Universität Kassel / Witzenhausen
Fachbereich Ökologische Agrarwissenschaften
Fachgebiet Agrartechnik
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Water loss management strategies for developing countries:

Understanding the dynamics of water leakages.

Dissertation zur Erlangung des akademischen Grades

Doktor der Agrarwissenschaften (Dr. agr.)

von

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aus Harare, Zimbabwe

2015

Die vorliegende Arbeit wurde vom Fachbereich Ökologische Agrarwissenschaften der Universität Kassel als Dissertation zur Erlangung des akademischen Grades “Doktor der Agrarwissenschaften” angenommen.

Tag der mündlichen Prüfung: 15.12.2015

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Acknowledgements

I humbly extend my sincere gratitude to my promoter and supervisors Professor Dr. Oliver Hensel and Professor Dr.–Ing. F. -B. Frechen for their advice, instruction, support, encouragement and for devoting their time and knowledge to help me complete my studies.

The VolkswagenStiftung Foundation is acknowledged for funding this research through a Junior Fellowship for African Scientists. My special mention is Dr. Cora Ziegenbalg and Dr. Christoph Kolodziejsky and all the team members in the Engineering Funding Initiative. The Engineering Team Fellows, Mbaye Mbeguere, Peter Olupot and Kouassi Dongo are acknowledged for their support and encouragement.

My mentors, Dr. Marloes Mul and Professor Daweii Han are hereby acknowledged for their encouragement and support throughout the fellowship and beyond.

I thank the City of Harare for the permission to carry out the study in Harare and all the City of Harare personnel who helped in project execution.

The Department of Agricultural Engineering of the University of Kassel is acknowledged. Special mention goes to Ing. Christian Schellet, Dr. Christian Dede and Dr. Uwe Richter for their moral and technical support.

The Department of Civil Engineering- University of Zimbabwe is hereby acknowledged for supporting my studies. Special mention goes to Professor Vasilleva, Dr. Salahuddin, Dr. Makurira, Professor Nhapi, Engineer Hoko, Dr. Misi, Dr. Mabiza, Engineer Mhizha, Dr. Tumbare and Mr. Michael Ndunguru.

My sincere appreciation also goes to my wife Theresa for her encouragement and to our children Shanell, Christian and Gracious, for enduring my absence when they needed me most.

Finally, there are too numerous to mention individuals and institutions who contributed directly or indirectly to this work. You made my study a success, thank you all.

Abstract

This dissertation deals with non-revenue water losses in urban settlements in developing countries. It attempts to bring out an understanding of the nature and mechanisms of water losses, and assesses if non-revenue water losses can be reduced to economic levels in developing countries. This dissertation explores non-revenue water and attempts to quantify leakages and develop leakage management tools for use in developing countries. A case study of the City of Harare, Zimbabwe was used in this dissertation.

Water losses in any water distribution system are inevitable; however, the water losses should be reduced to the lowest economic levels if water utilities are to operate sustainably. Water is being lost through illegal and unauthorised connections, leakages from water distribution networks as well as unsustainable metering and billing systems. Many attempts have been made to reduce water losses in water distribution systems and as such many methodologies and tools have been applied in order to minimise water losses. These tools range from computational approaches, legal and policy implementation, economic approaches as well as infrastructural rehabilitation approaches. The success of each attempt rests on the applicability and context in which the tools and or methodologies are applied.

The measure of performance of any water utility is based on the efficiency of the water distribution systems in place. Lately, performance indicators and benchmarking methodologies are the most important approaches used in assessing water distribution systems efficiency. The main indicators in use world-over are either financial or operational. This study discovered that many utilities in developing countries do not adequately use these assessment indicators in their water loss management strategies.

Many water loss management studies assess non-revenue water without evaluating the contribution of leakages to total water losses. As a result total water losses are not partitioned accordingly. Therefore, there is need for specialised application tools for assessing partitions of non-revenue water. One such tool is the South African Night Flow (SANFLOW) Analysis Model, developed by the Water Research Commission of South Africa for analysing flows and pressure within district metered areas. In this text, the SANFLOW analysis model was found to be suitable for partitioning water leakages. Thus, SANFLOW analysis model is an alternative tool, relevant and highly adaptable to the developing world.

Computational approaches can be used to detect leakages in water distribution networks. One other approach is the Artificial Neural Networks (ANNs) technique. ANNs can be trained to forecast flow dynamics in a water distribution network. Such flow dynamics can be compared with water demands in a particular area. A multi-layer feed-forward back-propagation artificial neural network was used for modelling water flow in a district metered area. In this regard a MATLAB algorithm was developed to simulate water demand. The difference between the actual and the simulated water demands represented the water leakage in a water distribution network. It was discovered that an ANN could be trained and be used to forecast flow with up to 99% confidence. Thus, ANNs technique is a flexible and efficient approach to detection of leakages in water distribution networks. The study concluded that 36% of the total water supply in the City of Harare, Zimbabwe was being lost monthly. Of the 36% water lost, 33% was lost as water leakage every month. Thus, the City of Harare was losing revenue in excess of one million dollars monthly, representing 20% of the total revenue of the city. Therefore, the City of Harare should be proactive in reducing leakages since leakage losses negatively affect service delivery.

Finally, the study proposed an integrated water leakage management framework that can be used by water utility managers to decide on the best water leakage management strategy for their water supply systems.

Kurzfassung

Diese Arbeit beschäftigt sich mit nicht in Rechnung stellbaren Wasserverlusten in städtischen Versorgungsnetzen in Entwicklungsländern. Es soll das Wissen über diese Verluste erweitert und aufgezeigt werden, ob diese auf ein ökonomisch vertretbares Maß reduziert werden können. Die vorliegende Doktorarbeit untersucht solche unberechneten Wasserverluste und versucht, neben der Quantifizierung von Leckagen auch Entscheidungswerkzeuge für ein verbessertes Management der Versorgungsnetze in Entwicklungsländern zu erarbeiten. Als Fallstudie dient Harare, die Hauptstadt von Simbabwe.

Wasserverluste in Verteilungsnetzen sind unvermeidbar, sollten aber auf ein ökonomisch tragbares Niveau reduziert werden, wenn ein nachhaltiger Betrieb erreicht werden soll. Wasserverluste können sowohl durch illegale und ungenehmigte Anschlüsse oder durch Undichtigkeiten im Verteilnetz, als auch durch mangelhafte Mess- und Berechnungssysteme entstehen. Es sind bereits viele Ansätze zur Verringerung von Verlusten in Wasserverteilsystemen bekannt geworden, entsprechend existieren dazu auch zahlreiche Methoden und Werkzeuge. Diese reichen von computergestützten Verfahren über gesetzliche und politische Vorgaben sowie ökonomische Berechnungen bis hin zu Maßnahmen der Modernisierung der Infrastruktur. Der Erfolg dieser Anstrengungen ist abhängig von der Umsetzbarkeit und dem Umfeld, in dem diese Maßnahmen durchgeführt werden.

Die Bewertung der Arbeitsgüte einer jeden Wasserversorgungseinheit basiert auf der Effektivität des jeweiligen Verteilungssystems. Leistungs- und Bewertungszahlen sind die meist genutzten Ansätze, um Wasserverteilsysteme und ihre Effizienz einzustufen. Weltweit haben sich zur Bewertung als Indikatoren die finanzielle und die technische Leistungsfähigkeit durchgesetzt. Die eigene Untersuchung zeigt, dass diese Indikatoren in vielen Wasserversorgungssystemen der Entwicklungsländer nicht zur Einführung von Verlust reduzierenden Managementstrategien geführt haben.

Viele durchgeführte Studien über die Einführung von Maßnahmen zur Verlustreduzierung beachten nur das gesamte nicht in Rechnung stellbare Wasser, ohne aber den Anteil der Leckagen an der Gesamthöhe zu bestimmen. Damit ist keine Aussage über die tatsächliche Zuordnung der Verluste möglich. Aus diesem Grund ist ein Bewertungsinstrument notwendig, mit dem die Verluste den verschiedenen Ursachen zugeordnet werden können. Ein solches Rechenwerkzeug ist das South African Night Flow Analysis Model (SANFLOW) der südafrikanischen Wasser-Forschungskommission, das Untersuchungen von Wasserdurchfluss und Anlagendruck in einzelnen Verteilbezirken ermöglicht. In der vorliegenden Arbeit konnte nachgewiesen werden, dass das SANFLOW-Modell gut zur Bestimmung des Leckageanteiles verwendet werden kann. Daraus kann gefolgert werden, dass dieses Modell ein geeignetes und gut anpassbares Analysewerkzeug für Entwicklungsländer ist.

Solche computergestützte Berechnungsansätze können zur Bestimmung von Leckagen in Wasserverteilungsnetzen eingesetzt werden. Eine weitere Möglichkeit ist der Einsatz von Künstlichen Neuronalen Netzen (Artificial Neural Network – ANN), die trainiert und dann zur Vorhersage der dynamischen Verhältnisse in Wasserversorgungssystemen genutzt werden können. Diese Werte können mit der Wassernachfrage eines definierten Bezirks verglichen werden. Zur Untersuchung wurde ein Mehrschichtiges Künstliches Neuronales Netz mit Fehlerrückführung zur Modellierung des Wasserflusses in einem überwachten Abschnitt eingesetzt. Zur Bestimmung des Wasserbedarfes wurde ein MATLAB Algorithmus entwickelt. Aus der Differenz der aktuellen und des simulierten Wassernachfrage konnte die Leckagerate des Wasserversorgungssystems ermittelt werden. Es konnte gezeigt werden, dass mit dem angelernten Neuronalen Netzwerk eine Vorhersage des Wasserflusses mit einer Genauigkeit von 99% möglich ist. Daraus lässt sich die Eignung von ANNs als flexibler und wirkungsvoller Ansatz zur Leckagedetektion in der Wasserversorgung ableiten. Die Untersuchung zeigte weiterhin, dass im Versorgungsnetz von Harare 36 % des eingespeisten Wassers verloren geht. Davon wiederum sind 33 % auf Leckagen zurückzuführen. Umgerechnet bedeutet dies einen finanziellen Verlust von monatlich 1 Millionen Dollar, was 20 % der Gesamteinnahmen der Stadt entspricht. Der Stadtverwaltung von Harare wird daher empfohlen, aktiv an der Beseitigung der Leckagen zu arbeiten, da diese hohen Verluste den Versorgungsbetrieb negativ beeinflussen.

Abschließend wird in der Arbeit ein integriertes Leckage-Managementsystem vorgeschlagen, das den Wasserversorgern eine Entscheidungshilfe bei zu ergreifenden Maßnahmen zur Instandhaltung des Verteilnetzes geben soll.

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List of acronyms and abbreviations

ADB	Asian Development Bank
AL	Apparent Losses
ALC	Active Leak Control
ALI	Apparent Loss Index
ANN	Artificial Neural Network
APL	Apparent Physical Loss
ARIMA	Auto-Regression Integration Moving Average
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
BABE	Bursts and Background Estimates
BIS	Bayesian Interface Systems
CAAL	Current Annual Apparent Losses
CAPL	Current Annual volume of Physical Losses
CARL	Current Annual Real Loss
CBD	Central Business District
DA	Discriminant Analysis
DDA	Demand Driven Analysis
DEA	Data Envelopment Analysis
DMA	District Metered Area
EMNF	Expected Minimum Night Flow
ENF	Excess Night Flow
EPA	Environmental Protection Agency
EPANET	Environmental Protection Agency Network Software
EPD	Environmental Protection Division
FAVAD	Fixed Area Variable Area Discharges

GAs	Genetic Algorithms
GDP	Gross Domestic Product
IBNET	International Benchmarking Network for Water and Sanitation
IFAD	International Fund for Agricultural Development
ILI	Infrastructure leakage Index
IPBA	International Pipe Bursting Association
IWA	International Water Association
IWRM	Integrated Water Resources Management
LNF	Legitimate Night Flow
MAAPL	Minimum Achievable Annual Physical Losses
MCDA	Multi-Criteria Decision Analysis
MDGs	Millennium Development Goals
MENA	Middle East and North Africa
MLP	Multi-Layer Perception
MNF	Minimum Night Flow
MSE	Mean Square Error
NHM	Network Hydraulic Modelling
NLI	National Leakage Index
NNF	Net Night Flow
NRW	Non Revenue Water
OFWAT	Office of Water Services (UK)
PAS	Performance Assessment System
PDD	Pressure-Dependent Demand
PDF	Probability Density Function
PI	Performance Indicator
PRV	Pressure Reducing Valve
PWS	Public Water System

SANFLOW	South African Night Flow Analysis Model
SIV	System Input Volume
SIWI	Swedish International Water Institute
SVM	Support Vector Machines
UARL	Unavoidable Annual Real Losses
UNDP	United Nations Development Program
UNICEF	United Nations Children’s Educational Fund
VEWIN	Association of Dutch Drinking Water and Sanitation Utilities
WBI	World Bank Institute
WDM	Water Demand Management
WDS	Water Distribution System
WHO	World Health Organization
WLM	Water Loss Management
WOP	Water Operators Partnerships
WRC	Water Research Commission
WRM	Water Resources Management
WSP	Water Supply and Sanitation Programme
WWAP	World Water Assessment Programme

List of papers

Parts of this thesis have been published or are submitted for publication as:

Chapter 2.	Makaya, E., and O. Hensel (2014). Water distribution systems efficiency assessment indicators –Concepts and application, International Journal of Science and Research Volume 3(7). pp. 219-228
Chapter 5.	Makaya, E and O. Hensel (2014). The contribution of leakage water to total water loss in Harare, Zimbabwe, International Researcher 3 (3) pp. 56-63.
Chapter 5.	Makaya, E., O. Hensel and G.M. Ndunguru (2015). Application of SANFLOW model in analyzing the contribution of leakage water to total water loss in developing countries, Greener Journal of Science, Engineering and Technology Research (Submitted).
Chapter 5.	Makaya, E., and O. Hensel (2015). Modeling flow dynamics in water distribution networks using Artificial Neural Networks-A leakage detection Technique, International Journal of Engineering, Science and Technology 7(1). pp 33-43

1 Background

Water is vital for human survival, health and dignity and a fundamental resource for human development (WHO, 2005). However, the world's freshwater resources are under increasing pressure due to increased population growth, increased economic activity and improved standards of living thereby leading to increased competition for, and conflicts over, the limited freshwater resource (Simbeye, 2010). Water withdrawals have increased more than twice as fast as population growth and currently one third of the world's population lives in countries that experience medium to high water stress. On the other hand, shortcomings in the management of water by focusing on developing new water sources rather than managing existing ones, and top-down sector approaches to water management have resulted in uncoordinated development and management of the resource (Simbeye, 2010). Thus, the more the attention is put towards new water developments, the greater would be the impacts on the environment. The importance of reducing water losses as a component of Integrated Water Resources Management (IWRM) is evident in the water governance crisis, the need to secure water for people, the need to secure water for food production, the need to protect the ecosystem and other uses such as hydropower generation (Gumbo, 2004). All these competing users have an obligation to use water resources efficiently in order not to negatively affect other users and ensure sustainability of water resources.

In as much as rural to urban migration is increasing posing serious problems regarding food supply, housing, water supply and public health; demand for water is highly pronounced. Urbanisation is more pronounced in urban areas of the developing countries (WHO, 2005). Rapid population growth and increased urbanization, cause water demand to rise globally and the finite water resources are diminishing as a result (Rosegrant et al., 2002). Ethical urban planning and infrastructure development have been seriously violated due to these random urban developments. Furthermore, water distribution network expansions have been done without proper consultation resulting in serious systems pressure deficiencies, systems head losses, poor quality water distribution network materials and poor water supply installation workmanship, and unpredicted future demand. The challenges of high water demand are exacerbated by the fact that there has been very limited capital investment in water infrastructure development especially in developing countries. Thus, the water demand pressures highlight the need for a paradigm shift to utilize water resources as efficiently as possible (Baietti et al., 2006). Without effective actions, scarce water resources will be diminishing even faster in the near future due to increasing demand for water. It is estimated that by the year 2025 the total water demand in developing countries will increase by 27% compared to the demand in 1995 (Rosegrant et al., 2002). Sub-Saharan Africa accounts for about 23% of the global total population without access to improved water resources (UNDP, 2003). While the rest of the world is on track in meeting the millennium target, Africa and particularly sub-Saharan Africa is not likely to meet this target (WHO and UNICEF, 2010), which aims to halve the proportion of people without sustainable access to safe drinking water by year 2015.

Another challenge in managing water resources in Africa is poverty; which makes cost recovery very difficult. For example, in Swaziland, 69% of the country is affected by poverty and cannot meet basic water and sanitation needs (IFAD, 2008). If Africa is to meet the Millennium Development Goals (MDGs), then it has to achieve 7% annual economic growth in order to halve extreme poverty by 2015 and the equivalent of at least 9% of the Gross Domestic Product (GDP) needs to be invested annually in infrastructure (Banerjee et al., 2008). Africa’s overall cost to build the required new infrastructure (including water), refurbish dilapidated assets, and operate and maintain all existing and new installations is estimated at almost $93 billion a year for 2006 through 2015, a 15 percent of African GDP (WWAP, 2009). Thus, the economic status of developing economies has ripple effects which even manifest in the way the water supply systems are managed. Poor operation and maintenance of water distribution systems always results in serious water losses.

Although in many developing countries water supply and sanitation services have been provided by state-owned public water utilities (Ndokosho et al., 2007), these public water utilities have failed to provide consumers with adequate water supplies due to high water losses in their distribution systems (Baietti et al., 2006). Non-revenue water loss is a problem for almost all water utilities in the world (Kingdom et al., 2006). In water distribution systems, water is being lost through physical means such as leakages as well as through apparent losses in the form of illegal connection and non-sustainable billing systems. Such water losses have resulted in some water utilities losing more than half of their treated and conveyed water. Water loss in the distribution system worldwide ranges from 15% to 60% of the total water supply (Balkaran and Wyke, 2002). This problem takes on a new dimension in developing countries where a combination of ageing infrastructure, intermittent supplies and illegal use worsen the problem (Rizzo, 2000). The World Bank recommends non-revenue water of less than 23% (Tynan and Kingdom, 2002), while 20% was set for well performing urban water utilities in Southern African Region (Gumbo, 2004). Kingdom et al., (2006) reported water losses in developing countries averaging 50%. An average of 36% non-revenue water was discovered for some district metered areas of the City of Harare, Zimbabwe (Makaya and Hensel, 2014a).

As part of a general move to market oriented systems in the 1980s and 1990s, a new paradigm emerged to transform water utilities into modern service delivery organisations that emphasise operational and financial sustainability. Public water utilities, which are likely to remain responsible for service provision for many years to come in developing countries, do not have satisfactory performance and provide inadequate services to their customers (Schwartz, 2006). The main cause of poor performance among other things is the high levels of water losses. Thus, water loss management is inevitable since it ensures sustainability of infrastructure, postponement of investment and enhances availability of water to new customers (Savenije and Van der Zaag, 2003). It is paramount for water utilities to come up with sustainable strategies for water loss management for them to fulfil their water supply mandates. The success of any water loss management endeavour lies in understanding the ways by which water is lost in the water distribution system and hence device methodologies and tools appropriate to minimise the water losses.

Although many water loss management strategies exist, little is understood about those water loss reduction initiatives involving partitioning of physical water losses. Physical water losses are partitioned into leakage on transmission and or distribution mains; and leakage and overflow at utility's storage tanks and leakage on service connections up to customer metering. However, physical water losses constitute the largest fraction of total water losses (Makaya and Hensel, 2014b). Of particular importance to developing countries is the contribution of leakages to total non-revenue water. In understanding water losses by partitioning physical water losses, computational tools and or methodologies such as the South African Night Flow Analysis model and the Artificial Neural Network Models play important roles. Thus, in furthering this assertion and hence answering the research questions, it is hypothesised that computational methodologies can be very helpful in understanding physical water losses (leakages) in water distribution systems in developing countries. Thus, the aim of the study was to develop a novel approach and practical tools for leakage management in order to improve the efficiency of water distribution systems in developing countries. To achieve that aim the study tried to understand the existing and develop adaptable water leakage management methodologies, tools and guidelines for developing countries. The study presents adaptable approaches and methodologies, experimental results and a proposed decision support framework for integrated water leakage management, for use in developing countries.

1.1 Objectives of the study

Management of water leakages is a key strategic undertaking that ultimately reduces water losses considerably; hence improve customer satisfaction and subsequently service delivery by water utilities. The main objective of this water loss management study is to understand and develop adaptable water leakage management methodologies and tools for developing countries.

1.1.1 Specific objectives

The specific objectives of the study are:

1. To investigate water leakage management methodologies widely used in developing countries.
2. To investigate performance assessment systems used by water utilities with a view of appraising their application in developing countries.
3. To evaluate the contribution of water leakages to total non-revenue water in water distribution systems.
4. To assess the applicability of SANFLOW Analysis Model in partitioning total water losses in order to predict water leakages.
5. To model flow dynamics in water distribution networks using Artificial Neural Networks and predict associated leakage water losses.
6. To develop a decision support framework for integrated water leakage management for use in developing countries.

1.1.2 Research questions

The following research questions were asked in seeking better understanding of the research problem:

1. What are the water leakage management methodologies widely used in developing countries?
2. To what extend are performance assessment systems used by water utilities in developing countries?
3. What is the contribution of water leakages to total non-revenue water in water distribution systems of developing countries?
4. How applicable is the SANFLOW Analysis Model in partitioning total water losses in district metered area?
5. How efficient are Artificial Neural Networks in modelling flow dynamics and in predicting associated leakages in water distribution networks?
6. How can systems and subsystems in water loss management be integrated into a decision support framework for integrated water leakage management?

1.2 The dissertation framework

Figure 1.1 shows a schematic representation of the dissertation outline from introduction to conclusion. The study is presented in the form of: Introduction, The of state of the art, Details of case study area, Materials and methods, Results and discussion, Overall discussions and Recommendations and suggestions. The introduction gives the overview of the research problem, aims and objectives and research questions. The state of the art reviews important literature on water loss management. The section on material and methods outlines the study design and data collection and analysis methodologies. The applicability of SANFLOW analysis model within the case study area was tested. Furthermore, an Artificial Neural Network (ANN) model was developed for modelling flow dynamics and predicting leakage water in the water distribution network. An Integrated Water Leakage Management Decision Support Framework was developed synthesising leakage management subsystems. The section on results and discussions presents the experimental results and discusses the validity of the scientific results obtained. Finally, an overall discussion, recommendations and suggestions are presented in summary of the whole study.

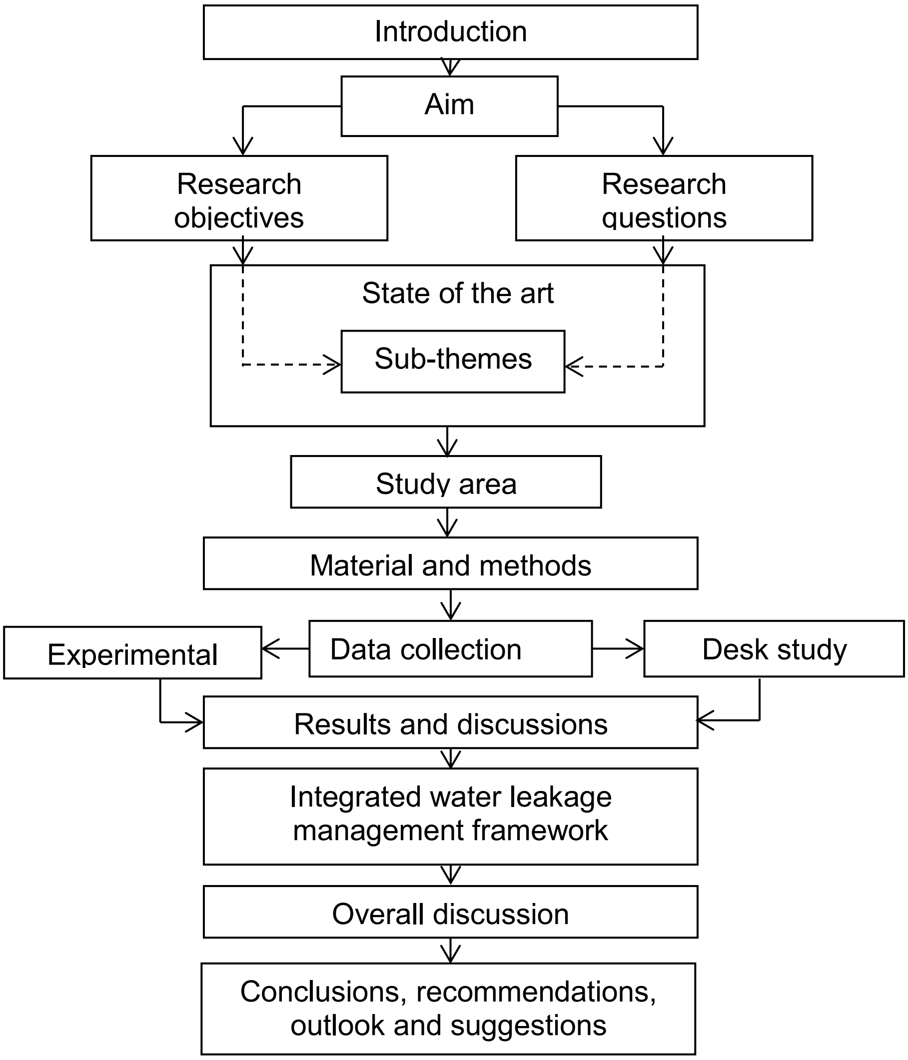


Figure 1.1 Schematic representation of the dissertation outline.

2 State of the art

2.1 Introduction

This study was conducted to understand water losses in developing countries and explore opportunities for reducing leakages in water distribution networks. This chapter reviews the most relevant literature on water loss management in developing countries. The state of the art tries to bring out better understanding of water losses in the form of non-revenue water. Water losses are partitioned in order to establish the component of water loss with the greatest percentage contribution. The methodological approaches used in understanding and reducing leakages are explored. Furthermore, the state of the art reviews computational approaches used in water loss management in a way of trying to appraise their application in developing countries. Finally, the state of the art reviews applications of performance assessment systems and benchmarking approaches in managing water losses.

2.2 An overview of water distribution losses

Water loss management strategies have been developed in many countries over a long period of time, since the development of water reticulation systems. However, in many developing countries the concept of water loss management has received very little attention compared with the severity of the problem of water loss. Because of the importance of water worldwide, its management is a key priority for all water utilities. Urban water distributions systems (WDSs) are often believed to be buried and are often forgotten. Action is always taken after such leakages erupt to the surface, otherwise they will continue leaking. Water losses of this nature can go unnoticed for a long time and hence the magnitude of the losses is high with time and may impact negatively on the operation and maintenance of the water distribution system.

Non-revenue water can generally be defines as the sum total of real and apparent losses and all unauthorised unbilled water consumption. Normally the authorised unbilled consumption includes water for fire fighting and water for cleaning the main network (Mutikanga et al, 2010b). Generally, NRW is an indicator of operational efficiency of WDS. A utility cannot operate efficiently if it does not realise all its revenue due to water losses. This notion is supported by Kingdom et al (2006) who indicate that an average of 48 billion cubic meters of water is lost yearly costing utilities about 14 billion dollars. They furthermore assert that of the total water lost globally, 55% is lost in developing countries. Consequently, infrastructure and operational efficiency in developing countries is highly compromised.

Furthermore, high water losses in WDSs present “untapped” water resources which can be recovered cost effectively. Unfortunately, these untapped and wasted resources are already treated to drinking water standards and energized to provide adequate pressure to reach the consumers.

Water losses do not only have economic and environmental dimensions but also have public health and social dimensions. In particular, leakage often leads to service interruption and may cause water quality deterioration through pathogen intrusion (Karim et al., 2003; Almandoz et al., 2005). The contaminated water is able to infiltrate the piped network through small leaks and cracks when the outside water pressure becomes greater than the water pressure within the pipe.

2.3 Global differences in water distribution losses

2.3.1 Water losses in some developed countries

The water loss management scenarios in developed countries differ from those in developing countries in many ways. The main difference is in the response strategies and response sensitivity of the water utilities and governments of these countries. Utilities in developed countries have managed to reduce their water losses to fairly acceptable and manageable ranges. In Greece’s Larissa city, NRW has been estimated at 34% of the SIV (Kanakoudis and Tsitsifli, 2010), while between 15 and 60% NRW is lost in Italy (Fantozzi, 2008). Furthermore, Portugal loses between 20 and 50% in NRW (Marques and Monteiro, 2003). The Netherlands have reported leakages of 3% to 7% of the water distribution input (Beuken et al., 2006). The USA has an average NRW of 15%, ranging from 7.5% to 20% (Beecher, 2002). In the UK, about 20%-23% of water delivered is lost through leakage (OFWAT, 2010). According to Carpenter et al (2003), the NRW levels for Australia ranges from 9.5 to 22%, with a mean value of 13.8%. On the other hand, leakage levels for Ontario, Canada, ranges from 7 to 34% of the SIV. In as much as the developed countries have made significant efforts in reducing water losses, there is room for improvement. The wide variation in water losses in one country implies inconsistence in the way water losses are managed within the same country.

2.3.2 Water losses in developing countries

Many water distribution systems in developing countries are operated under intermittent conditions (WWAP, 2014). As a result, water supply efficiency in these countries is compromised. Besides the problems associated with intermittent water supply conditions, water losses in developing countries have reached alarming rates, with non-revenue water levels in excess of 60% having been recorded in many of these countries. The slow progress in water loss reduction in developing countries is characterised by political interferences and institutional resistance to change (Savanije and van der Zaag, 2002; Gumbo and van der Zaag, 2002). One of the main causes of slow progress is that the utilities and water supply companies have not been ploughing back proceeds for network rehabilitation. Most of the revenue collected by water operators is diverted to other uses instead of maintaining and upgrading water distribution systems.

