KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

KUMASI GHANA

INTEGRATING HYDRAULIC AND GIS MODELING FOR ASSESSING WATER LOSSES

CASE STUDY; KUMASI SOUTHEAST DISTRICT

By

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DECLARATION

I hereby declare that this submission is my own work towards the award of Master of Science and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the university, except where due acknowledgement has been made in the text.

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ABSTRACT

There are several challenges facing water utility companies. One of such challenge is high level of water losses (non-revenue water) in a distribution network. Non-revenue water (NRW) is water that has been produced but cannot be billed. The loss can be as a result of leakages (real losses), theft of water (apparent losses) and free use (unbilled authorized consumption). In the Ashanti Region of Ghana, Non-revenue water (NRW) levels have been consistently high. This has affected revenue and quality of service to customers. The main objective of this research was to use an integration of a hydraulic model and GIS to estimate non-revenue water in Kumasi Southeast District. In determining the magnitude of non-revenue water, the International Water Association methodology and empirical flow rates were used. The hydraulic modeling software 'Epanet' was used in modeling the water distribution network. In modeling the pipe network, the Hazen-Williams algorithm for water flow rate, friction and headloss was used. Parameters such as pressure, flow, unit headloss, velocity and friction factor were obtained for the various pipes and nodes upon a successful run of the model. The pressure values generated by the hydraulic and the GIS model at each node were used to determine the background leakages at the various nodes. This was done using the standard hydraulic equation. GIS was used in modeling the water distribution network. The research shows that non-revenue water level was as high as 49% of the total water supplied to Southeast District of Ghana Water Company Limited (GWCL). The 49% of the system input volume (SIV) represented 283,146m^3 of treated water, out of which 215,068m^3 was lost through real losses. This represents 75.96% of the non-revenue water. Apparent losses contributed 67,948m^3, representing 24% of the total non-revenue water. Unbilled authorized consumption also contributed a loss of 129m^3 of the system input volume (SIV). This represents 0.04% of the total non-revenue water. The model also revealed the level of background leakages at each node. The highest level of background leakage was 0.087669m^3 while the lowest level of background leakage was 0.001854m^3. The study concluded that hydraulic and GIS models are complementary technologies and their integration provided access to more reliable, up-to-date information and reduces response time to tackle water losses.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMA	Accra Metropolitan Assembly
AVRL	Aqua Vitens Rand Limited
AWWA	American Water Works Association
CARL	Current Annual Real Loss
BL	Background Leakage
DMA	District Metered Area
DPU	Data Processing Unit
di	Demand allocated to node i,
di(t_{min})	Demand of node i at time tmin
ELL	Economic Level of Leakage
EPA	Environmental Protection Agency
FAVAD	Fixed and Variable Area Discharges
GIS	Geographical Information System
GSS	Ghana Statistical Services
GWCL	Ghana Water Company Limited
H	Node elevation
h	Total head
Hi	Total head at node i
HPZ	High Pressure Zone
ICF	Infrastructure Correction Factor
ILI	Infrastructural Leakage Index
IWA	International Water Association
i	Node index
k	Leakage coefficient
l(t)	Nodal leakage flow at time t
li	Leakage flow allocated to node i
KMA	Kumasi Metropolitan Assembly
KWSS	Kumasi Water Supply System
MNF	Minimum Night Flow
NRW	Non-Revenue Water
P(t)	Nodal pressure at time t
Pi(t_{min})	Pressure of node i at time tmin

$q(t_{min})$ Minimum night flow (MNF)

SIV System Input Volume

UARL Unavoidable Annual Real Loss

UFW Unaccounted For Water

WDS Water Distribution System

WHO World Health Organization

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

Water is an important resource that has a multitude of interdependent uses including irrigation, drinking water, sanitation, energy and environmental services (Vandycke & Saghir, 2010). In the 21st century, water issue has become one of the most important global issues, both in terms of development and environmental conservation (Chan, 2004). The global climate changes have threatened the water security. In Africa, population growth, rapid urbanization, industrialization and economic development put pressure on freshwater resources. As a result, proper water management is to be adapted to aid future demand of water distribution. One of the major challenges faced by water management in African cities is the high level of water loss in water distribution network. Heavy loss of water in distribution system could cause the water utilities harder to keep water tariffs at a reasonable and affordable level (Frauendorfer & Liemberger, 2010). The global volume of non-revenue water (NRW) or water losses is staggering. Each year more than 32 billion m^3 of treated water is lost through leakages from the distribution networks (Simbeye, 2010). An additional 16 billion m^3 per year is delivered to consumers but not invoiced because of theft, poor metering or illegal use (Simbeye, 2010). A conservative estimate of the total annual cost to water utilities worldwide is US$14 billion (Kingdom et al., 2006). In some low-income countries this loss represents 50 - 60% of water supplied, with a global average estimated at 35% (Kingdom et al., 2006). Saving just this amount would supply water to an additional 100 million people without further investment (Farley et al., 2008).

With regards to access to drinking water in Ghana, the 2010 WHO/UNICEF Joint Monitoring Programme (JMP) on sanitation and drinking water reports that there is improving water coverage with 90% water coverage in the urban areas. However, data from the Ghana Water Company Ltd indicates that the urban water coverage is only 59% (Barendrecht & Nisse, 2011). For example urban water supply coverage in 2005 was 57% with deteriorating quality (Barendrecht & Nisse, 2011). In 2006, non-revenue water (NRW) had reached about 60% based on real and apparent losses. Ghana has a total population of around 24.3 million (Ghana Statistical Service, 2012). The urban population of Ghana increased from 30% in 1975 to 48% in 2005 and is expected to reach 55% in 2015 (Ghana Statistical Service, 2012). This makes non-revenue water a cancer on the revenue performance of GWCL.

In most of the water supply systems in Ghana, reliable estimates of water loss components are not available. A crude figure of NRW which is reported by many water utilities does not give the water utility clues to prioritize and schedule on the operations and management of the system (Kingdom et al., 2006). As a result of this, NRW has become a persistent problem to water distribution companies. The causes of NRW in the Kumasi South East District are: the inability of the water company to quantify the various components of non-revenue water (NRW), inefficient maintenance of pipe network and high levels of leakages. These factors have led to: high financial losses to the utility company, low service coverage and customer dissatisfaction. This research aims at contributing to the search for more efficient, effective and practical way of dealing with the problem of non-revenue water (NRW).

1.2 PROBLEM STATEMENT

Water losses in the Kumasi water supply system is a persisting problem. This has led to some studies being carried out in the quest to find solution to the problem of water losses. Ampadu and Boakye (2004) study focused on assessing and monitoring water loss in Ghana Water Company distribution lines using GIS. Their research mapped the distribution lines and developed a GIS model that could effectively assess and monitor water losses in a distribution line. The conclusion of the study was that with the application of GIS, it is possible to assess and monitor water losses in a distribution network. Arthur–Mensah and Yatel–Kubin (2005) investigated and assessed the pressure effect on water loss in the Ghana Water Company. Their study focused on using EPANET (hydraulic modeling software) to determine nodal pressure and their effect on water losses. The study concluded that there is a direct relationship between pressure distribution and water losses. Therefore effective monitoring and the management of nodal pressure should reduce water losses in a distribution network. Gikunoo (2014) also assessed the components of Non-Revenue Water in the Kumasi Water Distribution System. The research focused on applying the International Water Association (IWA) methodology in calculating the various components of non-revenue water (NRW). The conclusion of this study was that the IWA methodology provides the most effective approach in assessing the components of non-revenue water.

This study integrates hydraulic and GIS modeling for assessing the various components of non - revenue water.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to use an integration of a hydraulic model and GIS in the reduction of the non-revenue water in Kumasi Southeast District.

The specific objectives of this research are: to analyze the existing situation and strategies for identifying and managing non-revenue water, to model pressure distribution on the pipe network and to integrate hydraulic modeling and GIS to determine water losses.

1.4 RESEARCH QUESTIONS

In order to keep focus and direct the research activities of this research work, the following research questions are formulated:

- What strategies are used for identifying and managing non-revenue water in Kumasi South East?
- How is the pressure along the water distribution network in the district distributed?
- How can hydraulic and GIS integrated models be used to evaluate non-revenue water in Kumasi South East?

1.5 RESEARCH METHODOLOGY

The approached used for the research is categorized into eight stages as shown in the Figure 1-1.

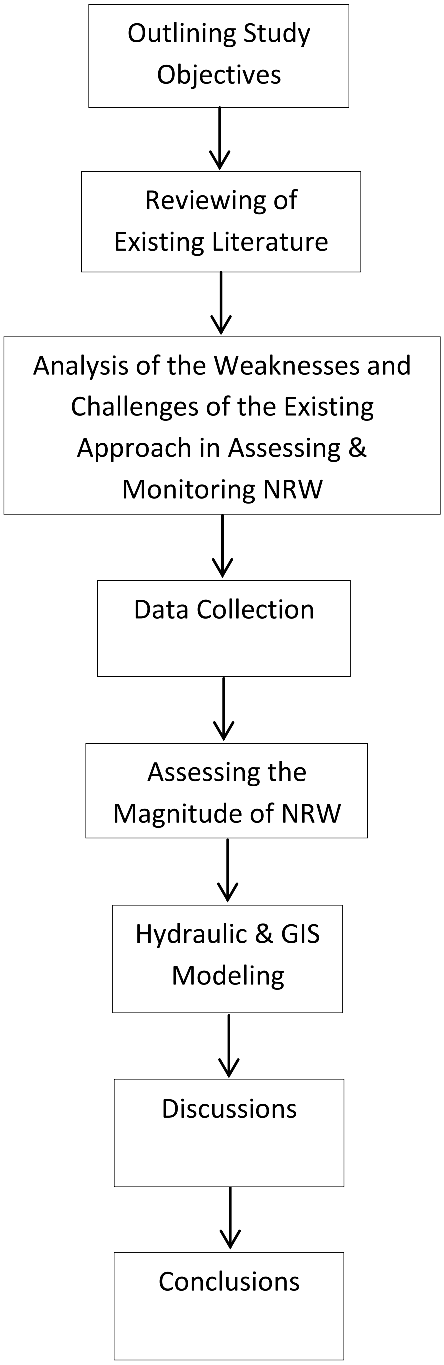

Figure 1-1: Research Methodology

The first stage of the study was to outline the objectives of the study (main objective and specific objectives). A clearly outlined objective forms an integral part of the success of the study. The second stage of the study involves reviewing all necessary literature in non-revenue water. This will aid in identifying the modern trends in NRW studies. The third stage deals with the analysis of the weakness and the challenges in the existing approach in dealing with NRW. This stage aids in developing an effective methodology to deal with NRW.

The fourth stage of the research is data collection. All data used in this research were collected from the offices of GWCL Kumasi. Data on customer information was obtained from the MIS office, while data on monthly system input was collected from the Statistics office. Data on pipelines and leakages was collected from the GIS office. The fifth stage of the research is the calculation of the various component of NRW. In calculating the various components of NRW, the IWA methodology and their empirical flow rates were used.

The sixth stage of the study is the GIS and Hydraulic modeling. Hydraulic modeling software called Epanet was used in modeling the WDS. It generated parameters for both nodes and the pipelines. The parameters generated for the nodes include pressure and head. While it generated parameters such as flow, velocity, unit headloss and friction factor for the pipelines. The data obtained from the Epanet were then fed into the GIS. The GIS model created identified the level of background leakages at the nodes and the level of reported leakages at the various communities.

The seventh stage focused on the discussions of the results obtained against literature. The last stage of the research represents the conclusions drawn from the research questions in the light of the research findings.

1.6 JUSTIFICATION OF THE PROJECT

In Ghana, the levels of NRW are mostly estimated and not modeled by any scientific means. The developing of a scientific approach in calculating NRW will go a long way in solving the problem of water shortage in the Kumasi Metropolis.

According to Liemberger (2002), real and apparent losses have to be quantified. No proper non – revenue water reduction strategy can be planned without the quantification of physical and apparent (commercial) losses (Kingdom et al., 2006). When the magnitude of the various components are known, it is possible to forecast potential savings (real losses) and potential revenue increase (apparent losses), develop real and apparent loss reduction strategies and set realistic targets (Liemberger, 2002). Thus developing a scientific approach in calculating NRW may assist the water utility to improve knowledge and documentation of the distribution system including problem and risk areas.

The breakdown of NRW into its various components becomes a valuable tool to manage resources, by getting a better understanding of what is happening to the water after it leaves the treatment plant. Thornton (2002) indicates that water loss reduction programs lead to reduced water losses, financial improvement, increased knowledge of the distribution system, more efficient use of existing supplies, safeguarding public health and property, improved public relations, reduced legal liability, and reduced disruption of water supply to customers.

1.7 THESIS LAYOUT

The thesis is structured into five chapters. Chapter one is an introduction which gives background information on NRW. This chapter also discusses the problem statement, aims and objectives, research questions, justification of the project and the project layout.

