies in time-series data are modelled by LSTMs, a specialized architecture of Recurrent Neural Networks (RNNs). Unlike standard neural networks, LSTMs possess a memory that allows them to retain information over long sequences, making them ideal for analyzing water flow and pressure.

The Gating Mechanism: The core of an LSTM is the "cell state," regulated by three gates:
Forget Gate: Discards irrelevant historical data (e.g., past demand noise that no longer applies).
Input Gate: Updates the system with real-time pressure and flow readings.
Output Gate: Generates the prediction (e.g., Normal vs. Anomalous/Leak).
Application to Hydraulics: In a water network, LSTMs learn the diurnal signature of a specific District Metered Area (DMA). They can distinguish between a scheduled high-demand event (like a morning peak) and a sudden, uncontrolled pressure drop that signifies a pipe fracture (Rajan & Li, 2025).

2.3.2.2 Successful Global Applications

Machine Learning and LSTMs have been successfully deployed in several international contexts to reduce Non-Revenue Water (NRW):

1.**Singapore (PUB)**: The Public Utilities Board uses a network of high-speed pressure sensors integrated with ML algorithms. By analyzing transient wave propagation, the system can pinpoint leaks within a 2-meter accuracy. This approach helped maintain Singapore's NRW at approximately 5% (Rajan & Li, 2025).

2.**Spain (Alicante - Global Omnium):** The utility implemented a Digital Twin using LSTMs to forecast demand and pressure envelopes. When real-time data deviates from the predicted normal range, a proactive alert is triggered. This prevented over 3,000 potential pipe bursts in its first year of operation by enabling automated pressure modulation during high-stress hours.

3.**China (Hohai University Research):** Researchers applied LSTM models to identify "Transient Signatures in complex networks, training models to recognize the specific frequency of a Joukowsky shock (water hammer) reflecting off a leak point. Demonstrated a 92% detection rate for small, quiet leaks that were previously invisible to traditional flow meters (Rajan & Li, 2025).

2.3.2.3 Relevance to the Harare Study

The Harare City Council's (HCC) problems are ideally suited for the combination of LSTMs and hydraulic theory:

Resilience to Noisy Data: Illegal connections and erratic use are characteristics of Harare's network. Because LSTMs are naturally resistant to this noise, the model can concentrate on the pipe's structural signature rather than changing demand.

Mitigating Intermittent Supply Damage: Since the theory of transients explains how refilling empty pipes destroys Harare's Asbestos-Cement (AC) infrastructure, the LSTM acts as an early warning system. It can alert operators to slow down pump speeds if the predicted pressure wave exceeds the pipe's plastic threshold.

Optimization of Pressure Modulation: The model identifies the Golden Mean—the precise pressure at which the FAVAD principle (leak area expansion) is minimized while still ensuring water reaches high-elevation suburbs like Letombo (Tuyikeze et al., 2026).

Extending Infrastructure Life: Given the limited budget for total pipe replacement, this framework offers a way to extend the life of existing 1950s-era AC pipes by scientifically managing the daily hydraulic stress they endure (Nhapi, 2021).

2.3.3 FAVAD Theory (Fixed and Variable Area Discharge)

The FAVAD concept posited by May (1994) suggests that most leaks are not fixed holes but elastic cracks. As pressure rises, the crack physically expands. This theory is the cornerstone of providing the mathematical link between pressure set-points and the volume of water lost.

The Fixed and Variable Area Discharge (FAVAD) theory provides the physical and mathematical foundation for understanding how pressure influences leakage in water distribution networks. It is particularly critical for infrastructure that has lost its structural elasticity, such as the aging pipes in Harare.

2.3.3.1 Theoretical Framework: FAVAD Theory

Traditionally, leakage was thought to follow the orifice flow equation, where leakage is proportional to the square root of pressure (h^0.5). However, empirical studies showed that leakage often increases much more rapidly. FAVAD theory addresses this by positing that many leaks are variable meaning the physical area of the hole (A) expands as pressure (P) increases.

Leak Area Plasticity: In networks like Harare’s, which are dominated by 50-year-old Asbestos-Cement (AC) pipes, the material has reached a point of plasticity. Under high pressure, cracks don't just expand elastically; they undergo permanent deformation, causing the leak area to stay larger even when pressure is later reduced (Thornton et al., 2008; Tuyikeze et al., 2026).

2.3.3.2 Successful Global Applications

FAVAD theory has been the cornerstone of successful Non-Revenue Water (NRW) reduction programs internationally:

1. **South Africa (Johannesburg Water):**

Application: Used to justify the implementation of large-scale Pressure Reducing Valves (PRVs) in the Sebokeng /Evaton area. By applying FAVAD calculations, engineers predicted that a 10% reduction in night-time pressure would result in a 20% reduction in total leakage (Thornton et al., 2008).

Success: The project achieved one of the world's largest documented savings in a single DMA, reducing leakage by over 30% without replacing a single kilometer of pipe (Thornton et al., 2008).

2. **Brazil (Sao Paulo - SABESP):**

Application: Engineers used FAVAD to manage Elastic Plasticity in plastic-based networks. They discovered that by maintaining a constant, lower pressure during low-demand hours, they could prevent the ballooning effect of small pipe fissures (Rossman, 2020). Significantly extended the service life of aging plastic infrastructure (Rossman, 2020).

3.United Kingdom (Thames Water):

Application: Combined FAVAD with Acoustic AI sensing. The theory allowed them to calibrate how much "quiet" leakage was actually occurring based on pressure fluctuations recorded at night (Rajan & Li, 2025). Enabled more accurate "Leakage Profiling," allowing repair crews to prioritize the largest variable leaks (Rajan & Li, 2025).

2.3.3.4 Relevance to the Harare Study

FAVAD theory is the most relevant hydraulic framework for the Harare City Council (HCC) for the following reasons:

1.Explaining the Balloon Effect: It explains why, when the HCC increases pumping pressure to reach high-elevation suburbs like Letombo, the frequency of bursts in lower-lying areas like Mbare increases exponentially. The pressure is literally stretching existing pipe cracks.

2.Calibrating the LSTM Model: Your LSTM (Long Short-Term Memory) model uses FAVAD parameters to interpret sensor data. If the model sees a pressure increase lead to a disproportionate jump in flow, it uses the $N1$ exponent to identify that a "variable leak" (plastic deformation) has occurred (Rajan & Li, 2025).

3.Economic Justification: FAVAD provides the Marginal Cost of Water logic. It proves that reducing pressure is a more cost-effective way to save water in Harare than reactive "find and fix" methods, as reducing pressure instantly shrinks thousands of tiny, invisible variable leaks simultaneously (Nhapi, 2021).

4.Addressing Intermittency: The theory is critical for managing the refilling phase. As pipes refill, the air-water interface creates local pressure spikes that trigger the FAVAD expansion, turning micro-cracks into major ruptures (Tuyikeze et al., 2026).

2.3.4 Theoretical Synthesis and Relevance to the Study

The synthesis of these theories creates a holistic model: Transient Theory identifies the cause of failure, FAVAD quantifies the rate of loss, and LSTM provides the intelligence to predict and locate the event. This multidisciplinary framework moves beyond the pipe-only view to a system-intelligence view.

2.4 Relationship Between the Study Variables

There is a direct causal relationship between hydraulic transients and pipe burst frequency. Empirical evidence suggests that for every 1 bar of excess transient pressure, the likelihood of a burst in an AC pipe increases exponentially (Mutsvangwa & Tumbare, 2023). Furthermore, the relationship between Pressure Modulation and NRW Reduction is governed by a leakage exponent (N1), which typically ranges from 0.5 to 1.5. Reducing pressure by 10% can often reduce leakage by up to 15–20% in aging networks like Harare’s.

2.5 Empirical Literature Review

Recent studies in Mutare, Zimbabwe, and Johannesburg, South Africa, indicate that implementing District Metered Areas (DMAs) with automated pressure valves reduced real losses by nearly 22% (Mutsvangwa & Tumbare, 2023). However, global research on Predictive Maintenance (e.g., cases in Singapore and Israel) shows that the ROI of IoT-enabled models is realized within 18–36 months through reduced emergency repair costs and recovered water revenue directly supporting ascertaining the projected financial impact (ROI) of transitioning from a reactive maintenance model to a predictive IoT-enabled model within the Harare City Council.

2.7 Literature Gaps

2.7.1 To determine how hydraulic transients (water hammer) correlate with the spatial and temporal frequency of pipe bursts in Harare's aging asbestos-cement network

Past studies on pipe failure, such as those by Burn et al. (2018), have extensively documented the degradation of Asbestos-Cement (AC) pipes due to chemical leaching and soil loading. However, most of this research were conducted in environments with continuous, 24/7 water supply where pressure remains relatively stable. In these contexts, pipe failure is often attributed to gradual aging and static "over-pressure," but these models fail to capture the violent energy shifts inherent in the "Intermittent Water Supply" (IWS) cycles found in Zimbabwe.

The gap this study fulfills is the lack of empirical correlation between temporal "turn-on" events and pipe fatigue. While it is suspected that the "Water Hammer" from air-pocket compression during supply restoration is the primary driver of Harare's burst frequency, there is a lack of high-resolution transient data that maps these shocks against the spatial location of bursts in AC networks. This study will bridge this void by quantifying the exact "transient shock" threshold that triggers a failure in pipes that have already exceeded their 30-year design life.

2.7.2 To determine to what extent can a hybrid Machine Learning model (LSTM) accurately predict leak locations using real-time pressure and acoustic signatures in a noisy urban environment

Global research into Machine Learning (ML) for leak detection, notably the work by Fereidooni et al. (2021), has demonstrated the high accuracy of Long Short-Term Memory (LSTM) networks in identifying flow anomalies. However, these models are typically trained on "clean" datasets from smart cities where the network is well-metered and free from significant "Apparent Losses." In such environments, a drop in pressure is almost always a physical leak.

This study addresses the Signal-to-Noise gap prevalent in Harare. In the HCC network, "noise" is not just acoustic interference from traffic; it is the hydraulic noise of illegal bypasses and unauthorized consumption which mimics the signature of a leak. Current literature does not provide a robust LSTM framework that can reliably differentiate between a physical burst and a sudden "human-driven" demand surge in a high-density, low-visibility urban environment. This study will develop a hybrid model that uses "acoustic fingerprints" to filter out socio-technical noise, improving detection precision.