In Latin American water utilities NRW of levels of 40% to 55% are documented, of which Brazil accounts for 39% of the SIV. On the other hand NRW ranging 4.4% in Singapore to 63.8% in Maynilad, Manila have been reported (ADB, 2010) while 50% to 65% of the NRW is due to apparent losses (McIntosh, 2003). In Africa NRW figures ranging from 5% in some South African towns to 70% in Liberia have been reported (WSP, 2009). Zimbabwe has recorded NRW of up to 60% of the SIV (City of Harare, 2011). The upper limit in developing countries signifies the severity of the water loss problem. Hence developing countries should seriously consider reducing their water losses in order to operate sustainably.

2.4 African initiatives for water loss reduction

Faced with a host of water loss management challenges, developing countries are making efforts to reduce water losses in their water distribution systems. In Africa, and particularly in South Africa, the Water Research Commission (WRC) developed various softwares for understanding and reducing non-revenue water. The initiative came about when the South African Water Research Commission discovered that the reduction of non-revenue water was one of the key problem issues facing the continent (McKenzie, 2002). To assist water suppliers in addressing their water losses, the commission developed a suite of models and associated documentation. The models currently available are:

- The SANFLOW minimum night flow analysis model.
- The PRESMAC pressure management model.
- The ECONOLEAK active leakage control assessment model.
- The AQUALITE water balance model.

Benchmarking is one other initiative adopted by many African cities in trying to manage their water losses. The approach is one where distribution service efficiency is correlated to improvement in water loss reduction. A benchmark of 0.3m^3/connection /day was agreed upon as a NRW indicator for optimum performance of water utilities in Africa (WSP, 2009). This benchmark value was arrived at from the participation of 70% of the 134 utilities from across Africa. Water supply efficiency improvement

Water utilities world-over are obliged to put as much effort as possible in improving their water supply efficiency. In practice, water supply efficiency can be improved using many approaches, including investing in technology and infrastructure development, fostering changes in user behaviour and developing integrated improvements in water management (WSP, 2009). However, any investment made in water supply infrastructure must take into account a variety of factors, including a country’s land, labour and capital endowments, and its ability to maintain the infrastructure it is investing in. Importantly, investment costs should never outweigh the benefits obtained in reducing leakage, as it is only cost-effective up to some point (Farley et al., 2008). Available options include investing in water loss reduction systems, strengthening regular maintenance programs, matching water supply to demand, encouraging recycling and reuse, and introducing better land management practices (Kleiner and Rajani, 2002; EPA, 2010). Regular maintenance of infrastructure also helps to maintain water efficiency levels and is more cost-effective than rehabilitation (Makaya, 2014c). The best ways of ensuring that structures don’t fall into disrepair is to get the users involved in their management and to set water user fees which are high enough to cover the cost of operation and maintenance (Farley et al., 2008). This is because it is of no good to develop new water infrastructure if the infrastructure is not going to be maintained.

The benefits of a more efficient water distribution system include: reduced system breakdowns and hence reduced water losses; improved and equitable water supply; customer confidence in the system which increases their willingness to pay for water usage; the price of water may go down and the net cost of operating the water distribution system may be reduced (Tiltnes, 1998). The importance of prioritizing efficiency control practices and procedures cannot be understated. A municipality applying efficiency management strategies and activities will benefit through extension of sustainable water supplies, reduced water losses, reduced operating costs to the utility, improved system hydraulics, improved environmental stewardship and utility efficiency (Makaya and Hensel, 2014a). Although it is important for water utilities to improve on their water supply efficiency, water utilities are confronted with a myriad of challenges, and the challenges result in reduced water distribution systems efficiency.

2.5 Water distribution challenges faced by water utilities

The provision of adequate water supply to the general population of any country is of paramount importance and has inherent developmental implications (Makaya and Hensel, 2014a). However, utilities in many developing countries mandated to supply the water are in a vicious cycle of challenges. In that regard, additional sources of water are becoming more difficult and more expensive to exploit, and substantial investment is needed to treat the water into a product suitable for human consumption.

Non-revenue water has stood out as one of the major challenges faced by water utilities. Although there are signs of knowledge of NRW by utility management, the problem seems to be continually haunting water utilities. The problem seems to be less understood by water managers since little attention is paid at mitigating both physical and apparent water losses. Each year more than 32 billion cubic metres of treated water is lost through leakages from the distribution networks. An additional 16 billion cubic metres per year is delivered to consumers but not invoiced because of theft, poor metering or illegal use (Simbeye, 2010). Such water losses would amount to about US$14 billion yearly. By avoiding such water losses, in excess of 100 million consumers would be serviced without new capital outlays (World Bank, 2006). The loss of treated water in the distribution system results in direct loss of revenue for the PWS. In the USA it is estimated that there are close to 237,600 pipe bursts per year translating to $2.8 billion lost in yearly revenue (AWWA, 2003).

Water operators and service providers in developing countries suffer from poor strategic management, weak financial and operational management, unskilled staff, low funding priority, weak customer service orientation, political interference and little or no independent regulation or oversight (WOP, 2009). Furthermore, few or no standards exist in many developing countries for evaluating performance with respect to non-revenue water (Marin, 2009).

Thus, it can be inferred that the challenges faced by water utilities in developing countries are centred on water leakage losses, and as such water loss management should be made a key priority, with water leakage management on the top list.

2.6 Non-revenue water reduction efforts

Many funding organisations, including the World Bank and Africa Development Bank, have made efforts to reduce non-revenue water in their projects which have included the following: prioritizing water loss reduction, inclusion of NRW reduction components, and setting targets for reduced NRW as a condition for funding.

However, many projects have not been as effective despite the above measures. According to EPA (2010), some of the reasons for the failure in reducing NRW include:

- Little understanding of the nature of water losses by the people tasked with this responsibility.
- Little or no appreciation of the impact of water losses.
- Poor project design.
- Grossly under estimated costs of water loss reduction resulting in this task being abandoned.
- “Lip service” to obtain international funding; “NRW reduction” used as a politically correct term that is included in project proposals when sourcing for international financing.
- Failure to realize that NRW reduction is not just an isolated technical problem, tied to overall asset management and operation and, not a once-off activity, but one requiring long term commitment.

2.7 The modes through which water is lost by water utilities

One of the reasons why water loss management initiatives have achieved limited success is that water utilities in many countries especially in developing countries have limited understanding of the drivers and water distribution systems dynamics that have to do with non-revenue water. In an effort to understand water losses in water distribution systems, the International Water Association (IWA) developed and published the best practices for water balance calculation and gave clear and proper definitions of the different components of water losses (Alegre et al., 2006; Lambert, 2002). Alegre et al., (2006) also presented the "Performance Indicators for water supply services" as developed by the IWA for the calculation of water balances with precise definitions and methodology. From the water balance computation (Table 2.1), components of water losses are easily partitioned. Non-revenue water includes unbilled authorised consumption (Lambert, 2002). Unbilled authorised consumption, though small as compared to other water loss components, includes water for fire fighting, flushing mains and sewers, street cleaning, watering municipal gardens, public fountains and frost protection among other things.

Table 2.1 Standard International Water Balance (Source: Lambert and McKenzie, 2002)

System input volume	Authorised consumption	Billed Authorised Consumption	Billed metered consumption	Revenue water
			Billed unmetered consumption	
		Unbilled Authorised Consumption	Unbilled metered consumption	Non-revenue water
			Unbilled unmetered consumption	
	Water losses	Apparent losses	Unauthorised consumption	
			Metering inaccuracies	
		Real losses	Leakage on transmission and or distribution mains	
			Utility storage tanks leakage	
			Service connections leakage up to customer metering	

Authorized consumption is divided into two parts, one part is billed to consumers (both metered and unmetered) and another is not billed. This unbilled portion of authorized consumption does form part of NRW, but it is by no means the whole of NRW.

Water losses also come in two forms: apparent or commercial losses, and real or physical losses. Water that is not physically lost, but apparently lost includes water supplied through illegal connections; water stolen for resale; water consumption undercounted by inaccurate meters; and water sales that cannot be invoiced because meter numbers cannot be accurately correlated with customer names and addresses (Lambert, 2003). Physical losses include leaks from reticulation systems (especially service connections), leaks from transmission or distribution mains and overflow and leaks from storage and balance tanks.

2.7.1 Hydraulic flow measurement errors

Like any other mechanical devices, water meters are subject to wear and tear and hence they lose their accuracy with time (Farley et al., 2008). Wear and tear can be attributed to environmental factors such as water quality impacts, heat or cold and in other areas they are affected by soil conditions as the meters are often laid directly in the ground. Other errors in flow measurement may result from poor workmanship during meter installation, lack of proper repair and lack of routine testing for meter tampering. Sometimes errors can be easily introduced through negligence and corruption (Liemberger, 2010).

2.7.2 Data management errors

The usual approach to billing involves the physical visit to the metered property by a meter reader. However, errors on the final bill to be received by the customer may arise from incorrect data capture, incorrect data transfer and water bills being send to the wrong address (Farley et al., 2008). These errors can be intentional (corruption) as some people can be deliberately omitted from monitoring records. Accounting data transfer errors and accounting data management errors can occur unintentional due to poorly structured billing and meter reading systems (Mutikanga et al., 2010b).

2.7.3 Unauthorized consumption

Unauthorised water consumption mainly covers water theft, meter bypass, illegal connections and misuse of fire hydrants (Farley et al., 2008). However, a proactive approach through investigations of suspicious trends of billing data can be used to locate the area of these unauthorized consumptions. To reduce illegal water use, informers (whistle blowers) could be engaged by a water utility. On the other hand stiffer penalty can be imposed on offenders to deter illegal water usage.

2.7.4 Human resources and financial management

By hiring unskilled personnel, a water utility suffers incompetence and poor performance (Matar, 2011). Lack of staff training and education can indirectly cause water loss as staff performance will be poor. Top management often does not address water loss due to unawareness of how the utility is being affected by water losses; and thus creating a wrong mind-set that can filter through the entire organization (Furlong, 2007). Some utilities might have tight financial positions and by abandoning water losses, less revenue is realised. In such situations water losses are not regarded a priority for such water utilities.

2.8 Water loss control programs for public water systems

Thousands of independent water utilities are dedicated to producing, treating and delivering safe water to the public. However, significant resources are required to install, operate and maintain the infrastructure of a public water system (EPA, 2010). The infrastructure of many drinking water systems were built decades ago and are currently in need of attention. Furthermore, Public Water Systems (PWSs) must address current growing concerns such as limited water availability, increasing water demands, climate change, increasing regulatory requirements, and limited resources and funding (EPA, 2010). For these reasons more water utilities are implementing water loss control programs. A well implemented water loss control program can protect public health by eliminating the threat of sanitary defects that may allow microbial or other contaminants to enter the treated water (EPD, 2007; Mutikanga, 2009; WWAP, 2014).

A water loss control program must be flexible and tailored to the specific needs and characteristics of a PWS. There are three major components to an effective program:

- The water audit.
- Intervention.
- Evaluation (EPD, 2007; EPA, 2010).

Each of these major components consists of additional steps and options.

2.8.1 The water audit

To understand and or quantify the water lost from the water distribution systems, water utilities should undertake water auditing where the total water supplied is compared with the amount of water billed (Lambert, 2003). Water auditing assesses the distribution metering, and accounting operations of the water utility using accounting principles to determine water amounts being lost (Hunaidi, 2010). The American Water Works Association (AWWA) recommends that an annual water audit be compiled by the water utility as a standard business process. Through water audit options should be compared and evaluated not only economically but with consideration of all other issues and concerns the PWS faces (EPA, 2010).

2.8.2 The intervention

The intervention process puts the options selected into action. More than one action may be selected as beneficial to a PWS and the public. For example, the water management administrator may decide that the PWS has three high priority items including additional metering in one neighbourhood, precisely locating and repairing a leak in a specific section of main pipeline, and replacing a one-mile section of a pipeline. Selecting the order of these actions should be based on budget constraints, public benefit and priority of other scheduled capital improvements (EPA, 2010). Intervention can include:

- Gathering further information, if necessary.
- Metering assessment, testing, or a meter replacement program.
- Detecting and locating leaks.
- Repairing or replacing pipe.
- Operation and maintenance programs and changes.
- Administrative processes or policy changes.

2.8.3 The evaluation

Evaluation is necessary to ensure that whatever the intervention was, it succeeded in its goal (Liemberger et al., 2007). If the goal of the intervention was not met, the evaluation process seeks to determine why and what can be done about it. A major portion of evaluation is benchmarking (EPA, 2010). The audit establishes performance indicators, which serve as benchmarks.

2.9 Impacts of non-revenue water on performance of water utilities

High levels of utility NRW often lead to low levels of efficiency, leading to increased cost of water collection, treatment and distribution (Farley, 2003). Furthermore, water sales decrease and capital expenditure programs become the last option to meet the ever increasing demand (Farley et al., 2008). For developing countries with serious capital constrains, the dilemma is unbearable, and often leads to deprivation of other sectors of the economy (Balkaran and Wyke, 2002; Farley, 2003). High physical water losses often lead to discontinuous water supply, either because of limited raw water availability or because of water rationing. In addition to substandard service, erratic water supply contributes significant health risks (Liemberger, 2007). Furthermore, erratic water supply will leave customers unsatisfied resulting in low willingness to pay for services received (Tiltnes, 1998). From the technical point of view, leakages often decrease flow rates in pipe networks, causing unnecessary pressure losses that affect customers and often lead to supply interruptions during peak demand hours (Girard and Stewart, 2007).

2.10 Theory of leakage

2.10.1 Burst and background leakage

Leaks found in any water supply system can be categorised as, those large enough to warrant serious attention and those that are too small to warrant such attention (McKenzie and Bhagwan, 2004). However, there are no rigid thresholds between countries. Thresholds in the United Kingdom stand at 0.50 m^3/h while in South Africa thresholds stand at 0.25 m^3/h. However, the lower threshold used in South Africa could apply for most Southern African countries.

Background leaks occur mainly at joints and fittings, and they run continuously, but do not generate sufficient noise to be detected by existing equipment (Balkaran and Wyke, 2003). Burst leakage on the other hand is loss of water resulting from annually occurring holes or fractures in the network pipe work, including customer service connections, which can be located using a range of specialised equipment (Morrison, 2004). Thus, burst leakages are typically of high flow rates, short duration, and hence moderate volumes (Morrison, 2004).

2.10.2 Leakage control

Leakage is normally addressed properly by breaking it down into the following types: transmission mains and reservoir leakage, reticulation mains leakage, connection leakage, and service pipe leakage (Seago et al., 2004). Frequency of these leak types and average leakage rates are provided in Table 2.2.

Table 2.2 Characterisation of reported and unreported bursts (Source: McKenzie et al., 2002)

Details	Reported bursts		Unreported bursts	
	Frequency	Leakage rate (m^3/h)	Frequency	Leakage rate (m^3/h)
Transmission mains	0.030/km/yr	30.0	0.00/km/yr	12.0
Reticulation mains	0.150/km/yr	12.0	0.008/km/yr	6.0
Connections	2.5/1000conn/yr	1.6	0.825/1000conn/yr	1.6
Service pipes	2.5/1000con/yr	1.6	0.825/1000conn/yr	1.6

Leakage management can be classified into two groups, namely passive leakage control and active leakage control (Farley and Trow, 2003).

2.10.2.1 Passive leakage control

Passive leakage control is reacting to reported bursts or a drop in pressure, usually reported by customers or noted by the utility's own staff while carrying out duties other than leak detection (Farley, 2003). The method can be justified in areas with plentiful or low cost supplies. McKenzie et al., (2002) indicated that this type of leakage control is often practised in less developed supply systems where the occurrence of underground leakage is less well understood. Except in exceptional circumstances, leakage will continue to rise under passive control (McKenzie et al*.,* 2002).

2.10.2.2 Active leakage control

Mathis et al., (2008) defined Active Leakage Control (ALC) as any water utility program that proactively seeks to discover leaks which have not been reported by customers or other means. The most typical methods of active leakage control are routine leak detection surveys and the use of minimum night flow measurement in DMA or pressure zones (Mathis et al., 2008). The usage of the DMA approach to leakage detection and localisation has become an international best practice. Sturm and Thornton (2007) indicated that the most appropriate leakage control policy will mainly be dictated by the characteristics of the network and local conditions, which may include financial constraints, equipment and other resources. In many developing countries, the method of leakage control is usually passive or low activity, mending only visible leaks (McKenzie, 2004).

2.10.3 Natural rate of rise of leakage

The phenomenon where leakages in water supply systems are always occurring and growing worse if left unchecked is known as natural rate of rise of leakage (Mathis et al., 2008). However, a leakage may continue to increase until it reaches a certain level at which it stabilises (McKenzie et al., 2002). In this regard, there is need for all water utilities to provide system maintenance and upkeep functions that include appropriate leakage management to avoid increase in leakage rates.

Fantozzi and Lambert (2005) mentioned that natural rate of rise of leakage is made up of two components, that is, the breakout of new leaks in the network and the growth (increase in volume) of existing leaks. Of this total natural rate of rise of leakage, a proportion will comprise visible (customer reported) leaks, which will be duly repaired. It is the remaining portion which is normally used in leakage economics studies (Fantozzi and Fantozzi, 2008). Furthermore UKWIR (2005) stated that natural rate of rise of leakage is an indicator of asset condition, and as such is central to mains replacement strategy.

2.11 Quantification of network leakage

Leakage in a network is quantified by a top-down water balance of total water supply against total metered consumption, with allowances for maintenance (i.e. flushing, cleaning), fire fighting, metering errors and unauthorised or illegal consumption (Park, 2006; Rizzo et al., 2004) as detailed in Equation 2.1.

$$\text{Leakage} = TS - MC - [MT_{Allwnc} + FF_{Allwnc} + ME_{Allwnc} + IC_{Allwnc}] \tag{2.1}$$

where: TS = Total supply,
MC = Metered Consumption,
MT_{Allwnc}= allowance for Maintenance,
FF_{Allwnc} = allowance for Fire Fighting,
ME_{Allwnc}= allowance for Metering Errors and
IC_{Allwnc}= allowance for Illegal Consumption.

Leakage in smaller areas can also be quantified by measuring minimum night flows in District Metered Areas (DMAs). After allowances for customer night flow, the balance of the flow is assumed to be due to leakage. Utilities employ a variety of measures to reduce leakage ranging from routine renewal of assets, reduction of service pressures and location of leaks by acoustic methods with follow-up repairs (known as active leakage control) (Farley et al., 2008). The level of leakage reduction achieved depends on the investment in leak detection and system rehabilitation. While savings, direct or indirect, justify the expenditure up to a critical point beyond which, the benefits of leakage reduction become less than the costs.

2.12 The relationship between pressure and burst frequency

There is a strong relationship between burst rates and pressure levels. Although it is believed that pipe burst frequency is proportional to pressure (Maggs, 2005), further work is needed to clearly establish the relationship. McKenzie et al., (2002) also pointed out that through considerable research it has been shown that burst frequency is very sensitive to maximum system pressure. A study conducted in Zimbabwe by Marunga et al., (2005) also found that with the increase in pressure, there was also an increase in number of bursts. Furthermore, data on changes in break frequency following pressure management in the Bahamas showed that there is a relationship between pressure and burst frequency (Fanner and Thornton, 2005). Conversely, UKWIR (2005) indicated that there is no evidence of a relationship between pressure and burst frequency. Similarly, Lambert (2001) on investigating data from UK concluded that there is no unique relationship between maximum pressure and new leak frequency, but evidence shows that excess pressures in systems subject to continuous supply, result in higher frequencies and higher repair costs than are necessary.

Thornton and Lambert (2005) indicated that the topic was not well studied and the IWA Pressure Management Team would seek good quality data of recorded burst frequencies "before" and "after" pressure management in order to improve the current practical methods of analysing and predicting the effect of pressure management on frequency of new bursts, using the provisional relationship that: "burst frequency varies with pressure to the power N2", where N2 is a coefficient relating pressure and burst frequency. N2 values normally ranges from 0.5 to 6.5 as reported by Thornton and Lambert (2005).

Thornton and Lambert (2005) suggested that investigations of the relationship between pressure and burst frequency should be done using the following provisional relationship:

$$\frac{BF_1}{BF_0} = \left(\frac{P_0}{P_0}\right)^{N2} \quad \text{or} \quad N2 = \frac{\ln\left(\frac{BF_1}{BF_2}\right)}{\ln\left(\frac{P_1}{P_0}\right)} \tag{2.2}$$

where: BF_o= burst frequency at initial pressure, P_o

BF_1= burst frequency at the changed pressure, P_1

$N2$ is burst frequency exponent (coefficient relating pressure and burst frequency).

The determined values were then used to determine pressure management opportunities (Lambert, 2001; Thornton and Lambert, 2005; Fantozzi et al., 2008) by computing frequency reduction from possible pressure reduction using the following equation:

$$\Delta BF = (1 - \left(\frac{P_1}{P_0}\right)^{N2}\Big) \text{ x } 100\% = \left(1 - \left(\frac{P_0 - \Delta P}{P_0}\right)^{N2}\right) \text{ x } 100\% \tag{2.3}$$

where: ΔBF is burst frequency reduction realized upon pressure reduction as a percentage.

However, Thornton and Lambert (2007) showed that the N2 approach is inappropriate and recommended that:

- The N2 approach to analysis should be abandoned as inappropriate
- Additional "before" and "after" break data should be collected and published
- An alternative conceptual approach, based on failures being due to a combination of factors, needed to be developed.

As years pass by adverse factors based on age (including corrosion) gradually reduce the pressure at which the pipes will fail (Thornton and Lambert, 2007). Depending upon local factors such as traffic loading, ground movement and low temperatures at some point in time the maximum operating pressure in the pipes will interact with the adverse factors, and break frequencies will start to increase. This effect can be expected to occur earlier in systems with pressure transients or re-pumping, than in systems supplied by gravity (Thornton, 2003; Thornton and Lambert, 2007). Warren (2005) affirms this in that he indicated that the link between burst frequency and pressure is related more to pressure variation, which may also influence the burst shape factor.

Overall, there is evidence that there is a relationship between pressure and burst frequency but it may be a complicated relationship.

2.13 Success factors for non-revenue water reduction

2.13.1 Prioritizing NRW reduction components

Certain components of the NRW are more pronounced than others. As a result there is need to prioritise components favouring least losses, for equitable water distribution. After setting the NRW targets, water utilities calculate and set baseline targets of the volume of the water to be saved. The saved volumes of water could be used by customers in water deficient zones or could be used to open up new connections for the marginalised communities.

2.13.2 Elements of physical water losses from distribution mains

Leakages occurring from transmission mains are usually large events, sometimes catastrophic, causing damage to highways and surrounding infrastructure. To quantify such leaks from the distribution mains, utility management would use repair records. From such records, the total number of leaks on the mains per day can be calculated. If the procedure is followed for a long period of time, the average leak flow rate can be estimated. The following computation could be used to establish the total number of yearly volume of leakages:

Total annual volume of leakage from mains = Number of reported bursts X Average leak flow rate x Average leak duration. (2.4)

In the absence of reliable data, estimates from Table 2.3 can be used.

Table 2.3 Flow rates for reported and unreported bursts (Source: IWA, 2003)

Location of burst	Flow rate for reported bursts (l/hour/m pressure)	Flow rate for unreported bursts (l/hour/m pressure)
Mains	240	120
Service connection	32	32

By definition, background losses comprise “small leaks and weeping joints” whose flow rates are rather extremely low for active leak detection. Such slow flow rates are only detected when they become so pronounced to evolve at the ground surface. The background losses originating from water distribution network with sound infrastructure conditions are shown in Table 2.4.

Table 2.4 Background losses calculation (Source: IWA, 2003)

Location of burst	Litres	Unit of Measure
Mains	9.6	Litres per km of mains per day per metre of pressure
Service connection: mains to property boundary	0.6	Litres per service connection per day per metre of pressure
Service connection: property boundary to customer metre	16.0	Litres per km of service connection per day per metre of pressure

Excess loss is the difference between physical water balance losses and the calculated physical losses. A negative difference is always not anticipated, however, if it is obtained, it means that the water balance computations are faulty. In that regard, either the SIV has been understated or the commercial losses are overstated. (Acknowledge the source).

2.13.3 Leakage and overflows from the utility's reservoirs and storage tanks

It has not been difficult to quantify leakages and overflows from water storage infrastructure. Due to the minimum night water usage, observation of the leakages and overflows is best done during night time. Data logging and physical inspection are the two main methods used to establish such water losses. Drop tests are the most fundamental methods used for calculation of leakages from water tanks. The volume of the water lost is calculated from the volume changes when both the inlet and outlet valves are closed. Once leakages have been discovered, the honours to repair the leakages lie on the utility.

2.13.4 Leakage on service connections up to the customer's meter

Leakage between the service connection and the customer meter is often not easily detected as it is sometimes not visible and leakage surveys have to be completed to identify these leaks. Due to the infrequent intervention period of the leakage survey programmes, these leaks result in the huge volumes of physical losses. Utilities estimate service connection leakages by subtraction mains and storage tank leakages from total physical losses.

2.13.5 Leakage management strategy development

A leak management strategy comprises active leakage control, asset management, pressure management and repairs (Pike, 2007). Such factors affect the management of leakages and hence leakage economics. The large square on Figure 2.1 is a representation of the Current Annual Volume of Physical Losses (CAPL), which tends to increase as the distribution network ages. The increasing CAPL due to deteriorating infrastructure integrity can be checked by an effective leakage management strategy. The Minimum Achievable Annual Physical Losses (MAAPL) is the unavoidable annual real losses.

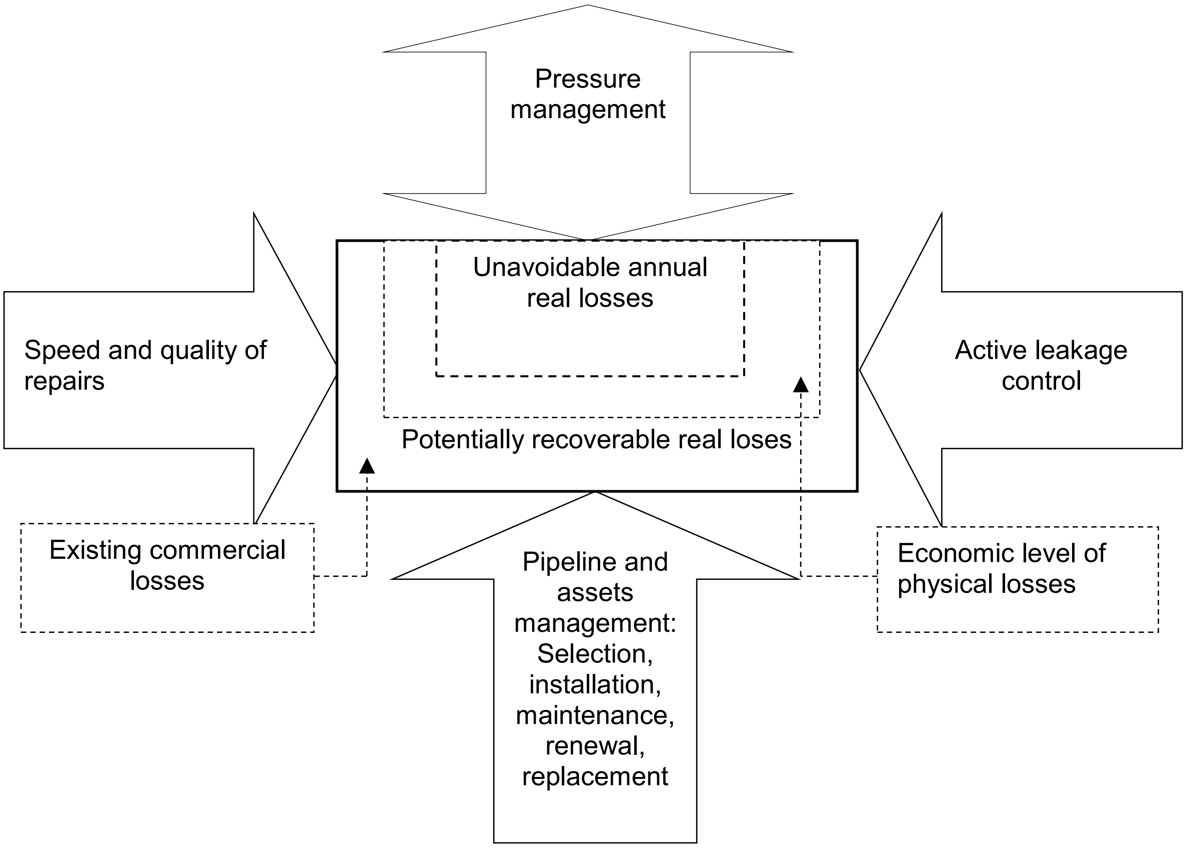


Figure 2.1 Four pillars of successful leakage management (Source : Pike. 2007)

2.13.6 Leak detection techniques

To detect and locate leakages utilities often used noise detectors. The effectiveness of such leakage detection techniques is dependent on the system pressure, the distance between listening points, the size and shape of the leak, the pipe material and the pipe diameter. The noise characteristics of a leak have been used for many years to locate leaks, listening on valves, hydrants, stop taps, or at the ground surface above the line of the pipe (De Silva et al., 2011). It is the sole responsibility of a water utility to localise and locate leaks. Due to the cost of excavation, great precision is needed to locate the leaks.