Chapter two gives a detailed literature review on NRW and how it can be modeled using a hydraulic and a GIS models. The chapter reviews the literature on the various components of non-revenue water. It also gives a detailed discussion on the integration of hydraulic and GIS modeling.

Chapter three discusses the methodology used in the research. Firstly it gives the profile of the study area and the reason for the choice of the area. It further describes the processes involved in calculating the various component of NRW. Lastly it describes the processes involved in the hydraulic and GIS modeling of the WDS.

Chapter four presents the results obtained, their analysis and the discussion of the results made against literature. Lastly, the chapter five gives the conclusions drawn from the study and makes recommendation for further researches.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews the existing literature to get a better view of the main issues involving non-revenue water. It examines the concept of NRW and an in-depth description of the component of NRW. The IWA methodology for calculating NRW is also discussed in this chapter. This section discusses modern technologies and approaches used in modeling NRW. The last section discusses how the integration of hydraulic modeling and GIS can aid in the reduction of NRW.

2.2 CONCEPTS OF NON-REVENUE WATER (NRW)

The term Non-Revenue Water (NRW) in a water distribution network, is defined as the difference between total inflow to the system and total metered and authorized un-metered consumptions (Farley & Trow, 2003). The term non-revenue water has substituted the term 'Unaccounted for Water (UFW)' as suggested by International Water Association (IWA), and as recommended by American Water Work Association (AWWA) and Environmental Protection Agency (Environmental Protection Agency, 2009). There are widely varying interpretations of the term unaccounted for water worldwide. Access to reliable and standard methods for accounting water losses was unavailable till the early 1990s. Utility companies measured leakage management performance in a WDS in terms of unaccounted-for water (UFW). Various countries had different interpretations for UFW because of the absence of a general accepted definition. Some utility companies expressed UFW as a percentage of system input volume. Because of this it was impossible to measure the utility performance. Also, it becomes difficult to track defined realistic targets and the utility's performance against these targets (Frauendorfer & Liemberger, 2010). Although there have been some progress addressing these challenges, this problem persist in most countries. Several suites of tools and methodology have been developed worldwide to help utility companies assess water losses in a WDS efficaciously.

The International Water Association (IWA) has developed a standardized water balance structure and terminologies because of the issue of differences in water balance formats, performance indicators (leakage) and methodologies (Alegre et al., 2000). Lately, IWA's water balance structure has been adopted by numerous national associations including the American Water Works Association (AWWA). The reason is the clearly defined terminologies in the water balance structure including NRW. Table 2-1 and Figure 2-1 shows IWA's water balance structure.

Table 2-1: The AWWA/IWA Water Balance Table

System Input Volume (corrected for known errors)	Authorised Consumption	Billed Authorised Consumption	Billed Metered Consumption (including water exported)	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorised Consumption	Unbilled Metered Consumption	Non-Revenue Water (NRW)
			Unbilled Unmetered Consumption	
	Water Losses	Apparent Losses	Unauthorised Consumption	
			Customer Metering Inaccuracies	
		Real Losses	Leakage on Transmission and/or Distribution Mains	
			Leakage and Overflows at Utility's Storage Tanks	
			Leakage on Service Connections up to point of Customer metering	

Source: Farley and Trow (2007)

Table 2-1 represents the various components of IWA Standard Water Balance using the term NRW. Unaccounted for water represents water losses in Table 2-1 while NRW is the difference between the system input volume (SIV) and billed authorized consumption (Farley & Trow, 2007). NRW has three components namely; real losses, apparent losses, and unbilled authorized consumption (Kingdom et al., 2006). Real and apparent losses are the main causes of NRW while unbilled authorized consumption contributes a small percentage in distribution network with high non-revenue water. The Figure 2.1 shows the various components of non-revenue water.

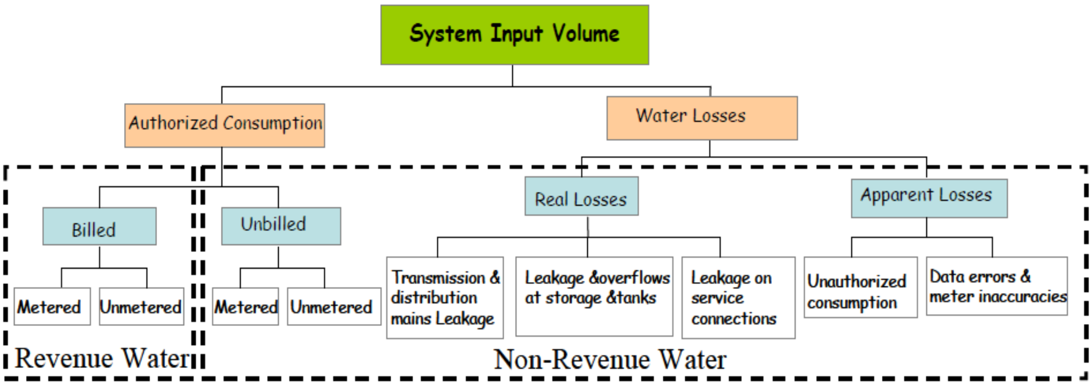

Figure 2-1: Components of IWA Standard Water Balance.

Source: Farley and Trow (2007)

Farley and Liemberger, (2005) summarizes five basic steps for conducting an IWA water balance;

- Determining system input volume
- Determining Authorized Consumption
- Calculating Apparent Losses
- Estimating Real Losses
- Estimating Real Loss Components

2.3 COMPONENTS OF NON - REVENUE WATER

The three main components of non-revenue water are as discussed below.

2.3.1 Commercial Losses (Apparent Losses)

Commercial (apparent) losses consist of water illegally used by consumers and water that has gone through the meters but is inaccurately recorded as well as faulty meters (customer meter inaccuracies). Most of these losses are not easily visible; this has cause most utility companies to focus their attention on leakages overlooking apparent losses.

Reducing apparent losses are of significant value to every water utility company. This is because their reduction results in a direct increase in revenue while reduction of real losses result in reduction of production cost. As such for any water utility company to be profitable, tariff must be higher than their production cost. Hence small volumes of apparent losses will have a huge financial effect on any utility company.

There are two main components of apparent losses namely; unauthorized consumption (illegal use and water theft) and meter inaccuracies (production and customer meters) (Thornton, 2002). According to Butler & Memon (2006), the definition of commercial losses must always include inefficient management and billing irregularities. This is because aside the two main components of commercial losses which are easy to detect; inaccurate meter readings, wrong calculations and bad billing system also contributes significantly to commercial losses.

The definition of apparent losses must be elaborated to include data handling errors (Kingdom et al., 2006). Usually commercial losses occur in the following types of connection; metered, unmetered and unregistered (Vermersch, 2005). Below are reasons why these connections result in commercial losses:

- Unregistered users (illegal connections or illegal water usage);
- Underestimation of water consumed when meters are out of function;
- Under metering when the meters being used are inappropriate;
- Theft on metered connections; and
- Under billing of unmetered authorized consumption.

The IWA standard water balance in Table 2-1 shows that apparent losses are broken down into four component errors (IWA, 2008). According to Rizzo et al., (2004) these four component errors namely water theft, meter reading errors, water accounting error, and meter under-registration can act and interact interchangeably. Figure 2-2 shows the four component errors of apparent losses.

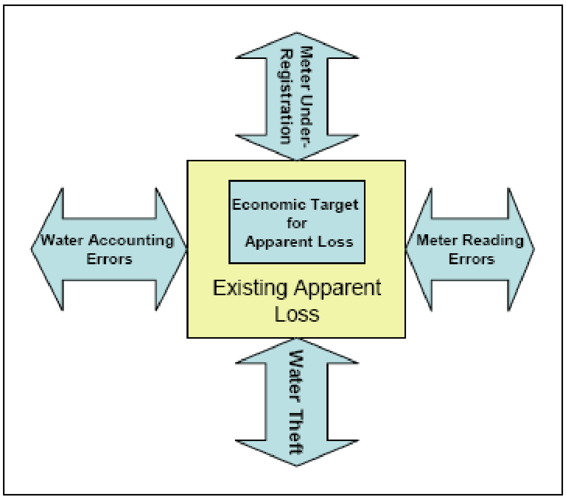

Figure 2-2: The Four Components of Apparent Losses.

Source: Rizzo et al., (2004)

Meter under-registration occurs when the meter read only part of the consumed water. They occur mostly in faulty meters. The meters record portions of water passing through it; resulting in customers being under billed. The causes of meter under-registration are; wrong installation, wrong meter sizing, worn-out meters and lack of maintenance or standardization of meters.

Errors resulting from meter readings are associated with inaccuracies in the manual recordings of meter reading by meter readers of the utility companies. Under reading of meters usually occurs when sometimes meter readers connive with customers to register lower meter readings in exchange for money from the consumers. The solution to this is automatic meter reading (AMR).

Water theft (illegal connection) occurs when consumers intentionally avoid water meters to access water for a time period without paying. Water theft are the simplest apparent loss to conceptualize, but are mostly hard to wipe out (Rizzo et al., 2004). Illegal connections are an integral cause preventing water utility companies from widening and increasing their service to customers. The main cause for illegal water usage are; lack of knowledge, inappropriate water tariff system and the denial of individuals from making house connections (Butler & Memon, 2006). Figure 2-3 illustrate illegal connection. According to Yeboah (2008), managers of water utility companies are faced with diverse challenges in their quest to eliminate water theft. The following are some of the challenges facing managers of utility companies from eliminating illegal connections;

- Some staffs of utility companies assume that water is a fundamental human need and as such should be used for free

- Political interference in the utility companies to win public sympathy at the disadvantage of the companies.

Some of the measures being used by water utility companies in the quest to eliminate water theft are stated below;

- Offering a time period of pardon for people illegally connected to the network to regularize their connections to the WDs;
- Public education to create the awareness for those illegally connected to the water distribution network to regularize their connections;
- Empowering managers of the WDS to enforce on the spot regularization of those illegally connected to the network;
- Stiffer punishment must be enforced on those engaging in water theft. But regularization of those illegally connected to the network must be preferred (Butler and Memon 2006). Punitive measures must be the last resort.

Figure 2-3: Illegal Connection

Source: Frauendorfer and Liemberger (2010)

Water accounting errors or billing errors refers to the changes and the set of methodologies used by water utility company's billing scheme which leads to inaccurate billing of customers (Rizzo et al., 2004). Usually billing errors results in under billing of consumers. A classic example of billing errors include the computerized approach in estimating water usage of a closed inaccessible area. This approach of calculating consumption often results in customers being under billed by the utility company. Below are some reasons for water accounting errors in a water distribution system;

- Lack of an effective approach in billing scheme being used by the operators of the WDS in estimation and collection of bills;
- Inaccurate recording of meter readings by meter readers upon being compromised by consumers.

According to Butler and Memon (2006), regular training of staffs and computerization of the billing system are effective means of reducing water accounting errors.

Measures to control commercial losses

Rizzo et al. (2004) suggests four categories of actions that are implemented to get the apparent water losses under control (Figure 2-4).

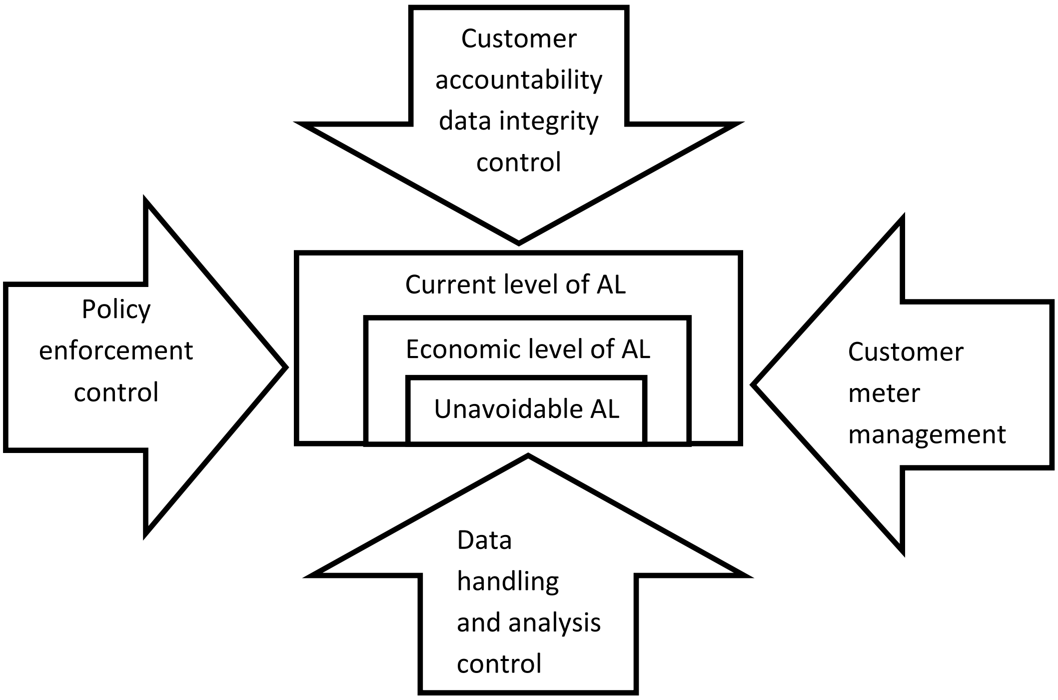

Figure 2-4: Components of a Proactive Apparent Loss Management Program

Source Rizzo et al., (2004)

One of the reasons for estimating commercial loss in a distributing network is to efficiently monitor and control the losses. Like physical loss; commercial loss in a water distribution network can also be estimated using a bottom-up or a top-down methodology. According to Rizzo et al. (2004), estimating commercial loss as a percentage of the system input volume is inaccurate and deceptive. The International Water Association's assessment terminologies recommend the usage of an approach like the one used for physical loss assessment (i.e. infrastructure leakage index) to measure and compare commercial losses. The apparent loss index used is estimated by dividing the commercial loss value by 5% of the water sold.

$$Apparnt\ Loss\ Index(ALI) = \frac{Apparent\ Loss\ Value}{5\%\ of\ Water\ Sales}$$

The International Water Association's methodology for estimating commercial loss is used in the top-down approach. It estimates commercial losses in a water distribution network as a percentage of the system input volume. The commercial loss value is computed as system input volume less the volume of water billed to customers and the current annual real loss (CARL) However this approach of estimating commercial losses is not precise to indicate the exact level of losses in the distributing network.