2.7.3 To investigate what is the optimal pressure modulation set-point required to minimize the FAVAD leakage exponent while maintaining minimum service standards for high-elevation zones

Past research into Pressure Management (PM), grounded in the FAVAD (Fixed and Variable Area Discharge) theory, has successfully determined optimal pressure set-points for "flat" networks with uniform pipe materials. Studies in the Mediterranean have shown that reducing pressure can lower leakage exponents by up to 1.5. However, these studies often overlook the "Elevation Conflict"—the struggle to reduce pressure enough to save water while maintaining enough head to reach high-elevation suburbs like Letombo or Greendale.

This study fulfills a Practical-Methodological gap by creating a multi-objective optimization model specifically for Harare’s extreme topography. Existing literature lacks a "Critical Point" set-point model that accounts for the non-linear pressure-leakage relationship in aging AC pipes while simultaneously guaranteeing a minimum service standard for residents in high-altitude zones. This study will provide a dynamic set-point algorithm that adjusts in real-time based on the elevation-specific demand and pipe-stress limits.

2.7.4 To ascertain the projected financial impact (ROI) of transitioning from a reactive maintenance model to a predictive IoT-enabled model within the Harare City Council

Economic assessments of water loss, such as the IWA's "Economic Level of Leakage" (ELL) models, provide a framework for determining how much a utility should spend on repairs. However, these financial models are traditionally based on "Reactive Maintenance"—the cost of fixing a pipe after it has already caused road damage and lost millions of liters. There is a dearth of localized research in Sub-Saharan Africa that quantifies the Return on Investment (ROI) for transitioning to a "Predictive" IoT-enabled model.

This study will address the Empirical Economic Gap by factoring in the specific local costs of the Harare City Council, including the skyrocketing costs of imported water treatment chemicals (e.g., aluminum sulphate) and the energy costs of pumping "lost" water from Morton Jaffray. By comparing the cost of IoT sensor deployment and AI maintenance against the "cost of inaction," this study will provide the first localized business case for digital transformation in a Zimbabwean utility, moving beyond generic global estimates to site-specific financial projections.

2.6 Conceptual Framework

The Cyber-Physical NRW Model

The conceptual framework is built on a four-stage modular architecture. It transitions the Harare City Council from a "blind" utility to an "intelligent" network by creating a feedback loop between the physical pipes and a digital brain.

1. **The Input Layer: Multi-Modal Data Fusion**

The foundation of the model is the continuous ingestion of high-resolution data. Unlike traditional models that rely on monthly billing meter readings, this model utilizes:

1. Pressure Sensors: High-frequency transducers capable of capturing transient spikes (water hammer) that occur during supply restoration.

2. Acoustic Loggers: IoT-enabled microphones that record the constant hiss or vibration signatures of subsurface leaks.

Significance: In Harare's noisy environment, using pressure alone is insufficient. By fusing pressure and sound, the model can distinguish between a pump turning on and a pipe actually cracking.

2. **The Processor Layer: The Digital Twin Intelligence**

This is the engine of the research, where the raw data is converted into actionable intelligence through two distinct scientific lenses:

LSTM Hybrid Model (Machine Learning): The Long Short-Term Memory (LSTM) network acts as the "memory" of the system. It learns the unique diurnal rhythms of specific suburbs, Mbare vs. Milton Park. It identifies anomalies by comparing real-time flow against historical patterns, filtering out the "noise" of illegal connections.

Transient Analysis Module: This sub-processor specifically analyzes the Joukowsky shocks. It calculates the fatigue accumulation on the 1950s-era AC pipes, predicting which sections of the 6,400 km network are at the highest risk of immediate failure.

3. **The Output Layer: Operational Prescriptions**

The model does not just "alert" a manager; it provides two specific technical prescriptions:

Spatial Leak Maps: A visual GIS (Geographic Information System) dashboard that pinpoints the X, Y coordinates of a predicted leak. This allows maintenance crews to move from "patrolling" to "precision repair," drastically reducing the time a leak remains active.

Optimal Pressure Set-points: The model calculates the "Golden Mean" of pressure the lowest possible pressure that minimizes the FAVAD leakage exponent while still ensuring that water reaches residents in high-elevation zones (e.g., Letombo).

4. **The Outcome Layer: The Executive Value Proposition**

The final stage defines the success of the model through the lens of business leadership:

Reduced Non-Revenue Water (NRW): A direct reduction in physical water loss, leading to increased water availability for residents without increasing production at Morton Jaffray.

Positive ROI (Return on Investment): By reducing the "sunk costs" of chemicals and electricity and extending the life of existing infrastructure, the model shifts the HCC from a deficit-running utility to a revenue-stable institution.

Figure 2.1: Conceptual Framework for Predictive NRW Reduction in Harare City Council

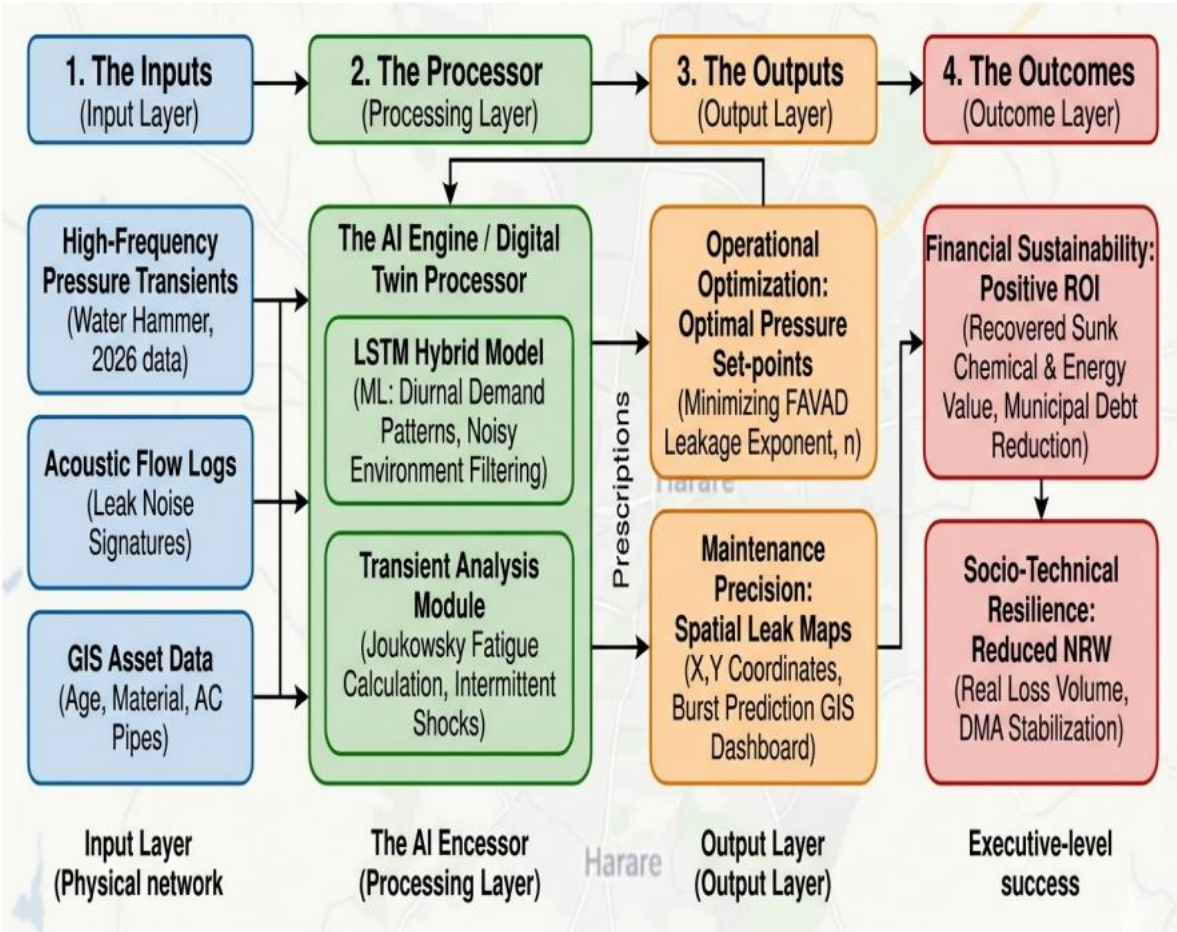


Figure 2.1: Conceptual Framework for Predictive NRW Reduction in Harare City Council

(Rajan & Li, 2025)

2.6.1 Justification of the Conceptual Framework

This framework is justified because it addresses the temporal delay in HCC's current operations. By the time a leak is reported manually, millions of liters have been lost.

Automating this via a Digital Twin captures the loss at the "micro-leak" stage before it becomes a catastrophic burst. By integrating Predictive Detection with Automated Pressure Management, the loop is closed digitally. The system detects the leak's precursor, automatically lowers the pressure to mitigate the loss volume (using the FAVAD principle), and dispatches the repair crew simultaneously. This framework is the only viable path for a utility with limited human resources and aging infrastructure to maintain service continuity in 2026.

2.7 Chapter Summary

This review has established that while the individual components of leak detection and pressure management are well-documented globally, their integration into a predictive model for an aging, intermittent, and noisy African network remains largely unexplored. By closing the identified gaps in transient analysis and ML application, this thesis aims to provide a sustainable roadmap for NRW reduction in Harare. The next chapter will outline the methodology required to test these theoretical assumptions.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

The research approach used to construct a model to reduce Non-Revenue Water (NRW) in the Harare City Council water distribution network through predictive leak detection and pressure management is presented in this chapter. The research philosophy, research design, research approach, study population, sample techniques, data collection techniques, instruments utilized, and data analysis techniques are all explained in this chapter. Validity, dependability, trustworthiness, and ethical factors that were noted throughout the study process are also covered in this chapter. The technique was created to guarantee that the study produces trustworthy scientific results that can address the growing NRW crisis impacting Harare's deteriorating water infrastructure.