The various leakage detection techniques fall into one of the LLP (Localise, Locate, and Pinpoint) principal categories. Listed below are some approaches that can be used but certainly not limited to those items shown below and also this list changes as new technology is developed (EPA, 2010):

- Sounding Surveys (Localise)
- Use of leak noise loggers (Localiser)
- Variations of the traditional step test (Localise)
- Other techniques e.g. thermal imaging (Localise and Locate)
- Correlators (Locate)
- Internal acoustic device (Locate and Pinpoint)
- Electronic Microphones (Pinpoint)
- Manual Listening device (Pinpoint)

2.13.7 Pressure management

An effective leakage management strategy should take into account the pressure dynamics of a water distribution network. This is because pressure plays a pivotal role in enhancing the magnitude of water leakage. This is because there is a physical relationship between leakage flow rate and pressure. Thus, the pressure exerted by either gravity or by water pumps results in a corresponding change in leakage rate. The frequency of new pipe bursts is also a function of pressure such that the higher or lower the pressure, the higher or lower the leakage. Pressure level and pressure cycling strongly influence burst frequency. Therefore water utilities should ensure that they monitor the pressure of their water distribution networks.

Some of the most important ways of managing pressure is by either using pressure reducing valves (manual or automatic) or by using variable speed pump controllers. Under normal circumstances a pressure reducing valve is used to maintain a fixed downstream pressure regardless of the upstream pressure dynamics.

2.14 Components of real loss management

The four components approach of real loss management is now widely used internationally for the effective management of Real Losses (Lambert and Taylor, 2010). Thus, water utilities managers are required to put aside appropriate investment in each of the four basic components of pressure management, active leakage control, speed and quality of repair and the component of pipes and assets management. Real losses include leakage and overflows from transmission and distribution systems up to the point of customer metering or consumption (Lambert, 2003). Figure 2.2 summarizes the "best practice" principles of managing real losses (Squeezing the Box theory). Suppose the large box in Figure 2.2 represents the Current Annual volume of Real Losses (CARL) for a system, calculated from a standard IWA annual water balance. Real Losses tend to increase as systems grow older, but can be kept in check by an appropriate combination of all the four leakage management activities shown as block arrows.

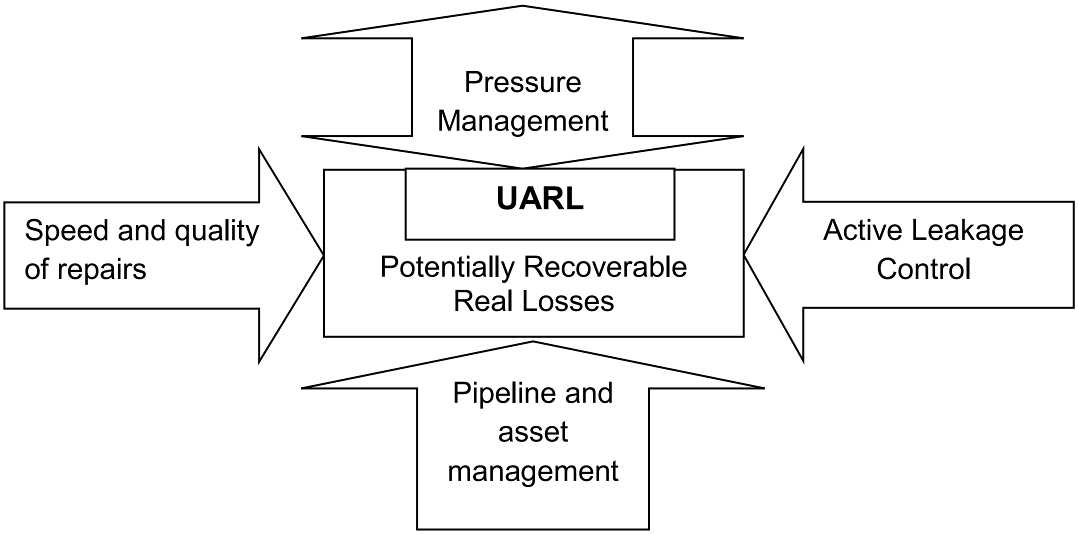


Figure 2.2 Components of a proactive real loss management (Source: Thornton, 2005)

The number of new leaks arising in water supply systems is influenced primarily by long term infrastructure or pipeline and asset management (Seago et al., 2005). This includes selection, installation, maintenance, renewal and replacement of mains. Lambert (2002), reported that pressure management can influence the frequency of new leaks and the flow rates of all leaks and bursts. The average duration of the leaks is limited by the speed and quality of repairs, that is, improved leak repair time, and the proactive leakage control strategy controls how long unreported leaks run before they are located (Thornton, 2005). The extent to which each of these four activities is carried out will determine whether the volume of annual real losses increases, decreases or remains constant (Lambert, 2002). To keep real losses at minimum, that is, to squeeze the real loss box, the four measures presented in Figure 2.2 explain the four basic management activities required for effective control of real losses and have to be employed effectively.

Leakage management practitioners recognize that all water supply systems leak to some extent and it is impossible to totally eliminate real losses from a large water distribution system (Thornton, 2003). The lowest technically achievable annual volume of real losses for well-maintained and well-managed systems is known as unavoidable annual real losses (UARL) (Radivojević et al., 2007). UARL is defined by Çakmakcı et al., (2007) as that portion of underground system leakage that is considered not economical to locate and repair or too small to detect using current technology. System-specific values of UARL can be assessed using a formula developed by the IWA Water Losses Task Force (Lambert et al., 1999). Data required for this assessment are the number of service connections (Nc), the length of mains (Lm in km) and the length of private pipes (Lp in km) between the streets, property boundary and customer meters, and the average operating pressure (P in metres). According to Lambert and Lalonde (2005) the general equation for UARL calculations is:

$$\text{UARL} = (18 \times L_m + 0.8 \times N_c + 25 \times L_p) \times P \qquad (2.5)$$

where:

UARL = Unavoidable Annual Real Losses (L/d)

Lm = Length of mains (km)

Nc = Number of service connections (main to meter)

Lp = Length of unmetered underground pipe from street edge to customer meters (km)

P = Average operating pressure at average zone point in meters

The equation is based on component analysis of real losses for well-managed water distribution systems with good infrastructure and has proven to be robust in diverse international situations (Lambert and McKenzie, 2002). It is the most reliable predictor yet of "how low you could go" with real losses for systems with more than 5000 service connections, connection density (Nc/Lm) more than 20 per km and average pressure more than 25 metres (Fanner, 2004; Seago et al., 2005). From these figures, it implies that the equation cannot be used for DMAs with less than the stipulated values. Lambert and Lalonde (2005) recommended that for systems operating not at the standard pressure of 50m, there is need to revise the UARL by the following equation:

$$UAL_r = UARL_{50} \text{ x } \left(\frac{P}{50}\right)^{N1} \qquad (2.6)$$

The current $UARL_r$ then becomes the revised UARL, while $UARL_{50}$ is UARL at standard pressure of 50m, P is operating pressure, and N1 is leakage exponent (coefficient relating pressure and leakage). The current annual real loss (CARL) comprises of physical water losses from the pressurised systems through to customer water meter, and is normally calculated as the total water lost less the apparent losses (Seago et al., 2004).

The inner small box (Figure 2.2) represents the lowest technically achievable real losses, or "Unavoidable Annual Real Losses" (UARL), for well managed systems with reasonably good infrastructure (Thornton, 2005). The UARL can be calculated on a system-specific basis, as a volume per day or year, based on mains length, number of service connections, customer meter location (relative to property line) and average pressure. The difference in volume between the Current Annual Real Losses (CARL: outer box) and the Unavoidable Annual Real Losses (UARL: inner box) represents the Potentially Recoverable Real Losses.

The ratio of CARL/UARL is known as the Infrastructure Leakage Index (ILI). Thus;

$$ILI = CARL / UARL \qquad (2.7)$$

where:

ILI= Infrastructure Leakage Index,

CARL= Current Annual Real Losses, and

UARL= Unavoidable Annual Real Losses.

2.15 Performance indicators in water loss management

2.15.1 Monitoring performance of NRW management

Water supply in many developing countries throughout the world is subject to varying problems. Arid and semi-arid areas are particularly facing severe water scarcity due to rapidly growing demand for water resources, (Lehmann, 2010). As a result, urban water utilities are characterised by intermittent supplies and illegal connections, (Rizzo, 2000). Although challenges affecting developing countries are more or less the same, Africa with the lowest water supply and sanitation coverage than any other region in the world, is worst affected (Lehmann, 2010). More than 30% of Africans residing in urban areas currently lack access to adequate water services and facilities (Doe, 2007). Water losses are seriously affecting performance of water utilities in developing countries. As a result many of the water utilities operate at technical efficiency levels well below a best-practice frontier that is determined by the relatively efficient ones from the same group (World Bank, 2002). Thus, there is considerable difference between the amount of water put into the distribution system and the amount of water billed to consumers (Balkaran and Wyke, 2002; Kingdom et al., 2006). High levels of non-revenue water (NRW) reflect huge volumes of water being lost through leaks, not being invoiced to customers, or both. Water availability challenges are worsened by high volumes of water losses and in the process, many water utilities fail to satisfy customer demands (Kingdom et al., 2006). The failure to satisfy customer demands is one reason why customers are unwilling to pay for water delivery services particularly in urban settings.

There is need for a paradigm shift to utilize water resources as efficiently as possible (Baietti et al., 2006). This is because non-revenue water is a measure of operational and financial performance. Thus, NRW can be used as a benchmarking yardstick.

2.15.2 Characteristics of performance indicators

According to (Kingdom et al., 2006) performance indicators help a water utility in many ways.

An effective NRW performance indicator is expected to be clear, understandable and sensible. As a result, standard performance indicators are developed which can be used universally as benchmarks for water utilities. In the advent of several PIs, decisions should be taken which consider the best PI option. Figure 2.3 shows a decision tree that can be used to choose the best PI. For instance, a DMA with more than 20 connections per kilometre of mains, the most appropriate PI would be litres/ service connection/day and if the density of connections is less than 20, the cubic metres per km of mains per day should be used. In the instance of WDS with fluctuating pressure, water losses could be expressed in in litres per connection per day per metre of pressure (l/conn/day/m).

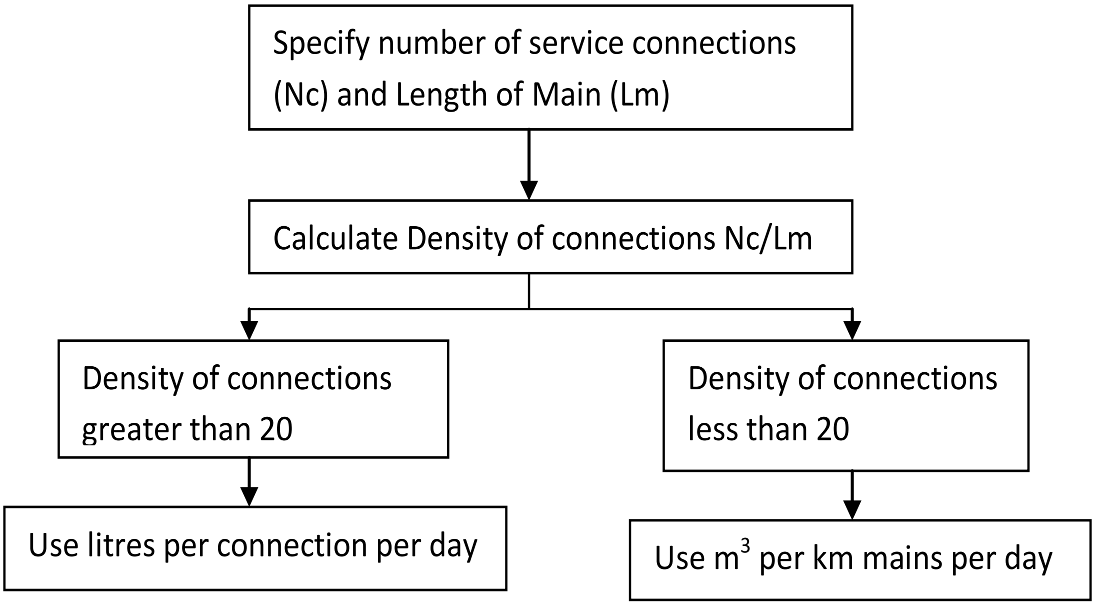


Figure 2.3 Decision tree for selecting performance indicators (Mutikanga et al 2010b)

2.15.3 Performance indicators for physical water losses: Expressing NRW as a percentage

Non-revenue water has traditionally been expressed as a percentage of input volume (Alegre et al., 2009). However, it is a subjective indicator as it advocates for high water consumption and intermittency in water distribution. Furthermore, the indicator does not give a clear-cut distinction between commercial and physical losses. Despite these drawbacks, the indicator is a very good proxy of water losses. According to Alegre et al., (2000) other indicators of physical losses include:"

- Litres per service connection per day (l/c/d),
- Litres per service connection per day per metre of pressure (l/c/d/m pressure),
- Litres per kilometre of pipeline per day (l/km/d)".

Several PIs have been proposed and Table 2.5 highlights Infrastructure Leakage Index (ILI) and NRW indicators. The same table also shows other IWA PIs for water supply systems. IWA proposed a more efficient indicator that takes into account NRW as a percentage of SIV, though the inclusion of systems pressure is believed to give a better indicator (AWWA, 2003).

Table 2.5 Recommended indicators for physical losses and NRW (Source: Alegre et al., 2000)

Function	Level	Performance Indicator	Comments
Financial: NRW by volume	1 (Basic)	Volume of NRW [% of system Input Volume]	Can be calculated from simple water balance, not too meaningful.
Operational: Physical losses	1 (Basic)	[Litres/service connection/day] or [litres/km of mains/day](only if service connection density <20/km)	Simple "traditional" performance indicators, useful for target setting, limited use for comparisons between systems.
Operational: Physical losses	2 (Intermed.)	[litres/service connection/day/m pressure] or [litres/km of mains/day/m pressure][only if service connection density is<20/km)	Easy to calculate if the ILI is not known yet, useful for comparisons between systems.
Financial: NRW by cost	3 (Detailed)	Value of NRW[% of annual cost of running system]	Allows different unit costs for NRW component, good financial indicator.
Operational: Physical Losses	3 (Detailed)	Infrastructure leakage index (ILI)	Ratio of current annual physical losses to unavoidable annual real losses, most powerful indicator for comparisons between systems.

The PIs categorized by function and level are defined as follows: "

- Level 1 (basic): Is a first layer of indicators that provides a general management overview of the efficiency and effectiveness of the water supply undertaking.
- Level 2 (intermediate): Additional indicators that provide a better insight than the Level 1 indicators; for users who need to go further in depth.
- Level 3 (detailed): Indicators that provide the greatest amount of specific detail, but are still relevant at the top management level".

2.15.4 Performance assessment systems

Performance Assessment Systems (PASs) are systems used by water utilities to assess their performance through identification of performance drivers and by measuring success in reaching their set objectives (Baietti et al., 2006; Coelli et al., 2003). Different institutions use different PASs to measure performance of water utilities. These include regulators, financial institutions, policy makers and utility management (Mutikanga et al., 2010b). Performance assessment systems play a very pivotal role in ensuring that a water service provider understands the drivers and level of performance of the system being operated. Poor performance creates a vicious spiral as the problems regenerate with time (Baietti et al., 2006). Utility performance could be described as a low level equilibrium where low prices lead to low quality, limited service expansion, operational inefficiency and corruption, thereby further eroding public support (Baietti et al., 2006; Rizzo et al., 2004). Policy analysis should be concerned both with prescriptions aimed at maximizing the efficiency of specific institutions in terms of the operators' efficiency, regulators' competence and endowments (Strub, 2009).

By conducting water audits, a water utility can monitor its water loss performance over time or compare itself with other water utilities (i.e. benchmarking) (Thornton, 2005). Benchmarking uses a collection of performance indicators to numerically evaluate different aspects of the distribution system. Performance indicators need to be consistent, repeatable, and presented in meaningful standardized units (EPA, 2010). The AWWA/IWA water audit methodology has a standard array of performance indicators that the public water system (PWS) can track annually when compiling the water audit.

Performance assessment plays a very important role in evaluating performances of water utilities with respect to their peers. There is need for water utilities to adopt performance assessment systems in order to enhance service delivery and match international standards. This is evidenced by a study of 21 water utilities in Africa, where 12.9% of the water utilities operate efficiently as compared to their peers (World Bank, 2002). These water utilities often operate under a weak governance and financial framework, with utility managers having to face multiple political and economic constraints (Kingdom et al., 2006; World Bank, 2002). Thus, this finding supports the commonly held view that Africa's water sector operates at unacceptable levels of technical inefficiency (World Bank, 2002). Water utilities have to provide some form of service to customers on a daily basis with mostly deteriorated infrastructure (Kingdom et al., 2006). This is evidenced by the Zimbabwean situation where despite the country having high access to water services, its dependency on surface water stands at 7% of the total demand (Makaya and Hensel, 2014b).

Following, are the generally applied water loss management systems performance indicators.

The assessment of an undertaking's performance using Performance Indicators (PIs) is a legitimate measure of the efficiency and effectiveness of a water utility (Dragan Radivojevic et al., 2007). Furthermore, performance indictors enhance comparative assessment of the objectives of a water utility's service provision and the sector-wide benchmarks (Alegre et al., 2006). The most popular and extensively used indicators for water loss management were developed by IWA (Alegre et al., 2006; Lambert, 2003) and adopted by the American Water Works Association. A selection of vital indicators prescribed by the IWA and AWWA (Alegre et al., 2006) for water loss management included the following: (a) Real losses (m^3/connection/day), (b) Mains break (number/km/year), a proxy measure for pipeline asset condition, and (c) Apparent losses (m^3/connection/day).

For benchmarking purposes, performance indicators can be classified as Operational, Asset serviceability, Meter management, Legal use management, Human Resources Management, and Economic and Financial (Koelbl et al., 2009). Ultimately, non-revenue water, a proxy of water losses, is a noble starting point in assessing water distribution systems efficiency (De Witte and Marques, 2010). It is worth noting that systems performance indicators are part of performance assessment systems adopted by water utilities.

The most widely used performance indicators (PI) for assessing water losses and target setting is percentage non-revenue water (Balkaran and Wyke, 2002; Kingdom et al., 2006; Lambert and Taylor, 2010). In particular, NRW has been used widely as a measure of performance of a water supply system's efficiency. That means citizen satisfaction with urban services is closely associated with the actual performance of the services with respect to the initial expectations about the services (Abebaw et al., 2009). The main disadvantage of using percentage NRW as an indicator is that it is influenced by consumption patterns, independent of the utility’s WLM (Lambert and Taylor, 2010).

The most widely used water loss management indicators are shown in Table 2.6. AWWA (2003) classified the levels as basic, intermediary and detailed.

Table 2.6 Indicators widely used for water loss management (Source: AWWA, 2003)

Level	Water resources	Operational	Financial
Basic	Inefficiency of use of water resources: Real losses as a percentage of system input volume	Water losses: (volume/service/conn/year)	NRW: NRW as a percentage of SIV
Intermediary		Real Losses: volume/service.conn/day (For pressurised systems)	NRW: value of NRW as a percentage of the annual cost of running the water system.
		Apparent Losses: volume/service.conn/year	
Detailed		Infrastructure leakage index (ILI)	

Because consumption normally makes up a very substantial part of system input volume or water supplied for most systems and sub-systems, this severely compromises the use of percentages by volume as a suitable PI for NRW and its components (Lambert, 2002; Liemberger et al., 2007). Calculation of percentage by volume is traditional and usually a simple "first step". However, the best simple traditional real losses PIs are "per service connection" or "per km of mains" (depending upon connection density); and they should be accompanied by an estimate of average pressure, and preferably with a calculation of Infrastructure Leakage Index (ILI) (Lambert, 2003). However, NRW percentage by volume takes no account of the different valuations of components of NRW, or the cost of operating the system (Lambert, 2003). A better financial PI for NRW is percentage by cost, which calculates the cost of each of the three principal components of NRW (Unbilled Authorised Consumption, Apparent Losses and Real Losses) by attributing different monetary valuations (per cubic metre) to each of these NRW components, and dividing by the operating cost of running the system (Lambert, 2003). However, problems that occur if percentages by volume are used as operational PIs for NRW and its components are well documented internationally (Alegre et al., 2006; Dragan Radivojevic et al., 2007; Lambert and Taylor 2010). Another vital operational performance indicator to be reviewed is the Infrastructure Leakage Index.

2.15.4.1 Infrastructure leakage Index

Infrastructure Leakage Index (ILI) is a proxy for level of management efficiency of a water utility. It is the best indicator for physical water losses. The ILI is a representation of the ratio of total leakage losses to the background leakage (McKenzie and Wegelin, 2009). Thus, ILI is a ratio of Current Annual Volume of Physical Losses (CAPL) to Minimum Achievable Annual Physical Losses (MAAPL).

$$\text{ILI} = \text{CAPL}/\text{MAAPL} \tag{2.8}$$

ILI is solely a technical indicator with no bearing on the utility management economics. Thus, a perfect (ILI = 1) water distribution system may be falling short in economic considerations.

The ILI indicators are provided as a rough guide and should not be taken as strict limits. However, in many parts of Africa and Asia, very high ILI values are often experienced and the limits given in Table 2.7 tend to become meaningless. The main purpose of the ILI indicator is to help identify areas where leakage/losses are abnormally high to ensure that action is taken in the most appropriate areas (Winarni, 2006).

The matrix in Table 2.7 shows the anticipated ILI levels and physical losses at different pressure levels.

Table 2.7 Physical loss target matrix (Source: Winarni, 2009)

Technical Performance category		ILI	Physical Losses[litres/connection/day] (When the system is pressured) at an average of				
			10m	20m	30m	40m	50m
Developed countries	A	1-2		<50	<75	<100	<125
	B	2-4		50-100	75-150	100-200	125-250
	C	4-8		100-200	150-300	200-400	250-500
	D	>8		>200	>300	>400	>500
Developing countries	A	1-2	<50	<100	<150	<200	<250
	B	2-4	50-100	100-200	150-300	200-400	250-500
	C	4-8	100-200	200-400	300-600	400-800	500-1000
	D	>8	>200	>400	>600	>800	>1000

To guide further network development and improvement, utility managers can use a matrix with the following categories (Farley et al., 2008):”

- Category A — Good. Further loss reduction may be uneconomic and careful analysis is needed to identify cost-effective improvements.
- Category B — Potential for marked improvements. Consider pressure management, better active leakage control and better maintenance.
- Category C — Poor. Tolerable only if water is plentiful and cheap, and even then intensifies NRW reduction efforts.
- Category D — Bad. The utility is using resources inefficiently and NRW reduction programmes are imperative.”

The ILI was developed to address the lack of an objective benchmarking indicator (Liemberger et al., 2007; Winarni, 2009). The ILI value in the range of 1-2 corresponds to performance Category A, meaning that the water utility has good performance with respect to real losses (Winarni, 2009).

An ILI index of 1.0 indicates that current annual real losses (CARL) are equal to unavoidable annual real losses (UARL) and the water utility is operating at the technically low level of leakage possible, a virtual rarity in actual practice. Limited data from water utilities who were the early adopters of the AWWA/IWA water audit methodology indicates that ILI values typically fall in the range of 1.5 to 2.5 (IWA, 2003;

Winarni, 2009). Another important indicator to be reviewed is the Apparent Loss Index, a performance indicator for commercial losses.

Commercial losses are at times known as apparent Losses (AL). Such losses represent those losses that are a result of faulty meter reading, meter inaccuracies, unauthorised water usage, and data mishandling (AWWA, 2009). Since AL is a commercial loss, its impact is closely linked to poor revenue generation. Because the control of AL is a new discipline, its applications are less understood by many water utilities (AWWA, 2003).

The apparent loss index (ALI), an analogy of ILI, was developed by IWA Water Loss Taskforce. The indicator uses a base value of 5% of water sales as a reference, and the actual commercial loss value is calculated against this benchmark.

$$\text{Apparent Loss Index (ALI)} = \text{Apparent loss value} \div 5\% \text{ of water sales} \qquad (2.9)$$

However, it has been argued that the 5% benchmark value is on the higher side especially for utilities in developing countries (Mutikanga et al 2010b; Koelbl et al., 2009). Thus, proper water meter management effectively reduces apparent water losses, thereby making much economic sense (Gumbo, 2004). Table 2.8 shows the variation of AL of water sales for different countries.

Table 2.8 Variation of AL of water sales for different countries (Source: Mutikanga et al., 2010b)

City and country	% AL	Data source
Kampala, Uganda	37	Mutikanga et al. (2010b)
Lusaka, Zambia	33	Sharma and Chinokoro (2009)
Manila, Philippines	16	Dinaano and Jamora (2010)
Jakarta, Indonesia	36	Schouten and Halim (2010)
Philadelphia, USA	9.6	AWWA (2009)
England and Wales	2.8	OFWAT 2010

Table 2.9 shows ALI performance bands for both developed and developing countries. The ball-valve effect that is associated with systems on direct mains pressure supply makes the system’s AL incomparable with systems fed from storage tanks (Lambert and Taylor 2010). Therefore, since ALI does not show the actual value of water lost, it can be a misleading indicator (Winarni, 2009). Thus, there is clear need for more appropriate PIs and indices to cover diversities in water distribution systems. To date,

the measurement of commercial losses as a percentage of authorised consumption is the preferred indicator.

Table 2.9 ALI performance bands (Source: Mutikanga et al., 2010b)

Region	Technical performance group	ALI	Remarks
Developed countries	A	1-2	Acceptable performance. Further reduction may be uneconomical unless if the cost of water is very high.
	B	2-3	There is room for improvement.
	C	3-4	High revenue losses, acceptable where cost of water is very low.
	D	>4	Very inefficient with poor meter management practices and in adequate policies for revenue protection. Urgent action required to minimise revenue losses.
Developing countries	A	1-2	Acceptable performance. Further reduction may be uneconomical unless if the cost of water is very high.
	B	2-4	There is room for improvement.
	C	4-6	High revenue losses, acceptable where cost of water is very low.
	D	>6	Very inefficient with poor meter management practices and in adequate policies for revenue protection. Urgent action required to minimise revenue losses.

Due to the diversity of financial indicators, only those that are auditable should be considered by water utilities. Auditable indicators should have high priority over those that are not. This is because revenue and revenue collection exercises are key to the operational efficiency of water utilities (WHO, 2000).

2.15.4.2 District metered area management approach

When a district metered area (DMA) is incepted its respective NRW values should be calculated, the Net Night Flow (NNF) and commercial losses, and identify the main areas of concern (USAID and WBI, 2010). Once the DMA leakage is found to be high, respective NRW reduction activities should be implemented. It can be shown that the NRW level within a DMA does not remain the same, but rather as the infrastructure variables like age of the pipeline, the wear and tear of the components of the network and system's pressure dynamics change, so does NRW (Farley et al., 2008). Therefore it is the prerogative of the water utility to ensure that the major components of NRW, physical and commercial losses are monitored accordingly. The calculation for NRW within a DMA is defined as follows:

DMA NRW = Total DMA Inflow - Total DMA Consumption (2.10)

The level of metering of a DMA generally affects the water consumption. The higher the water meter density, the higher the consumption. Thus, if all consumers in a DMA are metered, the total consumption is the sum total of all individual meters while for systems partially metered, DMA consumption is approximated using per capita consumption. In such a case further information about water demands and average per capita values are needed (Farley et al., 2008).

2.15.5 Benchmarking

Benchmarking can be described as a "best practice" process approach for comparing systems efficiency with respect to others regarding quality and work processes (Liemberger et al., 2007). Normally, the main applications of benchmarking are: (i) internal improvement of productivity and efficiency by learning from "best practice", and (ii) to control the systems efficiency in terms of quality development with respect to other sectors (Lambert, 2002). Benchmarking is usually used for enhancing systems integrity and optimizing systems operation (Liemberger et al., 2007). However, benchmarking will not solve all water supply challenges faced by water utilities.

Although there are numerous benchmarking methods widely used in the water industry, the methods are usually categorized as metric or process benchmarking (Koelbl et al., 2009).

2.15.6 Successes of benchmarking

Water loss management has evolved over time and for instance, in England and Wales leakages were reduced from about 5 million cubic meters per day around 1995 to about 3 million cubic litres per day by 2010 (OFWAT, 2010). Such a decrease in water leakages represents about 35% of the SIV. Technological advancement, improved regulatory frameworks and continuous performance improvements are the main causes of such a milestone.

Furlong (2007) and McCormack (2005) have reported on Canada’s water loss management using benchmarking approaches. Other reports on WLM were made for South Africa (Lambert, 2002), New Zealand (McKenzie and Wegelin, 2009), Australia (Lambert and Taylor 2010), Austria (Koelbl et al., 2009), Asia (Asia Development Bank, 2011), Africa (WSP, 2009), and Latin America (van Den Berg and Danilenko, 2011).

Benchmarking on Indian water utilities using Data Envelopment Analysis (DEA) methodology revealed inefficiency in the Water Distribution Systems with possibilities for further lowering down of NRW (Singh et al., 2010). Using the same approach in Palestine, it was revealed that water distribution systems inefficiencies were a result of water losses (Balkaran and Wyke, 2002). A similar benchmarking initiative was done in America on 100 water utilities using linear regression. The findings showed that systems efficiencies were correlated to WLM strategies adopted (Park, 2006). It is only if the data used in any benchmarking initiative is authentic that the outcome can be relied on, otherwise other methods could be used to ascertain causes of water supply inefficiencies in WDS.