In using the bottom-up methodology, the physical loss component of NRW is estimated using minimum night flow (MNF) assessment or any precise assessment methodology. While the top-down approach estimates the billed water, the button-up approach estimates the physical loss component. The difference between these two values and the system input volume provides a much accurate value for commercial loss. Figure 2-5 gives a brief description of approach for controlling commercial loss in a WDS.

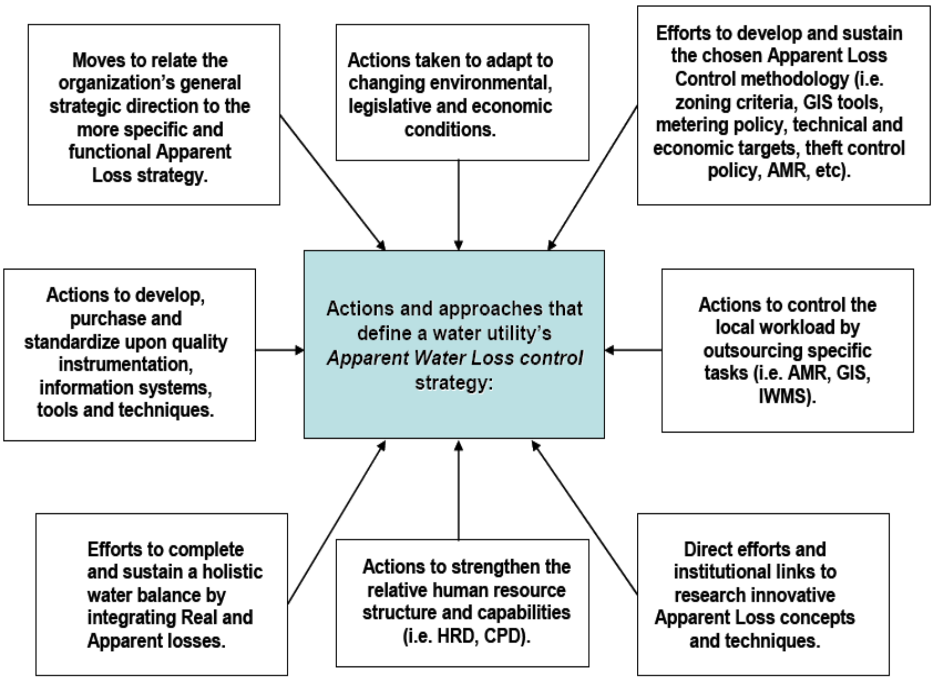

Figure 2-5: Apparent Loss Control Strategy

Source Rizzo et al., (2004)

2.3.2 Unbilled Authorized Consumption

According to Thornton (2002), unbilled authorized consumption is defined as the yearly volume of the unbilled metered consumption and the unmetered water consumption usage by regularized consumers. Mostly the utility companies and a few other users are authorized to consume water under unbilled authorized consumption for their residence, industry and commercial functions. Below are examples of water usage classified under unbilled authorized consumption:

- Water used for the purpose of fighting;
- Water used for training;
- Water used for the purpose of maintenance; flushing of mains and sewers and the cleaning of the application storage tanks.
- Water used for the purpose of protecting frost, cleaning streets and fountains in public places (Farley & Trow, 2003).

According to Vermersch (2005), the above water usage can be categorized into two groups: water used by the utility companies and free usage. Unbilled authorized usage in a WDS must constitute a small amount of loss on the water balance table. It should constitute about 1% or less of the water supplied. Although small, it is important to meter this usage when possible. This is because if not checked unbilled authorized usage can contribute significantly to non-revenue water. Applying efficient operational practices can help reduce the levels of unbilled authorized consumption without affecting operational effectiveness of the WDS. Misuse of unbilled authorized consumption is on the increase; this is because the uses tend to take advantage of bad record keeping habits and the estimation of this usage by the utility companies. Example is water meant for firefighting being sold to private users. An updated list of free water supply exit should be by the utility company. Farley and Trow (2003) outlined some process if enforced could ensure a reduction in the levels of unbilled authorized consumption. It includes managers of the utility system answer these set of question:

- Has the water utility fixed meters on all free supply outlets?
- How the utility company does calculate the volume of water supplied from these outlets?
- Are the volumes of water being monitored?
- Is there a contract stipulating the legal basis for unbilled authorized consumptions?

Also the following measures can be enforced in the quest to reduce unbilled authorized consumption:

- Classifying all unbilled water usage into legal and illegal use;
- Optimizing the legal use of free water to reduce waste;
- Removing or billing illegal water outlet.

2.3.3 Physical (Real) Losses

Physical (real) loss constitutes all forms of leakage on the water distribution network and the overflows that occurs at various storage tanks. They occur as a result of inefficient operational and maintenance practices, the absence of active leakage control and poor quality of underground assets (Kingdom et al., 2006). Physical loss refers to the volume of water lost yearly from transmission and distribution network via the various kinds of leakages, bursts and overflows occurring on the mains, service reservoirs and service connections up to the point of the customer meters.

Physical losses are the physical water lost from the pressurized network up to the customer meters (Farley, 2001). Also according to Tabesh & Asadiani Yekta (2005), physical loss consist of water lost from reported and unreported bursts, background leakages, reservoir leakage and overflow and the leakages from pumps and valves. Because this water did not pass through a customer's meter, it indicates that these losses are incurred at the production rate.

Since physical loss comprises physical water lost from the water network which leads to reduced supply to customers. The International Water Association recommended definition for physical loss is 'the annual volumes lost from transmission and supply network through the various types of leakages, bursts and overflows on mains, service reservoirs and service connections, up to the point of customer metering' (Thornton & Lambert, 2005).

The success or failure of any water utility company is dependent on how leakages are managed in the distribution network. Adhering to standard practice on leakage management will yield both social and financial gains to the water utility company. When leakages in the WDS are managed successfully; it results in a sustainable system likewise enabling the utility company provide affordable water to customers (Butler and Memon, 2006).

One of the dangers of having a leaking system is the potential of being a menace to public health. This is because when the network is under low pressure, there is the likelihood for the infiltration of polluted groundwater into the system (Tabesh & Asadiani Yekta, 2005). It is important to adhere to standard practice such as active leakage control program to efficiently minimize leakages and solve smaller problems before they escalate (Water Audit Guidance, 2008). Thus real loss control through leak management is essential not only to avail water to customers but to protect the public health as well. Figure 2-6 presents the components of physical losses.

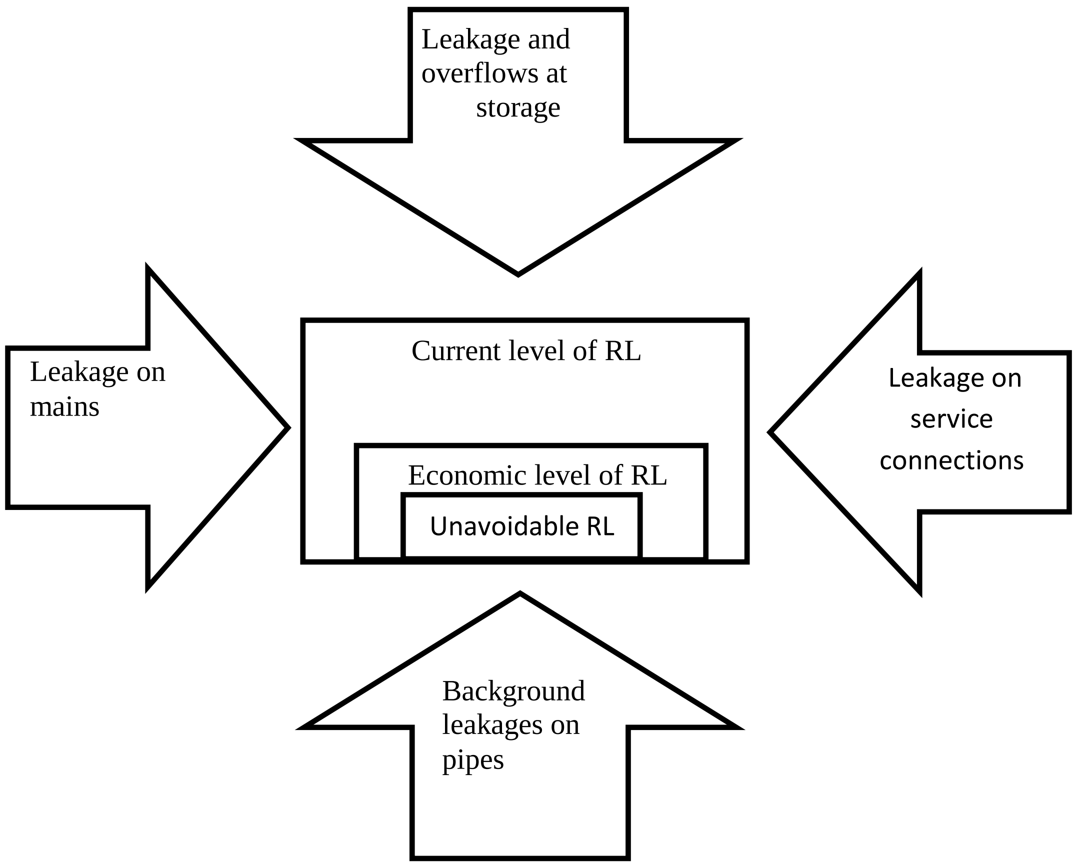

Figure 2-6: Components of Real Losses

Source: Thornton and Lambert (2005)

There are damaging effects on properties when leakages occur on transmission and distribution mains. They sometimes result in damaging roads and vehicles. Less severe leakages on transmission and distribution mains can even disturb water supply to customers. Most utility companies are able to respond quickly to these leakages because of their huge sizes, making visible for people to report them. For managers of a utility system to estimate the volume of water lost through these leakages, data from repairs showing the start and end time of the leakages must be kept. Also an average flow rate must be estimated for those leakages. With this information, volume of water lost for a particular period (12 months) can be estimated.

Leakages and overflows on reservoirs and storage tanks can be easily estimated. Managers of the water distribution network can determine the level of water lost to reservoir overflow by observing and estimating the duration of these overflows as well as their flow rates. However since most overflows occurs at night when demand is low, it is important to make night observations to detect these overflows. Data logger can also be used to record reservoir levels intermittently at night when installed. Leakages on reservoirs and storage tanks can be estimated using the drop test approach. It involves the utility closing all the inlet and outlet channels to the reservoir and measuring the rate of water level drop.

The most difficult type of leakage to detect is those occurring on the service connections to the customer meters. As a result of they being difficult to detect, they contribute significantly to real loss magnitudes in a water balance table. Their volumes can be estimated by subtracting reported and unreported leakages and the leakages and overflows at reservoir from the total real loss value.

Unavoidable annual real losses

Physical losses cannot be annihilated totally from a WDS. Unavoidable Annual Real Losses (UARL) is defined as the lowest technically and practically achievable annual physical loss volume. Determining the unavoidable annual real losses form an integral part in calculating the infrastructural leakage index.

Measures to control physical losses

Although water losses in a distribution network is inevitable, it is however important for managers of utility companies to do their best to eliminate leakages and the other forms of water losses. In the process of eliminating losses, there is a limit to which further injection of resources to reduce water losses will not be economically beneficial to the utility. Companies should have a tolerable level to which leakages must be kept and managed since they cannot be eliminated entirely. The principle behind this practice is the law of diminishing returns; where dividend on money invested starts to decrease in connection to the production cost. There are four methods of controlling and managing physical losses as shown in Figure 2-7.