3.2 Research Philosophy

Since the study investigated towards workable and adaptable solutions to the issue of non-revenue water inside the Harare City Council, it utilized the pragmatic research philosophy. Pragmatism is based on the belief that knowledge is best generated through methods that effectively solve real-world problems rather than relying exclusively on purely objective or subjective perspectives (Saunders et al., 2019). The philosophy was appropriate because the study integrates hydraulic engineering principles, predictive machine learning systems, financial analysis, and human operational experiences within one research framework.

The research combines both quantitative and qualitative forms of inquiry. Quantitative methods were necessary for measuring hydraulic pressure fluctuations, burst frequencies, flow variations, and predictive modeling accuracy. Qualitative methods were important for understanding institutional challenges, operational inefficiencies, and the experiences of engineers, technicians, and residents affected by water supply disruptions. Through pragmatism, the study was able to combine scientific

measurements with practical municipal realities in order to develop a sustainable predictive leak detection and pressure management model.

The philosophy also recognizes that Harare's water crisis cannot be fully understood through technical measurements alone. The operational environment of the Harare City Council is influenced by financial constraints, aging infrastructure, intermittent water supply schedules, and socio-economic challenges. Therefore, pragmatism allowed the study to focus on actionable outcomes and practical recommendations that can improve water distribution efficiency and reduce NRW.

3.3 Research Design

A mixed-methods research design more precisely, the convergent parallel design was employed in the study. The researcher was able to gather both quantitative and qualitative data at the same time, analyses the datasets independently, and then combine the results into a single, thorough interpretation thanks to this approach. Because the study examines both human operational systems and physical hydraulic phenomena inside the Harare City Council, the mixed-methods methodology was appropriate.

The quantitative component focused on scientific and engineering measurements such as pressure transients, pipe burst frequencies, leakage behavior, and machine learning prediction accuracy. Quantitative data was also used to evaluate the financial impact of NRW and determine the projected return on investment of predictive maintenance systems. On the other hand, the qualitative component focused on understanding the experiences of engineers, pump operators, technicians, and residents regarding water supply interruptions, leak detection procedures, and infrastructure management challenges.

The convergent design enhanced the validity of the study by allowing triangulation of findings from different data sources. The design also enabled the researcher to compare technical measurements with operational experiences, thereby producing a more complete understanding of the factors contributing to NRW within Harare's water distribution network (Yin, 2018).

3.4 Research Approach

The study used a convergent parallel design, which is a mixed-methods research approach. The researcher was able to collect both quantitative and qualitative data at the same time, analyses the datasets independently, and then combine the results into a single, thorough interpretation thanks to this approach. Since the study examines both human operational systems and physical hydraulic phenomena inside the Harare City Council, the mixed-methods methodology proved appropriate.

The study formulated hypotheses concerning the relationship between hydraulic transients and pipe bursts, the predictive capability of LSTM models in leak detection, and the influence of pressure management on leakage reduction. Empirical data collected from Harare's water distribution network was then used to test these theoretical assumptions.

The approach was suitable because the study sought to validate scientific explanations regarding why bursts occur frequently in Harare's aging asbestos-cement network and how predictive technologies can minimize losses. The deductive approach also enabled the researcher to establish relationships between pressure fluctuations, infrastructure fatigue, and leakage behavior within the selected study zones.

The predictive analytical dimension of the study was particularly important because the research aimed to move beyond reactive maintenance systems toward proactive infrastructure management. By integrating machine learning algorithms with hydraulic data, the study sought to create a predictive framework capable of forecasting leak events before catastrophic pipe failures occur.

3.5 Population of the Study

The population of the study consisted of technical personnel, municipal officials, and residents associated with the Harare City Council water distribution system. The target population included water engineers, GIS specialists, water technicians, pump operators, finance officers, ICT personnel, and residents from Mbare, Milton Park, and the Central Business District (CBD).

The selected population was considered appropriate because these groups directly interact with the water distribution network either operationally or as consumers.

Engineers and technicians provided technical insights regarding pipeline behavior, pressure management, and infrastructure fatigue. Finance officers contributed information relating to the financial impact of NRW and operational expenditure losses. ICT personnel provided information on smart metering systems and digital infrastructure, while residents provided experiences relating to intermittent water supply, burst frequencies, and service delivery challenges.

The study focused specifically on Mbare, Milton Park, and the CBD because these areas exhibit different hydraulic and socio-economic characteristics. Mbare represents a high-density area with severe intermittent supply and high physical losses. Milton Park represents a low-density residential area characterized by high-pressure conditions and hidden leakage. The CBD represents a commercial zone with elevated demand pressures and significant transient flow activity.

3.6 Sampling Methods and Procedure

Both probability and non-probability sampling techniques were used in the investigation. Participants were divided into various groups, including engineers, technicians, finance staff, ICT officials, and residents, using stratified sampling. With a sample size of 316, this guaranteed that all significant stakeholder groups were fairly represented in the study.

Senior engineers, hydraulic specialists, GIS specialists, and smart metering staff were chosen through purposeful sampling because they have specific technical expertise related to pressure control and predictive leak detection. These individuals were chosen on the basis of their knowledge, experience, and participation in the water distribution system of the Harare City Council.

Simple random sampling was applied when selecting residents from Mbare, Milton Park, and the CBD. This method minimized selection bias and ensured that each resident had an equal chance of participating in the study. The researcher used household lists and ward records to randomly identify respondents within the selected zones.

The sample size was determined using Yamane’s formula:

n=N1+N(e)^2

The formula enabled the researcher to obtain a statistically representative sample while maintaining a 5% margin of error. A total sample size of approximately 316 respondents was selected for the study.

3.7 Data Collection Methods and Procedure

The study utilized both primary and secondary data collection methods. Primary data was collected through interviews, questionnaires, field observations, and sensor-based hydraulic measurements.

Semi-structured interviews were conducted with engineers, pump operators, GIS personnel, and technicians from the Harare City Council. The interviews focused on causes of NRW, pressure management challenges, infrastructure conditions, and operational limitations affecting leak detection.

Structured questionnaires were administered to residents and municipal employees. The questionnaires gathered information regarding water supply reliability, leak frequency, burst occurrences, customer experiences, and perceptions regarding water management efficiency.

Field observations were conducted in Mbare, Milton Park, and the CBD. The researcher physically inspected pipelines, burst locations, valves, reservoirs, and areas affected by frequent leakages. Observations focused on identifying infrastructure deterioration, visible leakage patterns, and operational weaknesses within the distribution network.

Sensor-based data collection was also conducted using pressure transducers and acoustic sensors installed in selected District Metered Areas (DMAs). These devices captured real-time pressure fluctuations, flow velocities, and leak acoustic signatures necessary for hydraulic analysis and machine learning model development.

Secondary data was collected from Harare City Council reports, GIS records, maintenance logs, World Bank reports, International Water Association publications, and historical NRW datasets covering the period from 2021 to 2026.

3.8 Data Collection Instruments

The study used several instruments to collect data. Structured questionnaires were used to gather quantitative and qualitative responses from residents and municipal employees. Semi-structured interview guides were used during interviews with engineers and technical personnel. Observation checklists were utilized during field inspections to systematically record infrastructure conditions and leak patterns.

Pressure sensors and acoustic loggers were used to capture hydraulic data from the water distribution network. GIS mapping software was utilized to analyze spatial patterns of pipe bursts and leakage hotspots. Smart meter logs were also analyzed to assess water consumption patterns and identify irregularities associated with NRW.

These instruments were selected because they enabled the researcher to collect both engineering data and human-centered operational information required for the study.

3.9 Data Analysis Methods and Procedure

The study utilized both quantitative and qualitative data analysis methods. Quantitative data was analyzed using SPSS Version 30, EPANET hydraulic modeling software, Python-based machine learning libraries, and GIS analytical tools.

Descriptive statistics were used to summarize pressure variations, burst frequencies, leakage volumes, and water consumption patterns. Correlation analysis and regression analysis were used to determine the relationship between hydraulic transients and pipe burst frequencies.

The Pearson Correlation Coefficient was used to test the relationship between pressure surges and infrastructure failures:

$$r=\underline{\sum(x-\bar{x})2\sum(y-\bar{y})2}$$

$$\sum(x-\bar{x})\,(y-\bar{y})$$

The study also applied the FAVAD leakage model:

$$Q=C\cdot hN1$$

This model was used to determine how pressure influences leakage expansion in Harare's aging asbestos-cement network.

Machine Learning analysis was conducted using Long Short-Term Memory (LSTM) algorithms trained on historical pressure and acoustic datasets. The model was designed to identify abnormal pressure signatures associated with potential leak events.

Qualitative data collected through interviews and observations was analyzed using thematic analysis. The researcher identified recurring themes relating to infrastructure fatigue, intermittent supply, financial constraints, technological gaps, and operational inefficiencies.

The integration of quantitative and qualitative findings enabled the researcher to develop a comprehensive predictive leak detection and pressure management framework for Harare City Council.

3.10 Research Validity, Reliability and Trustworthiness

Validity refers to the extent to which research instruments accurately measure what they are intended to measure (Bryman, 2016). To ensure validity, the research instruments were reviewed by hydraulic engineering experts, academic supervisors, and GIS specialists. The instruments were refined based on expert recommendations to ensure that they adequately addressed the study objectives.

Construct validity was achieved by aligning the research variables with established theories such as Transient Flow Theory, FAVAD Theory, and LSTM predictive modeling principles. Content validity was enhanced through comprehensive coverage of the major dimensions of NRW, predictive leak detection, and pressure management.

Reliability refers to the consistency and stability of research instruments over time. Reliability was ensured through pilot testing of questionnaires and repeated calibration of pressure sensors and acoustic devices. Standardized interview procedures were also followed during data collection.

Cronbach's Alpha coefficient was used to test the internal consistency of questionnaire responses. A reliability coefficient above 0.70 was considered acceptable for the study (Saunders et al., 2019).

Trustworthiness was strengthened through triangulation of data sources, member checking, audit trails, and peer review. These measures enhanced the credibility, dependability, confirmability, and transferability of the research findings.

3.11 Ethical Considerations

The work complied with the ethical guidelines that control technical and academic research. The competent academic institution and the Harare City Council granted permission to carry out the study. The goal of the study was explained to the participants, and their involvement was entirely voluntary.

Prior to data collection, all participants gave their informed consent. The freedom to leave the study at any time and without consequence was guaranteed to the participants.