2.16 The South Africa Night Flow analysis model: Application in leakage management

Assessment of pressure and flows within a water supply area can be done by employing data loggers designed to record the pressure and flows, a method popularly known as night flow analysis (McKenzie, 1999). The components of night flow are bursts, background leakage and normal night use as shown in Figure 2.4

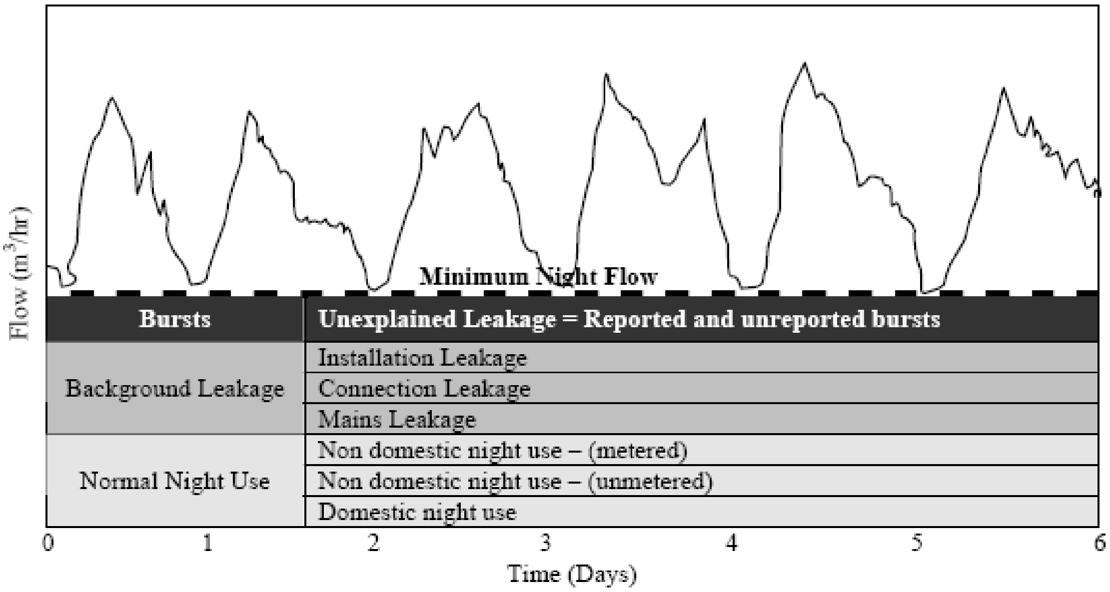


Figure 2.4 Components of the Minimum Night Flow (Source: McKenzie, 1999)

The minimum night flow (MNF) methodology is the best practice analysis and monitoring strategy for water leakage within a District Metered Area (Hunaidi, 2010). The analysis is done when the customer demand is at its minimum and therefore the leakage component is at its largest percentage of the flow. The MNF method puts emphasis on problematic areas with a high percentage of NRW in real time especially if night consumption is expected to be fairly small. Normally, it presents the flow starting from 12 midnight to 04:00 hours where most of the consumers are inactive. Unfortunately, not all water utilities are privy to these methodologies for various reasons. Some of the reasons include poorly laid out distribution networks, non-availability of pressure and flow logging equipment, and lack of skilled personnel to do the analysis.

The South Africa Night Flow (SANFLOW) analysis model is based directly on the BABE (burst and background estimate) and Fixed Area Variable Area Discharges (FAVAD) principles and is written in DELPHI computer language for the Windows operating system (McKenzie, 1999). It includes the ability to undertake sensitivity analyses based on basic risk management principles in order to provide a likely distribution of the number of bursts in a zone (or district). By using the sensitivity analysis feature of the model, potential problems can be addressed.

The methodology used in SANFLOW is a very empirical method based on a large number of test results from the United Kingdom and elsewhere in the world (McKenzie, 1999). Despite the empirical approach, the methodology has been used with great success in many parts of the world including Europe, the Middle East, Malaysia, South America, Africa and the United States of America. Apart from South Africa, Chiipanthenga (2008) and Chipwaila (2009) used the model in Malawi successfully. From such registered successes, water losses in developing countries can be reduced to economic levels and water utilities in these countries can enhance their service delivery systems (Makaya and Hensel, 2014b). Thus, developing countries should also embrace the relevant technological tools that would be very helpful in planning water loss management as well as operation and maintenance programmes.

Therefore the literature reviewed clearly points out to the work that has been done in trying to reduce water losses. Programs and methodologies have been developed to aid water loss reduction in water distribution systems. However, developing countries are lagging behind in their endeavours to reduce water loses in their water distribution systems. Water distribution systems in developing countries are characterised by low operation and maintenance, systems redundancy, very old water supply infrastructure and poor management strategies. By properly applying the right methodologies and programs in water loss management, developing countries can significantly reduce their water losses to economical levels and hence improve their service delivery.

2.17 Computational approaches to leak detection

2.17.1 Network hydraulic modelling in leakage assessment

With the advent of the information and communication technology, computation methodologies have been developed and these methodologies are taking their toll in many water utilities. Of the most widely used water leakage assessment tools Network Hydraulic Modelling (NHM) is finding wide application world over. The method uses computational strength of computers for forecasting and investigating the operational functionalities of WDS (AWWA, 2005).

EPANET 2 is one other extensively used network hydraulic modelling (NHM) software found on public domain (Rossman, 2000). Its hydraulic solver is based on an expandable open source code using the gradient method. In leakage management the NHM can be can be used for pressure management, network zoning and decision making about pipeline replacement (Wu et al., 2011).

Germanopoulous (1985) applied empirical functions to correlate water supply with network pressures. In such an application functions in the mathematical formulation were used for network analysis. As a result the pressure-consumption relationship for a given node was expressed as:

$$C_i = C_i^k a_i e^{-b_i P_i / P_i^k} \tag{2.11}$$

where: Pi = pressure at node $i.$

Ci = the consumer outflow at node.

$i;$ = the nominal consumer demand.

$ai, bi,$ = constants for the particular node.

The network model includes leakage using Equation 2.12

$$V_{ij} = c_l\left(L_{ij} P_{ij}^{av}\right)^{N1} \tag{2.12}$$

where: V_{ij}= leakage flow rate from the pipe connecting nodes i
j; c_l= a constant depending on the network;
L_{ij}= pipe length
P_{ij}^{av} = average pressure along the pipe
N1 = the pressure exponent

An extension of the method was done (Vela et al., 1991) factoring pipe size and condition parameters as shown in Equation 2.12.

$$V_{ij} = c_l\left(L_{ij}D_{ij}^{d}e^{a\tau}P_{ij}^{av}\right)^{N1} \tag{2.13}$$

where "*D* and τ are pipe diameter and age respectively; *d* is 1 for (*D* < 125 mm) and is -1 for (*D* >125 mm); and *a* is a leakage shape parameter". The only draw-back about this methodology is the required data. The field measurements required to determine parametric values of a_i, b_i, P_i^k for every node is the major disadvantage of the method. As a result many utilities in developing countries cannot afford the cost of experimental procedures. Another disadvantage of the method is that leakage flow is assumed to be uniformly distributed along the pipeline. This, in reality is not the case because of the differences in types of pipeline materials and positioning of joints and fittings.

Rossman (2007) proposed another approach where leakage is assumed to behave as an orifice flow. According to emitter hydraulics of EPANET 2, the respective pressure-dependent outflow relationships shown in Equation 2.14, allowing for leakage modelling using emitter nodes.

$$Q_{i,l}(t) = K_i[P_i(t)]^{N1} \tag{2.14}$$

where $Q_{i,l}(t)$ is the leakage aggregated at node $i$at time t; $P_i(t)$ is the pressure at node $i$at time $t$and $K_i$is the emitter coefficient for the node i, and a positive K_i is an indicator of leakage demand at node i

Whereas the aforementioned methods for leakage assessment are of great importance, their main drawback is that they cannot pinpoint the actual location of the leakage.

2.17.2 Artificial neural network predictions

Artificial Neural Networks (ANN) comprise of a network of neurons and take the cue from their biological counterparts. ANNs have found wide application in modelling water resources management problems including leakage detection, water distribution network optimisation, water pipeline replacement and rehabilitation, water demand forecasting, and pressure monitoring. In this study, the uncertainties resulting from bulk meter inaccuracies and/ or breakdowns could be offset by using the predictive abilities and capabilities of artificial neural networks.

Neural networks are made up of a series of layers with each layer comprising at least one neuron (Shamseldin, 1997). While intermediate layers (hidden layers) perform the data processing functions of the network, the first and last layers input and output variables respectively. Within the hidden layers, weights to the neurons are adjusted by training the network in accordance with the stipulated learning rule (Zealand et al., 1999). The neuron transfer function plays the role of transforming the input to output for each neuron. The log-sigmoid transfer function is commonly used for hidden layer neurons; especially with the back propagation algorithm (The Mathworks, 2002). Back propagation algorithms are based on multi-layered feed forward topology with supervised learning.

An optimisation algorithm is used to select the control input that optimises future performance. Figure 2.5 shows a typical example of one hidden layer feed-forward neural network architecture. The *S* neuron *R* input one layer network also can be drawn in abbreviated notation.

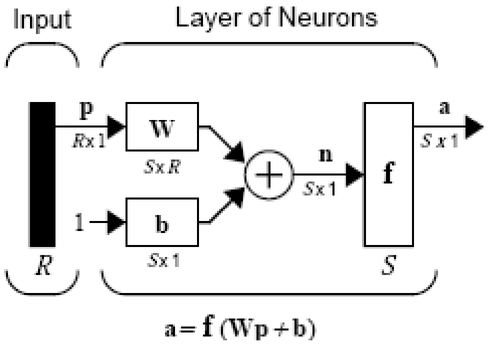


Figure 2.5 Sample one layer neural network (Source: The Mathworks, 2002)

where: *R* = number of elements in input vector;

S = number of neurons in layer 1.

Here **p** is an R length input vector, W is an *SxR* matrix, and ***a*** and ***b*** are ***S*** length vectors. The neuron layer includes the weight matrix, the multiplication operations, the bias vector b, the summer and the transfer function boxes**.**

The Multi-Layer Perception Neural Network (MLP) is a network made from an input layer consisting of nodes that merely accept input variables and the outputs of neurons in a layer become the inputs to the neurons in the next layer. The intermediary layers are the hidden layers. With the exception of the input neurons, there are two separate steps involved in the retransformation of inputs to outputs for neurons in a network (Parida et al., 2006).

Step 1.

Each neuron in a layer receives a summation of weighted activations from all neurons in the preceding layer of inputs to the network. A constant term, usually referred to as neuron threshold value is added to this summation to yield the net input, Y_{net}, to the neuron ;

$$Y_{net} = \sum_{i=1}^{N} Y_i W_i + W_o \tag{2.15}$$

where: N is the total number of neurons in the preceding layer or input array.

Yi is the neuron input received from the i^{th} neuron in the preceding layer or input array.

W_i is the connection weight or strength of the neuron to an i^{th} neuron in the preceding layer or input array.

W_o is the neuron bias/threshold value.

For a linear output, a bias term is equivalent to an intercept in a regression model. A bias term can be treated as a connection weight from a special unit with a constant value of negative one.

Step 2.

The second stage entails transformation of the net input, Y_{net}, into output, Y_{out},

$$Y_{out} = f(Y_{net}) = f(\sum_{i=1}^{N} Y_i W_i + W_o) \tag{2.16}$$

where f (.) denotes the selected neuron transfer function.

There is no rule of thumb on determining the number of hidden layers and neurons in such layers, and thus the design and comparisons of different network architectures from the same data sets seems to be the best option in obtaining an optimum network structure. The strategy of selecting the optimal number of hidden layer(s) is through varying the number of neurons, hidden layers and training functions.

2.17.3 Applications of ANN

Neural networks operating on quasi-static pressure and flow readings have been used for leak detection in pipe systems. Makaya and Hensel (2015) developed a methodology by using ANN to model leakages in the water distribution network of the City of Harare. Caputo and Pelagagge (2003) have described an approach to detecting spills and leakages from pipeline networks using a multilayer perceptron back-propagation ANN. In order to determine the location and size of leaks in the pipe network, a two level architecture composed of a main ANN at the first level and several branch specific second level ANNs were used. The branch in which the leakage occurs is estimated by the main ANN while a specific second level ANN is activated to estimate the magnitude and location of the leakage in the selected branch.

A similar approach utilising pressure readings only was described by Shinozuka et al., (2005). The methodology described, identified the location and severity of damage in a water delivery system by monitoring water pressures on-line at some selected positions in the system. Another application of ANNs operating on steady state process parameters for leak detection in pipe systems was delivered by Belsito et al., (1998), describing an approach to leak detection in liquefied gas pipelines.

A neural network for leak detection operating on sound signals emanating from a pipe network was used by Zhang et al., (2004). Their work described a method for detecting gas leaks in pneumatic pipe systems. A system using fuzzy logic acting on flows in a pipe system for leak detection was described by De Silva et al., (2005). Their system was used for the detection of leaks in petroleum pipelines. The authors reported an accuracy level greater than 90% in leak detection. Feng and Zhang (2006) described an approach to pipeline leak detection using a Discrete Incremental Clustering fuzzy ANN.

Another fuzzy ANN system for fault detection in water supply systems was described by Izquierdo et al., (2007). Their method was based on a mathematical model of the system and the application of a fuzzy neural network. It was found that this system had good classification accuracy for large leaks.

2.17.3.1 Traditional methods of forecasting/prediction

The traditional methods widely used world-over for predictive purpose are mainly stochastic approaches. The Box-Jenkins methodology or auto-regression integration moving average (ARIMA) has been widely used in the 1960s (Zhang et al., 1998).

2.17.3.2 Comparison of ANN with traditional methods

Blackard and Dean (1999) compared the Discriminant Analysis (DA) method and the ANN methodology in predicting forest cover types from cartographic variables. The ANN model produced better classification results, with greater accuracies than those produced by the DA model. Along with those results obtained from previous ANN studies, these findings suggest that while the ANN approach does have its own drawbacks, it can still be a viable alternative to traditional approaches to developing predictive models. Dobrzański and Honysz (2009) applied ANN in modelling of normalised structural steels mechanical. Although the prediction of steels mechanical parameters after normalisation process is not an easy process at all, ANN considerably simplifies the modelling methodology.

2.17.3.3 Prediction ability of ANN

Ostadi and Azimi (2015) in predicting the price of steel compared and ARIMA and found that ANN are good at tackling the problem of over-fitting, neural network prediction error was less than the usual method of ARIMA, which shows the high performance and power of this method in predicting. Zhang et al., (1998) indicate that, as opposed to the traditional model-based methods, ANNs are data-driven self-adaptive methods in that there are few a priori assumptions about the models for problems under study. ANNs learn from examples and capture subtle functional relationships among the data even if the underlying relationships are unknown or hard to describe. Artificial neural networks, which are nonlinear data-driven approaches as opposed to model-based nonlinear methods, are capable of performing nonlinear modelling without a priori knowledge about the relationships and generally are a flexible modelling tool for forecasting.

2.17.3.4 Advantages of ANN

Maind and Wankar (2014) laid out the following advantages of ANN:"

- Adaptive learning: An ability to learn how to do tasks based on the data given for training or initial experience.
- Self-Organisation: An ANN can create its own organisation or representation of the information it receives during learning time.
- Real Time Operation: ANN computations may be carried out in parallel, and special hardware devices are being designed and manufactured which take advantage of this capability.
- Pattern recognition is a powerful technique for harnessing the information in the data and generalizing about it. Neural nets learn to recognize the patterns which exist in the data set.
- The system is developed through learning rather than programming. Neural nets teach themselves the patterns in the data.
- Neural networks are flexible in a changing environment. Although neural networks may take some time to learn a sudden drastic change they are excellent at adapting to constantly changing information.
- Neural networks can build informative models whenever conventional approaches fail. Because neural networks can handle very complex interactions they can easily model data which is too difficult to model with traditional approaches such as inferential statistics or programming logic.
- Performance of neural networks is at least as good as classical statistical modelling, and better on most problems."

2.17.3.5 Disadvantages of ANN

Zhang et al., (1998) posit that ANN model building needs lengthy experimentation and tinkering which is a major drawback for the extensive use of the method in forecasting. Rather, fuzzy expert system (Bakirtzis et al., 1995; Bataineh et al., 1996) and wavelet analysis (Zhang et al., 1995; Yao et al., 1996) have been proposed as supplementary tools to ANNs.

Thus, depending on the application, ANN can be a very robust, adaptive and easy to use alternative tool for predictions.

3 The study area

3.1 Harare water distribution infrastructure

A case study of the City of Harare, Zimbabwe was used in this study. Lake Chivero, the Harare water supply infrastructure was originally constructed in 1952 to supply 350,000 people. The infrastructure was upgraded progressively with the last phase commissioned in 1994 to supply 1, 5 million people. However, there has not been any upgrading of the infrastructure since the last phase of Morton Jaffray Water Treatment Works in 1994.

On the other hand, the population (which includes Harare, Chitungwiza, Epworth, Ruwa and Norton Town Councils) which is the main driver of demand has been increasing and currently estimated at 4.5 million (Zimbabwe National Statistics Agency, 2012). The water supply infrastructure can no longer cope with the increasing demand. Some of the infrastructure has been in use for over 50 years, way beyond its economic life.

The 890 km^2 area of Harare is traversed by about 5,500 km of transmission and distribution mains with pipe diameters ranging from 50 mm to 1,500 mm. Pipe materials used are mainly asbestos cement (AC) and steel. UPVC pipes were introduced into the system in the late 1990s.The distribution network also has 15 booster pump stations and 28 storage reservoirs with total capacity of 850,000 m^3. There are approximately 192,000 consumer connections.

3.2 Modes of water supply

There are three water supply modes in Harare. The first is the pumping mode, where the areas are supplied off primary pumping mains. Second, there is the gravity supply mode where areas are supplied from storage tanks by gravity. The last category is supplied from both pumping and gravity. These are areas that can continue to access water after pumping failure such as the Central Business District (CBD). Various pressure zones were created in Harare but owing to system failures, most zone valves have been opened and this is exacerbating water losses.

Figure 3.1 shows the location of the City of Harare and the selected four district metered areas (DMAs). The four DMAs are Budiriro, Glenview, Belvedere and Mabelreign respectively, in the order of the age of the water distribution network. The choice of these areas was based on reliability of water supply to these DMAs. The four DMAs have about 27 600 connections, serving a population of about 138 300 people. The average volume of water supplied to the four DMAs is about 2,500,000 m^3 /month. The age of the pipe network ranges between 25 years and 50 years.

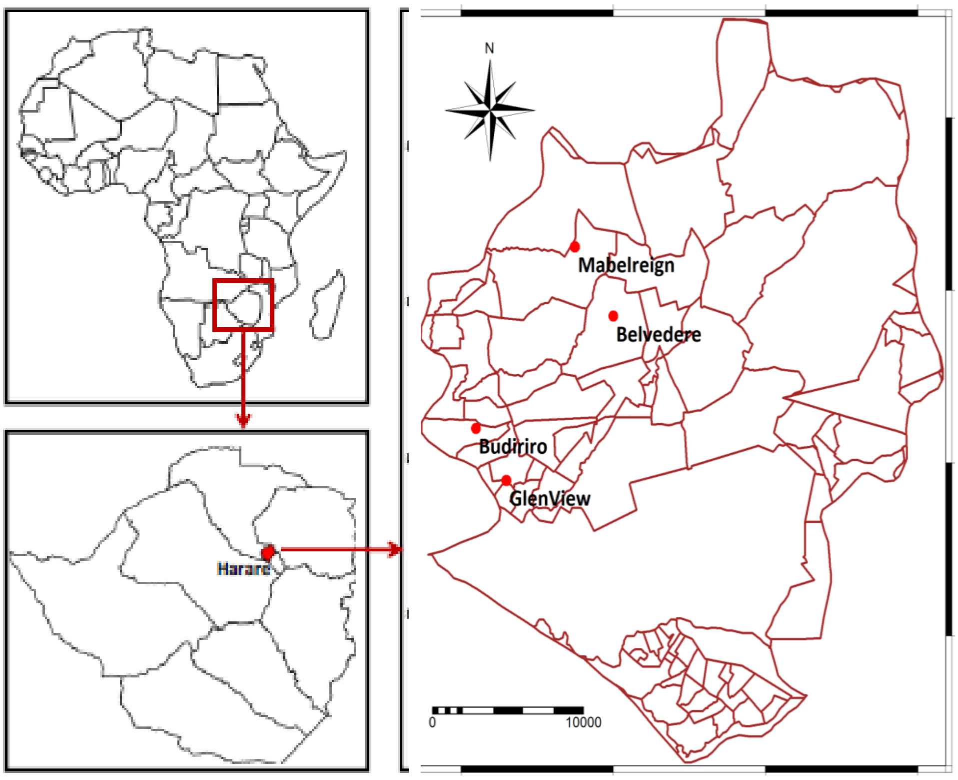


Figure 3.1 Map of Harare showing selected District Metered Areas (Ndunguru, 2012)

3.3 Performance challenges for water service delivery

Since water demand has outstripped supply, the City of Harare is now under a water stress situation where water shortages are frequent. Due to the nature of the distribution system, some areas which are on higher ground and further from the treatment works are experiencing longer periods without water (City of Harare, 2011). In undertaking its mandate, the Harare City Council is currently faced with various challenges which include the following:-

(a) Increasing population against a deteriorating services infrastructure

The increase in population and deteriorating service infrastructure has led to a decline in service delivery. The total population of the City of Harare (Greater Harare-Harare and its satellite towns) stands at 4.5 million people as of 2012 (Zimbabwe National Statistical Agency, 2012) against a population of 350,000 as of 1963 when Lake Chivero, the sole water supply was commissioned. This means a 13 times dependent population rise in 50 years. Minimal rehabilitation works have since been done on the infrastructure but the city and its satellite towns remain susceptible to water losses which is approximated to 60% of the water production (City of Harare, 2011).

(b) Meters are operating beyond their design life

Water utility is losing revenue through meter errors, as water meters tend to under-register when they are getting old. Most of them are more than 15 years old. According to the meter replacement policy residential meters should be checked, cleaned, and calibrated every seven to ten years (Zane and Bhardwaj, 2004).

(c) Efforts to improve service delivery

Harare Water is currently engaged with carrying out major urgent rehabilitation works which entail achieving the following goals:

- Increase water supply coverage from the current 3.0 million to 4.0 million (increase by 33%),
- Increase water treatment capacity from the current 600ML/d to 744ML/d (increase by 25%),
- Customer base to increase from current 192,000 to 240,000 and;
- Increase monthly revenue collection from the current 5.0 million dollars to a minimum of 12.0 million dollars by year 2018.

4 Material and methods

4.1 Study design

The study used literature review and field work in gathering important information. The data collection was carried out on Harare water distribution system from January to May, 2012. Selection of Harare to be the study area was based on the reporting that it has high levels of NRW of up to 60% of water production and it is the highest in Zimbabwe. On the other hand the contribution made by water leakages from distribution mains was unknown. The components studied include water production and non-revenue water trends, non-revenue water management practices and water leakage contribution to the water losses in selected water supply zones (suburbs) of Budiriro, Glen View, Belvedere and Mabelreign. These suburbs were selected based on their unique characteristics in the sense that they were distinct metered zones which do not supply water to any other areas. The entire water supply zones had residential or individual customers and the bulk meters installed were compatible with the loggers that were used for flow logging.

4.2 General research methods

The research methodology applied to this study was divided into two main stages. The first stage consisted of a thorough desk study and accounted for about 30% of the workload. The second stage was the actual field work (experimentation) and questionnaire survey, representing about 70% of the task. Thus, the stages can also be referred to as the theoretical stage and the practical implementation stage. The desk study was based upon an extensive literature review to study various techniques and technologies, methods and concepts of NRW management and a foundation for the practical stage was established. The methodological approach is as shown in Figure 4.1. The figure shows the method used, the objective statement and the objective that is being addressed.

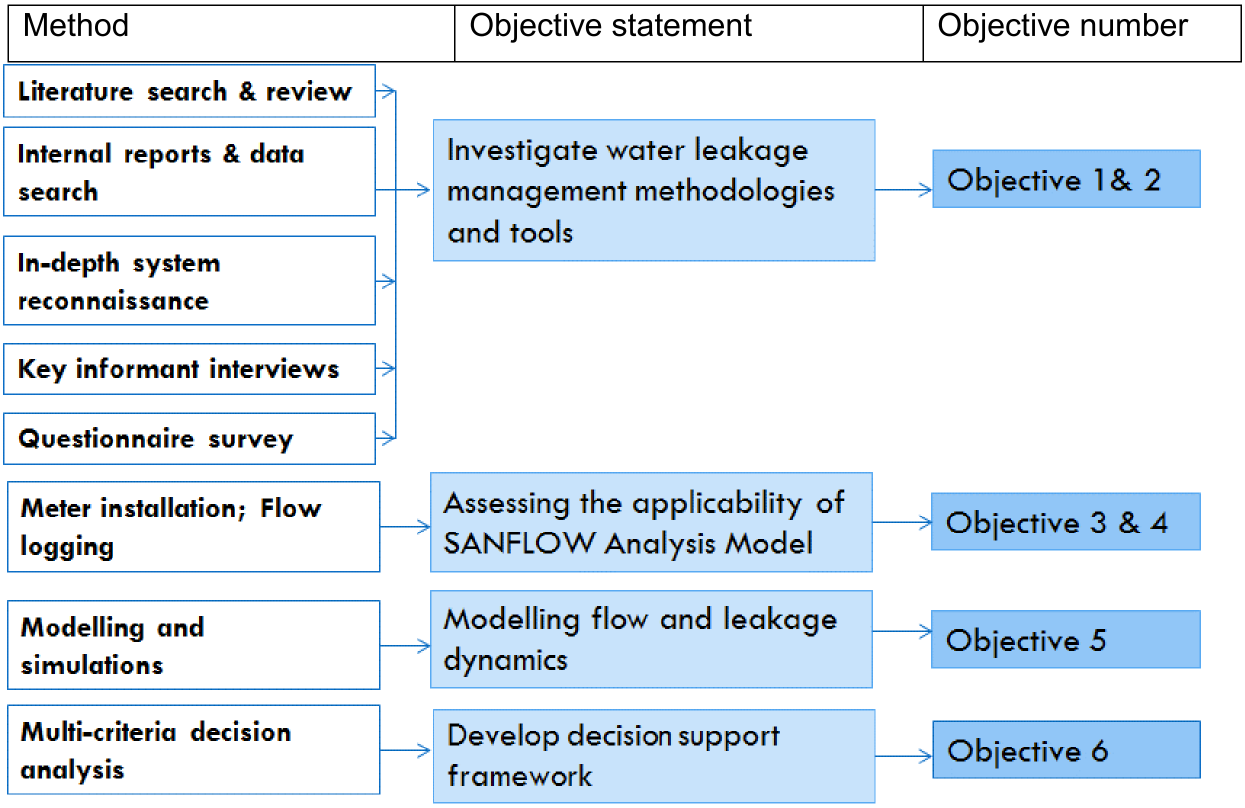


Figure 4. 1 Methodological approach

The research work involved obtaining information about the operation of Harare water distribution system. Meetings were done with key personnel to gather first-hand information about the challenges that the city was facing with their water distribution programmes. Of great importance was to establish the level of management of NRW within the city. Filed observations were also another approach that was adopted. This involved moving around the selected DMAs, from the mains to the customer meters. Harare water staff was incorporated during the direct observations in the field, since they are the ones with the institutional memory and first-hand knowledge about the system. Then both water flow and pressure observations were made on selected points in the distribution system of four district metered areas of Budiriro, Glen View, Belvedere and Mabelreign. Minimum night flows were also recorded for each metered area to assist in water leakage quantifications.

4.3 Data collection and experimental procedure

The information about water metering levels and water meter functionality was collected using a questionnaire survey. Equation 4.1 was used to determine the sample size.

$$n = \frac{N}{1+N(e)^2} \quad (4.1)$$

Where: *n* = sample size.
N = total number of households.
e = level of precision (Israel, 2009).

At a level of precision of 7% and a total number of households of 28911, the ultimate sample size obtained was 203 households, representing an average of 51 households per district metered area.

4.4 Data analysis

4.4.1 Metering and NRW strategy implementation

Descriptive statistics and graphical representation of data was used to analyse data collected from the City of Harare. The level of implementation of NRW strategies was analysed statistically while the trend of water production and NRW was analysed graphically. The Statistical Package for Social Sciences (SPSS) version 17 was also used to analyse data. Data cleaning was done manually. Single transfer coding, where the response was already in the form which had to be entered into the computer was done with questionnaires as they were coded.

4.4.2 Artificial neural network

This study was based on Multi-Layer Perception which was trained and tested using DMA flow data. The objective was to develop an ANN-based model using flow data generated by flow loggers in selected DMAs in Harare, Zimbabwe.

4.4.2.1 Building the network

In building the network, the designer specified the number of hidden layers, neurons in each layer, transfer function in each layer, training function, weight/bias learning function, and performance function. The development of optimal network architecture was done using the graphical user interface of MATLAB, and validation of the water flows.

For the learning algorithm, the feed-forward back-propagation algorithm was used. Regarding the transfer functions, the log-sigmoidal transfer function was used. The output layer neuron however used purelin transfer function so that the outputs can take any value between negative and positive infinity meaning that no scalings are needed on the outputs. Figure 4.2 shows the ANN graphical interface showing input, hidden layer and the output.

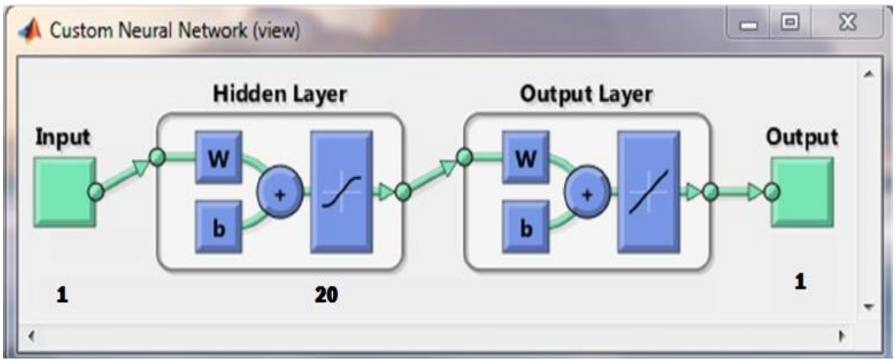


Figure 4. 2 Graphical interface of a neural network

4.4.2.2 Training the network

In network building several configurations were tried and the one with the "best" prediction efficiency was chosen to be used in network training and testing. The weights were adjusted in order to make the actual outputs (predicated) close to the target (measured) outputs of the network. In this study, flow logging data from one DMA (Budiriro 22 April - 26 April 2012) was used as input data while flow logging data from another DMA (Belvedere 22 April – 26 April 2012) was the target data.