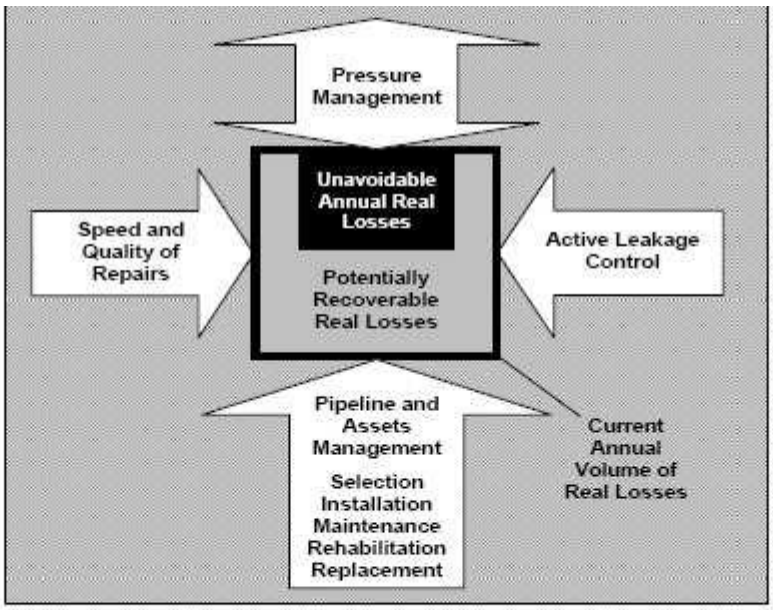

Figure 2-7: The Four Basic Methods of Managing Water Loss

Source: Farley and Liemberger (2005)

When the basic methods as described in Figure 2-7 are enforced, they will go a long way to reduce physical losses in a WDS. Utility managers ensuring proper pipe and assets managements as shown in Figure 2-7 will end up reducing the rate of occurrence of new leakages yearly. Applying appropriate pressure management practices will also end up reducing the rate of occurrence of new leakages and the flow rates of bursts and leakages. Undertaking active leakage control will ensure a quick detection of unreported leakages. Lastly when utility companies increase their speed and quality of repairs, the average duration of leakage is reduced (Farley & Trow, 2003).

Economic level of real losses (ELL)

In reducing the level of leakages in a distribution network to the unavoidable annual real loss (UARL) value, it is important to ensure that the cost of reducing these losses does not overly affect the production cost of utility company. The level of leakage where the marginal cost of active leakage control equals marginal cost of the leaking water is termed as the economic level of leakages (ELL) (Butler & Memon, 2006).When the ELL value is attained, any investments made to further reduce leakages will not commensurate the investments made. Figure 2-8 shows the recommended practices that can help attain ELL.

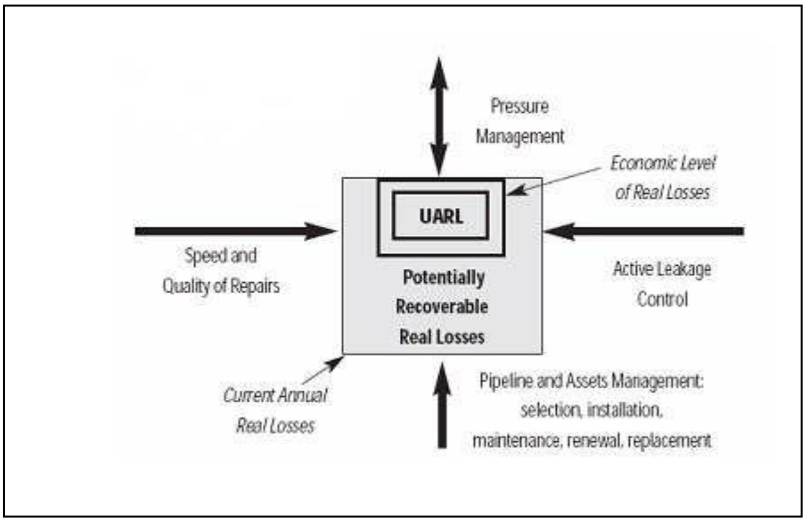

Figure 2-8: Economic Level of Leakage

Source IWA (2003)

According to Yeboah (2008) water distribution system can attain ELL when the amount of money spent in undertaking physical loss reduction strategies and the cost of water lost through leakages are at a minimal level. Farley and Trow (2003) defined ELL as the level below which cost of water saved from leakages is lower than the amount of money spent on reducing the leakages. Economic level of leakage can only be attained when the level of leakages in the distribution network are at their minimal level.

A similar explanation can be made for the term economic level of non-revenue water; it is attained when the cost of reducing NRW levels is lesser than the cost of water saved. The factors that can influence the economic level of non-revenue water are salaries of staff, cost of equipment, chemical and electricity cost and water tariffs. Managers of utility companies must set realistic NRW targets based on yearly assessed economic level of non-revenue water (Farley, 2010). The NRW target set compares the amount of money lost in water losses to the amount spent on water loss reduction strategies being implemented as illustrated in Figure 2-9.

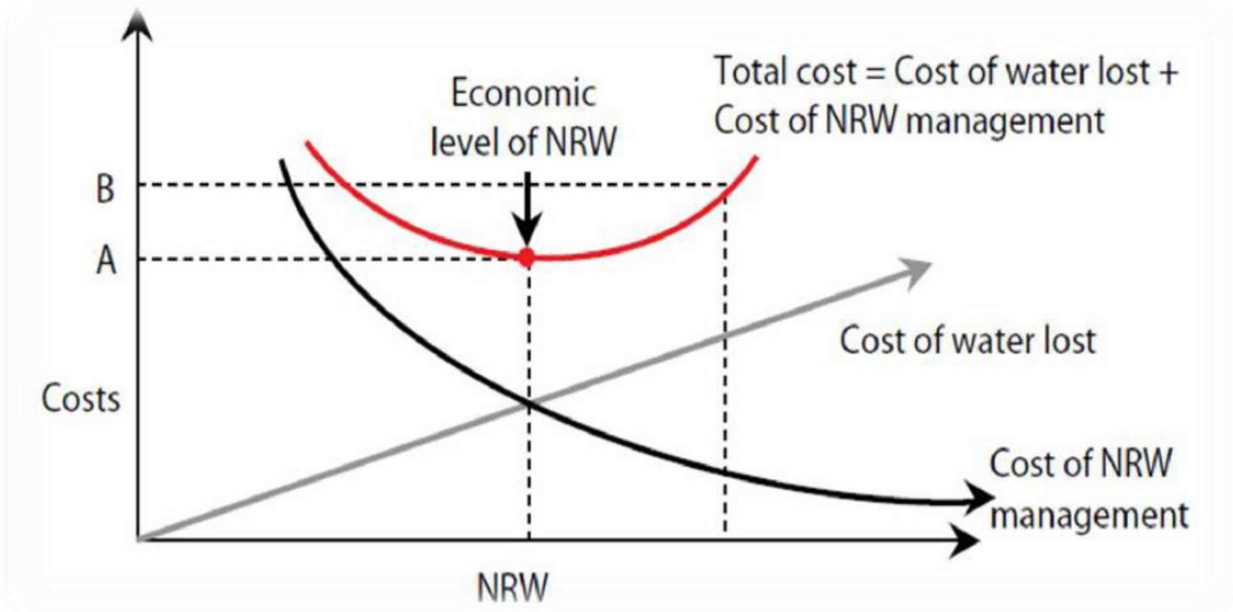

Figure 2-9 Identifying the Economic Level of NRW

Source: Farley (2010)

The infrastructure leakage index (ILI)

The best real loss indicator which gives managers of a water distribution system a fair idea of how the system is being managed is the Infrastructure Leakage Index (ILI). Since ILI is an indicator of physical losses, it is highly recommended by both International Water Association (IWA) and the American Water Work Association (AWWA) to know how well the system is being managed. At the given operational pressure, ILI gives an indication of how the network is being maintained, repaired and rehabilitated to help manage real losses (Farley et al., 2008). Mathematically, ILI is the ratio of the Current Annual Real Loss (CARL) to the Unavoidable Annual Real Loss (UARL); ILI = CARL/ UARL Since the value of ILI is a ratio (no unit), the value in one utility can be compared with the values of other utilities; i.e. a standard indicator to monitor how utilities are being managed. UARL is computed as shown below;

$$UARL\ (liters/day) = (18 \times Lm + 0.8 \times Nc + 25 \times Lp) \times P$$

Where Lm = mains length (km)

Nc = number of service connections

Lp = total length of private pipe, property boundary to customer meter (km)

P = average pressure (m)

Table 2-2 shows the real loss assessment matrix. The table gives four categorizes to the ILI value.

Table 2-2 Real Loss Assessment Matrix

Technical Perfomance Category		ILI	Liters/Connection/Day (when system is pressurized) at an average of:				
			10 m	20 m	30 m	40 m	50 m
Developed Country Situation	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 Country Situation	A	1 - 4	< 50	< 100	< 150	< 200	< 250
	B	4 - 8	50 - 100	100 - 200	150 - 300	200 - 400	250 - 500
	C	8 - 16	100 - 200	200 - 400	300 - 600	400 - 800	500 - 1000
	D	> 16	> 200	> 400	> 600	> 800	> 1000

Source: Ranhill Utilities Berhad and the United States Agency for International Development (2008)

The description of technical performance categories based on the above table is as follows:

Category A - Good. Further loss reduction may be uneconomical unless there is a shortage of water; requires careful analysis to identify cost effective improvements.

Category B - Potential for further improvements; needs to consider pressure management, active leakage control and maintenance of pipe networks.

Category C - Poor leakage records; appropriate only if water is plentiful and cheap; however, level of analysis and leakage and active effort to reduce leakage need to be continued.

Category D - Inefficient use of resources; leakage reduction programme is crucial and needs to be given priority.

2.4 DISTRICT METER AREAS (DMA)

To track the level of leakages in a distribution network, it is important to apply the practical method of installing flow meters at various locations within the network. The purpose of installing these flow meters is to record the flow into specific areas within the WDS with a predefined and permanent boundary also known as District Meter Area (DMA) (Farley, 2001). The development of a leakage tracking system has two main functions:

- To partition the WDS into various regions or DMA; each with fixed and well-defined boundary. The creation of DMA helps manager of the utility to detect unreported leakages in the network. This is because a regular observation of night flows into each zone will aid the detect anomalies in the flow into each zone.
- To handle effectively the pressure in each zone or group of zones in order to operate the WDS at the most favorable pressure value. A leakage monitoring system must constitute of various zones with permanent flow meters installed

to determine the flow into each zone. Most often flow meters must be incorporated with pressure reducing valves.

Based on the attributes of the water distribution system, a district metered area must be:

- an area which cascades into an adjacent DMA.
- furnished by way of single or multiple feeds;
- a distinct region (i.e. there should be no flow into neighboring zones)

According to Farley (2001), district metered areas must be limited from five hundred to three thousand houses per zone. Gumbo et al., (2003), states that DMAs must contain two thousand to five thousand properties. The boundary of the zones may be either permanent or temporary. Flow meters attached to each zone are tracked regularly. DMAs with high demand are critically examined for leakages or water theft. Zones with persistently high leakages must be further divided into smaller zones by the temporal closure of valves to identify the specific area with the leakage (Farley, 2001). In areas where the temporal closure of valves would highly disrupt water supply, the creation of an internal zone would be necessary. The installation of other flow meters in the district will create an additional zone with one flowing into the other (Thornton, 2002). These practices become relevant only when night flows shows an increase in supply. Closing of internal valves can be done concurrently with the installation of flow meters for efficient monitoring of DMAs.

Leakages in each zone are calculated by deducting consumers' night use from the water supplied to the zone as recommended by Farley (2001). The advantage of using night flow measurement to monitor leakages is that it helps managers of the WDS identify zones with high leakages and thus commit more resources to those zones. Another advantage is that information on flow and use of water is made readily available for the daily management of the WDS and also aid future planning and designing of extension. The drawbacks to this method are; insensitive to variation in leakages and the inability to detect leakage location. Mckenzie et al., (2002), state that though night flow measurement can aid the detection and the calculation of water loss, it is highly dependent on the range of measurement, accuracy and sensitivity of the water meter.

2.5 GIS AND HYDRAULIC MODELLING

2.5.1 Hydraulic Modeling of Water Supply Network

Network modeling is the process of constructing a computer simulation of a pipe network using specialized computer software (Ranhill Utilities Berhad and the United States Agency for International Development, 2008). Utility managers then verify the simulation by comparing the simulated flows and pressures with real flow and pressure data recorded onsite. Adjustments are made to the model to ensure that the simulated and the real data correlate, thus creating a calibrated hydraulic network model. Hydraulic simulation models perform steady-state and extended period simulations of the hydraulic behavior of water distribution networks (Deuerlein, 2007). Mathematical hydraulic models are utilized for modeling the leakage rate in terms of pressure changes. Some of the challenges that occur in developing a hydraulic model are:

- understanding of complex concepts related to the field of hydraulic,
- wasting of time for deriving a suitable mathematical relation.