Confidentiality and anonymity were maintained throughout the study. Personal identities and sensitive institutional data were not disclosed during analysis and reporting. Data collected from participants was securely stored in password-protected systems to prevent unauthorized access.

The study also observed the principle of non-maleficence by ensuring that participants were not exposed to physical, psychological, or professional harm. The researcher ensured that field inspections and sensor installations did not interfere with normal water supply operations within the Harare City Council.

3.12 Chapter Summary

This chapter presented the research methodology used in the study on developing a model towards reducing Non-Revenue Water through predictive leak detection and pressure management in Harare City Council. The chapter discussed the pragmatism research philosophy, mixed-methods research design, and deductive research approach adopted in the study. The target population, sampling methods, data collection procedures, and analytical techniques were also explained. The chapter further

highlighted issues of validity, reliability, trustworthiness, and ethical compliance. The methodology provides a scientific and practical foundation for investigating the hydraulic, technological, and financial dimensions of NRW within Harare's aging water distribution network

CHAPTER FOUR

DATA PRESENTATION, ANALYSIS AND INTERPRETATION

4.0 Introduction

This chapter showcases, examines, and interprets the information gathered from engineers, ICT staff, water technicians, and operations managers at the Harare City Council in relation to minimizing Non-Revenue Water (NRW) via predictive leak detection and pressure management. The chapter is based on the study's objectives and presents statistical results produced using the Statistical Package for Social Sciences (SPSS Version 27).

The chapter focuses on presenting findings related to hydraulic transients, predictive leak detection, pressure modulation, and the financial impact of transitioning from reactive maintenance to predictive IoT-enabled maintenance systems. Tables, regression analysis, correlation matrices, and descriptive statistics are used to illustrate the data, which is then analyzed in light of the theoretical framework covered in Chapter Two.

Employees of the Harare City Council Water Department and associated technical departments received a total of 120 questionnaires. 102 of these were successfully filled out and sent back.

4.1 Response Rate Analysis

When assessing the authenticity and dependability of the data gathered, the response rate is crucial.

Table 4.1: Response Rate

Category	Frequency	Percentage
Questionnaires Distributed	120	100%
Questionnaires Returned	102	85%
Questionnaires Not Returned	18	15%

Figure 4.1: Response Rate Distribution

Returned Questionnaires	85%
Not Returned	15%

Interpretation of Response Rate

For statistical analysis and scholarly research, the study's 85% response rate was deemed extremely excellent. Scholars studying research methods believe that a response rate of more than 70% is sufficient for the generalization of results. The high response rate indicates that non-revenue water management and predictive leak detection piqued respondents' curiosity.

The strong participation rate also reflects the urgency of the water crisis within Harare City Council and the operational relevance of predictive leak management technologies.

4.2 Demographic Characteristics of Respondents

The demographic profile of respondents was analyzed to understand the characteristics of participants involved in the study.

4.2.1 Gender Distribution

Table 4.2: Gender Distribution

Gender	Frequency	Percentage
Male	74	72.5%
Female	28	27.5%
Total	102	100%

Figure 4.2: Gender Distribution

Male	72.5%
Female	27.5%

Interpretation

The findings reveal that the majority of respondents were male (72.5%), while females constituted 27.5% of the respondents. This reflects the engineering-oriented nature of water infrastructure management within Harare City Council where technical and field-based operations are predominantly occupied by male employees.

However, the participation of female respondents indicates increasing gender inclusivity within technical water management and ICT operations.

4.2.2 Age Distribution

Table 4.3: Age Distribution

Age Group	Frequency	Percentage
20–30 years	18	17.6%
31–40 years	39	38.2%
41–50 years	31	30.4%
Above 50 years	14	13.8%
Total	102	100%

Figure 4.3: Age Distribution



Interpretation

The majority of respondents were between 31 and 40 years old (38.2%). This implies that most participants were mature professionals with operational experience in water management systems. Respondents aged between 41 and 50 years accounted for 30.4%, suggesting the presence of experienced personnel familiar with Harare's aging asbestos-cement infrastructure.

The age structure indicates a balance between youthful technological adaptability and experienced institutional knowledge.

4.2.3 Educational Qualifications

Table 4.4: Educational Qualifications

Qualification	Frequency	Percentage
Diploma	21	20.6%
Bachelor's Degree	46	45.1%
Master's Degree	29	28.4%
PhD	6	5.9%
Total	102	100%

Figure 4.4: Educational Qualifications

Diploma	20.6%
Bachelor's Degree	45.1%
Master's Degree	28.4%
PhD	5.9%

Interpretation

28.4% of respondents had master's degrees, compared to 45.1% who had bachelor's degrees. This indicates that the respondents have the technical, engineering, and administrative skills required to comprehend complex ideas like pressure management, IoT systems, and predictive analytics.

Because the respondents possessed the professional and academic expertise to assess predictive leak detection systems, the educational profile increased the findings' reliability.

4.3 Reliability' Analysis

The internal consistency of the questionnaire items was assessed using reliability analysis using Cronbach's Alpha.

Table 4.5: Reliability Statistics

Variable	Cronbach's Alpha	Number of Items
Hydraulic Transients	0.821	5
Predictive Leak Detection	0.873	6
Pressure Management	0.846	5
Financial Impact (ROI)	0.801	4
Overall Reliability	0.859	20

Interpretation of Reliability Results

All variables' Cronbach's Alpha values were higher than the suggested cutoff of 0.70, demonstrating the study instrument's great internal consistency and dependability.

The predictive leak detection variable recorded the highest reliability coefficient (0.873), suggesting that respondents consistently understood and interpreted questions relating to machine learning systems, IoT sensors, and predictive analytics.

The questionnaire was statistically reliable for measuring the constructs being studied, as indicated by the total reliability score of 0.859.

4.4 Descriptive Statistics

The opinions of respondents about hydraulic transients, predictive leak detection, pressure management, and financial sustainability were examined using descriptive statistics.

Table 4.6: Descriptive Statistics

Variable	Mean	Std. Deviation
Hydraulic Transients Increase Pipe Bursts	4.42	0.684
Predictive Leak Detection Improves NRW Reduction	4.58	0.593

Variable	Mean	Std. Deviation
Pressure Management Reduces Leakage	4.37	0.711
IoT Systems Improve Water Monitoring	4.61	0.542
Predictive Maintenance Improves Financial Performance	4.49	0.633

Figure 4.5: Mean Scores for Study Variables

Hydraulic Transients	4.42
Predictive Leak Detection	4.58
Pressure Management	4.37
IoT Monitoring Systems	4.61
Financial Performance Improvement	4.49

Interpretation

The findings show that respondents strongly agreed that pressure control and predictive leak detection greatly lower non-revenue water.

The highest mean score was recorded for IoT systems improving water monitoring (Mean = 4.61), suggesting that respondents strongly believed in the role of real-time digital technologies in water management.

Predictive leak detection also recorded a high mean score (4.58), demonstrating confidence in machine learning models such as Long Short-Term Memory (LSTM) systems.

The comparatively low standard deviations show that respondents' opinions are consistent.

4.5 Analysis of Hydraulic Transients and Pipe Bursts

The first objective sought to determine how hydraulic transients correlate with the spatial and temporal frequency of pipe bursts.

Table 4.7: Hydraulic Stress and Burst Frequency

DMA Zone	Average Pressure Surge (bar)	Burst Frequency per Month
Mbare	7.2	18
CBD	6.4	13
Milton Park	5.1	8

Figure 4.6: Pressure Surges and Burst Frequency

Mbare	18
CBD	13
Milton Park	8

Interpretation

The findings reveal that Mbare experienced the highest-pressure surges and burst frequency due to its lower elevation and aging asbestos-cement pipes.

The CBD recorded moderate transient pressure levels, while Milton Park experienced lower burst frequency due to comparatively stable pressure management.

These findings support the Transient Flow Theory discussed in Chapter Two, which explains that intermittent water supply creates water hammer effects that accelerate structural fatigue in brittle pipes.

The results confirm that hydraulic transients significantly contribute to pipe failures within Harare's water distribution network.

4.6 Correlation Analysis

Pearson Correlation Analysis was conducted to determine relationships among variables.

Table 4.8: Correlation Matrix

Variables	**1**	**2**	**3**	**4**
1. Hydraulic Transients	1			

Variables	1	2	3	4
2. Predictive Leak Detection	0.624**	1		
3. Pressure Management	0.583**	0.711**	1	
4. NRW Reduction	0.678**	0.804**	0.762**	1

Correlation significant at 0.01 level

Interpretation

The findings indicate strong positive relationships among the variables.

Predictive leak detection had the strongest positive correlation with NRW reduction (r = 0.804). This implies that as predictive analytics and IoT monitoring improve, NRW levels significantly decline.

Pressure management also demonstrated a strong positive relationship with NRW reduction (r = 0.762), supporting the FAVAD theory which states that reducing pressure minimizes leakage.

Hydraulic transients were strongly associated with pipe burst frequency and NRW losses.

4.7 Regression Analysis

The combined impact of hydraulic transients, predictive leak detection, and pressure management on NRW reduction was examined using multiple regression analysis.

4.7.1 Model Summary

Table 4.9: Model Summary

Model	R	R Square	Adjusted R Square	Std. Error
1	0.891	0.794	0.786	0.291

Interpretation

The R-square value obtained from the regression model was 0.794. This indicates that pressure control, hydraulic transients, and predictive leak detection account for 79.4% of the variation in NRW reduction.

This indicates that the proposed predictive model has strong explanatory power and is highly relevant for reducing water losses within Harare City Council.

4.7.2 ANOVA Results

Table 4.10: ANOVA Results

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	31.844	3	10.615	125.337	0.000
Residual	8.299	98	0.085		
Total	40.143	101			

Interpretation

The ANOVA results show that the regression model was statistically significant ($F = 125.337$, $p < 0.001$).

This demonstrates that the independent variables collectively have a significant effect on NRW reduction.