4.4.2.3 Testing the network

The next step was to test the performance of the developed ANN model. Data from another DMA (Mabelreign 22 April – 26 April 2012) was used. In order to evaluate the performance of the developed ANN model quantitatively and verify whether there is any underlying trend in performance of ANN model, statistical analysis involving the coefficient of determination (R^2), and the root mean square error (RMSE) was computed. RMSE provides information on the short term performance which is a measure of the variation of predicated values around the measured data. The lower the RMSE the more accurate is the estimation.

Information about the water supply and network characteristics was obtained from the City of Harare's water utility, Harare Water. Water demand was obtained from flow logging campaigns that ran from 22nd of April 2012 to the 5th of May 2012 in four DMAs. The flow logging was done over a 24-hour period in 15 minute intervals, meaning that 96 data sets were collected over 24 hours on each of the days per DMA. Therefore over the entire sampling period of 14 days, 1344 data sets were obtained. The data chosen was divided into three groups, the training group corresponding to 70% of the data, the validation group representing 15%, and the test group, which corresponds to 15% of data; so that the generalization capacity of network could be checked after the training phase. Furthermore, MATLAB was used as a simulation tool; and the first step was loading the data and visualizing it then removal of 'abnormal' data was done for training the data. Comprehensive statistical analysis and data characterisation was done to help identify the boundaries of study domain as well as potential deficiencies in the data sets. The next step was the construction of training inputs and targets, and pre-processing for training inputs and targets. Then the Neural Network (NN) was constructed and training of the NN was done. This was followed by the testing of the network performance. Finally, the comparison of the simulated water flow and the actual flow was done followed by computation of the forecast accuracy. The number of neurons and layers were changed to achieve maximum accuracy and or retaining was done to obtain the best fit.

In order to detect leakage a MATLAB based algorithm (the optimal ANN model) was developed based on a continuous comparison between the measured water supply from flow logging data and the predicted water demand in a district metered area. The predicted water demand was compared with the DMA water consumption (figure obtained from metering), the difference of which represents water lost. It was assumed that water was lost through leakages and any other means were insignificant. In validating the simulated leakages, SANFLOW simulated bulk meter volumes were compare with the sub-meter readings. The sub-meters are as shown in Figure 4.3.

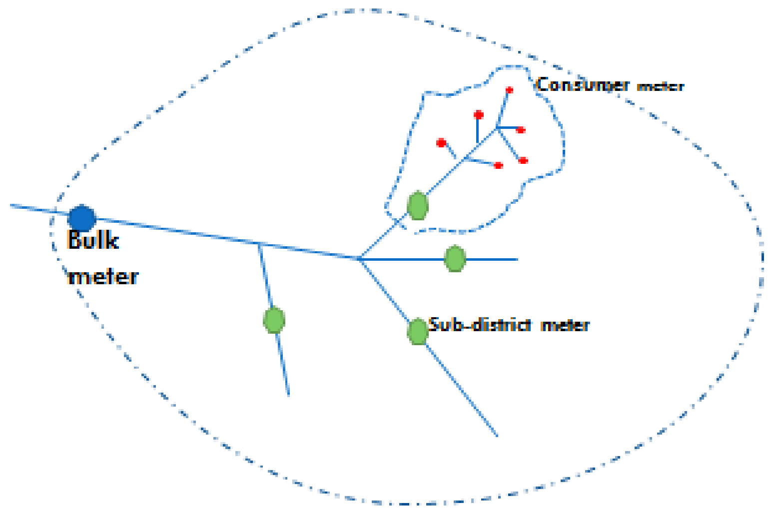


Figure 4. 3 Location of sub-district meters

4.4.3 Quantification of water leakage and its contribution to water losses

The amount of leakage water contributing to the total water loss for the selected water supply zones was analysed using the South African Night Flow (SANFLOW) Analysis Model version 2.03. Basically the estimation of leakage water was calculated as the system's Excess Night Flow (ENF), which was determined by subtracting the Expected Minimum Night Flow (EMNF) from Minimum Night Flow (MNF). The MNF is the lowest flow into the DMA over a 24-hour period, which generally occurs between 00:00hours and 04:00hours when most consumers are inactive. Table 4.1 presents the components of night flows used in this study.

Table 4.1 Components of the night flow (Source: McKenzie, 1999)

Components of night flow	Composition	Abbreviation	Unit	Component value
Expected Minimum Night Flow (EMNF)	Domestic users	Qdom	[L/h]	Estimated
	Small Non-Domestic users	Qbulk,small	[L/h]	Estimated
	Large Non-Domestic users	Qbulk, large	[L/h]	Measured
Transfer	Transfer of water to neighbouring zones	Qtrans	[L/h]	Measured
Excess Night Flow (ENF)	Background losses	Qloss,BG	[L/h]	Estimated
	Burst pipes	Qloss,B	[L/h]	Calculated

4.4.4 Application of SANFLOW analysis model

Although customer demand is minimal at night, researchers still have to account for the small amount of Expected Minimum Night Flow (EMNF), i.e. the night-time customer demand, such as toilet flushing, washing machines, etc. Typically, in urban situations, about 6% of the population will be active during the minimum night-time flow period (McKenzie, 1999). Apart from the MNF data, the SANFLOW model also uses basic infrastructure variables such as length of mains, number of connections number of properties, estimated population, average zone night pressure and major water users. Where there was no data such as leakage coefficients and pressure correction factors, some assumptions were made and SANFLOW default values which were recommended by McKenzie (1999) were used. Tables 4.2 and 4.3 provide the base information and assumed parameters which were used in the SANFLOW model for each of the study areas.

Table 4.2 Infrastructure variables used in SANFLOW Model (City of Harare, 2011)

Description	Value			
	Budiriro	Glen View	Belvedere	Mabelreign
Length of mains (km)	90.17	109.86	98.45	93.97
Number of connections	11421	11100	1899	3241
Number of properties	11421	11100	1899	3241
Estimated population	57105	55500	9495	16205

Table 4.3 Leakage parameters used in SANFLOW Model (Ndunguru, 2012)

Description	Value				
	Default	Budiriro	Glen View	Belvedere	Mabelreign
Background losses from mains (l/km.hr)	40	40	40	40	40
Background losses from connections (l/conn.hr)	3	3	3	3	3
Background losses from properties (l/conn.hr)	1	1	1	1	1
% of population active during night	6	6	6	6	6
Quantity of water used in a cistern (l)	10	10	10	10	10
Background losses pressure exponent	1.5	1.5	1.5	1.5	1.5
Burst/leaks pressure exponent	0.5	0.5	0.5	0.5	0.5
Exceptional use m^3/h	-	-	-	-	-

Expected Minimum Night Flow = Background losses + Normal night use (4.2)

Excess Night Flow = Measured MNF – Expected Minimum Night Flow (4.3)

Leakage (m^3/month) = ENF (m^3/hr) × (hour/day factor) × 30 days/month (4.4)

(Adapted from Fanner, 2004)

5 Results and discussions

This section outlines the results obtained from desk study and fieldwork; and discusses them accordingly. The first section is about benchmarking and performance indicators in water loss management. The second section presents and discusses results on the contribution of leakage water to the total water losses of the City of Harare. The third section presents and discusses the application of SANFLOW Analysis model in water loss management. The fourth section presents and discusses results on the application of Artificial Neural Networks in water loss management, and the last section proposes an integrated water loss management framework for developing countries.

5.1 Performance indicators in water loss management

Non-revenue water has serious impacts on water utilities efficiency, and impacts on customers and the urban poor (Farley et al., 2008). Although it is a generalisation, non-revenue water is a good indicator of the efficiency of performance of water utilities (Farley, 2003). Figure 5.1 shows performance of water utilities in the IBNET database (a public domain database with more than 2000 water utilities), where less than 10% of the utilities have 3% NRW, between 10% and 20% of the utilities have NRW of 7%, between 20% and 30% of the utilities have NRW of 24%, between 30% and 40% utilities have NRW of 28%, between 40% and 50% of the utilities have NRW of 19% while greater than 50% of the utilities have NRW of 16% (Makaya and Hensel, 2014a). From Figure 5.1, it can be easily inferred that the utilities in developing countries (30-40%) have the highest levels of NRW. This is also confirmed by (Winarni, 2009). Each year more than 32 billion cubic metres of treated water is lost through leakage from distribution networks while 16 billion cubic metres of treated water per year is conveyed to customers but is not invoiced (Farley et al., 2008).

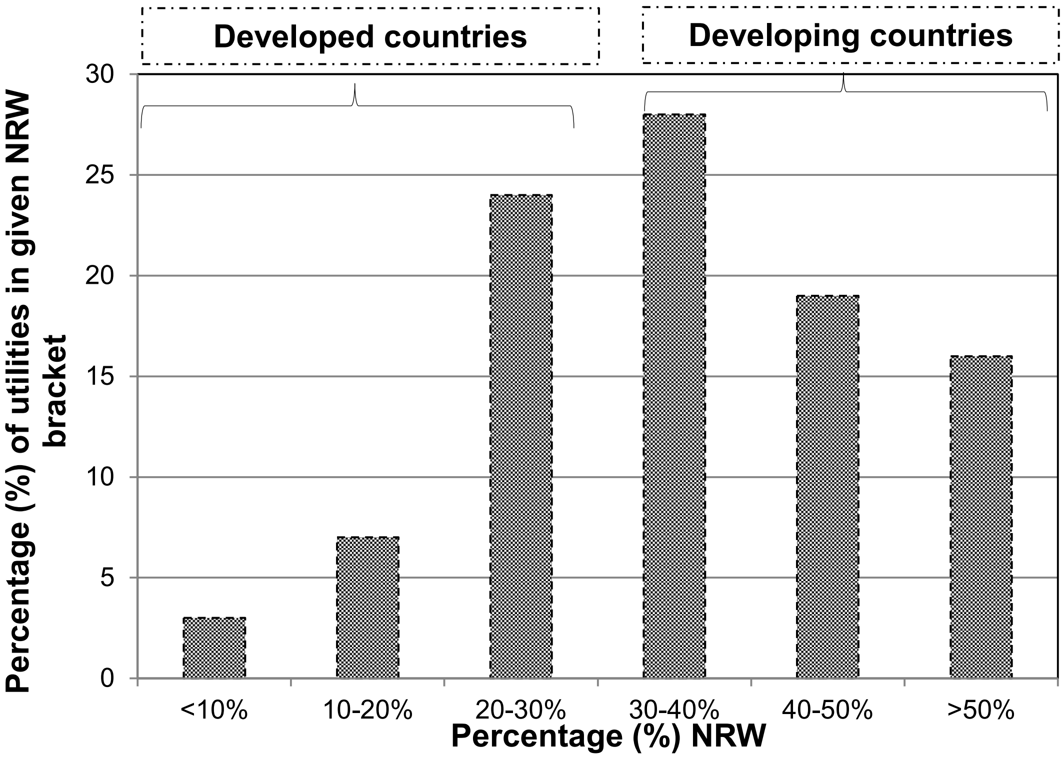


Figure 5.1 Performance of water utilities in terms of NRW

A conservative estimate of the total annual cost of non-revenue water to water utilities worldwide is 14 billion United States Dollars (SIWI, 2008). By saving half of this amount an additional 100 million people would be supplied with water without further capital investment (USAID and WBI, 2010).

5.2 Performance indicators as a comparison tool

Figure 5.2 shows non-revenue water levels of different countries for the year 2001-2013. The IBNET database was the source of the data used in the comparative assessment. The graph shows that the developed countries, New Zealand and Australia have the least levels of NRW while the developing countries Zambia and Mozambique have the highest levels of NRW. Thus the non-revenue water trends can be compared given data over a long period of time. Countries are encouraged to frequently monitor their non-revenue water levels in order to make it possible to compare the different trends. When water loss reduction initiatives are put in place, their effectiveness can be easily noticed as compared with their earlier trends.

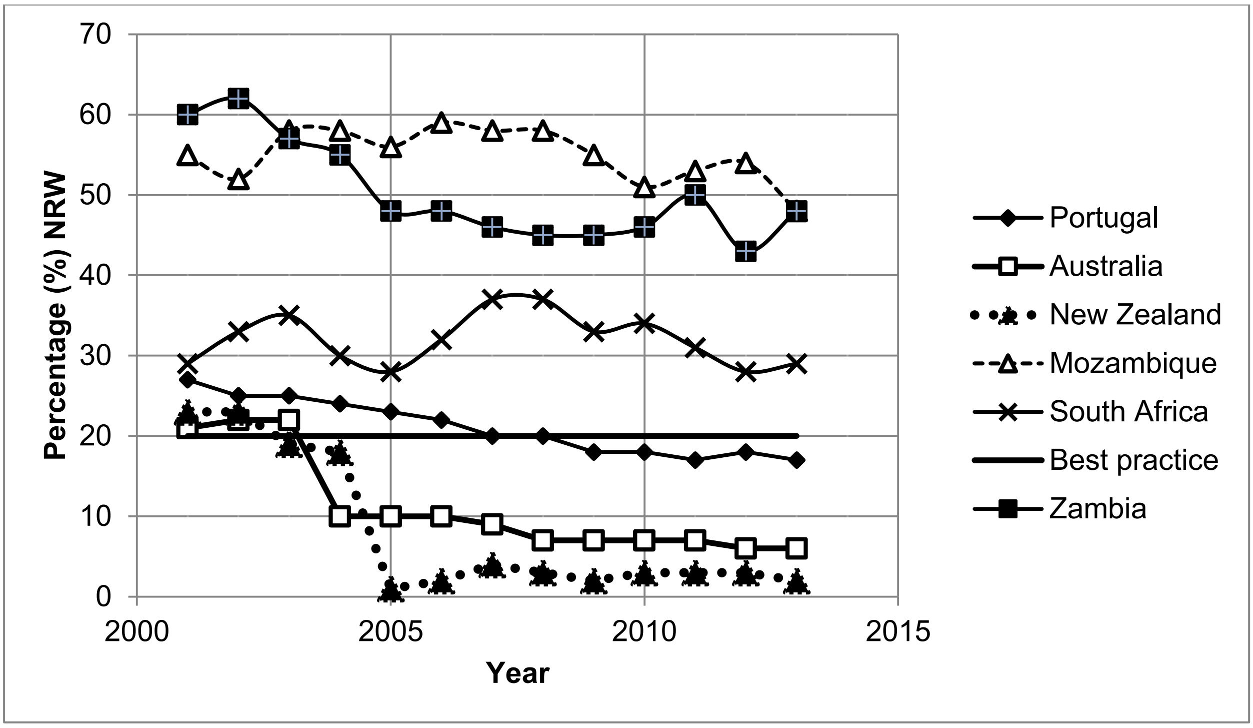


Figure 5.2 Comparative non-revenue water for developed and developing countries

5.3 Non-revenue water management

The causes of water losses observed were; old pipe networks dating back to the 1960s, lack of knowledge of the water networks (inadequate records), and low awareness of non-revenue water by water utility management. Discussing NRW management in Harare, key informants reported that they implement different strategies to combat water losses, which is an effort to improving service delivery to customers at the same time improving utility’s revenue. Strategies being implemented are targeting four areas of system leakages (both trunk and distribution mains), poor revenue collection (metering and illegal consumptions), poor customer focus and the fourth area is poor and inadequate system maintenance. For the system leakages minimization strategies, Harare Water is implementing pipe replacement, pressure controls valves servicing, leaks and burst pipe repairs, customers meter replacement, surveillance of trunk and distribution mains in different areas of Harare. For the poor revenue collection, Harare Water bought 40,000 customers meters in 2010 and is replacing 12,000 non-functional meters in one suburb (Mabvuku Tafara) and the other 28,000 meters in different areas of Harare. Harare Water normally disconnects the service for the non-paying customers until they pay their outstanding bills. Lobbying the government for subsidizing outstanding payments is also another strategy used. For poor customer focus, the informants said they use 24 hours call centre while for poor and inadequate system maintenance increased lobbying for funds and increased allocation of revenue towards repairs are the two strategies used. Key informants proposed other strategies which should be introduced at Harare Water so as to improve performance. It was seen that, most of the strategies implemented currently are more on reactive side than proactive side of the non-revenue water management. The following are the strategies that were proposed to be employed together with the current implemented strategies:-

- Implementation of pressure zones (DMAs)
- Reduction of night pressures
- Improve metering (bulk, zones, customer)
- Task Force for active leakage detection
- Awareness campaign programme
- Implementation of prepaid water meters
- Implementation of cell phone meter reading through Advanced Meter Management (AMM) system
- Surveillance for water theft and illegal connections

There was a pilot study done by the City of Harare on advanced meter management using cell phone meter reading in Mabvuku Tafara in 2011. The overall project of using cell phone in water meter reading is a meter management solution that efficiently and effectively collects accurate in-field data for water meters. Basically, it provides a central content management system where the monthly meter readings can be controlled. The content management system would enable the Revenue Officer to monitor the daily activities of his/her designated meter readers. Reading would be captured on the cell phones and automatically pulsed back to the content manager (Revenue Officer) in set intervals.

Informants reported that the overall business objectives and success criteria are to increase the efficiency of meter readers and reduce the amount of human error when taking the meter reading and transferring for further processing. Cell phone meter reading increases the efficiency of the meter readers and escalates the volume of meters read per reader. From the pilot study done in Mabvuku Tafara, the total estimated increase in reading accuracy observed was 80% while the total increase in efficiency was 65%. The system allow for overall control of the meter reading, ensuring that the release dates of the data back into the billing system are adhered to. It minimizes human errors in the process and thus reducing the number of bills queried by the consumer. Cell phone send results while in the field, thereby reducing logistical cost, increasing data capturing time and real-time management process. It eradicates the need for human interaction, thereby acting as the first line defence for corruption and manipulation of the system. Thus, to combat such water supply inefficiencies, water utilities should be transformed into more productive and efficient entities.

5.4 Application of benchmarking and performance indicators in water loss management

A case study of the City of Harare, Zimbabwe was used in this study. The case study sought to assess the level of management of NRW. The assessment was done following the self-assessment methodology proposed by the International Water Association (IWA, 2003).

Harare Water NRW performance assessment

Self-assessment matrix on non-revenue water management for the best practice developed by Africa Development Bank (2011) was adopted to assess levels of interventions for each NRW management strategy employed by Harare Water. According to Harare Water utility assessment matrix, which was done for the Urgent Water Supply and Sanitation Rehabilitation Program for Harare in 2011, it was reported that the level of NRW management in Harare was 3 out of 5 scores developed for the excellence in NRW management as shown in Table 5.1. This self-assessment methodology was adapted from the International Water Association (IWA) to assess the efficiency of water utilities (USAID and WBI, 2010). The NRW implementation level is divided into 5 levels. For each level, there is a range of scenarios that describes the implementation level in a given area ("1" is poor and "5" is excellent).

Table 5.1 International NRW management assessment matrix (City of Harare, 2011)

Level of management				
1 (Poor)	2	**3**	4	5 (Excellent)
No monitoring of NRW indicators. No NRW management strategy.	% NRW Monitored. Water balance is available. No NRW Management strategy.	% NRW monitored. Water Balance available. Some actions are undertaken to reduce commercial or physical losses but without NRW management strategy	Some actions are undertaken to reduce commercial or physical losses but without NRW management strategy.	IWA Water Balance available and regularly updated. Physical and commercial Losses' performance indicators monitored. Regular NRW reduction activities as per a comprehensive NRW management strategy. Sufficient budget for NRW management.

The proposed assessment parameters for a utility's NRW management are shown in Table 5.2. Table 5.2 presents the enabling factors for each of the strategies currently implemented and proposed respectively.

This study showed that NRW management situation in Harare Water, considering strategies used and according to the ranking that was done referring to individual strategies, was 2.67 out of 5 representing 53.4% implementation of NRW strategies. This result is consistent with the result obtained by the Harare Water Utility assessment for the Urgent Water Supply and Sanitation Rehabilitation Program which reported that the level of NRW management in Harare was 3 out of 5 scores developed for the excellence in NRW management (City of Harare, 2011). Thus the outlined methodology (Table 5.2) can be effectively used to assess the level of non-revenue water management of a water utility. Such an indicator would prompt the water utility to embrace other water loss management approaches such as active monitoring and leakage management.

Table 5.2 Enabling factors and challenges for each implemented strategy (Africa Development Bank, 2011)

Strategies		Strengths (enabling factors)	Weaknesses (barriers to implementation)	Opportunities (for increasing the levels of interventions)	Threats (to the strategy)
CURRENTLY IMPLEMENTED	Pipe replacement	Mains data for the areas that require pipe replacement is known	Construction difficulties in built up areas and water cut off during replacement	Employment of zone based customers in pipe replacement to increase participation	Financial resources
	Pressure Release Valve (PRV) servicing	Data on PRV available	Corroded PRV	Use of PRV which can control pressure during off-peaks period	Resources
	Leaks and burst repairs	Data on networks available	Manual maps in use	GIS asset management system	Resources
	Meter replacement	All connections metered. Need replacement	Leaking and corroded service pipes and water cut off during repairs	Proper metering will increase revenue	Resources (funding, manpower) Vandalism (destroying)
	Taskforce for active leak detection	Pipe routes are known and accessible	Current slow pace of repairs – turnaround time	Increasing support for demand management	Funding
	DMAs and pressure management	Zones are well defined	Failure of valves, meters, pressure control valves	Increased water supply control -	Resources
	Improve metering (Bulk meters in supply and distribution mains)	Data known, areas accessible	Water cut off during repairs	Employment of zone based customers in pipe replacement to increase participation	Resources
	Reduction of night pressure	Data on PRV available	Use of Fixed PRV which are not flexible	Flexible PRV to control pressure during off-peaks period	Resources

From the case study it was concluded that the implementation of NRW management strategies is just intermediate to minimize losses to the acceptable values as suggested by Tynan and Kingdom (2002) and Gumbo (2004). The improvement in the efficiency of the sector should go a long way in financing the need to improve access and/or quality of water production and distribution. Continuing the public or private financing of the sector without significant efficiency improvement is a major waste of scarce resources. If efficiency savings exceed revenue from user fees it implies that average tariff levels would continue to be too high as compared to what they would be if firms were operated efficiently (World Bank, 2002). The main challenges are however not only in the water sector but governance issues and the weakness of institutions as these have been and continue to contribute to a large share in the excess of costs (World Bank, 2002).

Non-revenue water percentage by volume, Infrastructure Leakage Index and benchmarking methodologies play a pivotal role in assessing the efficiency of performance of water utilities worldwide. However, the application of performance assessment systems and benchmarking is still at its infancy, especially in developing countries. The systems and tools developed for the water industry may not be directly applicable to WDSs of the developing countries. As a result water utilities in developing countries should be more proactive in their operations and adopt international standards in order to match their developed countries counterparts.

Operational performance efficiency is very vital for perpetuation of a sound service delivery. Since many water utilities fail to identify and apply indicators appropriate and relevant to their operations, developing countries utilities should be capacitated to be able to apply assessment indicators in order to elevate their systems efficiency to international standards. This is mainly because their systems suffer from inadequate water supply, poor billing, and poor operation and maintenance records, resulting in exceptionally high NRW, and poor service delivery coupled with unrealistic water prices. Water utilities and regulators of the operations of water utilities should make it a top priority that utilities operate within the right frameworks of efficiency assessment indicators. Thus, performance assessment systems including self-assessment methodologies are applicable to the developing countries.

5.5 Water billing process

Discussing water billing processes, the City of Harare has 189 staffs recruited for the customer meter readings every month. The meter reading circle starts from the 1st day of the month to the 25th day of the same month. Depending on the customer's location, one meter reader can read 90 to 120 meters in a day. The total customer connections currently are reported to be 192 000 connections giving a meter reader productivity of 1 person attending 1016 connections. Based on meter reading, faulty metering rate for the year 2006 was 25% for the whole Harare water supply chain while in 2012 the faulty metering rate was reported to be 35%. Reporting the recent faulty metering rate for the selected areas; Budiriro faulty meters were 18%, Glen View was 21%, Belvedere was 27% and Mabelreign was 30%. Customers with stuck meters' monthly consumptions are estimated from the previous consumption when meter was working by taking an average of monthly consumption for one year.

Customer bills are processed using computer software BIQ and deliverance of the bills is done both door to door and through post office. It was reported some customers are not paying their bills on time despite the effort made by the authority of making sure bills are delivered on time. In terms of water tariffs, Low and Medium Density areas pay 0.4 US$ for each cubic meter consumed. High density areas are paying 0.25 US$ and Industries are paying 0.8 US$ for each cubic meter of water consumed. In terms of challenges faced in billing department, it was reported that, mainly lack of transport facilities for meter readers to move around big area. Also some consumers are rude when meter readers want to access their properties, some houses have dogs which makes it difficult to enter the property without their presence. Meter readers also reported that customers used to buy their own meters once noticed they are not working in close consultation from Harare water staffs. Due to increasing number of non-working meters now the council has started replacing customer meters in an effort to improve water billing. Many water meters were reported to be older than 10 years which also affects their accuracy. Recommended domestic meter replacement time is seven years (Zane and Bhardwaj, 2004). Taking a case study of Kampala Uganda, it was noted that meter inaccuracies contributed to 22% NRW due to under registering consumptions (Mutikanga et al., 2010b). It can be concluded that the faulty metering rate of 35% city wide is higher and the method of monthly consumption estimation can affect both parties (customers and utility) especially with the erratic water supply.

Information on metering and their functionality was also gathered from the household survey. Figure 5.3 show the results of metered customers and working meters respectively. These two issues were assessed from the customers so as to supplement data on how Harare Water manages NRW water based on the metering strategy. Figure 5.3 shows that the majority of customers are metered (98%), but on the other hand 23% of the interviewed households reported to have non-working meters.

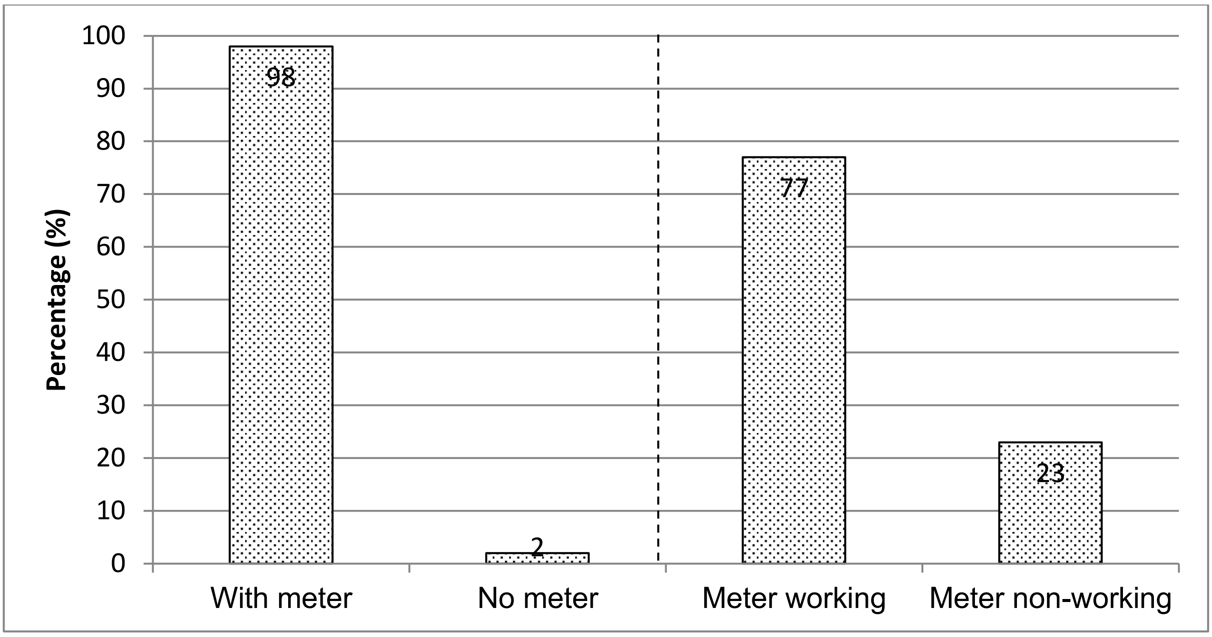


Figure 5.3 Metering in selected four DMAs

The monthly water consumptions for the customers with stuck meters were reported to be estimated from the previous consumptions. This method of estimation can affect both service providers and costumers especially with the erratic water supply currently undergoing. Some household informants complained that the bills that they get sometimes are not real; they differ from the meter readings.

5.6 The contribution of water leakages to total non-revenue water

In partitioning the total water loss for the City of Harare, this study was seeking to establish the contribution of leakage water to total water loss in the city. Such information is very vital for the water utility management to direct their efforts towards the appropriate components of water losses and achieve effective results.

From the computations of night flow, Table 5.3 was developed showing the total water lost in the four DMAs. An average of 64% was consumed of which 36% was lost. Water consumption in Belvedere was 71%, in Glen View it was 63% while in Mabelreign it was 58% of the total water supplied.

Table 5.3 Estimated water loss in the DMAs

Water Supply Area	Monthly Average (m^3)		% Consumption	% Loss
	Water supply	Water consumption		
Budiriro	421,959	268,769	64	36
Belvedere	130,419	92,987	71	29
Glen- view	287,333	182,036	63	37
Mabelreign	167,110	96,290	58	42
Average				36

This information gives equivalent water loss of 36% for Budiriro, 29% for Belvedere, 37% for Glen View and 42% for Mabelreign.