The Epanet

In recent years, successful applications of soft computing techniques in water distribution networks have been widely published. The Epanet software is employed in this research. This is because of its linked with GIS models. The software also has the advantage of being able to simulate both hydraulic and quality of the system. Epanet is a computer program that executes extended period simulation of hydraulic and water quality behavior within pressurized pipe networks (Rossman, 2000). A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. Epanet monitors the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. The software can also simulate water age and tracing of water source.

Epanet is designed to be a research tool for improving understanding of the movement and fate of drinking water constituents within a water distribution system. It can be used for different kinds of applications in water distribution system analysis. They include sampling program design, hydraulic model calibration, chlorine residual analysis, and consumer exposure assessment. The software provides an integrated environment for editing network input data, running hydraulic and water quality simulations, and viewing the results in a variety of formats. These include color-coded network maps, data tables, time series graphs, and contour plots.

Full-featured and accurate hydraulic modeling is a prerequisite for doing effective water quality modeling. Epanet contains a state-of-the-art hydraulic analysis engine that includes the following capabilities (Rossman, 2000):

- places no limit on the size of the network that can be analyzed

- computes friction headloss using the Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas
- includes minor head losses for bends, fittings, etc.
- models constant or variable speed pumps
- computes pumping energy and cost
- models various types of valves including shutoff, check, pressure regulating, and flow control valves
- allows storage tanks to have any shape (i.e., diameter can vary with height)
- considers multiple demand categories at nodes, each with its own pattern of time variation
- models pressure-dependent flow issuing from emitters (sprinkler heads) availability, popularity and capability to be can base system operation on both simple tank level or timer controls and on complex rule-based controls.

Background leakage and burst model

Background leakage occurs mostly at the numerous connections, joints and fittings. They depend on the operational services pressure in pipes. Pressure control for leakage reduction is appropriate to the background leakage. For non-metered WDSs, the minimum night flow (MNF) is used as an indicator of the total leakage (AbdelMeguid, 2011). The estimated total value of network background leakage needs to be distributed over the nodes in the network model. Most of background leakage is through connections and fittings and therefore, the leakage flow has been assumed to be distributed between the nodes proportionally to the number of properties connected to each node or to the node demand. Leakage-pressure relationship is represented by equation (1),

$$l(t) = k \cdot P(t)^{\alpha} = k \cdot (h(t) - H)^{\alpha} \tag{1}$$

Source: AbdelMeguid, (2011)

where l(t), P(t) and h(t) are nodal leakage flow, nodal pressure and total head at time t, k and α denote the leakage coefficients and exponent respectively, and H denotes the elevation of the node. The leakage has been assumed to be distributed between all nodes proportional with demand. The leakage exponent α changes from 0.5 to 2.5 depending on the type of leakage material of pipes and the soil (Giustolisi et al., 2008). In the current study the leakage exponent α has been chosen to be a constant and equal 1.1 as recommended by AbdelMeguid (2011). The coefficient k depends on the demand at each node and has been computed as depicted by equations (2 to 4). In equation (2), it has been assumed that the summation of the total leakage is equal to MNF, $q(t_{min})$, which occurs at the time t_{min}.

$$q(t_{min}) = \sum_i li = \sum_{i \in N_d} k_i \cdot P_i(t_{min})^{1.1} \tag{2}$$

Also $d_i(t_{min})$ and $P_i(t_{min})$ denote the demand and pressure of node i at time t_{min}, respectively. As the leakage at any node has been assumed to proportional with the node demand, then the coefficient k_i is proportional with the demand of node i at the time of the MNF, t_{min} as in equation (3).

$$k_i \propto d_i(t_{min}) \tag{3}$$

By introducing proportional coefficient β_i, the coefficient k_i can be expressed as below

$$k_i = \beta_i \cdot d_i(t_{min}) \tag{4}$$

The pressure at node *i* is a difference between node head, *hi*, and node elevation, *Hi*, as given in equation (4).

$$P_i(t_{min}) = (h_i(t_{min}) - H_i) \quad (5)$$

Substitute equations (4 & 5) for k_i and $P_i(t_{min})$ in equation (2)

$$q(t_{min}) = \sum_i l_i = \sum_{i \in N_d} \beta_i \cdot d_i(t_{min}) \cdot (h_i(t_{min}) - H_i)^{1.1} \quad (6)$$

Hence the MNF, the demand and total head of node *i* at *tmin* are known from the data provided in the hydraulic model and simulation results, the proportional coefficient β*i*, which has been used to calculate the leakage coefficient *ki*, is estimated as below

$$\beta_i = \frac{q(t_{min})}{\sum_i d_i \cdot (h_i(t_{min}) - H_i)^{1.1}} \quad (7)$$

2.5.2 GIS and Hydraulic Modeling Integration

The primary function of a geographic information system (GIS) for a water or wastewater utility companies was to map capital assets of the WDS. It is obvious that GIS is more than just a mapping tool. When GIS is integrated with a hydraulic model, it provides managers the opportunities for data management and spatial analysis. GIS has gradually become a system of record for all assets in water utility systems. Integrating hydraulic modeling with GIS is reasonable because it allows the two systems (hydraulic and GIS) to share a single database. It makes data entry simple, since elevation data, pipe sizes, devices, and other parameters are normally identified in GIS (Atkinson, 2014). This will make the use and implementation of hydraulic modeling software much easier.

In integrating the two models, GIS becomes the best place to collect this information and edit it from time to time. When a hydraulic model is integrated with GIS, it provides utility companies with a powerful tool to let them know how the system is performing at the time the model was created, as well as how the model should perform. GIS and hydraulic modeling will not be beneficial if the data is not accurate or up-to-date. Integrating the two systems will only be meaningful or necessary when the GIS systems are updated or upgraded. This will ensure effective integration of the two systems.

According to Atkinson (2014), the integration of GIS and hydraulic models provides the following benefits:

- Provides planners and technical men access to a more accurate, up-to-date information, reduced response time, and accessibility of modeling elements and data.
- Provides ready access to mission critical information. Due to this, risk of failure analysis, repair and replacement, capacity assessment, capital improvement planning, and other water utility applications will run more efficiently and effectively.
- Allows utility companies to get the best from their GIS investment.
- Enables utility companies to run scenarios for capital improvement plans, fire flow analyses, water quality, and future growth of the water distribution system. It also improves the ability to update and enhance modeling efforts and minimizes costs of hydraulic model development and maintenance, while

using the most correct and best data available, and limiting risk and unnecessary assumptions.

- Creates a connected communication decision support platform which allows operators and managers to make the best, most efficient decisions about how to operate the integrated systems.
- There is no use to maintain and update two systems. When one system is updated, the other system automatically updates. It also means that no updates are required whenever models for additions or upgrades need to be performed.
- Results for "what if" scenarios can be obtained quickly, minimizing costs and maximizing efficiency. These close relationships between systems also ensure a more robust model analysis and also allow data to be shared with other systems not related to hydraulic modeling.
- Water loss auditing and modeling, this is because you can identify the age of your system and various pressures in each zone. For example, with the knowledge of zonal pressure, water losses can be estimated for zones having high pressure. Also water losses can be estimated in those zones when the pressure is reduced in those zones.

Some challenges and their remedies in integrating hydraulic and GIS models

The main issues in integrating hydraulic and GIS models are data deficiencies problems and pipeline connectivity. These challenges can be fixed through a combination of the following processes; standard operating procedures, tools within GIS and modeling software that are used to improve data accuracy, as well as protocols that can be established to permit the transfer of data corrections and modifications between the model and the GIS (Atkinson, 2014).

Further information, such as modeling results under different scenarios, can be provided back to the GIS system. This requires a closer coordination between engineers/modelers and the GIS data management staff. Challenges can be caused by how the various departments are structured within a utility company, by communications and data sharing between departments, by read/write access to databases, by integrating the modeling analysis results from third parties (consultants), or by the designing of data schemas to hold or link GIS and modeling information. The key to overcoming these problems is to define objectives, to document and follow protocols and guidelines, and to ensure coordination and communication between interested parties in a given utility company.

GIS data available may not be accurate enough for the hydraulic model to develop useful data. The GIS data that might be available include pipe diameters, pipe length, and elevations. Updating and maintenance of the databases are paramount to overcome these problems. The utility company needs to ensure that hydraulic modeling software and GIS used, or planned to be used, are compatible with each other (Atkinson, 2014). The utility company needs to ensure that data in GIS is up-to-date and accurate; that correct information is available, that no duplicates exist. Data in GIS should be complete and accurate enough for use with hydraulic models.

CHAPTER THREE

3.0 RESEARCH MATERIALS AND METHODS

3.1 INTRODUCTION

The chapter describes the study area, materials and the methods used for collecting and analyzing the data. The characteristics of the study area and the water supply systems are described in section 3.2. The materials and software used for the study are described in section 3.3. The methods used in this research are described in section 3.4.

3.2 STUDY AREA

3.2.1 Location of Study Area

The Kumasi Southeast District of the Ghana Water Company Limited was used as study area. The district is located between latitudes 6°35'N - 6°45'N and longitudes 1°28'W - 1°36'W. It is surrounded by three other districts. It makes boundary with Kumasi Central District in the northwest, Kumasi South District in the west and Kumasi East District in the east. GWCL has two booster stations; they are located at Kumasi Southeast and the Offinso District respectively. The main reason for using Kumasi Southeast District as the study area was because of the availability of a booster station at KNUST which provided information on system input volume. This makes it possible to determine the total volume of water supplied to the district. Also Kumasi Southeast is one of the districts in the Kumasi water supply system with persistently high levels of non – revenue water. Ghana Water Company limited (GWCL) monitor its distribution system by dividing each administrative region into districts. Each district comprises of various towns. The composition of the district is different from that of the administrative district. Kumasi Southeast District comprises of the following towns; Adako Jachie, Abankro, Ayeduase, Akokoamon, Anwomaso, Apiadu, Apromasi, Asaman, Bebre, Boadi, Deduako, Domeabra, Donyina, Ejisu, Emena, Fumesua, Kentinkrono, Kokoben, Kotei, Kwamo, Kyerekrom, Missuam, Nsenie, Oduom, Old Krapa, Paakoso and Tikrom. The major uses of treated and distributed water for Kumasi Southeast are mostly for residential purposes. There are a few light industries and hospitals which also make use of water supplied by GWCL.

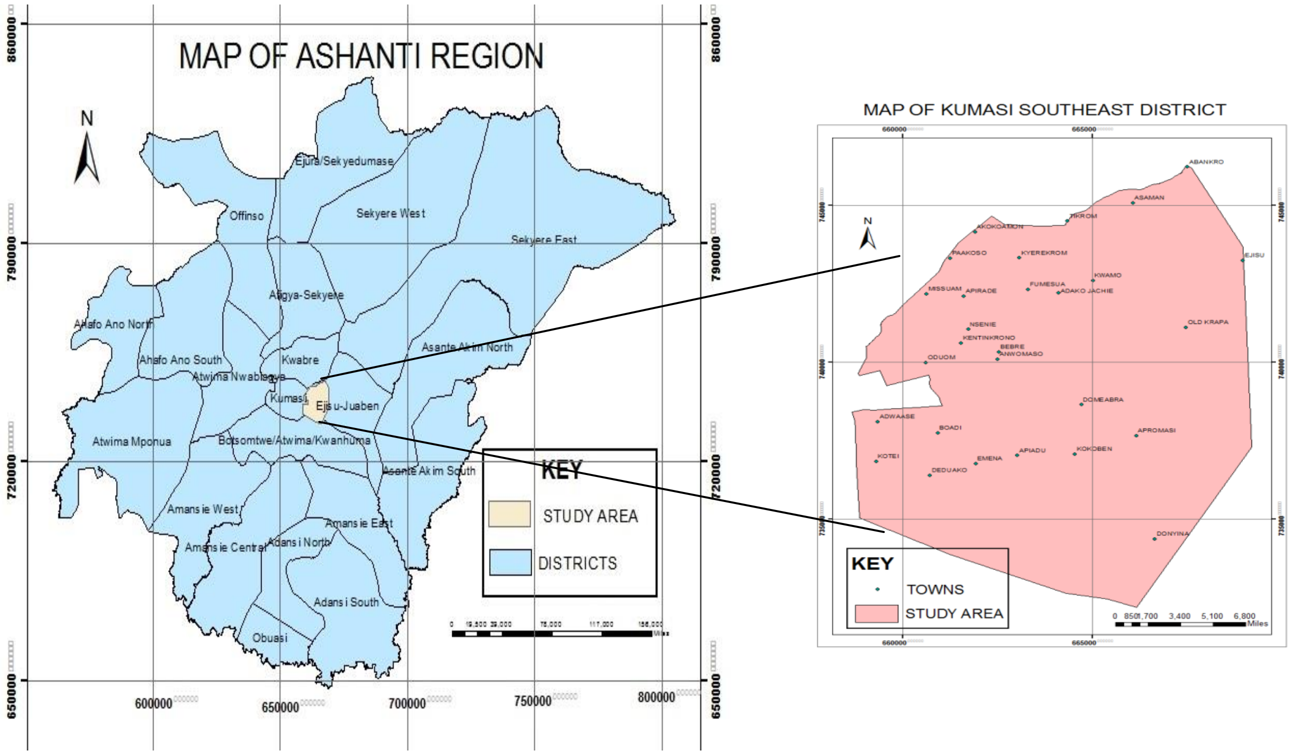

Figure 3-1 Study Area

3.2.2 Network Structure in Kumasi Southeast District

The district is supplied with water from the KNUST booster station located on the Kumasi - Accra highway. The booster station is supplied with water from the Barekese treatment plant. The water distribution network in Kumasi Southeast District consists of various pipelines, nodes, valves, pumps and a reservoir. There are 147 different pipelines in the district totaling 42,133.21m in length. The pipe materials used in the district are Asbestos Cement (AC), High Density Polyethylene (HDPE), Unplasticized Polyvinyl Chloride (uPVC) and Copper. Pipe sizes in the district ranges from 75mm to 250mm. The Asbestos Cement (AC) pipelines in the district are mostly between 36 – 40 years while Unplasticized Polyvinyl Chloride (uPVC) pipe age averages around 24 years. These aging pipes are a major contributing factor to the high level of leakages in the district (Unwin, et al., 2003). Figure 3-2 shows the Kumasi Southeast water distribution network.