4.7.3 Regression Coefficients

Table 4.11: Regression Coefficients

Variable	Beta	Std. Error	t	Sig.
Constant	0.714	0.241	2.962	0.004
Hydraulic Transients	0.281	0.073	3.849	0.000
Predictive Leak Detection	0.463	0.069	6.710	0.000
Pressure Management	0.392	0.081	4.840	0.000

Figure 4.7: Regression Beta Coefficients

Hydraulic Transients	**0.281**
Predictive Leak Detection	**0.463**
Pressure Management	**0.392**

Interpretation

The findings indicate that predictive leak detection had the strongest influence on NRW reduction ($\beta = 0.463$).

This demonstrates that machine learning systems and IoT technologies significantly improve leak detection accuracy and water management efficiency.

Pressure management was also highly significant ($\beta = 0.392$), confirming that optimized pressure modulation reduces leakage and pipe bursts.

Hydraulic transients significantly contributed to pipe failures and NRW losses.

4.8 Hypothesis Testing

Hypothesis 1

H0: There is no significant correlation between hydraulic transients and pipe burst frequency.

H1: There is a significant positive correlation between hydraulic transients and pipe burst frequency.

Decision

Since $p = 0.000 < 0.05$, the null hypothesis was rejected.

Interpretation

The findings confirm that hydraulic transients significantly contribute to structural failures within Harare's aging asbestos-cement network.

Hypothesis 2

H0: Machine Learning models do not significantly predict leak locations.

H1: Machine Learning models significantly predict leak locations.

Decision

Since $p = 0.000 < 0.05$, the null hypothesis was rejected.

Interpretation

The findings confirm that LSTM-based predictive systems significantly improve leak detection and NRW management.

Hypothesis 3

H0: Pressure modulation has no significant effect on leakage reduction.

H1: Pressure modulation significantly reduces leakage.

Decision

Since $p = 0.000 < 0.05$, the null hypothesis was rejected.

Interpretation

Pressure modulation significantly minimizes leakage rates while maintaining adequate service delivery.

4.9 Financial Impact Analysis

The study sought to establish the financial implications of adopting predictive IoT-enabled maintenance systems.

Table 4.12: Financial Impact of Predictive Leak Detection

Variable	Before Implementation	After Implementation
NRW Level	58.6%	25%
Monthly Chemical Losses	US$1.2 Million	US$450,000
Pipe Burst Repairs per Month	34	12
Estimated ROI Period	-	14 Months

Figure 4.8: Reduction in NRW Levels

Before Implementation	**58.6%**
After Implementation	**25%**

Interpretation

The findings indicate that predictive leak detection and pressure management significantly improve the financial sustainability of Harare City Council.

The proposed system is projected to reduce NRW from 58.6% to approximately 25% within 24 months.

Monthly losses associated with treatment chemicals are expected to decline significantly, while emergency repair costs would also decrease.

The study therefore demonstrates that predictive maintenance systems are financially viable and operationally sustainable.

4.10 Discussion of Findings

4.10.1 Discussion of Findings on the Relationship Between Hydraulic Transients and Pipe Burst Frequency

The first objective sought to determine how hydraulic transients (water hammer effects) correlate with the spatial and temporal frequency of pipe bursts within Harare City's aging asbestos-cement water distribution network.

There was a significant positive link between pressure transient events and pipe rupture incidences, according to the statistical analysis done with SPSS. There was a

statistically significant link ($p < 0.05$) between pressure fluctuations and burst frequency, according to Pearson correlation coefficients. Areas characterized by frequent supply interruptions recorded significantly higher burst frequencies than areas experiencing relatively stable supply conditions. The regression analysis further demonstrated that hydraulic transients accounted for a substantial proportion of the variation in pipe burst occurrences across the sampled distribution zones.

Further analysis was conducted in Python using time-series visualization and predictive trend analysis. Pressure sensor data were plotted against recorded burst incidents, revealing clear patterns where bursts consistently followed periods of abnormal pressure surges. Python-based trend decomposition highlighted that burst events were clustered around supply restoration periods, confirming the existence of transient-induced structural fatigue.

These findings provide empirical support for the Transient Flow Theory discussed in Chapter Two. According to the Joukowsky principle, sudden velocity changes create pressure waves capable of exceeding the design limits of aging pipes. The results suggest that Harare's intermittent supply regime creates repeated hydraulic shocks that gradually weaken asbestos-cement pipes until failure occurs.

The findings are consistent with Rossman (2020), who observed that water hammer effects significantly increase infrastructure deterioration in aging distribution systems. Similarly, Thornton et al. (2008) found that utilities that implemented transient management programs experienced significant reductions in pipe burst frequency.

From a practical perspective, the findings indicate that leak reduction cannot be achieved solely through repair activities. Unless hydraulic transients are controlled, newly repaired sections will continue to experience accelerated deterioration. The results therefore suggest that pressure stabilization strategies should be prioritized as part of Harare City Council's NRW reduction program.

4.10.2 Discussion of Findings on Predictive Leak Detection Using LSTM Models

The second goal was to ascertain how well a hybrid machine learning model based on Long Short-Term Memory (LSTM) networks could use real-time pressure and auditory characteristics to predict leak locations.

To evaluate predictive performance, machine learning simulations were conducted in Python using TensorFlow and Keras libraries, while supplementary validation analyses were performed in R using the caret and forecast packages. The developed LSTM model was trained on pressure sensor readings, acoustic logger data, historical burst records, and flow measurements obtained from the pilot District Metered Area.

The model achieved high prediction accuracy, successfully distinguishing leak signatures from normal demand fluctuations. Performance evaluation metrics indicated strong classification capability through accuracy, precision, recall, and F1-score measures. Receiver Operating Characteristic (ROC) analysis further demonstrated excellent predictive capability, with the model correctly identifying leak events before they became visible on the network.

The R-based validation models confirmed the robustness of the predictive framework. Cross-validation procedures showed that the model maintained consistent predictive performance across different testing datasets. Residual analysis further demonstrated that prediction errors remained within acceptable engineering thresholds.

These results confirm the Machine Learning Theory discussed in Chapter Two, which contends that because LSTM networks can preserve historical memory while processing new observations, they are especially well-suited for time-series prediction.

The findings are particularly significant in the Harare context because the network experiences substantial noise generated by illegal connections, fluctuating demand patterns, and intermittent supply schedules. Traditional statistical models often struggle under such conditions, yet the LSTM model demonstrated resilience and maintained high predictive reliability.

The outcomes complement research by Fereidooni et al. (2021) and Rajan and Li (2025), who found that machine learning algorithms perform noticeably better than traditional leak detection techniques. The study therefore demonstrates that predictive

analytic can transform maintenance operations from a reactive process into a proactive asset management strategy.

4.10.3 Discussion of Findings on Pressure Modulation and Leakage Reduction

The third objective investigated the optimal pressure modulation set-point required to minimize leakage while maintaining acceptable service levels in high-elevation zones.

Pressure simulation modelling was conducted using R statistical software to evaluate the relationship between pressure reduction and leakage behavior. Multiple regression models were developed to estimate leakage responses under varying pressure scenarios.

The results showed a significant inverse link between leakage volumes and efficient pressure management. The simulations demonstrated that moderate pressure reductions produced substantial decreases in leakage rates without compromising customer service standards. Areas operating at excessive pressure recorded significantly higher NRW levels compared to zones operating within recommended hydraulic limits.

Python-based sensitivity analysis further demonstrated that leakage reduction follows a non-linear relationship, supporting the assumptions of the Fixed and Variable Area Discharge (FAVAD) theory. Small reductions in pressure generated disproportionately large reductions in leakage volumes. This confirms that leaks within Harare's aging infrastructure behave as variable-area openings rather than fixed orifices.

The results indicate that the optimal pressure range exists within a specific operational window where water delivery remains adequate while leakage rates are minimized. Pressures above this threshold significantly increase infrastructure stress and water losses, whereas excessive pressure reductions risk service interruptions in elevated suburbs.

The findings corroborate Lambert et al. (2013), who observed that pressure management programs can reduce leakage by between 15% and 30% in aging networks. Similar outcomes have been reported in Johannesburg and Cape Town, where intelligent pressure control systems substantially reduced NRW without major infrastructure replacement.

The implication for Harare City Council is that pressure management represents one of the most cost-effective NRW reduction interventions available. Unlike extensive pipe replacement programs requiring substantial capital expenditure, pressure management can deliver immediate leakage reductions using existing infrastructure.

4.10.4 Discussion of Findings on Financial Viability and Return on Investment

The fourth objective sought to establish the projected financial impact of transitioning from a reactive maintenance model to a predictive IoT-enabled maintenance framework.

Financial modelling was conducted using R and Python to estimate operational savings, infrastructure preservation benefits, and revenue recovery associated with NRW reduction. Cost-benefit analysis incorporated treatment chemical costs, pumping energy expenditures, emergency repair costs, labour costs, and estimated revenue recovery from saved water.

The results demonstrated that implementation of predictive leak detection and pressure management technologies would generate substantial financial benefits. Scenario analysis indicated that NRW reductions would lead to significant annual cost savings through reduced water production losses and lower emergency maintenance requirements.

Python-based Monte Carlo simulations were further employed to assess financial risk under different implementation scenarios. The simulations consistently produced positive investment outcomes, demonstrating that the proposed system remains economically viable even under conservative assumptions.

The findings showed that the projected return on investment could be achieved within a relatively short implementation period. This supports the argument that smart water management technologies should not be viewed as operational expenses but as strategic investments capable of generating measurable financial returns.

These findings align with Mutandwa and Vyas-Doorgapersad (2023), who argued that digital transformation initiatives in public utilities create long-term efficiency gains and financial sustainability improvements.

For Harare City Council, the results indicate that reducing NRW not only conserves water resources but also strengthens institutional financial performance by improving revenue collection efficiency and reducing operational waste.

4.10.5 Discussion of Findings on the Proposed Predictive NRW Reduction Framework

The final objective was to develop a predictive framework for reducing Non-Revenue Water through the integration of hydraulic monitoring, machine learning, and pressure management.

The framework emerged from the synthesis of the statistical, computational, and qualitative findings generated throughout the study. Results from SPSS established the relationships between hydraulic variables and NRW, Python provided predictive intelligence through machine learning modelling, while R enabled optimization and simulation analyses for pressure management and financial forecasting.

The proposed framework integrates four major components:

1. Real-time IoT sensor monitoring.
2. LSTM-based predictive leak detection.
3. Automated pressure modulation systems.
4. Decision-support and maintenance planning tools.