Table 5.4 computes the water leakages in the four selected DMAs. An average of 33% leakage water was recorded, amounting to 510 litres per capita per day. This value is far above the African Development Bank best practice of 300 litres/connection/day. For Budiriro, out of 36% total water loss, water leakage was 27%, for Glen View out of 37% total water loss, water leakage was 31% and for Mabelreign area out of 42% total water loss, the amount of water leakage was 37%. These three areas of Budiriro, Glen View and Mabelreign gave positive results.

Table 5.4 Water leakage partitioning using SANFLOW

Water supply area	Average excess night flow m^3/hr	Average monthly Leakage m^3	Average zone Daily flow m^3/hr	Equivalent monthly supply m^3	Estimated water leakage		
					% supply	m^3/conn./ month	l/conn./d
Budiriro	156	112,474	586	42,1959	27	9.85	328
Belvedere	64	46,015	181	130,419	35	24.23	808
Glen-View	62	89,537	200	287,333	31	8.07	269
Mabelreign	29	61,743	77	167,111	37	19.05	635
Average					33	15.30	510

However, a negative response was obtained in Belvedere whose leakage water was 35% out of a water loss of 29%. A discussion with the Billing Manager revealed that Belvedere has the largest number of non-working water meters and as such the water authority relied on estimate readings.

A similar study was done in Kampala, Uganda by Mons (2010) where it was found that the contribution of water leakage to the water loss was 29%. Based on the study by Seago et al., (2004) which benchmarked water leakage to 276 litres/connection/day, the amount of leakage ranged from 269 litres/connection/day to 808 litres/connection/day (average of 510 litres/connection/day), which was above the international benchmark derived from 27 water supply systems data in 19 countries. Also, Seago et al., (2004) reported an average leakage value of 340 litres/connection/day based on 30 South African water supply systems. Thus, Harare with 510 litres/connection/day is still 50% way above the average of the 30 water supply systems of South Africa.

This study further endeavoured to estimate the average cost of water leakage in the selected four DMAs. Table 5.5 shows the computation of the estimated cost of leakage water.

Table 5.5 Estimated cost of leakage water

Water supply area	% Leakage fraction of total loss (Monthly average)	Volume lost per connection per month (m^3/conn./month)	Water tariff (USD/m^3)	Estimated cost of leakage water (USD/conn./month)
Budiriro	27	9.85	0.25	2.46
Belvedere	35	24.23	0.40	9.69
Glen view	31	8.07	0.25	2.02
Mabelreign	37	19.05	0.40	7.62

Thus, for the case of Harare, high water losses for Belvedere and Mabelreign are due to aged infrastructure in excess of 40 years. From Table 5.5, the high-density suburbs of Budiriro and Glen-View have a tariff of USD 0.25/m^3 while the low density suburbs (Belvedere and Mabelreign) have a tariff of USD 0.40/m^3 within normal domestic consumption tariff band. With the Greater Harare area having almost 200,000 connections and each connection loses an average of $5.50 every month, it means that the City of Harare is losing over one million dollars very month. With a monthly revenue of five million dollars (City of Harare, 2011), the city is losing 20% of its revenue in leakages alone monthly. For such a city, the amount is relatively significant; as the amount could be used to improve systems performance hence improved service delivery. Thus, the city of Harare should be more proactive and actively invest in leakage reduction initiatives in order to save and reinvest so as to improve water supply service delivery. By reducing total leakage water, the city would be able to postpone capital investment on new water supply and distribution system.

Therefore, non-revenue water management practice in general and water leakage practice in particular for Harare are poor as evidenced by an average water loss of 36% and an average water leakage of 33%. The four selected DMAs are the ones performing well in Harare since the NRW for the entire Greater Harare region is in excess of 40% (City of Harare, 2011). However, this is on a higher side compared to 23% which was recommended by the World Bank and 20% which was set for well performing urban water utilities in Southern African Region (Gumbo, 2004). The level of implementation of NRW management strategies (53%) (Ndunguru, 2012) is just intermediate and the City of Harare will not minimize these losses to the acceptable value unless increased intervention is initiated urgently.

Based on a benchmark value of NRW of less than 23% as recommended by World Bank (Tynan and Kingdom, 2002) and 20% for well performing water utilities in Southern Africa as recommended by the study done by Gumbo (2004), it can be concluded that the level of NRW for the city of Harare is on the higher side. A similar study was done in Zomba City-Malawi by Chipwaila (2009) where she found the amount of unaccounted for water was averaging 36.2% which was also concluded to be higher than recommended for well performing water utilities in Southern Africa.

Currently the water utility is not conducting full scale water balance auditing to know how much water is actually consumed and paid for, how much water is lost and how it is lost as suggested by Lambert (2003). The areas where water is being lost were reported to be along the transmission mains, distribution mains and service connections. The reasons for the loss are pipe bursts driven by age of infrastructure, tree roots and sometimes damaged by contractors. The other reasons stated were failure of pressure reducing valves, vandalism and water thefts. The causes of NRW in Harare water, informants reported to be caused by system leakages both in trunk and distribution mains, poor revenue collection resulted from non-functional meters and illegal consumptions, lack of 24 hours customer care centres and also poor and inadequate system maintenance were reported to contribute. These were also addressed by African Developed Bank and developed best practice assessment of strategies to combat these causes (African Development Bank, 2011).

Thus, there is need for Harare to take a more proactive approach to NRW management; including periodic water audits, procurement of leak detection equipment and sustained meter testing and replacement. Harare water supply is erratic and inadequate to meet customers demand; this leaves the majority of customers with poor water supply service. The City of Harare should increase lobbying of funds to assist in employing all

NRW management practices for the ultimate improvement of water service delivery. Through this, the City can plan for water mains replacement programme, metering programme and buy leakage detection equipment. Furthermore, the City of Harare could periodically conduct community awareness campaigns to give consumers practical tips on how to conserve water and may also form a Task Force for leak detection.

5.7 Application of SANFLOW analysis model in water loss management

5.7.1 Water production in Harare

The water production and NRW trends for the period 2009 to 2011 show an average of 45% NRW over the entire period; however, the selected four DMAs have an average of 40% NRW (City of Harare, 2011). Furthermore, water balance analysis indicated that the four DMAs have an average leakage of 33% (Makaya and Hensel, 2014b).

5.7.2 Water flow pattern assessment

Figure 5.5 presents the flow pattern for Budiriro area for the period of 20 April to 1 May, 2012. It is evident that the minimum night flow usually occurs during the night between midnight and 04:00 hours (Thornton, 2005), and was ranging from 193 m^3/hr to 199 m^3/hr during the entire logging period. The flow observed was erratic and the average flow was calculated to be 586 m^3/hr during the logging period. Almost every alternative day there was a time with no flow to the area due to rationing. The days without the minimum night flow were skipped in the analysis of results.

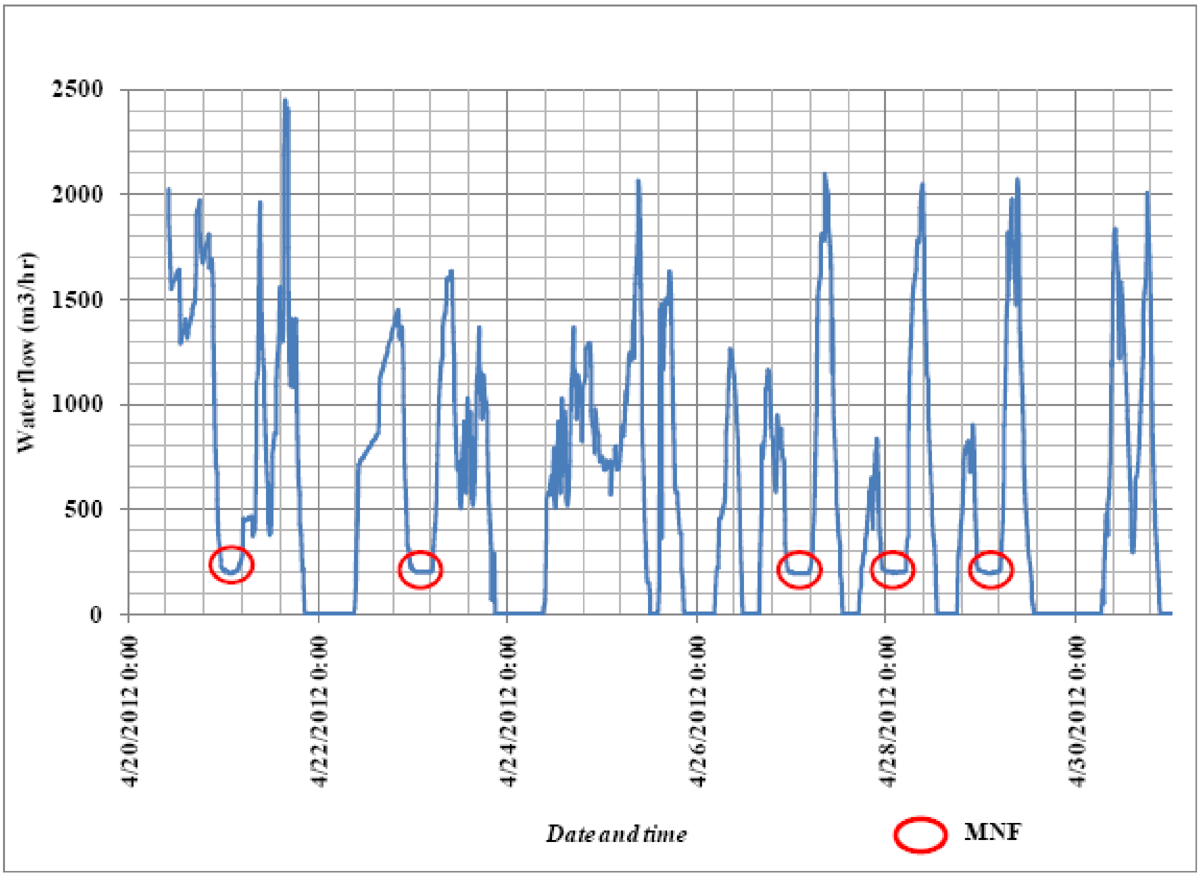


Figure 5.4 Budiriro area water supply inflow pattern

Belvedere area

Figure 5.6 shows the results of inflow pattern to Belvedere water supply area from 20 April to 1 May 2012. The minimum night flow was ranging from 74 m^3/hr to 83 m^3/hr during the entire logging period. The flow observed was erratic and the average flow was calculated to be 181 m^3/hr during the logging period. There were two days where the area had no water due to power cuts. The area was reported to have continuous supply of water through an 800mm pipeline.

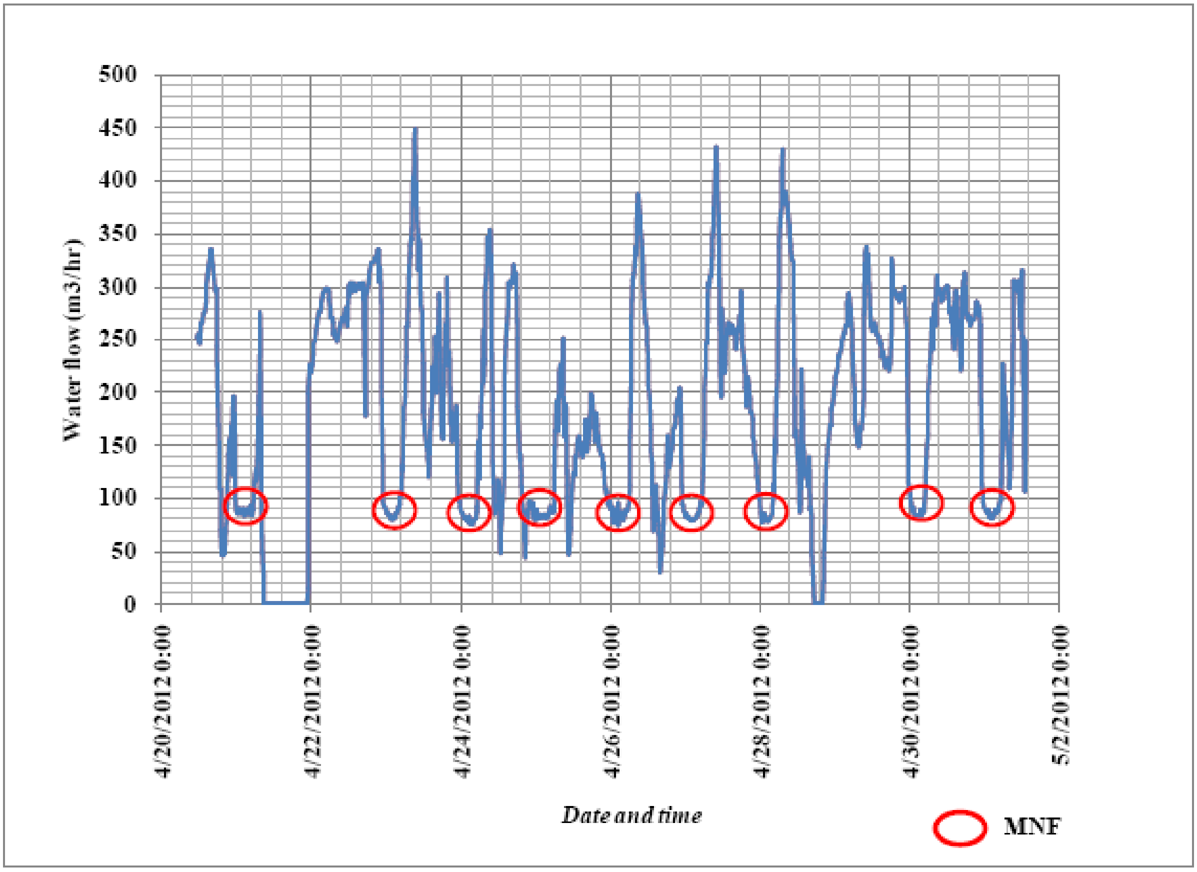


Figure 5.5 Belvedere area water supply inflow pattern

Glen View area

Figure 5.7 and 5.8 show the results of inflow pattern for the two feeders to Glen View water supply area from 20 April to 01 May 2012.

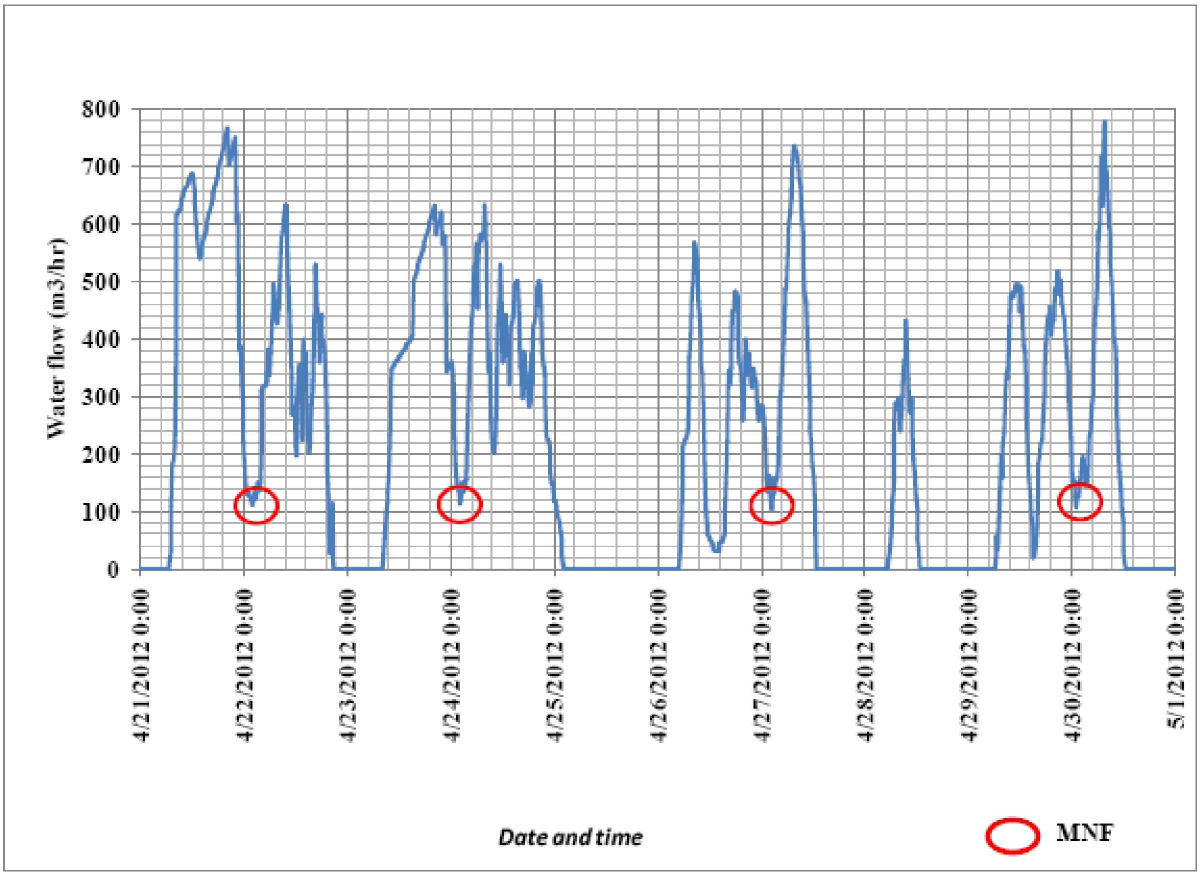


Figure 5.6 Glen View area water supply inflow pattern from feeder one

From Figure 5.7 the minimum night flow was ranging from 105 m^3/hr to 113 m^3/hr during the entire logging period. The flow observed was erratic and the average flow was calculated to be 203 m^3/hr during the logging period. There were four days where the area had no flows due to water rationing. Figure 5.8 presents the flow to Glen View area from feeder two and also the minimum night flow was recorded as ranging from 101 m^3/hr to 106 m^3/hr during the entire logging period. The flow observed was also erratic and the average flow was calculated to be 196 m^3/hr. There were five days of no flows due to rationing.

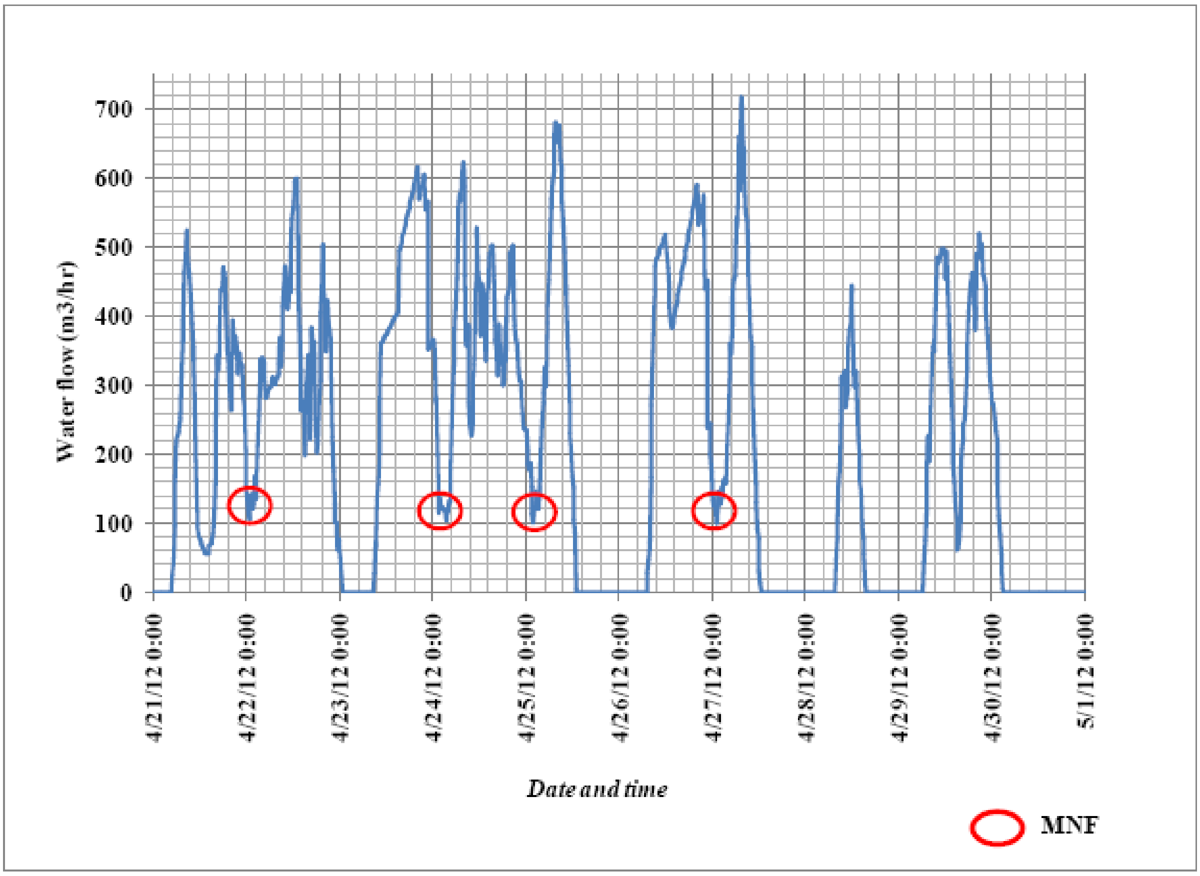


Figure 5.7 Glen View area water supply inflow pattern from feeder two

Mabelreign area

Figure 5.9, 5.10 and 5.11 show the results of inflow pattern for the three feeders to Mabelreign water supply area from 20 April to 1 May 2012. Figure 5.9 shows the minimum night flow ranging from 56 m^3/hr to 59 m^3/hr during the entire logging period. The flow observed was erratic and the average flow was calculated to be 95 m^3/hr and there was a three day period of no flows due to water rationing.

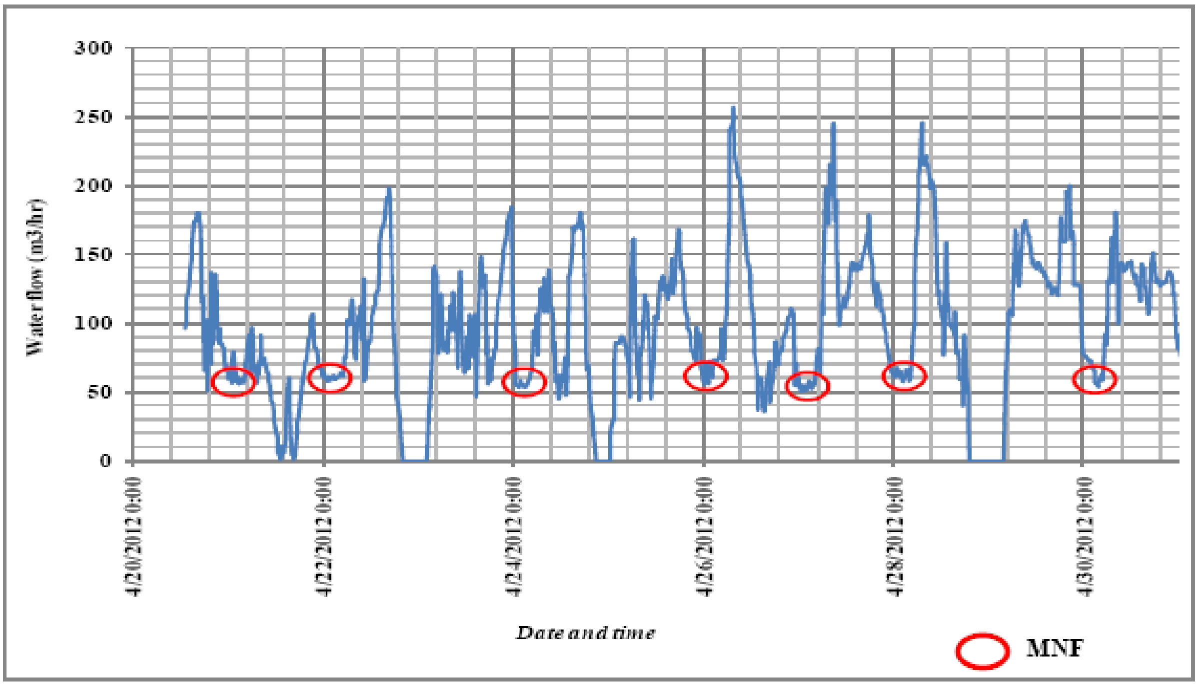


Figure 5.8 Mabelreign area water supply inflow pattern from feeder one

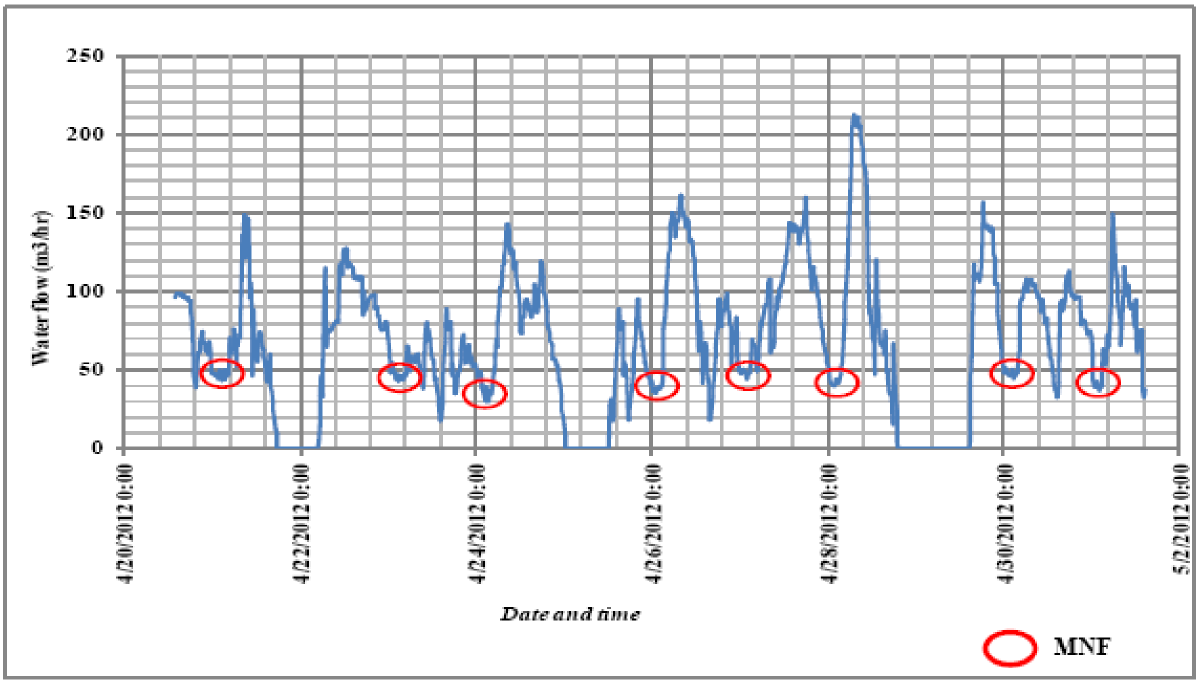


Figure 5.9 Mabelreign area water supply inflow pattern from feeder two

From Figure 5.10 the minimum night flow ranged from 40 m^3/hr to 44 m^3/hr during the entire logging period. The flow observed was erratic and the average was calculated to be 67 m^3/hr and there was a period in three days where no flows were recorded due to water rationing.

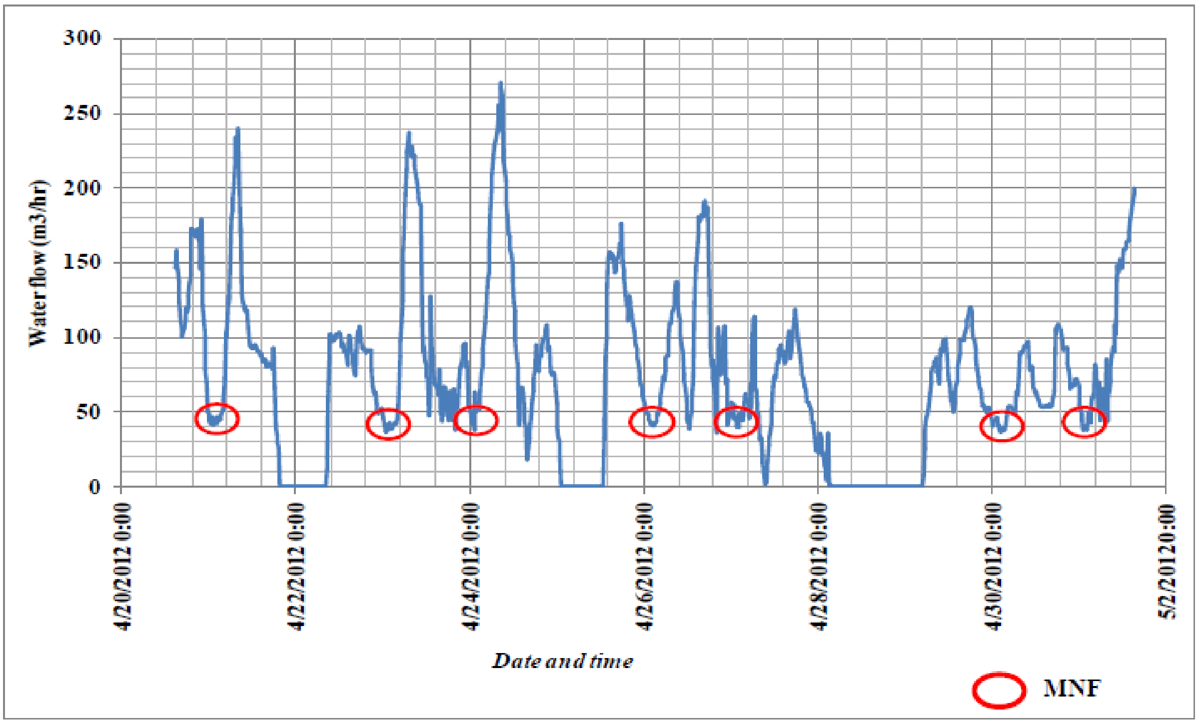


Figure 5.10 Mabelreign area water supply inflow pattern from feeder three

Figure 5.11 shows the minimum night flow to Mabelreign area ranging from 36 m^3/hr to 41 m^3/hr during the entire logging period. The flow observed was erratic and the average flow was calculated to be 72 m^3/hr and for three days no flow was recorded due to water rationing.