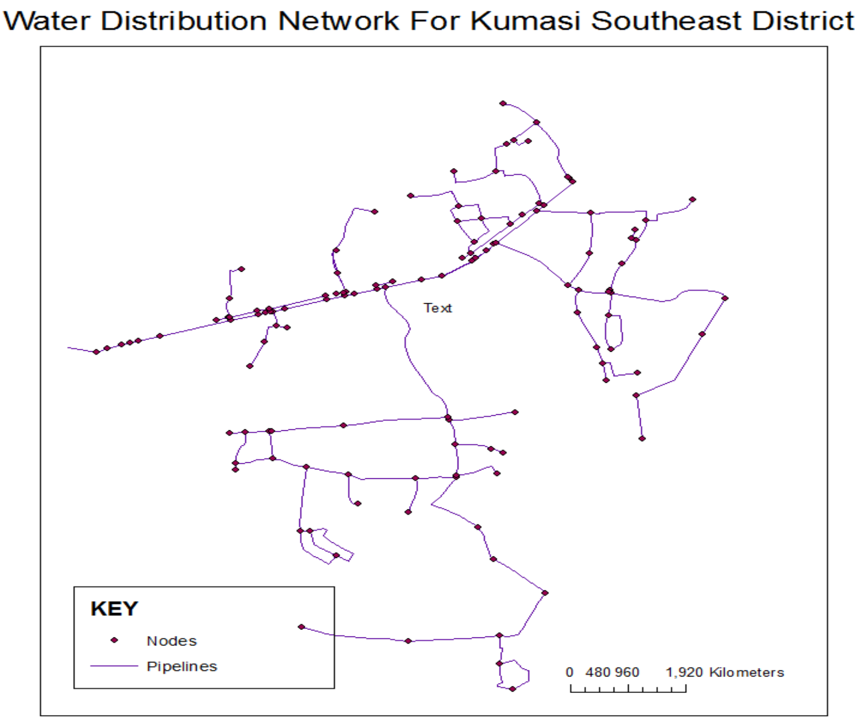

Figure 3-2 Kumasi Southeast Water Distribution Network

3.2.3 Existing Mechanism for Reducing NRW

Water losses along a distribution network are inevitable. It is important for managers of every WDS to know where and how much water is being lost. Although Kumasi water supply system (KWSS) has no comprehensive approach in dealing with NRW; the managers of the KWSS undertake periodic meter inspection to identify illegal connections in the district. Also periodic active leakage control management is undertaken to identify background leakages. Lastly a record of reported leakages is kept to identify areas prone to leakages. These steps being taken by the managers of the water distribution network are highly commendable but the absence of the computation of NRW and its components and the modeling of water losses makes these steps being taken yield little result. The computation of NRW as a percentage of water billed to the total water supplied to the district by the statistical department of GWCL is highly inaccurate.

$$NRW = \left(\frac{Billed\ Consumption}{System\ Input\ Volume}\right)\%$$

This approach of determining NRW does not take into consideration other component of non-revenue water such as unbilled authorized consumption. Also the approach does not break water losses into the various components; real losses, apparent losses and unbilled authorized consumption.

This approach of determining water losses does not enable the managers of the utility company to determine the various components of NRW. Since this is not an in-depth approach in determining water losses, it creates a difficult in every approach taken to mitigate the losses. As a result of this water losses have remained constantly high year after year. These high losses are a major factor resulting in low coverage, low service level, high non-revenue water, and intermittent water supply.

3.3 DATA AND SOFTWARES

All data used in this research were secondary data collected from the offices of GWCL and Ashanti Region Survey and Mapping Division of the Lands Commission. Below are the various data and software used for the research.

3.3.1 Data

- Topographic map of Ashanti Region (obtained from aerial photograph in the year 2000). The map was used to extract the elevation of nodes of the water distribution network.
- Pipe network of Kumasi Southeast District. This network consists of both pipe mains and service lines of the entire district.
- Customer information data which entails information on billed customers and customers on flat rate.
- Pipe burst and leakage report. This report gives information on the duration of leakages and the locality in which they occur. A summary of the leakage data is shown in Appendix 4.
- Daily System Input Logs contains information on the daily pumping hours and the average pumping rates.
- Compilation of all the data on illegal connection during the period of the study.

- Data on unbilled unmetered consumption; data on water used for the purposes of firefighting, flushing of mains during scheduled cleaning and after-repair work of burst pipes and GWCL offices and bungalows.

3.3.2 Software

The main softwares used for the study were Epanet 2.0 and ArcGIS 10.1. The Epanet software was used for developing a hydraulic modeling while ArcGIS was used for the analysis and visualization of the hydraulic model. AutoCAD software was also used in extracting nodal elevation of the WDS. Lastly all computations were done using the MS Excel.

In this research, Epanet a network modeling software was employed because of its availability, popularity and capability to be linked with GIS models (Rossman, 2000). Another advantage for using Epanet was its ability to simulate both hydraulic and quality of the WDS. A well modeled pipe network system can be used as a reference for asset replacement, flow and pressure requirement program.

3.4 RESEARCH METHODS

The research methodology is categorized into three main stages. The first stage deals with secondary data collection from GWCL. The data collected from GWCL are as stated in the data used. The second stage involved the calculation of the various components of NRW using the IWA methodology. The third stage involves modeling of the pipe network using hydraulic modeling software (Epanet) and GIS. Below are the detailed descriptions of these processes.

3.4.1 Data Collection

The data collected from GWCL and the Ashanti Region Survey and Mapping Division of the Lands Commission is as stated in the section three of this chapter.

3.4.2 Calculating NRW and Its Components

To determine NRW in Kumasi Southeast District, the following parameters were computed.

i. *System input volume*

To be able to determine the amount of water losses, the system input volume was estimated. The system input volume was computed as shown in equation 3.1;

$$\text{Volume (m3)} = 253\left(\frac{m^3}{hr}\right) * Pumping\ hours(hr) \qquad (3.1)$$

Source: Innerebner (2008)

ii. *Authorized consumption*

Authorized consumption helps in determining the permitted water usage in the district. It is classified into billed authorized consumption and unbilled authorized consumption. The billed authorized consumption is estimated as shown in equation 3.2

$$\begin{pmatrix} Billed \\ Authorised \\ Consumption \end{pmatrix} = \begin{pmatrix} Billed \\ Metered \\ Consumption \end{pmatrix} + \begin{pmatrix} Billed \\ Unmetered \\ Consumption \end{pmatrix} \qquad (3.2)$$

Source: Liemberger, (2010)

Although unbilled consumption is authorized consumption, it is calculated as a component of NRW. This is because it consumption brings no revenue to the utility company. There are two components of unbilled consumption: unbilled metered consumption and unbilled unmetered consumption. For Southeast District, the only component of unbilled unmetered consumption was the consumption made by the GWCL office. Appendix 8 shows the estimated demands for GWCL offices and bungalows.

iii. Unauthorized consumption

Unauthorized consumption refers to illegally consumed water. To obtain the volumes involved, house-to-house random investigations was conducted in the study area. Equation 3.3 shows the estimation of unauthorized consumption.

$$\begin{pmatrix} Unauthorized \\ Consumption\,(m3) \end{pmatrix} = \begin{pmatrix} Estimated\ No.of\ Illigal \\ Connection\ per\ District \end{pmatrix} * \begin{pmatrix} Average\ Consumption \\ per\ Month\,(m3) \end{pmatrix} * No.of\ Month \qquad (3.3)$$

Source: Liemberger, (2010)

iv. Leakage components

Leakages are a major component of NRW. They are categorized into three main groups; reported, unreported and background leakages. These three main categories of the leak component were calculated for both the pipe mains and service lines.

Reported leakages refer to visible leaks. They were the type of leakages that were seen and reported to GWCL. Equation 3.4 was used in calculating reported leakages.

$$(RL) = Leak\ Duration * Average\ Pressure * Average\ Leak\ Flowrate(RL) \qquad (3.4)$$

Source: Liemberger, (2010)

Unreported leakages were those leakages that were located by leak detection teams as part of their normal everyday active leakage control duties. The formula for calculating UL is as stated in equation 3.5.

(UL) = (pipe length Average Pressure*Average Leak Flowrate(UL)*No. of Leaks per km*Supply Hour)* *(3.5)*

Source: Liemberger, (2010)

Background losses in Kumasi Southeast District referred to individual events (small leaks and weeps). They continued to flow with flow rates too low to be detected by an active leakage control campaign. Equation 3.6 was used in calculating background leakages.

$$(BL) = Pipe\ Length * Average\ Pressure * Average\ Leak\ Flowrate(BL) * Days \qquad (3.6)$$

Source: Liemberger, (2010)

v. Empirical flowrate

For this research, empirical flow rates based on the IWA methodology were used to estimate the volume of water lost. Appendix 5 shows values for unavoidable background leakage flow rates, while Appendix 6 shows the values for reported and unreported burst.

vi. Infrastructure leakage index (ILI)

The ILI was computed as shown in equation 3.7.

$$ILI = CARL/\ UARL \quad (3.7)$$

Source: Liemberger, (2010)

CARL equal to the summation of all the components of real losses

UARL (liters/day) = (18 x Lm + 0.8 x Nc + 25 x Lp) x P

Where Lm = mains length (km)

Nc = number of service connections

Lp = total length of private pipe, property boundary to customer meter (km)

P = average pressure (m).

3.4.3 Hydraulic Modeling

To develop an efficient hydraulic model with Epanet, all the default parameters like map units and the various hydraulic properties were set-up before the modeling of the WDS. The first step in hydraulic modeling with Epanet is to introduce pipe network shapefiles into the Epanet environment. The approach of introducing pipe network was used. This was because the shapefile from GWCL was full of duplicate making it unsuitable for hydraulic modeling. The approach used involved loading the image of the network, scaling and digitizing of the pipe network.

After a successful loading and scaling of the image, the network was populated with nodes, pipes and a pump. The software was then employed in editing of the model. Epanet allows for both group editing and individual editing of the various components of the model. On completing model set up and editing of the various parameters, the information is enough for running a single period analysis. Running the model must be successful before any further analysis can be made from the model. Figure 3-4 is an Epanet interface showing a successful run of a single period analysis.

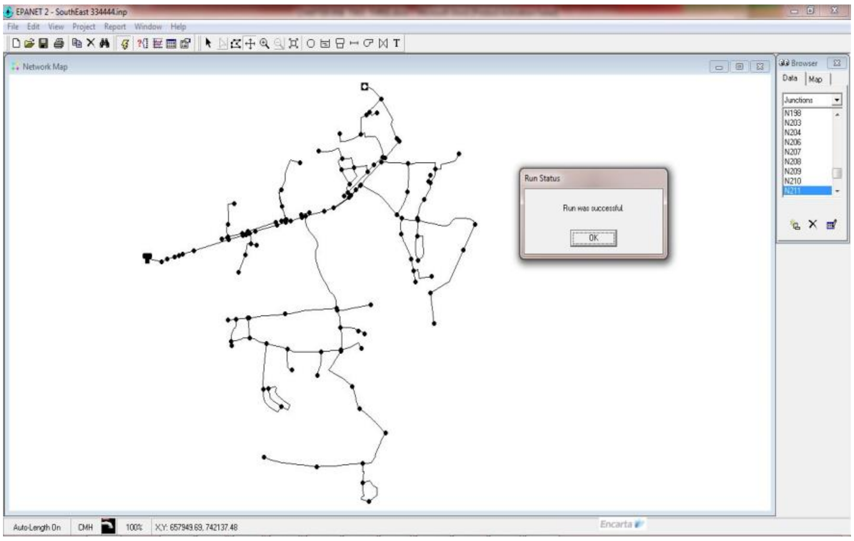

Figure 3.3 Epanet Interface Showing a Successful Run of a Single Period Analysis

The leakage-pressure relationship is represented by equation 3.8.

$$l(t) = k\,.P(t)^{\alpha} = k\,.(h(t) - H)^{\alpha} \qquad (3.8)$$

Source: AbdelMeguid, (2011)

where l(t), P(t) and h(t) are nodal leakage flow, nodal pressure and total head at time t, k and α denote the leakage coefficients and exponent respectively, and H denotes the elevation of the node. To attain the level of background leakage at each node, the background leakage calculated were assumed to be distributed among the nodes based on their demand.