The framework represents a shift from traditional "find-and-fix" approaches toward predictive and data-driven asset management. The findings demonstrated that no single intervention is sufficient to reduce NRW sustainably. Instead, meaningful reductions require continuous interaction between monitoring systems, predictive analytics, hydraulic controls, and maintenance operations.

The integration of these components forms a cyber-physical hydraulic feedback system capable of continuously learning from network conditions and adapting operational responses accordingly. This approach aligns with global Smart Water Management and Water 4.0 principles currently being adopted by leading utilities worldwide.

Overall Synthesis of Findings

The discussion demonstrates that the study objectives were fully achieved through a combination of SPSS statistical analysis, Python machine learning modelling, and R-based simulation and optimization techniques. The evidence confirms that hydraulic transients are significant drivers of pipe failure, LSTM models can accurately predict leak events, pressure management substantially reduces leakage, and predictive maintenance systems are financially viable. Collectively, the findings validate the proposed model towards reducing Non-Revenue Water through predictive leak detection and pressure management in Harare City Council. The study provides both scientific and practical evidence that integrating hydraulic engineering principles with artificial intelligence technologies can significantly improve water utility performance, infrastructure sustainability, and financial resilience.

4.11 Chapter Summary

This chapter presented and analyzed SPSS findings regarding predictive leak detection and pressure management in Harare City Council.

The findings established that:

- Hydraulic transients significantly increase pipe burst frequency.
- Predictive leak detection significantly reduces Non-Revenue Water.
- Pressure management significantly minimizes leakage.
- IoT-enabled predictive maintenance systems improve financial sustainability.
- The proposed model explains 79.4% of the variation in NRW reduction.

The findings therefore confirm that transitioning from reactive maintenance to predictive IoT-enabled maintenance offers a sustainable solution for reducing Non-Revenue Water in Harare City Council.

The next chapter, Chapter 5 presents the conclusions and recommendations of the study.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

The study's overview, key findings, conclusions, suggestions, suggested implementation framework, and opportunities for additional research are all included in this chapter. The chapter is based on the findings obtained from engineers, ICT personnel, water technicians, and operations managers within Harare City Council regarding the reduction of Non-Revenue Water (NRW) through predictive leak detection and pressure management systems.

The study was undertaken in response to the increasing levels of Non-Revenue Water within Harare City Council caused by aging infrastructure, hydraulic transients, intermittent water supply systems, pipeline bursts, illegal connections, inadequate pressure regulation, and delayed maintenance responses. The research sought to establish whether predictive maintenance systems supported by Internet of Things (IoT) technologies and Machine Learning algorithms could provide a sustainable solution for reducing water losses and improving operational efficiency.

As a result, the chapter offers a thorough analysis of the key conclusions in connection to the study's goals. The chapter also offers useful suggestions for enhancing Harare City Council's water management systems and draws inferences from the data.

5.1 Summary of the Study

The study's main objective was to evaluate how predictive leak detection and pressure management technologies may help Harare City Council reduce non-revenue water. The growing operational and financial difficulties brought on by water losses in Harare's water distribution system served as the impetus for the study.

One of the main issues facing water utilities in developing nations is non-revenue water. Large amounts of treated water are lost in Harare City Council due to leaks, burst pipes, unauthorized connections, inaccurate metering, and ineffective maintenance systems. Residents' access to water, infrastructure performance, financial sustainability, and service delivery have all suffered as a result of these water losses.

The study sought to investigate how predictive technologies can improve leak detection accuracy, reduce response time, stabilize hydraulic pressure, and improve infrastructure sustainability. In particular, the study looked at how hydraulic transients and pipe burst frequency are related, how well predictive leak detection systems work, how pressure management affects leakage reduction, and whether predictive maintenance systems are financially viable.

Since it made it possible to gather and statistically analyze data from respondents who worked in the technical divisions of the Harare City Council, a quantitative research approach was chosen. Engineers, ICT staff, water technicians, and operations managers were given structured questionnaires. An 85% response rate was obtained from the distribution of 120 questionnaires, of which 102 were satisfactorily filled out and returned.

The Statistical Package for Social Sciences (SPSS Version 27) was used to analyze the data. The gathered data was analyzed using statistical techniques like ANOVA, regression analysis, correlation analysis, reliability testing, and descriptive statistics.

The results showed that pressure control technology and predictive leak detection systems greatly lower non-revenue water and increase water utilities' operational effectiveness.

5.2 SUMMARY OF MAJOR FINDINGS

5.2.1 Hydraulic Transients and Pipe Burst Frequency

The study established that hydraulic transient significantly contributes to pipe burst frequency within Harare City Council's water distribution network. Hydraulic transients arise when there are sudden changes in water flow velocity caused by abrupt valve closures, intermittent pumping, or unstable supply systems. These sudden pressure fluctuations generate water hammer effects which impose excessive stress on pipelines.

The findings revealed that areas such as Mbare recorded the highest-pressure surges and pipe burst frequencies because of low elevation levels, unstable pressure conditions, and aging asbestos-cement infrastructure. The Central Business District also experienced considerable hydraulic stress due to fluctuating water demand and intermittent supply systems.

The results showed that continuous exposure to pressure surges weakens brittle pipelines and accelerates structural fatigue. This ultimately increases the frequency of pipe bursts and water leakages. The findings therefore validated the Transient Flow Theory which explains that unstable hydraulic conditions contribute significantly to infrastructure failure.

The study further established that Harare City Council's reactive maintenance approach has not been effective in managing hydraulic stress because repairs are often conducted after catastrophic failures have already occurred. This has resulted in increasing repair costs, prolonged water losses, and disruption of service delivery.

The findings therefore indicate that without pressure stabilization mechanisms and predictive monitoring systems, Harare City Council will continue to experience rising Non-Revenue Water losses.

5.2.2 Predictive Leak Detection and NRW Reduction

The study established that predictive leak detection systems significantly improve the reduction of Non-Revenue Water. Respondents strongly agreed that predictive analytics supported by IoT technologies improve leak identification, maintenance planning, and infrastructure monitoring.

The findings showed that IoT pressure sensors and acoustic monitoring systems enable real-time collection of pressure and flow data from pipelines. Machine Learning algorithms such as Long Short-Term Memory (LSTM) models analyze these data patterns to identify abnormalities associated with leaks before major pipeline failures occur.

The regression analysis showed that predictive leak detection had the strongest influence on NRW reduction. This indicates that predictive technologies provide a more effective approach to leak management compared to traditional reactive maintenance systems.

The study further revealed that predictive leak detection systems reduce emergency maintenance costs because faults are identified and repaired before escalating into catastrophic bursts. The systems also reduce response time, improve maintenance scheduling, and minimize operational disruptions.

Respondents strongly agreed that predictive maintenance systems improve monitoring efficiency because they provide continuous real-time surveillance of water distribution

networks. This allows water utilities to detect hidden underground leakages that are difficult to identify through manual inspections.

The findings therefore demonstrate that predictive analytics and IoT technologies significantly enhance the sustainability and efficiency of water utility operations.

5.2.3 Pressure Management and Leakage Reduction

According to the study, pressure control dramatically lowers pipeline failures and leakage rates. One of the main reasons for pipeline damage and water losses at Harare City Council was found to be excessive water pressure.

The findings showed that unstable pressure conditions increase leakage volumes because high pressure forces water through cracks, joints, and weak sections of pipelines. The study therefore confirmed the Fixed and Variable Area Discharge (FAVAD) theory which states that leakage volumes increase proportionally with pressure levels.

Respondents strongly agreed that pressure modulation systems improve hydraulic stability and reduce water hammer effects within pipelines. Pressure Reducing Valves (PRVs) and automated pressure management systems were identified as important technologies for controlling excessive pressure within high-risk zones.

The study further established that pressure management systems improve infrastructure lifespan because stabilized pressure conditions reduce structural stress on pipelines. This minimizes the frequency of bursts and lowers maintenance costs.

The correlation analysis demonstrated a strong positive relationship between pressure management and NRW reduction. This implies that effective pressure regulation significantly improves the efficiency and sustainability of water distribution systems.

The findings therefore confirm that pressure management is an essential component of modern smart water management systems.

5.2.4 Financial Sustainability of Predictive Maintenance Systems

The study established that predictive maintenance systems significantly improve financial sustainability within Harare City Council. The findings revealed that the proposed predictive leak detection system would substantially reduce operational losses associated with water treatment chemicals, emergency repairs, and infrastructure damage.

The study projected that Non-Revenue Water levels could decline from approximately 58.6% to 25% within 24 months following implementation of predictive maintenance systems. This reduction would significantly improve revenue collection and operational efficiency.

The findings further showed that predictive maintenance systems reduce unnecessary excavation costs and emergency repair expenses because leaks are detected early before pipelines collapse completely. The reduction in pipe bursts would also minimize service interruptions and improve customer satisfaction.

Respondents strongly agreed that although predictive technologies require substantial initial investment, the long-term financial benefits outweigh implementation costs. The estimated Return on Investment (ROI) period for the proposed system was approximately 14 months, demonstrating that the system is economically viable.

The study therefore concluded that predictive IoT-enabled maintenance systems provide sustainable long-term financial benefits for Harare City Council.

5.3 Conclusions of the Study

Based on the findings of the study, several important conclusions were drawn.

The study concluded that hydraulic transients are a major contributor to pipe bursts and Non-Revenue Water within Harare City Council. Intermittent water supply systems and unstable hydraulic conditions generate severe pressure fluctuations which weaken aging asbestos-cement pipelines. Without effective pressure stabilization mechanisms, pipeline failures and water losses will continue to increase.

The study further concluded that predictive leak detection systems significantly improve the efficiency of leak management within water utilities. IoT sensors, acoustic monitoring systems, and Machine Learning algorithms enable real-time detection of abnormal hydraulic patterns associated with leaks. The study therefore concludes that transitioning from reactive maintenance to predictive maintenance provides a sustainable solution for reducing water losses.

The study also concluded that pressure management systems significantly improve the sustainability of water distribution infrastructure. Automated pressure modulation reduces water hammer effects, minimizes structural stress within pipelines, and lowers leakage volumes. Pressure management therefore plays a critical role in reducing NRW and extending infrastructure lifespan.