Data on monthly water consumptions for the study areas were collected from Harare Water to establish the proportion of water supplied and water consumed. From Table 5.6, Budiriro area water consumption for April 2012 was 64% of the total supplied. Belvedere was 71%, Glen View was 63% and Mabelreign was 58%. This information gives equivalent water loss of 36% for Budiriro, 29% for Belvedere, 37% for Glen View and 42% for Mabelreign. However, these figures show crude values of water losses.

Table 5.6 Average water supply and consumption (2002-2012)

Water Supply Area	Monthly Average		% Consumption	% Loss
	Water supply (m^3)	Water consumption (m^3)		
Budiriro	421,959	268,769	64	36
Belvedere	130,419	92,987	71	35
Glen- view	287,333	182,036	63	37
Mabelreign	167,110	96,290	58	42
Average			64	36

Thus, the City of Harare water balance analysis indicated that the selected four DMAs have an average of 40% of total water loss and an average of 30% water lost as leakage water. The results from SANFLOW analysis model show an average of water loss of 36% and an average water leakage of 33%. Thus, the results show a 10% deviation in total water loss and a 10% deviation in water leakage meaning fair leakage prediction efficiency. It can therefore be concluded that SANFLOW Analysis Model is applicable to the Harare, Zimbabwean situation, as it is in Malawi as outlined by Chiipanthenga (2008) and Chipwaila (2009), in partitioning total water loss. It can be deduced that SANFLOW analysis model could be used successfully by utilities in other developing countries with similar characteristics as the City of Harare in partitioning water losses and in predicting water leakages. Thus, SANFLOW analysis model is a very useful aid in understanding water leakages in developing countries.

5.8 Application of artificial neural networks in water distribution networks

5.8.1 Leakage detection by comparing measured and predicted water demand

In order to detect leakage, a MATLAB based ANN Model was developed based on a continuous comparison between the measured water demand and the predicted water demand in a district metered area. The model processed the unfiltered flow measurements for the detection of leakages. In this study the water demand (supply into a DMA) was measured directly using a flow logger at the entrance of the DMA. Table 5.7 shows the statistical analysis of the inputs and target data used in the ANN for network training. The table shows summarised flow logging data for Budiriro and Belvedere in terms of the mean, the maximum and the minimum flows.

Table 5.7 Statistical data for Budiriro and Belvedere DMAs used in ANN model

	Date	Mean (m^3/h)	Max (m^3/h)	Min (m^3/h)
(Inputs) Budiriro	22/04/12	336	449	83
	23/04/12	195	346	82
	24/04/12	157	379	81
	25/04/12	160	432	81
	26/04/12	207	429	80
(Targets) Belvedere	22/04/12	274	383	29
	23/04/12	200	449	80
	24/04/12	157	346	81
	25/04/12	132	250	48
	26/04/12	160	387	47

In the case study of the City of Harare, the prediction algorithm (the optimal network) was run using the original flow logging data (model input data) and compared with the actually measured data.

5.8.2 Network architecture

After trying several configurations, the optimum network architecture developed was based on one input layer and one hidden layer with twenty neurons using the training algorithm (trainlm) with early stopping. With early stopping data were divided as 70% training, 15% validation and 15% testing. To avoid over fitting more data sets were used, i.e. 1344 data sets. The training was stopped when the validation error increases for some specified and or default number of iterations. The weights and biases with minimum validation errors were returned finally. The network converged after 11 epochs with a mean square error (MSE) of 0.055 for training the subset. Also, through principal component analysis all the input variables were retained at 0.001 confidence level. This gave the best optimisation of the performance function with the least MSE. The output flow obtained through simulation (by the developed network) was found to have a very good correlation with the target flow at 0.997.

The mean daily volumes of water into the Budiriro DMA are shown in Table 5.8. The table shows the 1-20-1 ANN model, the actual model inputs, the model simulated outputs and a mean percentage prediction deviation of 0.39%. Thus, Table 5.8 shows the mean value of the modelled flows into the DMA. With a mean simulation efficiency of 99.61%, it can be inferred that the model is quite efficient in modelling the daily (24 hours) flow dynamics of the water entering the DMA.

Table 5.8 ANN Flow Simulation results: Budiriro DMA

Budiriro DMA			
Configuration: 1-20-1	ANN Model		Mean Deviation 0.39%
Date	Actual inputs (m^3)	Simulated outputs (m^3)	% Deviation
22/04/12	15,898	15,966	0.42
23/04/12	19,385	19,421	0.19
24/04/12	15,402	15,349	0.33
25/04/12	19,352	19,275	0.39
26/04/12	18,105	18,217	0.62

The mean daily volumes of water entering the Belvedere DMA are shown in Table 5.9. The simulated outputs deviated from the mean by 0.36%, thus showing a simulation efficiency of 99.64%

Table 5.9 ANN Flow Simulation results: Belvedere DMA

Belvedere DMA			
Configuration: 1-20-1	ANN Model		Mean Deviation 0.36%
Date	Actual Inputs (m^3)	Simulated outputs (m^3)	% Deviation
22/04/12	16,099	16,163	0.40
23/04/12	19,619	19,668	0.25
24/04/12	26,587	26,703	0.44
25/04/12	12,698	12,733	0.28
26/04/12	15,201	15,268	0.44

Table 5.9 shows the computation of the leakage detection using simulated water consumption in the Budiriro DMA. The difference between the simulated water consumption and the actual metered consumption represents the water leakage. Thus, Table 5.9 shows an average of 2.2% difference from the actual water consumption (metering value) indicating that 2.2% of the water supplied to the Budiriro DMA was lost through leakages from 22 April 2012 to 26 April 2012.

Table 5.10 Network configuration, actual and simulated demands

Model 1	Configurations 1-20-1	MSE 0.055	R^2 0.97
Budiriro DMA			
	Actual Metered Consumption (m^3)	Simulated Water Consumption (m^3)	% Difference
Figure 5.2	15,073	15,966	5.6
Figure 5.3	19,241	19,421	0.9
Figure 5.4	15,393	15,349	0.3
Figure 5.5	19,834	19,275	2.8
Figure 5.6	18,488	18,217	1.5

Figures 5.12, 5.13, 5.14, 5.15 and 5.16 show the graphs of the actual water demand obtained from flow logging data and the predicted flows obtained from testing the ANN.

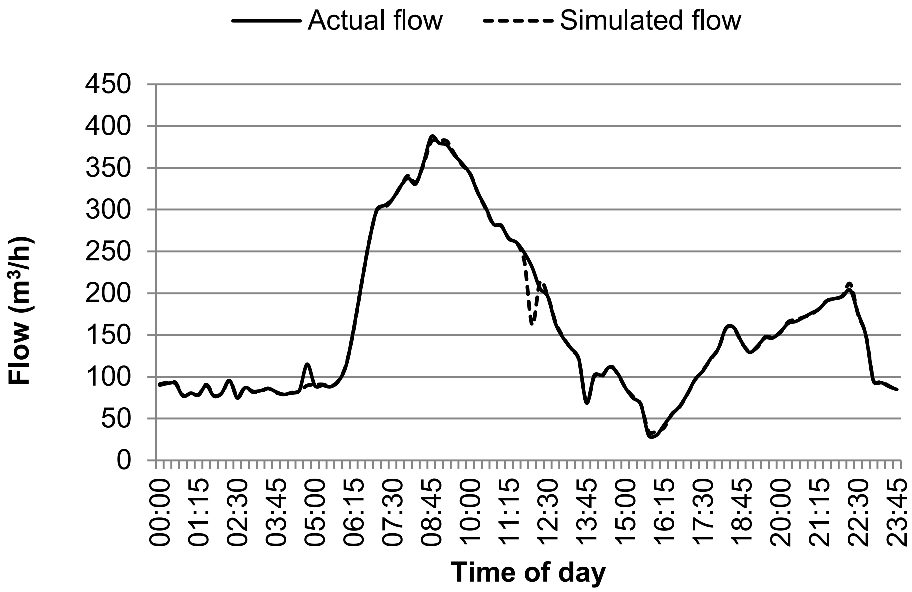


Figure 5.11 Actual flow and simulated flow (22/04/12)

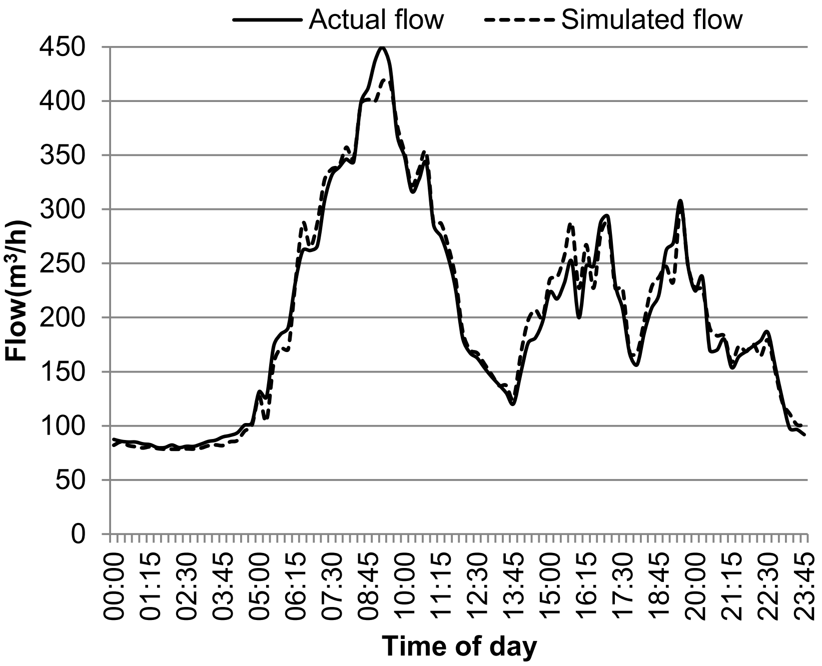


Figure 5.12 Actual flow and simulated flow (23/04/12)

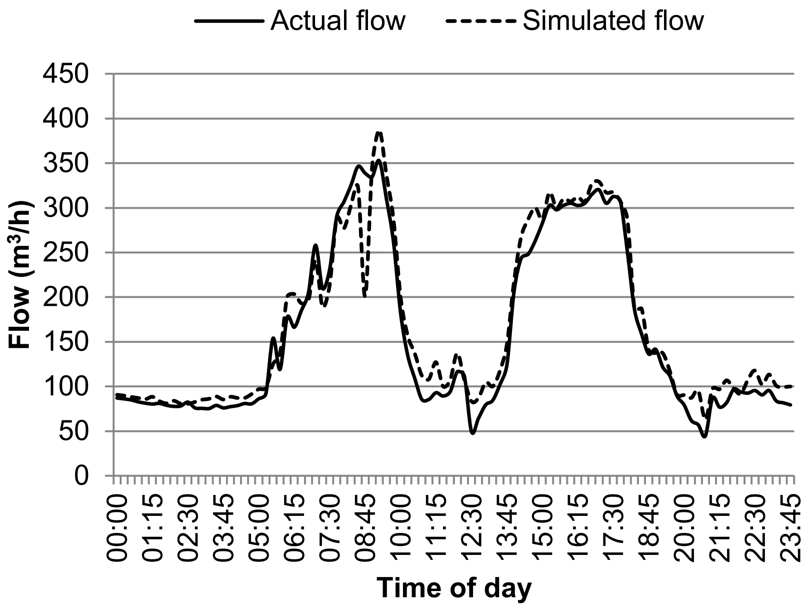


Figure 5.13 Actual flow and simulated flow (24/04//12)

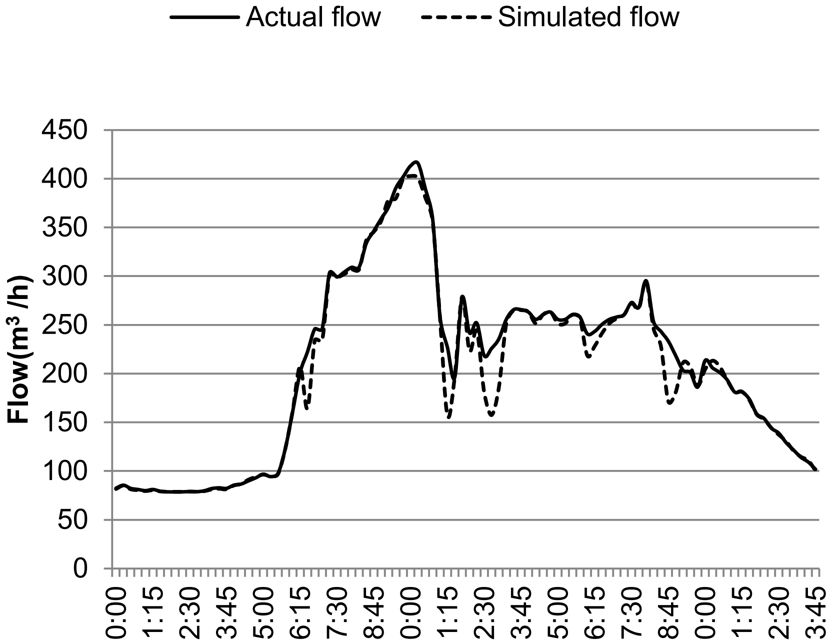


Figure 5.14 Actual flow and simulated flow (25/4/12)

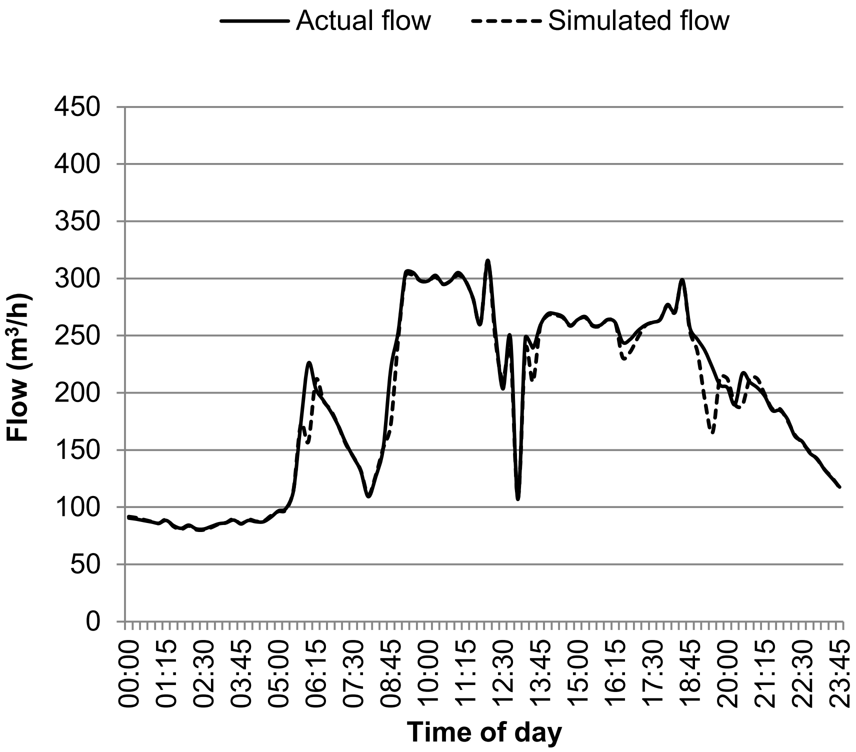


Figure 5.15 Actual flow and simulated flow (26/04/12)

Table 5.11 summarises the water actual metered consumption and the simulated water consumption in the Belvedere DMA over the period 22 April to 26 April 2012.

Table 5.7 Network configuration, actual metered consumption and simulated water consumption

Model 1	Configurations 1-20-1	MSE 0.055	R^2 0.97
Belvedere DMA			
	Actual Metered Consumption (m^3)	Simulated Water Consumption (m^3)	% Difference
Figure 5.7	15,417	16,163	4.6
Figure 5.8	19,241	19,668	2.2
Figure 5.9	26,346	26,703	1.3
Figure 5.10	12,695	12,733	0.3
Figure 5.11	15,074	15,268	1.3

Figures 5.17, 5.18, 5.19, 5.20 and 5.21 show the actual metered consumption (actual flow) and the simulated water consumption (Simulated flow) for the Belvedere DMA. The percentage difference between the actual metered consumption (sub-meter reading) and the simulated water consumption represents the water lost through leakages. Thus over the 5 day period an average of 1.94% of the water supply to the DMA was lost through leakage.

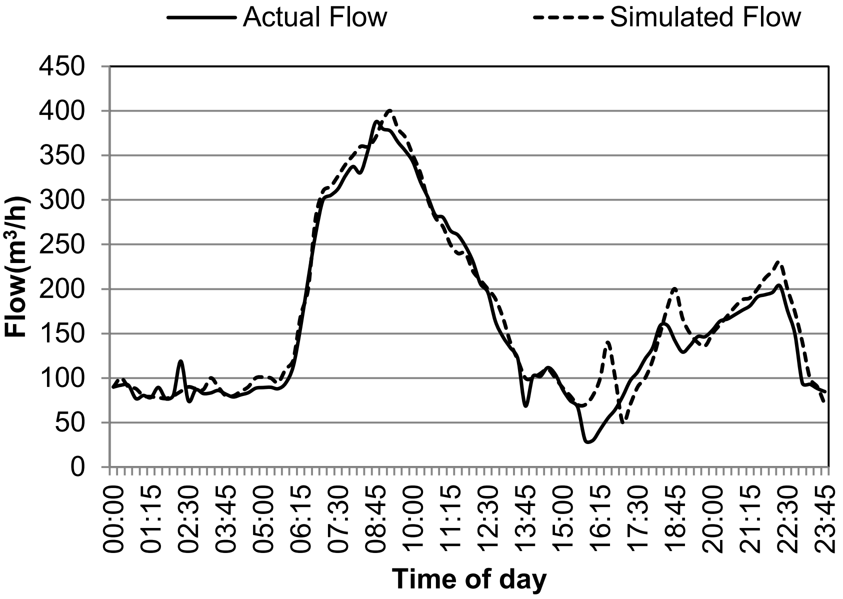


Figure 5.16 Actual flow and simulated flow (22/04/12)

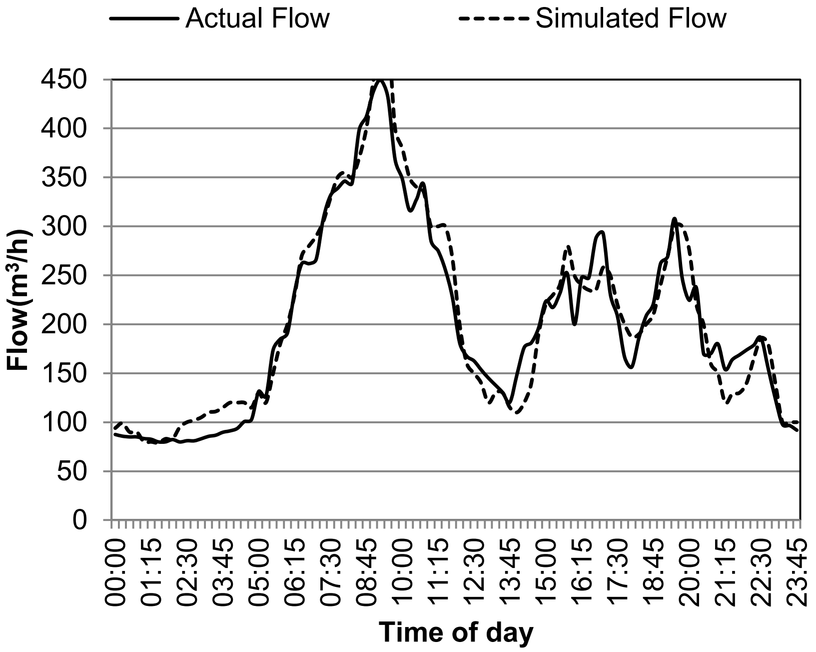


Figure 5.17 Actual flow and simulated flow (23/04/12)

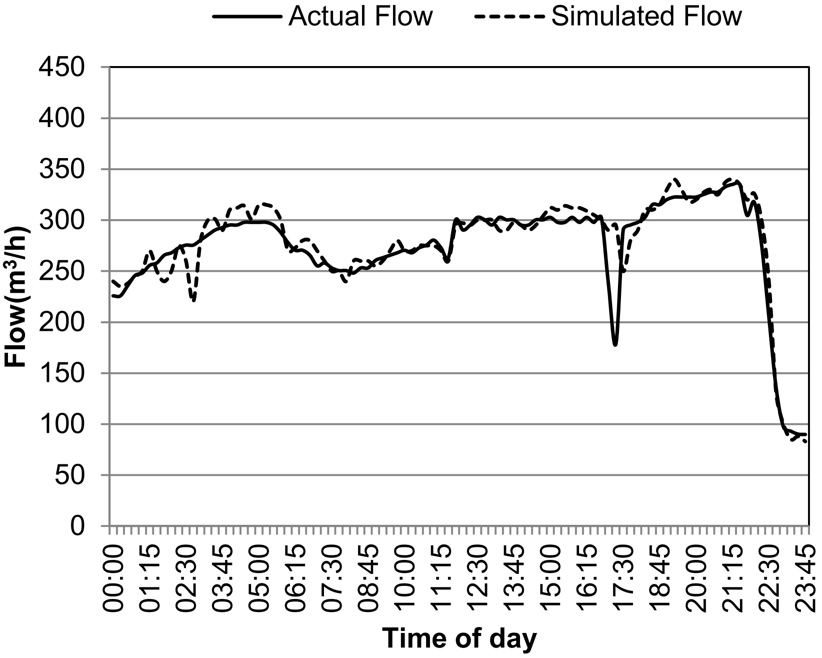


Figure 5.18 Actual flow and simulated flow (24/04/12)

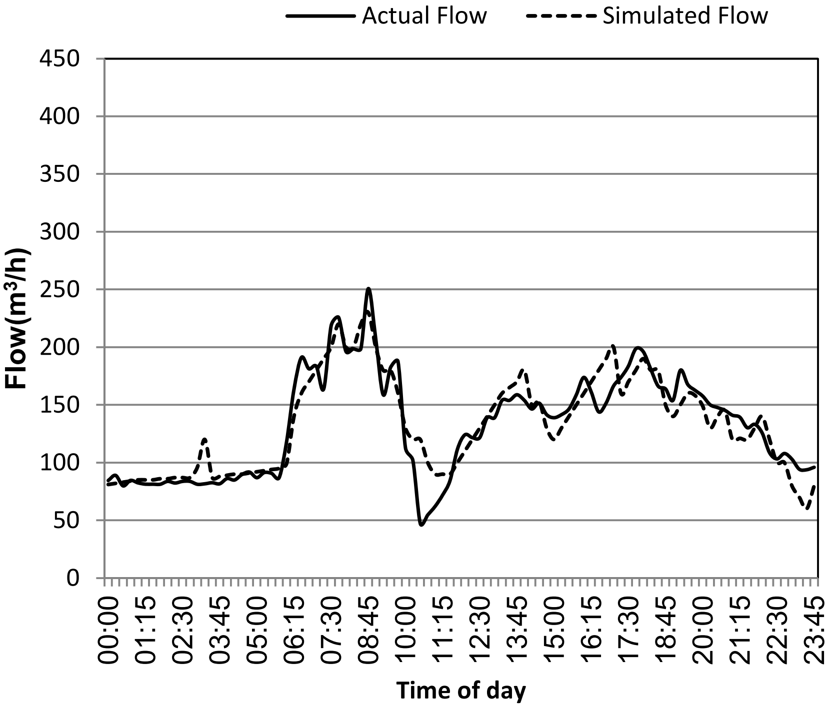


Figure 5.19 Actual flow and simulated flow (25/04/12)

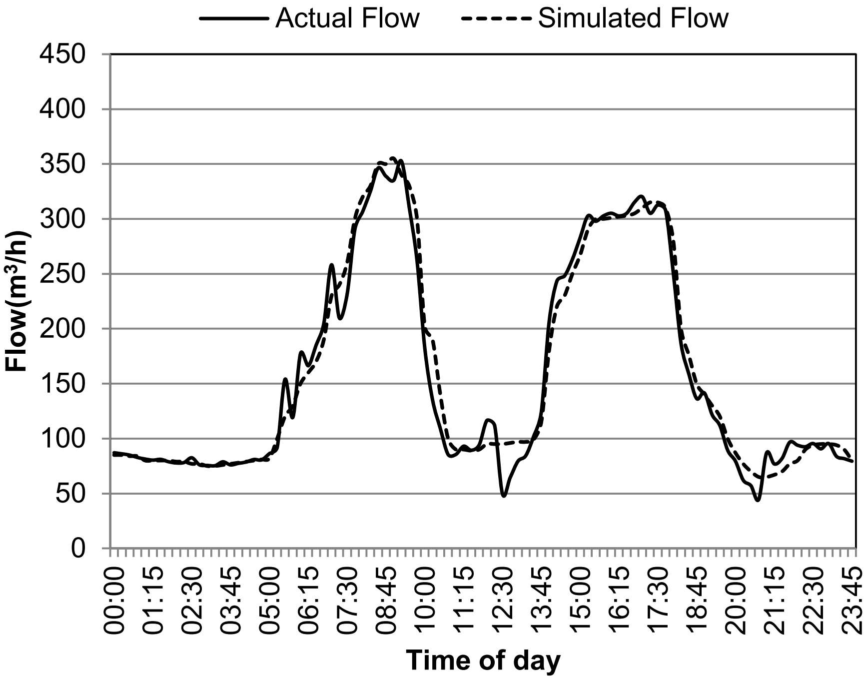


Figure 5.20 Actual flow and simulated flow (26/04/12)

Figure 5.22 shows the graphs of actual water demand versus predicted demand of the City of Harare for the period January 2009 to December 2011. The percentage leakage represents the percentage difference between the actual water consumption (according to DMA metering) and the predicted water demand according to the developed ANN model. The average actual water consumption is 16.1 million litres per month and the simulated average water demand is 10.8 million litres per month. The difference represents an average water leakage of 33%. This leakage result is consistent with the estimated leakage value of 36% for the City of Harare (City of Harare, 2011). Thus, the developed ANN model for modelling flow into a DMA and the leakage model (simulated water demand less metered water consumption) are quite effective and efficient tools for water utilities to understand and assess the water losses in their water distribution networks.