Based on the reviewed literature, the leakage exponent α was chosen to be a constant and equal 1.1. The coefficient k depends on the demand at each node and was computed using equations (3.9 to 3.11). In equation (3.9), it has been assumed that the summation of the total leakage is equal to MNF, $q(t_{min})$, which occurs at the time t_{min}.

$$q(t_{min}) = \sum_i li \; = \; \sum_{i \in N_d} k_i \; . P_i(t_{min})^{1.1} \qquad (3.9)$$

Source: AbdelMeguid, (2011)

Also $d_i(t_{min})$ and $P_i(t_{min})$ denote the demand and pressure of node *i* at time t_{min}, respectively. As the leakage at any node has been assumed to proportional with the node demand, then the coefficient k_i is proportional with the demand of node *i* at the time of the MNF, t_{min} as in equation (3.9).

$$k_i \; \propto \; d_i \; (t_{min}) \qquad (3.10)$$

By introducing proportional coefficient β_i, the coefficient k_i can be expressed as shown in equation 3.11

$$k_i = \; \beta_i \; . d_i \, (t_{min}) \qquad (3.11)$$

The pressure at node *i* is a difference between node head, *hi*, and node elevation, *Hi*, as given in equation (3.12).

$$P_i(t_{min}) = (h_i(t_{min}) - \; H_i) \qquad (3.12)$$

Substitute equations (3.11 & 3.12) for k_i and $P_i(t_{min})$ in equation 3.9.

$$q(t_{min}) = \; \sum_i l_i = \sum_{i \in N_d} \beta_i \; . d_i(t_{min}) \; .(h_i(t_{min}) - \; H_i)^{1.1} \qquad (3.13)$$

Hence the MNF, the demand and total head of node *i* at *tmin* are known from the data provided in the hydraulic model and simulation results, the proportional coefficient βi, which has been used to calculate the leakage coefficient *ki*, is estimated as shown in equation 3.14.

$$\beta_i = \frac{q(t_{min})}{\sum_i d_i.(h_i(t_{min}) - H_i)^{1.1}} \qquad (3.14)$$

3.4.3 GIS Modeling

The purpose of the GIS modeling is to aid in the visualization and the analysis of the water distribution system (WDS). This is to help decision makers respond quickly to NRW. To create the GIS model, the hydraulic modeled water distribution system was converted to shapefile and imported into a GIS environment. The imported shapefile is checked for errors such as duplicates. Network topology was also ensured. This was done to help explore the spatial relationships between the nodes and pipes. Other properties of the pipes, nodes and pump in excel format were added to the different layers. The GIS data created holds all necessary information about the pipes and the nodes.

In modeling the leakages, GIS was used in categorizing the leakages into class range. The different class ranges are distinguished by different color code. The color coding makes each class range unique from each other. With this, background leakages along the distribution network are classified into five main class ranges. The class ranges varies from the lowest to the highest level of background leakages. The class ranges are then displayed in a map format for visualization. The same approach was used in modeling reported leakages and pressure. Their outputs were also displayed in map format.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter outlines the results obtained from the study. The results on the NRW calculations are tabulated mostly in tables and charts, while the result for hydraulic and the GIS models are presented mostly in charts and diagrams. The last section of this chapter discusses the results obtained against literature.

4.2 RESULTS

4.2.1 System Input Volume (SIV) and Consumptions

i. System input volume (SIV)

The volume of water supplied to Southeast District was obtained by a manual volume calculation. The computed SIV was 573,818m^3. There was no adjustment made to the computed SIV. This is because the error recorded after the meter was tested was negligible.

ii. authorized consumption

The total volume of authorized water consumed in Kumasi Southeast District for 2013 was 270,628m^3. It is comprised of the summation of billed authorized consumption and unbilled authorized consumption.

The two components of billed authorized consumption are billed metered consumption and billed unmetered consumption. The total volume of billed authorized consumption for 2013 in Kumasi Southeast District was 270499m^3. This represents 47.14% of the total water supplied in the district. The summation of all billed metered consumption and billed unmetered consumption for the year 2013 is as shown in Table 4-1.

Table 4-1 Annual Billed Consumption

Consumption	Volume(m^3)	%
Billed Metered Consumption	238,683	41.60
Billed Unmetered Consumption	31,816	5.54
Total Annual Billed Consumption	270,499	47.14

There are two components of unbilled authorized consumption: unbilled metered and unbilled unmetered consumption. There was no unbilled metered consumption for the period of the research. The only component of unbilled unmetered consumption was the consumption made by the GWCL office. Table 4-2 shows the calculation of water consumed at the GWCL office in the district. The calculation is based on the estimated water usage as shown in Appendix 8.

Table 4-2 GWCL Offices Water Consumption

GWCL Office Consumption	
No. of Staff	13
Average Daily Usage/Staff (l)	30
Average Staff Usage/Day (l)	390
Misc Usage/Day (l)	100
Total Usage/Day (l)	490
Average Working days	264
Annual Consumption(l)	129360
Annual Consumption(m^3)	129.36

4.3 WATER LOSSES

4.3.1 Apparent Losses

The components of apparent losses are estimated in the study area are unauthorized consumption, customer metering inaccuracies and data handling errors.

i. Unauthorized consumption

Illegal connections were the main component of unauthorized consumption in the study area. The data from the GWCL shows that out of 100 customers searched 8 connections were found to be illegally connected. From this data an estimation of the total number of illegal consumption for the district was computed as shown in the Appendix 9.

ii. Inaccuracies of customer metering and data handling errors

Appendix 10 shows the results of test conducted by GWCL on meters from the district. From the result, there was overbilling with respect to the meter test conducted. The negative value of the NRW shows that the system was over-registered. This indicated that customers were being over charged due to metering inaccuracies. There was no record for data handling errors. The checks and balances practiced by the Data Processing Unit (DPU) of GWCL revealed and eliminated all types of data processing errors; hence no value for NRW was recorded. The apparent losses in the distribution network are shown in Table 4-3.

Table 4-3 Apparent Losses

Consumption	Volume (m^3)	Volume (%)
Unauthorized Consumption	68,880	12.00
Inaccuracies Of Customer Metering And Data Handling Errors	-931.73	-0.16
Total Apparent Losses	67,948.27	11.84

Most of the apparent losses occurred from unauthorized consumption (illegal connection). From the table 12% of water supplied in the district was lost through unauthorized consumption. However the total apparent losses reduced to 11.84%, this was because meter inaccuracies were over-registered hence its value was deducted from the unauthorized consumption.

4.3.2 Real Loss

There are three components of real loss:

- Leakage and overflows from the utility's reservoirs/storage tanks
- Leakage from transmission and distribution mains
- Leakage on service connections up to the customer's meter

The Kumasi Southeast District has only one reservoir. The GWCL log books for the district shows no record of reservoir overflow or leakage was recorded. The computed volumes and the percentages of losses on both pipe mains and service connections are shown in Table 4-4.

Table 4-4 Real Losses

Leakages	Main Pipelines (m^3/yr)	Main Pipelines (%)	Service Pipelines (m^3/yr)	Service Pipelines (%)
Reported Leakage (RL)	4,046.40	0.71	286.4	0.05
Background Leakage (BL)	4,099.68	0.71	4,591.7	0.80
Unreported Leakage (UL)	95,191.2	16.59	106,852.8	18.62
Total	103,337.28	18.01	111,730.9	19.47

The above calculations were based on data obtained from the GWCL (Appendix 4) and empirical flow rates from IWA (Appendix 5 & 6). Most of the losses were unreported leakages; 16.59% for pipe mains and 18.62% on service connections. This was because they were mainly background leakages which worsened and were detected by through an active detection survey. Reported leakages resulted in 0.71% losses on the main pipelines and 0.80% on the service lines. Background leakages also resulted in 0.71% losses on the main pipelines and 0.05% on the service lines. The infrastructure leakage index **(**ILI) obtained was 3.9.

Table 4-5 shows the water balance table drawn for Kumasi Southeast District. The Table is a representation of water consumed and lost in the district.

Table 4-5 Water Balance Table for Kumasi Southeast District

System Input Volume 573818	Authorized Consumption 270628	Authorized Consumption 270499	47.14%	Billed Metered Consumption 238,683	41.60%	Revenue Water 270,499	47%
				Billed Unmetered/ Estimated Consumption 31,816	5.50%		
		Unbilled Authorized Consumption 129	0.02%	Unbilled Metered Consumption 0	0.00%	Non-Revenue Water 283,146	49%
				Unbilled Unmetered Consumption 129	0.02%		
	Water Losses 283,016	Apparent Losses 67948	11.84%	Unauthorized Consumption 68,880	12.00%		
				Metering Inaccuracies and Data Error -932	-0.16%		
		Real Losses 215068	37.48%	Leakage on Mains 103,337	18.00%		
				Overflows at Storage Tanks 0	0.00%		
				Leakage on Service Connections 111,731	19.50%		

4.4 HYDRAULIC AND GIS MODELS

4.4.1 Hydraulic Model

Figure 4-1 shows hydraulic model of a section of the Kumasi Southeast District WDS. It depicts the various nodes and pipes. The arrows on the pipes show the direction of water flow in the pipes.

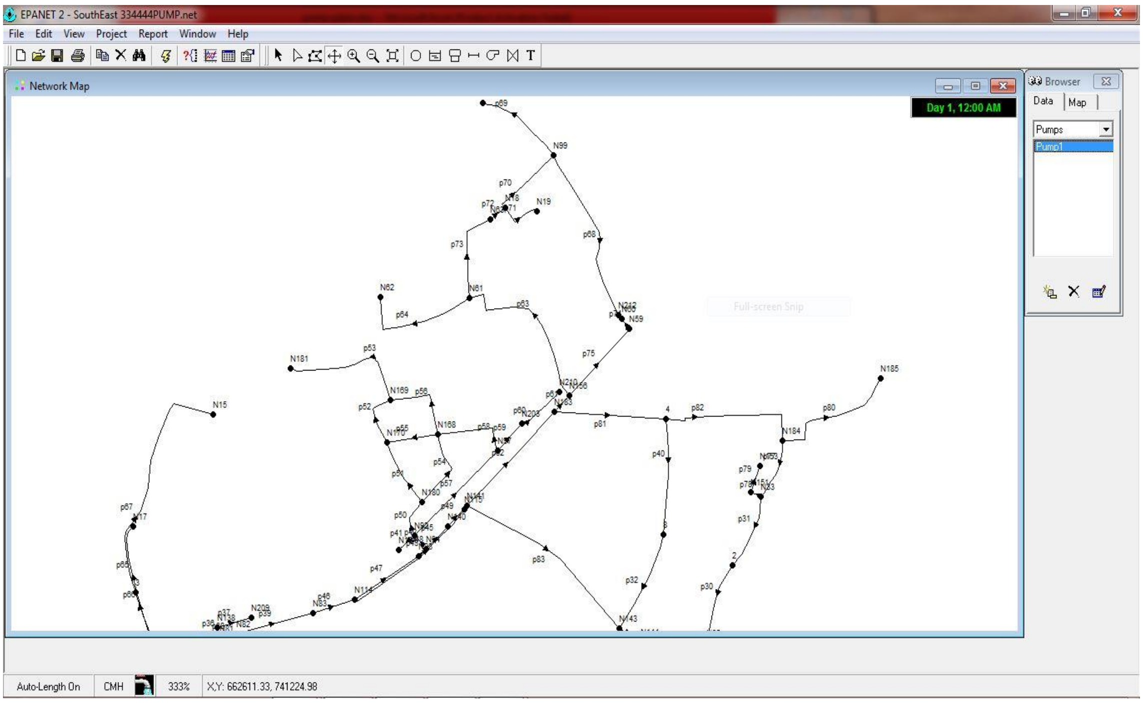

Figure 4-1 Epanet Showing Nodes, Pipes and Flow Direction

The computed pressure and head at the various nodes on the distribution network are as shown in Appendix 1, while the computed flow, headloss, velocity and friction factor for the various pipes are shown in Appendix 2.

Figure 4-2 shows a pressure distribution graph among the nodes. The graph shows that less than 5% of all the pressure readings were between 20m -135m whilst 95% of the readings were between the ranges of 135m -175m.