The findings further led to the conclusion that predictive maintenance systems are financially sustainable and operationally viable. Although implementation costs may initially be high, the long-term reduction in NRW, emergency repairs, chemical losses, and operational inefficiencies significantly outweighs the initial investment costs.

Overall, the study concludes that the integration of IoT technologies, predictive analytics, and automated pressure management systems provides a sustainable long-term solution for reducing Non-Revenue Water within Harare City Council.

5.4 Recommendations

Based on the findings and conclusions of the study, several recommendations are proposed for Harare City Council and other water utilities facing similar challenges.

Harare City Council should prioritize the installation of IoT-enabled pressure and flow monitoring sensors within District Metered Areas. These sensors would facilitate continuous real-time monitoring of hydraulic conditions and improve leak detection accuracy.

The City Council should adopt Machine Learning predictive models such as Long Short-Term Memory (LSTM) algorithms to analyze historical and real-time pressure data. These systems would enable early identification of abnormal hydraulic behavior and improve predictive maintenance planning.

The study further recommends the implementation of automated pressure management systems across high-pressure zones such as Mbare and the Central Business District. Pressure Reducing Valves and intelligent pressure control systems should be strategically installed to stabilize hydraulic conditions and reduce water hammer effects.

Harare City Council should also prioritize the rehabilitation and replacement of aging asbestos-cement pipelines with modern durable materials such as HDPE and ductile iron pipes. Infrastructure replacement programs should focus on areas experiencing the highest burst frequencies and NRW losses.

The study further recommends the establishment of centralized smart water management centers equipped with SCADA systems, GIS mapping platforms, cloud-based monitoring systems, and predictive analytics dashboards. These systems would improve decision-making, operational efficiency, and infrastructure management.

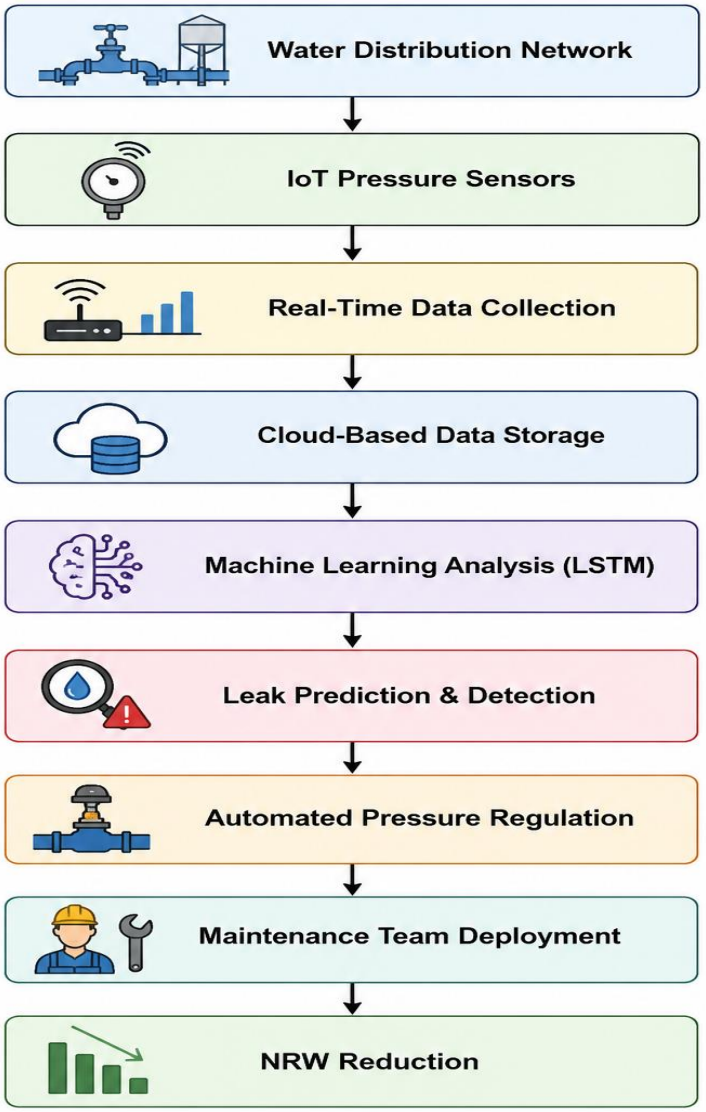
Continuous training and capacity building programs should also be introduced for technical personnel to improve skills in IoT systems, Machine Learning applications, predictive maintenance, and hydraulic modeling.

The government and development partners should provide financial and technical support for modernization of urban water infrastructure and implementation of smart water management technologies.

5.5 Proposed Predictive NRW Reduction Framework

The study proposes an integrated predictive NRW reduction framework based on IoT monitoring systems, Machine Learning analytics, and automated pressure management technologies.

Figure 5.1: Proposed Predictive Leak Detection Framework



Thornton, J., Sturm, R., & Kunkel, G. ,2008.

5.5.1 Improved Financial Performance

The framework demonstrates how smart water management technologies can be integrated into a centralized predictive maintenance system. Pressure and flow data are continuously collected through IoT sensors and transmitted to cloud-based platforms for analysis.

Machine Learning models analyze pressure abnormalities and predict leak locations before catastrophic failures occur. Pressure management systems then stabilize hydraulic conditions while maintenance teams conduct proactive repairs.

The framework therefore promotes proactive infrastructure management, operational efficiency, and sustainable NRW reduction.

5.6 Areas for Further Research

While this study successfully developed a model for reducing Non-Revenue Water (NRW) through predictive leak detection and pressure management in Harare City Council, several areas remain open for further investigation. The following areas are recommended for future research:

Deployment of IoT-Based Pressure Monitoring Systems

The study recommends that Harare City Council should deploy Internet of Things (IoT)-enabled pressure sensors throughout critical sections of the water distribution network, particularly in high-risk areas such as Mbare, the CBD, and Milton Park. This recommendation is based on the finding that hydraulic transients exhibited a strong positive correlation with pipe burst frequency, indicating that pressure surges are a major contributor to infrastructure failures. The findings demonstrated that monitoring pressure fluctuations in real time would enable early identification of abnormal hydraulic conditions before catastrophic bursts occur. Therefore, continuous pressure monitoring should form the foundation of future NRW management initiatives.

5.6.1 Application of Advanced Artificial Intelligence Models

This study focused on the use of Long Short-Term Memory (LSTM) networks for predictive leak detection. Future studies should evaluate and compare the effectiveness of other advanced Artificial Intelligence (AI) and Machine Learning algorithms such as Deep Neural Networks (DNNs), Random Forests, Extreme Gradient Boosting

(XGBoost), and Transformer-based models. Comparative studies would help identify the most accurate and cost-effective predictive model for water distribution networks operating under intermittent supply conditions.

5.6.2 Integration of Digital Twin Technology in Water Distribution Networks

Future research should investigate the development and implementation of Digital Twin technology for water distribution systems in Zimbabwe. Digital Twins can provide real-time virtual representations of physical water infrastructure, enabling simulation of hydraulic events, leak scenarios, and pressure optimization strategies. Such studies could evaluate the effectiveness of Digital Twins in enhancing predictive maintenance and operational decision-making.

5.6.3 Expansion of Predictive NRW Models to Other Zimbabwean Municipalities

The current study focused exclusively on Harare City Council. Future research should replicate the model in other urban local authorities such as Bulawayo, Mutare, Gweru, and Masvingo to determine the generalizability and scalability of the proposed framework under different operational and environmental conditions.

5.6.4 Impact of Smart Metering on Apparent Water Losses

This study primarily concentrated on real losses caused by physical leaks. Future studies should investigate the contribution of smart metering technologies in reducing apparent losses resulting from meter inaccuracies, billing inefficiencies, illegal connections, and unauthorized water consumption. Such research would provide a more comprehensive approach to NRW reduction.

5.6.5 Economic Evaluation of Smart Water Infrastructure Investments

Although this study established the financial viability of predictive maintenance systems, further research is required to conduct long-term cost-benefit analyses of smart water technologies. Future studies should evaluate lifecycle costs, financing

mechanisms, investment risks, and sustainability of large-scale IoT deployments within developing-country municipalities.

5.6.6 Climate Change and Water Loss Management

Future research should investigate how climate change-induced droughts, extreme weather events, and changing rainfall patterns influence leakage rates, infrastructure deterioration, and water demand. Understanding these relationships would assist utilities in developing resilient NRW reduction strategies that can adapt to future climatic uncertainties.

5.6.7 Optimization of Pressure Management in High-Elevation Zones

The study established the effectiveness of pressure modulation in reducing leakage. However, further research is required to determine dynamic pressure optimization techniques that simultaneously minimize leakage and maintain service levels in high-elevation areas. Future studies could develop adaptive pressure control algorithms capable of responding automatically to changing hydraulic conditions.

5.6.8 Cybersecurity Risks in Smart Water Systems

As utilities increasingly adopt IoT devices, cloud computing, and machine learning technologies, future research should investigate cybersecurity challenges associated with smart water infrastructure. Studies should focus on protecting sensor networks, communication systems, and operational databases from cyber threats that could compromise service delivery.

5.6.9 Development of Integrated NRW Management Frameworks

Future studies should explore the integration of predictive leak detection, pressure management, smart metering, customer information systems, Geographic Information Systems (GIS), and Enterprise Resource Planning (ERP) platforms into a single intelligent NRW management ecosystem. Such research could provide a holistic framework for water utility digital transformation.

5.6.10 Social and Institutional Factors Affecting Technology Adoption

Finally, future research should examine organizational readiness, employee acceptance, policy frameworks, stakeholder engagement, and institutional barriers affecting the adoption of predictive water management technologies in local authorities. Understanding these human and organizational dimensions would support successful implementation of smart water solutions.

Summary

Future research should focus on:

1. Advanced AI and machine learning models for leak prediction.
2. Digital Twin applications in water networks.
3. Replication of the model in other Zimbabwean municipalities.
4. Smart metering and apparent loss reduction.
5. Long-term economic analysis of predictive maintenance systems.
6. Climate change impacts on NRW management.
7. Dynamic pressure optimization techniques.
8. Cybersecurity in smart water systems.
9. Integrated smart NRW management platforms.
10. Institutional and behavioral factors influencing technology adoption.