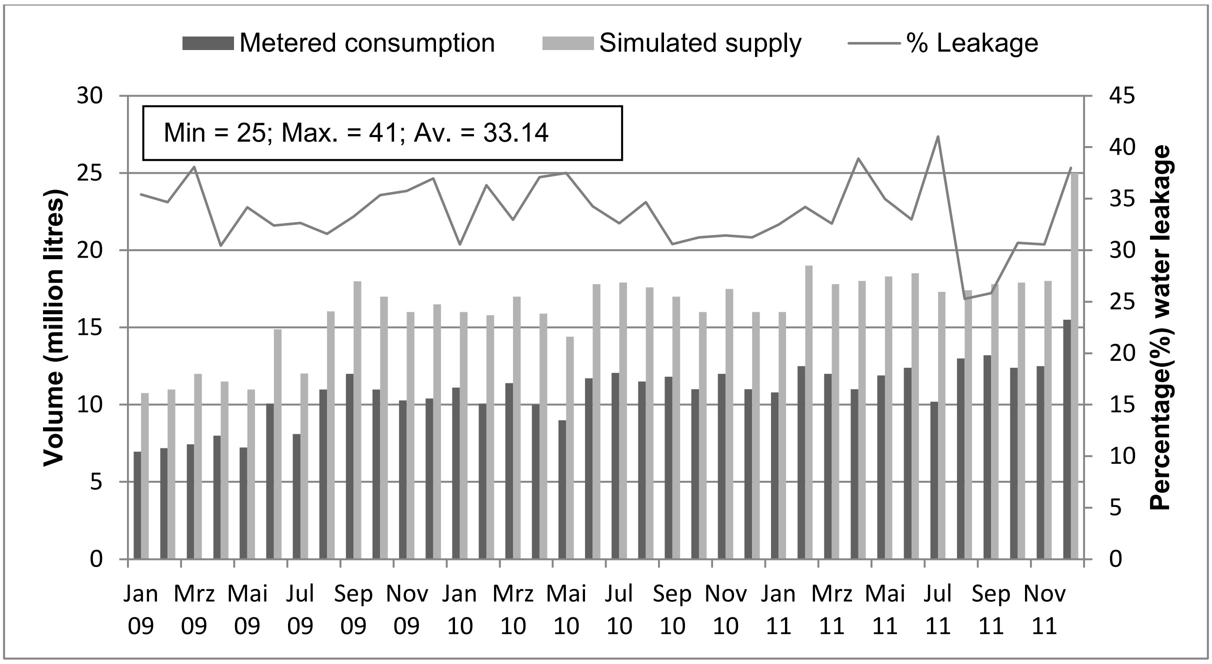


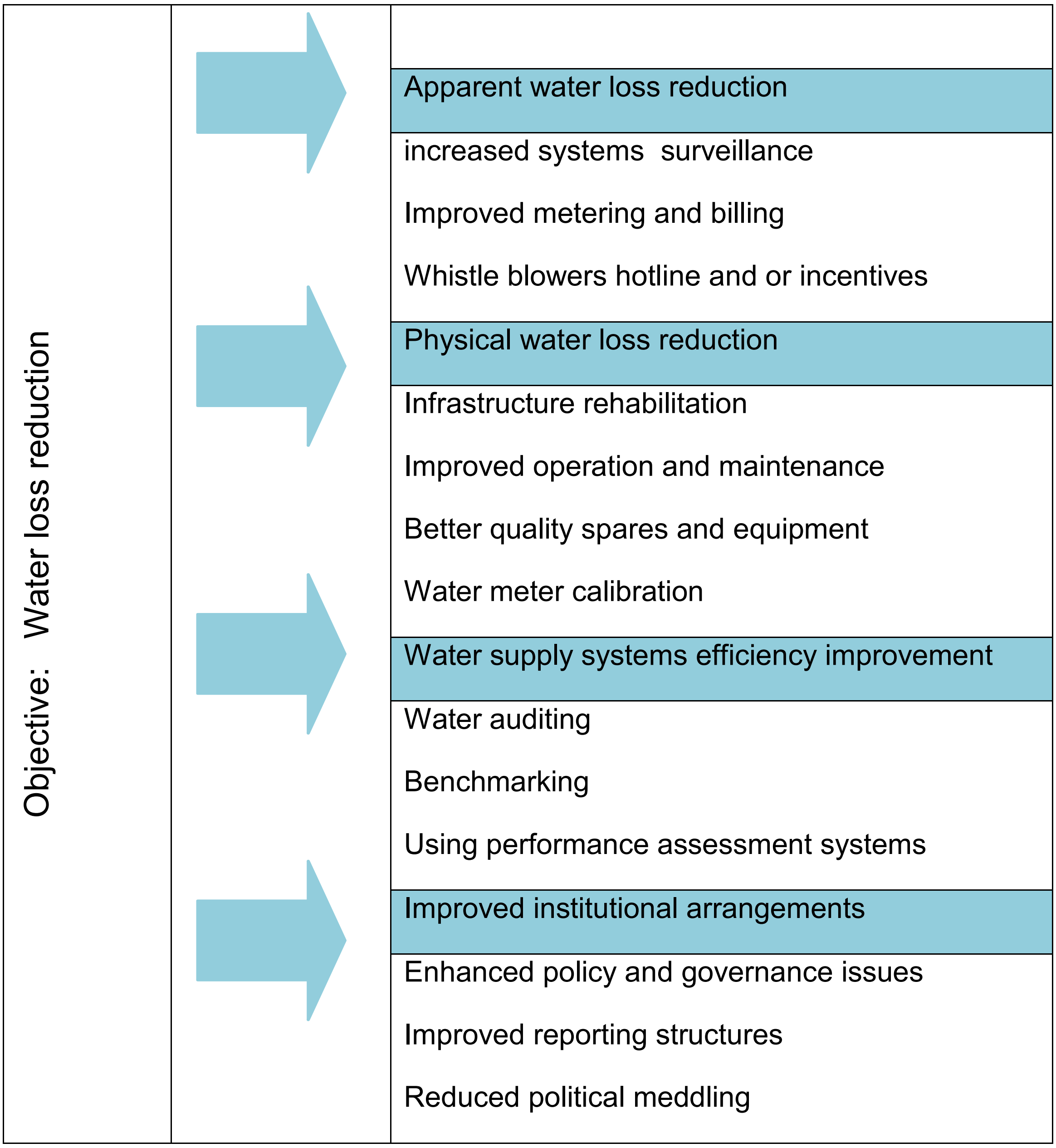
Figure 5.21 Historical leakages from January 2009 to December 2011

Thus, a feed-forward ANN model with early stopping, using back-propagation was developed to simulate flow into DMAs of the City of Harare. The results show that an appropriate (99%) accuracy can be achieved using the developed network. It is therefore concluded that the neural network approach for modelling flow dynamics is capable of yielding good results and can be considered as an alternative to traditional flow logging approaches. Furthermore, the developed methodology can be used to detect leakages in the water distribution networks with good precision. The developed ANN model is peculiar in that it can detect small leakages of less than 5%. The developed methodology is compact, adaptable, cost effective and simple to apply. Thus, the weaknesses of the traditional flow logging approaches entailing data collection costs and time delays as well as data handling errors, are therefore offset. In spite of the achieved milestone, the work can be further extended to simulate pressure dynamics in water distribution networks and hence quantify background leakages.

5.9 Proposed integrated water leakage management framework

5.9.1 General

The integrated water leakage management framework is a subset of the whole general water loss management framework. Although it is not the main objective of this study to look at water loss in its totality, the general water loss management framework is presented as it helps as a source of background information for water leakage management. Figure 5.23 shows the proposed general water loss management framework for developing countries. Figure 5.24 shows the general leakage management approaches that can be used by utilities in developing countries. Figure 5.25 shows an operation and maintenance decision framework outlining the operation and maintenance activities that can be adopted by water utilities. This is followed by Figure 5.26 which shows a schematic of water leakage systems analysis protocol. The water supply system, metering system, leakage detection system and the DMA management system, all feed into the data management system. The approach is one that attempts to visualise water leakage from a systems perspective. Such an approach helps management in planning for water leakages easily.



Objective: Water loss reduction

Apparent water loss reduction

increased systems surveillance

Improved metering and billing

Whistle blowers hotline and or incentives

Physical water loss reduction

Infrastructure rehabilitation

Improved operation and maintenance

Better quality spares and equipment

Water meter calibration

Water supply systems efficiency improvement

Water auditing

Benchmarking

Using performance assessment systems

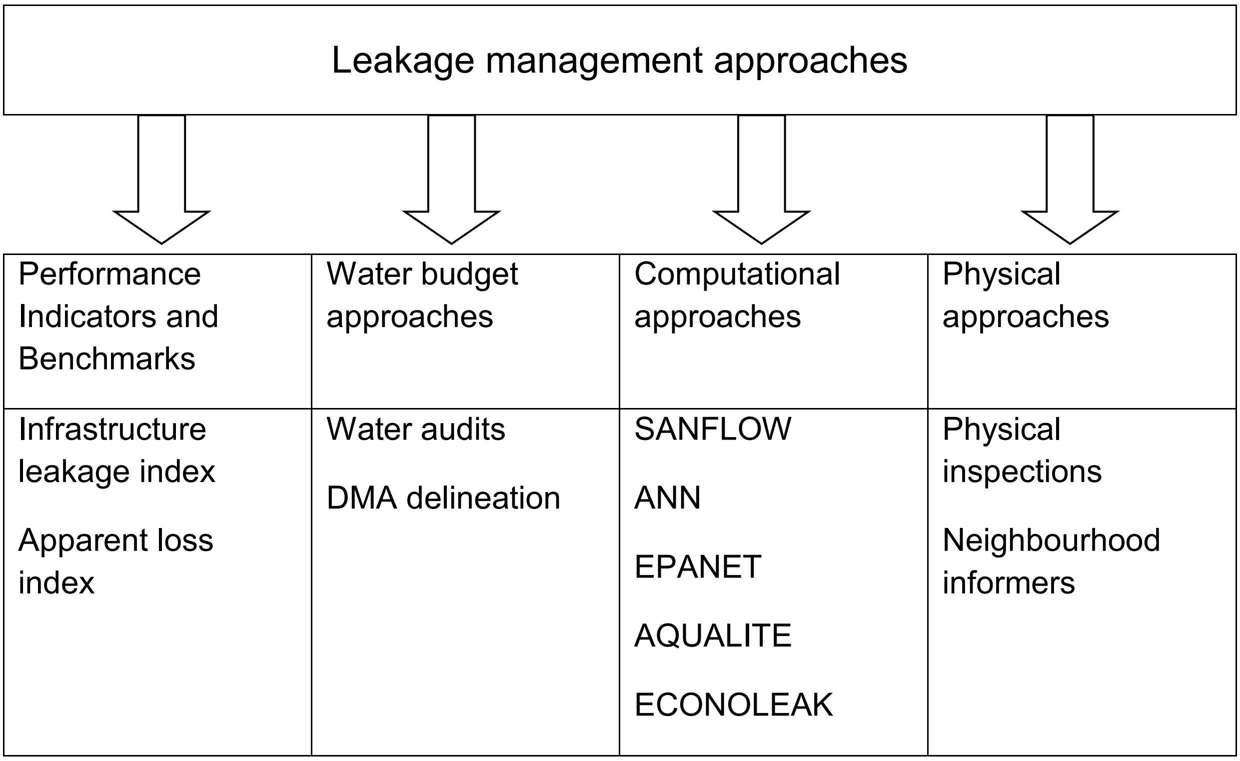
Improved institutional arrangements

Enhanced policy and governance issues

Improved reporting structures

Reduced political meddling

Figure 5.22 General water loss management framework



Leakage management approaches

Performance Indicators and Benchmarks	Water budget approaches	Computational approaches	Physical approaches
Infrastructure leakage index Apparent loss index	Water audits DMA delineation	SANFLOW ANN EPANET AQUALITE ECONOLEAK	Physical inspections Neighbourhood informers

Figure 5.23 Leakage management approaches

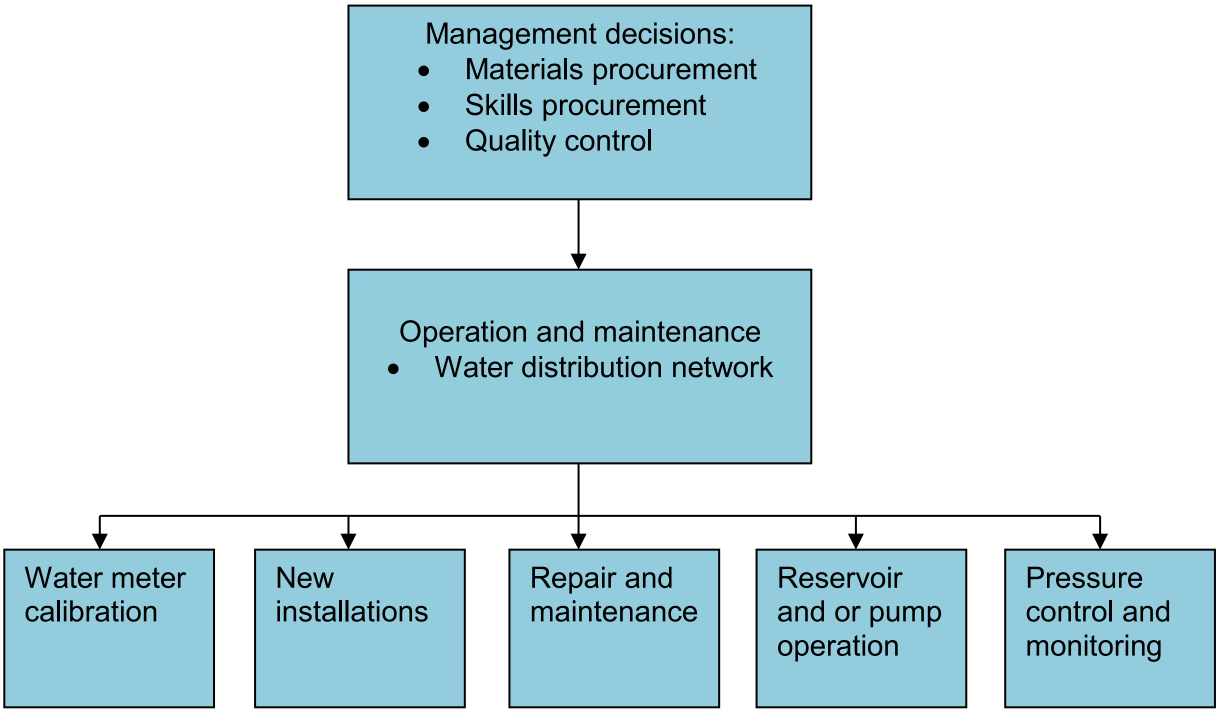


Figure 5.24 Decision making by operation and maintenance taskforce

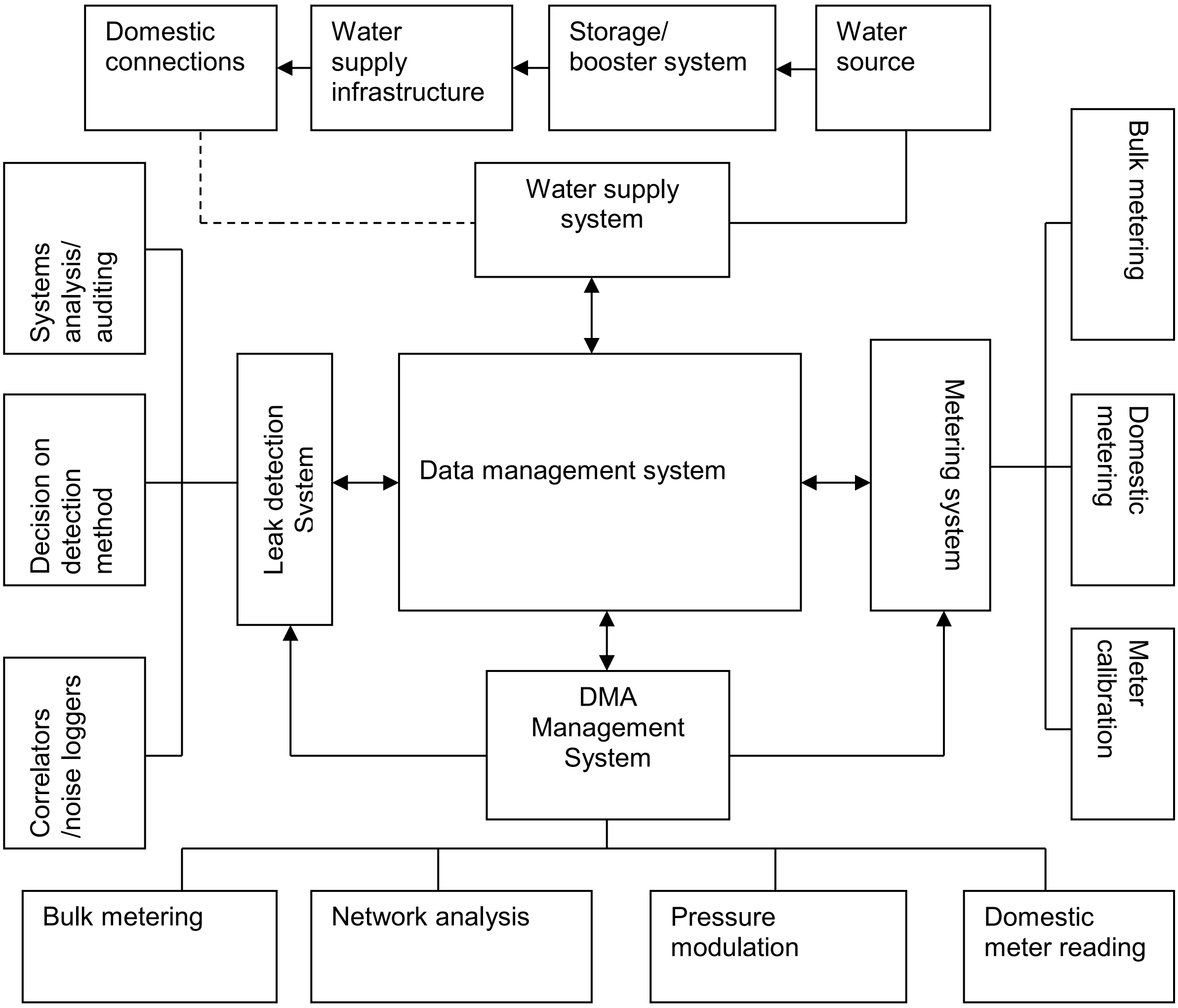


Figure 5.25 Schematic water leakage systems analysis protocol

5.9.2 Steps in decision making

Depending on the management criteria for a particular water utility, decision making has proven to be a big challenge for many water utilities. This is mainly because lines of command for each utility are peculiar to that utility. As a result, there is no hard and fast approach to the decision making process. A nine-step decision making process approach has been proposed (Lu et al., 2007; Simonovic, 2009):"

- Define the problem.
- Determine the requirements.
- Establish objectives and goals.
- Generate options.
- Determine criteria.

- Select a decision-making method or tool.
- Evaluate options against criteria.
- Validate solutions against problem statements
- Implement the problem''.

The final stage is to apply the obtained solution to the decision problem.

For effective water leakage management, there is need to develop an associated decision support framework. The framework evokes subsystems in Figure 5.26 and attempts to address the following questions:

(i) How is water lost in a water distribution system?
(ii) Where is water lost in a water distribution system?
(iii) When is water lost?
(iv) How to anticipate for water leakages?
(v) How prepared is a water utility to deal with leakages?
(vi) What is the best method for leak detection?
(vii) What is the best leakage management methodology?
(viii) What is the best leak fixing method?
(ix) How fast can a leak be attended to?
(x) Who is responsible for leakage management decisions?

The integrative framework is a problem structuring method which provides guidance for stakeholder engagement, criteria selection and alternative development (Lai et al., 2008). The best water loss reduction option is therefore selected Although there are many decision making methods or tools, multi-criteria decision analysis (MCDA) is the most commonly used in water resources management. Such a tool, member of the decision theory, can solve a huge range of operational research problems with a finite number of decision options amongst which decision-makers have to evaluate and rank based on the weights of a finite set of evaluation criteria (Lu et al., 2007; Simonovic, 2009). MCDA is a structured framework for analysing decision problems characterized by complex multiple objectives and criteria. It is generally used as an analytical tool but can also be applied as an integrated framework by coupling it with appropriate problem structuring methods. Figure 5.27 is the proposed Integrated Water Leakage Management Decision Support Framework. The framework has been developed in a way that Multi-Criteria Decision Analysis approach could be used in making water leakage management decisions.

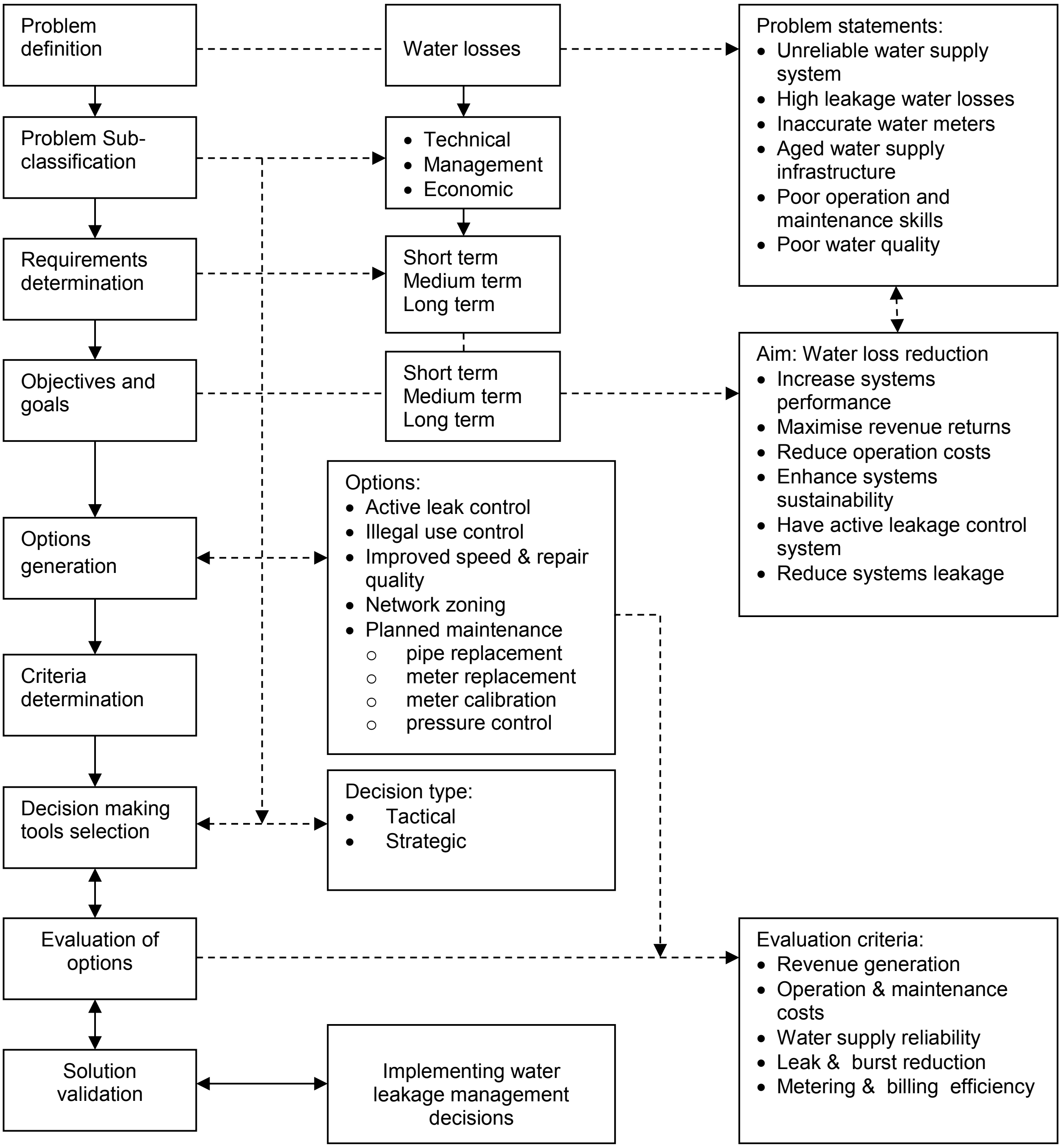


Figure 5.26 Proposed integrated water leakage management decision support framework

The proposed integrated water leakage management decision support framework uses a nine step approach, from problem definition to implementation of water leakage management decisions. The selection of decision making tools and methods, evaluation of options and solution validation processes, have feedback loops to allow for the refinement of the decisions so made.

Thus, Figures 5.23-5.27 are a condensation of the water loss management problem analysis approach which helps utilities in developing countries to clearly visualise their water supply systems in order to understand water leakages and device appropriate water leakage management interventions.

6 Overall discussion

This study reviewed many publications on water loss management. The publications were on NRW concepts, tools and methodologies for managing water losses, benchmarking and performance assessment and computational approaches to water loss management. Thus, the study drew a lot of insights about leakage management, first looking at what the developed world has done so far, then the status quo in developing countries. It was discovered that developing countries lag behind in their leakage management, and their leakage management is passive hence non-proactive. With passive leakage management, leakages are not anticipated and the reaction time to a leakage event is very long resulting in a lot of revenue being lost coupled with poor service delivery. Because of unpreparedness of the water utilities that do not adopt the active leakage management strategy, they won't be having the right skilled personnel, right specialised tools and equipment to deal with some leakage and hence may cut-off supplies to certain consumers in order to avoid further water losses. Poor technological development in many developing countries has resulted in many utilities losing a lot of water because they do not have the right leak detection tools and equipment. In trying to understand leakages, this study discovered that leakage water constitutes the largest fraction of the total physical water losses. Thus, the methodologies in developing countries should be streamlined to specifically address leakages in all fronts. Utilities in developing countries should adapt computational approaches and methodologies that will help them detect even small background leakages. These leakages have gone for a long time undetected and have ultimately resulted in extremely huge amounts of water losses over years.

It was also the objective of this study to assess the applicability of performance assessment systems with a view to appraising their application in developing countries. In that regard the systems and tools developed for the water industry may not be directly applicable to WDSs of the developing countries. Operational performance efficiency is very vital for perpetuation of a sound service delivery. Many water utilities fail to identify and apply indicators appropriate and relevant to their operations. Thus, developing countries utilities should be capacitated to be able to apply assessment indicators in order to elevate their systems efficiency and to meeting international standards. This is mainly because their systems suffer from inadequate water supply, poor billing and poor operation and maintenance records, resulting in exceptionally high NRW and poor service delivery coupled with unrealistic water prices. Water utilities and regulators of the operations of water utilities should make it a top priority that utilities operate within the right frameworks of efficiency assessment indicators. The regulatory authorities should also stipulate consistent reporting on the performance of a utility based on a specific performance system of indicators.

As a management practice, water losses should be partitioned in order to correctly direct water loss reduction efforts towards those sectors that require emergency attention. In this study, the amount of water leakage contributing to the total water loss for the selected water supply zones was analysed using the SANFLOW Analysis Model version 2.03. Apart from the minimum night flow data, the SANFLOW model uses basic infrastructure variables such as length of mains, number of connections, number of properties, estimated population, average zone night pressure and major water users. High water leakages were found in the selected DMAs. This was due to poorly maintained infrastructure, aged water distribution network infrastructure, pressure surges in the distribution network and generally prevalent transient conditions. Based on its applicability to partition water losses, it was concluded that SANFLOW is a good alternative tool, relevant and highly adaptable to the developing world. Although the study did not look at the other ways through which water was lost, the contribution of leakages were correctly quantified.

The other objective of this study was to model flow dynamics in a water distribution network using ANNs in order to assess the level of water being lost through leakage. In that regard, artificial neural network approach was adopted as a computational approach to water loss management. After simulating the flow dynamics, flows can be compared with water demands in a particular district metered area. The difference between actual water consumed as registered by district sub-meters and the simulated water demand for a district metered area represents the water leakage in the water distribution network, provided there are no other non-physical water losses. This study discovered that an ANN could be trained and be used to forecast flow with up to 99% accuracy. The ANNs technique is a flexible and efficient approach to detection of leakages in water distribution networks. The neural network approach for modelling flow dynamics is capable of yielding good results and can be considered an alternative to traditional flow logging approaches. Furthermore, the developed methodology can be used to detect small leakages of less than 5% precisely. Thus, the weaknesses of the traditional flow logging approaches entailing data collection costs and time delays as well as data handling errors, are therefore offset.

Finally, the study attempted at developing an integrated water leakage management system for use in developing countries. In view of that, water leakage management should not be viewed through individual leakage management activities, but rather as an integrated system, with inputs and specific outputs. The water leakage management approach should seek to integrate drivers of water losses and the systems operation modalities in order to make the right management decisions which would feed into the universal water loss management entity. The proposed water leakage management system is premised on the understanding that reliable data is fed in so as to get the right feedback/ decision. The proposed Integrated decision support framework bases decisions on MCDA methodology and follows a nine-step approach and is based on a systems approach. Therefore, water utilities in developing countries should embrace change to their systems and be proactive in all water loss management initiatives. There is need for utilities to properly understand their water distribution networks, understand the pressure and flow dynamics and water supply and demand dynamics of their systems, ensure proper metering and have well defined DMA. Minimum night flow analysis plays a very important role in clearly defining supply-demand dynamics of water distribution networks.

7 Recommendations and suggestions

- The current study has been conducted using flow logging data. It is therefore recommended that pressure logging data be used concurrently with flow logging data. This would help in doing a flow-pressure comparative analysis in order to make conclusive evaluation.
- The performance assessment approach used in Harare gave similar results as in literature, but the infrastructure leakage index could be used to give a better picture of the maintenance state of the infrastructure.
- The water loss partitioning undertaken correctly managed to show a fraction of leakage water only, however, the study could be extended to show all the fractions of the total water losses.
- The ANN model developed should be used with a leakage correlator in order to pinpoint the leaks and also establish the magnitude of the leakage.
- The developed water leakage detection shows a gross leakage value which incorporates illegal connections and as such the model should find a way of eliminating losses due to illegal connections and find the exact water lost through leakages.
- Finally, the developed integrated water leakage management system could be validated in a case study to establish its applicability and effectiveness.

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9 Appendices

9.1 Questionnaire survey

Enumerator Name ………………… …………………
Suburb: ………………… …………………
Date: ………………… …………………

Section A: Accessibility of water

1. Demographic and socio-economic status of household
   (a) No. of adults ☐ Females ☐ Males ☐
   (b) No. of children ☐ Females ☐ Males ☐

2. What is the main water source used by the household?
   Piped water ☐ River/Pond ☐ Borehole/well ☐
   Other……………………………………………

3. If it is piped, where is the source connected?
   In own house ☐ In own yard/plot ☐
   In neighbours house ☐ Other…………………………

4. On average how frequently do you receive piped water?
   Once a day ☐ Twice a day ☐ Once a week ☐
   Every alternate day ☐ Continuous 24hrs supply ☐
   Other ………………….

5. Is this frequency of receiving water satisfactory? Yes ☐ No ☐

6. If not satisfactory, which frequency will be satisfactory?
   Once a day ☐ Twice a day ☐ Once a week ☐
   Every alternate day ☐ Continuous 24hrs ☐

Section B: Affordability and reliability

7. What is the average water consumption per day for the household use?
   30-50Litres ☐ 50-100Litres ☐ 100-150Litres ☐
   150-200Litres ☐ Others :………………… …………………

8. Is water consumed in part 7 above adequacy for the daily household use?
   Yes ☐ No ☐

9. Is your piped water supply metered? Yes ☐ No ☐

10. If yes in 9 above, is it working? Yes ☐ No ☐ Not sure ☐

11. If yes in 9, do you know how much are you paying per cubic meter of water?
    Yes ☐ No ☐

Section C: Sufficiency and effectiveness

12. Do you receive your water bill in time every month? Yes ☐ No ☐

13. If no, how long does it take to receive your water bill? 1-2months ☐
2-4months ☐ 4-6months ☐ >6months ☐ Others . . . .

14. Have you ever made any complaint to the authority about water services?
Yes ☐ No ☐

15. If yes, what type of complaint? Water bills ☐ Pipe burst ☐
Poor water quality ☐ Other specify……………………………………

16. Was your complaint handled? Yes ☐ No ☐
If yes, were you satisfied with the way your complaint was handled?
Yes ☐ No ☐

17. When piped water is available, how do you rate the water pressure?
High ☐ Average ☐ Low ☐ Don't know ☐

18. In your opinion, do you think City council is providing good services?
Yes ☐ No ☐