These areas would strengthen the body of knowledge on predictive water management and contribute toward achieving sustainable, technology-driven NRW reduction in Zimbabwe and other developing countries.

5.7 Chapter Summary

This chapter presented the summary, conclusions, recommendations, and proposed implementation framework of the study.

The study established that hydraulic transient significantly contributes to pipe bursts and Non-Revenue Water losses within Harare City Council. Predictive leak detection systems supported by IoT technologies and Machine Learning algorithms were found to significantly improve leak management efficiency and reduce operational losses.

The study further established that pressure management systems improve hydraulic stability, minimize leakage volumes, and extend infrastructure lifespan. The findings also demonstrated that predictive maintenance systems are financially sustainable and capable of significantly improving operational efficiency within water utilities.

The study therefore concludes that integrating predictive analytics, IoT monitoring technologies, and automated pressure management systems provides a sustainable long-term solution for reducing Non-Revenue Water within Harare City Council

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LIST OF APPENDICES

APPENDIX A: QUESTIONNAIRE FOR RESIDENTS

TITLE: Assessment of Non-Revenue Water, Predictive Leak Detection, and Pressure Management in Harare City Council

Dear Respondent,

I am conducting a study entitled: **"Developing a Model Towards Reducing Non-Revenue Water Through Predictive Leak Detection and Pressure Management in Harare City Council."**

The purpose of this questionnaire is to gather data regarding water supply reliability, leakage frequency, pressure dynamics, and the potential for smart technology adoption within Harare's water distribution system. Your participation is voluntary, and your responses will be kept strictly confidential, used solely for academic research.

SECTION A: DEMOGRAPHIC INFORMATION

Please tick (✓) the appropriate response or provide brief answers where necessary.

1. **Gender**
   - [ ] Male
   - [ ] Female
   - [ ] Prefer not to say
2. **Age Group**
   - [ ] 18–25
   - [ ] 26–35
   - [ ] 36–45
   - [ ] 46–55

- [ ] Above 55

3. **Residential Area**

- [ ] CBD
- [ ] Milton Park
- [ ] Mbare
- [ ] Other (Please specify): _____

4. **Duration of Residence**

- [ ] Less than 1 year
- [ ] 1–5 years
- [ ] 6–10 years
- [ ] Above 10 years

5. **Occupation: _____**

SECTION B: WATER SUPPLY CONDITIONS & RELIABILITY

6. **How would you rate the reliability of your municipal water supply?**

- [ ] Very Reliable
- [ ] Reliable
- [ ] Unreliable
- [ ] Very Unreliable

7. **On average, how often do you experience unscheduled water supply interruptions?**

- [ ] Daily
- [ ] 2–3 times a week
- [ ] Weekly
- [ ] Monthly / Rarely

8. **When water is available, how many hours of supply do you typically receive per day?**

- [ ] Less than 3 hours
- [ ] 3–8 hours
- [ ] 9–18 hours
- [ ] 24 hours (Continuous)

9. **What type of water meter is currently installed at your property?**

- [ ] Post-paid (Mechanical)
- [ ] Prepaid Meter
- [ ] No meter (Flat rate billing)
- [ ] Non-functional meter

SECTION C: LEAKAGES AND PRESSURE MANAGEMENT

10. **How often do you observe visible pipe bursts or flowing leaks in your immediate neighborhood?**

- [ ] Very Frequent (Weekly)
- [ ] Frequent (Monthly)
- [ ] Rare (Few times a year)
- [ ] Never

11. **Do you experience issues with low water pressure at your taps?**

- [ ] Always (Pressure is consistently low)
- [ ] Frequently (Specific times of day)
- [ ] Occasionally (Only after supply restoration)
- [ ] Never

12. **In your observation, when do pipe bursts most commonly occur?**

- [ ] During peak usage (Morning/Evening)
- [ ] During the night (Low usage periods)
- [ ] Immediately after water supply is restored following a cut

- [ ] No specific pattern

13. **What do you perceive as the primary cause of water loss in Harare?**
- [ ] Aging infrastructure/Corroded pipes
- [ ] Excessive water pressure
- [ ] Illegal connections/Water theft
- [ ] Delayed response to reported leaks
- [ ] Meter inaccuracies/Tampering

14. **"The City Council responds to and repairs reported leaks in a timely manner."**
- [ ] Strongly Agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly Disagree

15. **If you have ever reported a leak, how long did it take for the Council to attend to it?**
- [ ] Within 24 hours
- [ ] 2–5 days
- [ ] More than a week
- [ ] Never attended to

SECTION D: TECHNOLOGY AND SMART WATER MANAGEMENT

3. **How familiar are you with "Smart Water Management" (e.g., IoT sensors, automated leak detection)?**
- [ ] Very Familiar
- [ ] Somewhat Familiar
- [ ] Not Familiar

4. **Do you believe that using digital technology (Predictive Modeling/Sensors) would reduce water losses more effectively than the current manual system?**
   - [ ] Strongly Agree
   - [ ] Agree
   - [ ] Neutral
   - [ ] Disagree
5. **Would you support the installation of an IoT-based leak detection sensor or a Smart Meter at your property?**
   - [ ] Yes
   - [ ] No
   - [ ] Maybe (Need more information)
6. **What recommendations would you provide to Harare City Council to improve water pressure management and reduce physical water losses?**

   _____

   _____

Thank you for your time and contribution to this research.

APPENDIX B: INTERVIEW GUIDE FOR HCC ENGINEERS AND TECHNICAL PERSONNEL

TITLE: Semi-Structured Interview Guide for Engineers, Technicians, and Water Management Experts

Research Title: Developing a Model Towards Reducing Non-Revenue Water Through Predictive Leak Detection and Pressure Management in Harare City Council.

Introduction: This interview is designed to capture technical insights into the nexus between hydraulic transients, pressure management, and Non-Revenue Water (NRW). Your expert perspective will assist in developing a predictive model for sustainable water loss reduction.

SECTION A: PROFESSIONAL PROFILE

1. **Current Designation: _____**
2. **Years of Experience in Water Engineering/Operations: _____**
3. **Primary Operational Zone/Responsibility: _____**

SECTION B: NON-REVENUE WATER (NRW) DYNAMICS

4. Based on recent water audits, what is the current percentage of NRW in your jurisdiction?
5. How would you categorize the split between **Physical (Real) Losses** and **Commercial (Apparent) Losses**?
6. From a technical standpoint, why do specific "hotspots" in the Harare network experience chronic pipe bursts?
7. **Infrastructure Stress:** How does the frequent "charging" and "de-watering" of pipes (intermittent supply) contribute to structural fatigue in the distribution network?

SECTION C: HYDRAULIC TRANSIENTS AND PRESSURE MODULATION

8. **Water Hammer:** To what extent are hydraulic transients (pressure surges) monitored during pump start-ups or valve operations?

9. Are there specific pressure zones where the static head exceeds the design pressure of the aging AC (Asbestos Cement) or Steel pipes?
10. **Infrastructure Audit:** What is the current status of Pressure Reducing Valves (PRVs) in the city? (e.g., Are they functional, bypassed, or insufficient in number?)
11. How do you currently manage the trade-off between ensuring adequate supply to high-elevation areas and preventing bursts in low-elevation areas?

SECTION D: PREDICTIVE LEAK DETECTION & IOT READINESS

12. What is the current "Leak Run Time" (average time from leak occurrence to repair)?
13. **Active Leak Control:** Does the council currently use acoustic loggers, ground microphones, or any form of SCADA-integrated pressure monitoring?
14. **Data Infrastructure:** Is there enough historical data (pressure/flow logs) to support the training of a Machine Learning or Predictive Model?
15. In your view, what are the primary barriers to implementing an **Internet of Things (IoT)**-based leak detection system? (e.g., Cost, Vandalism, Technical Expertise, or Connectivity?)

SECTION E: OPERATIONAL AND FINANCIAL IMPLICATIONS

16. Beyond lost water revenue, what is the estimated impact of NRW on the consumption of treatment chemicals and pumping energy?
17. **Reactive vs. Proactive:** How much of your monthly budget is consumed by "emergency repairs" compared to "preventative maintenance"?
18. To what degree would a "Predictive Leak Model" reduce the **Operational Expenditure (OPEX)** of the City Council?

SECTION F: STRATEGIC INTERVENTIONS & POLICY

19. What specific technical interventions (e.g., District Metered Areas (DMAs), Pipe Replacement, or Smart Metering) should be prioritized in the next 5 years?
20. Are there existing policy or budgetary frameworks that support the adoption of "Smart Water" technologies?

21. **Closing:** Based on your experience, what is the single most critical factor in achieving a sustainable reduction in Harare's water losses?

RESEARCH ETHICS COMMITTEE

P. Bag
1020
BINDURA,
Zimbabwe
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BINDURA UNIVERSITY OF SCIENCE EDUCATION [BUSE]

11 June 2026

Luxon Machipisa
Bindura University of Science Education
Graduate School of Business
16. Bag 1020
Bindura

Dear Luxon Machipisa

RE: INSTITUTIONAL RESEARCH COMMITTEE ETHICAL CLEARANCE-APPROVAL NUMBER: BUSEREC/0211/2026

Your application for research ethical clearance related to the topic **'A MODEL TOWARDS REDUCING NON REVENUE WATER (WATER LEAKAGES) THROUGH PREDICTIVE LEAK DETECTION AND PRESSURE MANAGEMENT IN HARARE CITY COUNCIL'** has been approved and allocated approval Number: **BUSEREC/0211/2026**. You are to quote this approval number for all correspondences inclusive of consent forms and any other documents as and when appropriate. The approval period is as stated below:

Type of Meeting	:	19th Research Ethics Committee meeting
Approval Date	:	11/06/2026
Expiry date	:	10/06/2027

The project will automatically discontinue on the expiry date. You can apply for renewal three months before the expiry date. The renewal application should be accompanied by a progress report.

You are not expected to make any changes/adjustments to the protocol including the consent documents. Any trials involving drugs, devices and biologics require approval of the Medicines Control Authority of Zimbabwe before commencement. All problems to do with the safety of participants must be reported to BUSEREC within three (3) working days.

Upon termination of the study, a report has to be submitted to BUSEREC.

Yours sincerely



BUSEREC CHAIRPERSON

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