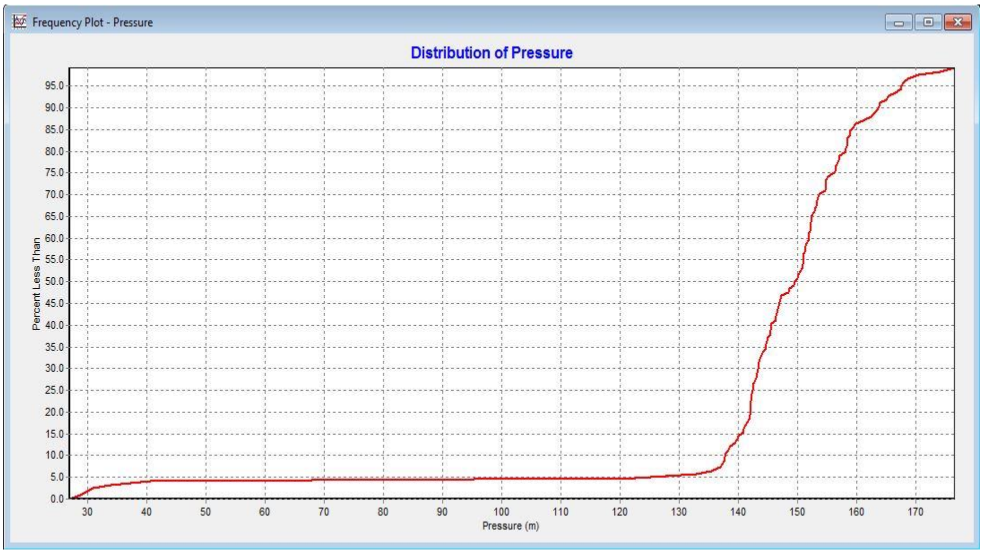

Figure 4-2 Frequency Plot - Pressure

The standard hydraulic equation of water network was used to create an extended model suitable for pressure control and leakage analysis. Equation (3.7) shows a direct relation between pressure (*P*) and leakage (l). An increase in pressure will correspond to an increase in leakage and vice versa. Sample calculation of *βi, ki* and *li* is as shown in Appendix 1.

Figure 4-3 shows the distribution of the leaked water among the nodes. The highest leak level occurred at node 11 with $2.2m^3$ of water being lost hourly. There were other significant peaks at nodes 8, 35, 55, 76, 103 and 114 respectively. Appendix 7 also shows the computed Ki among the node.

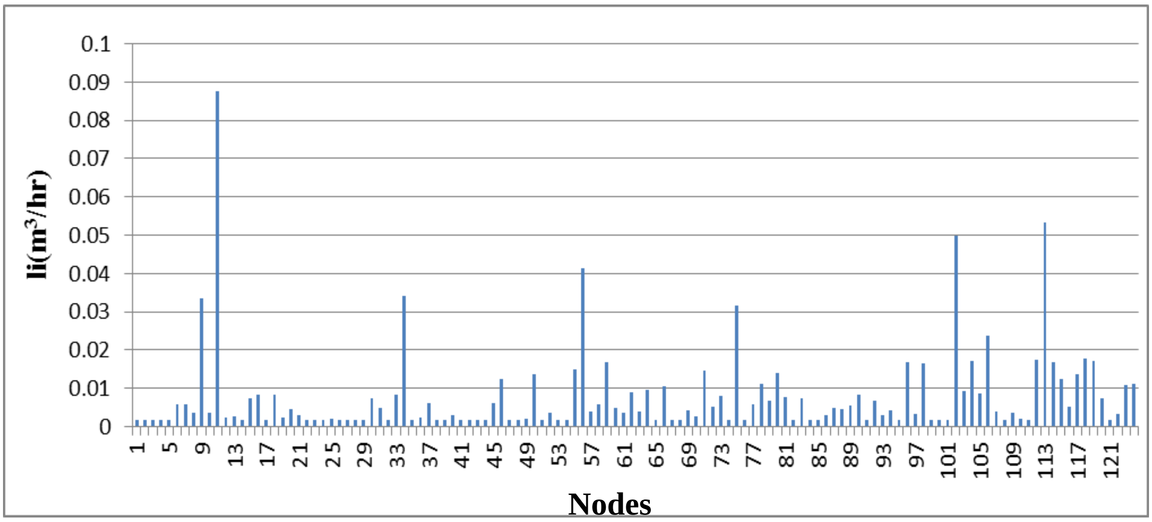

Figure 4-3 Background Leakage Distribution among Nodes

4.4.2 GIS Model

A comprehensive modeling of the distribution network played an important role in mapping and identification of water losses. The background leakages map in Figure 4-4 shows the level of background leakages across the nodes. The map shows nodes with higher level of background leakages and nodes with lower levels of background leaks. The leakages were classified into five classes. Each class represents a range of the background leakages. The lowest class ranges from 0.001854m^3/hr – 0.004767m^3/hr while the highest class ranged from 0.041319m^3/hr - 0.087669m^3/hr. Majority of the nodes were in the range of the lower levels of leakage, while a few recorded high levels of leakages.

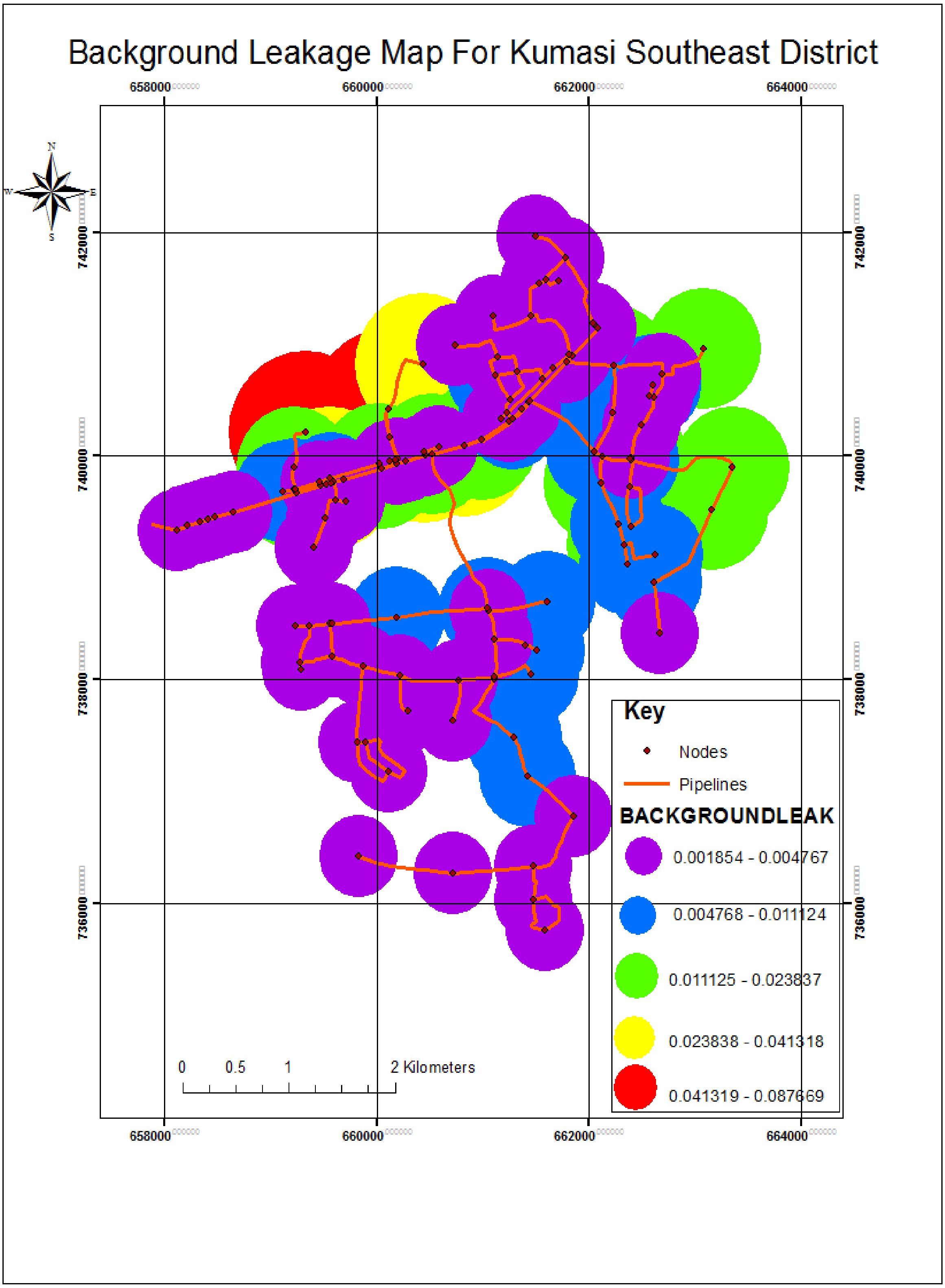

Figure 4-4 Background Leakage Map

Figure 4-5 represents Ki distribution across the nodes. The map shows nodes with higher level of Ki values and nodes with lower levels of Ki values.

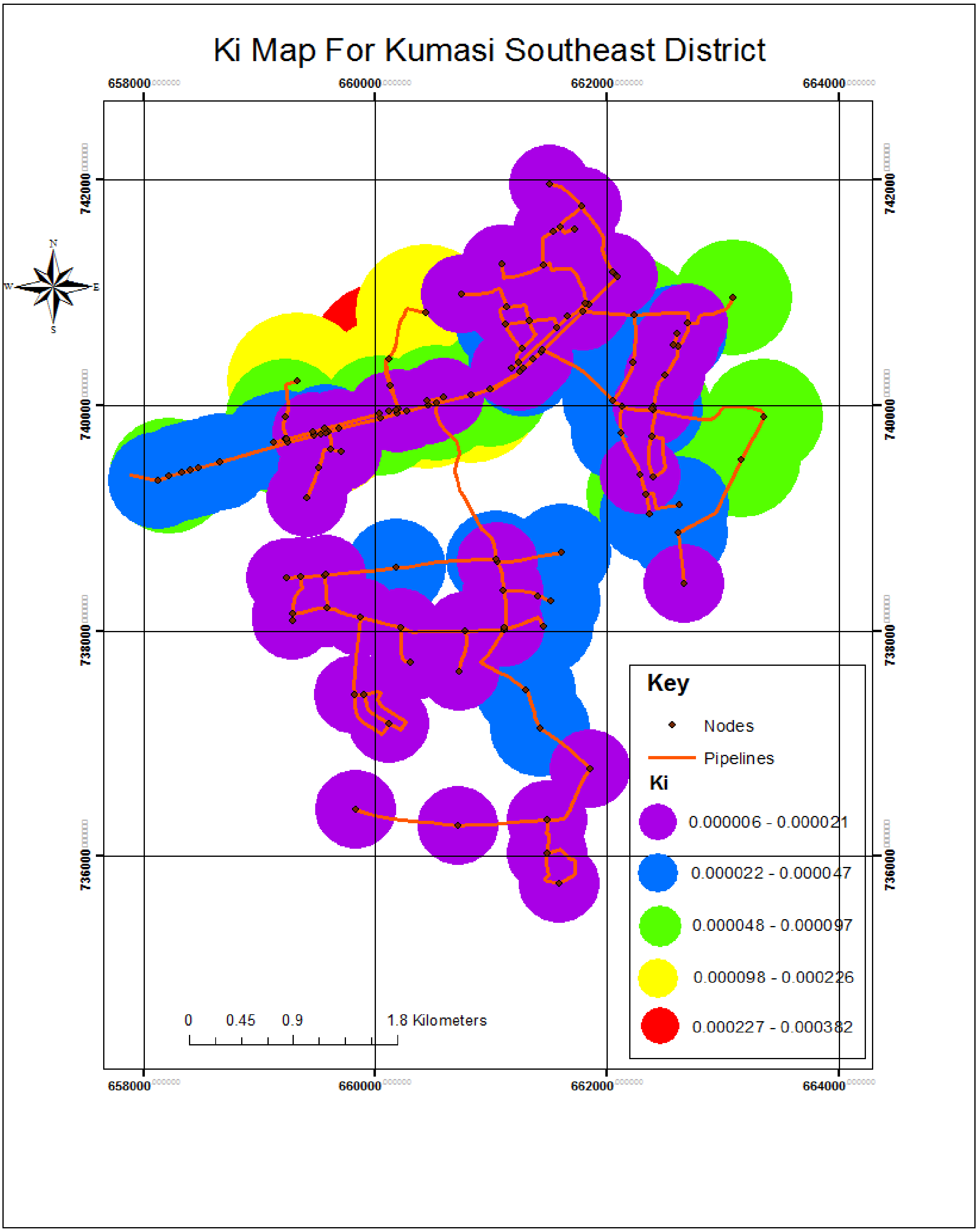

Figure 4-5 Distribution of Computed Ki among Nodes

The Ki values across the nodes were classified into five classes. Each class represents a range of the Ki values. The lowest class ranges from 0.000006 – 0.000021 while the highest class ranged from 0.000227 - 0.000382. Majority of the nodes fell in the range of the lower levels of Ki values, while a few recorded high levels of Ki values. Figure 4-6 is a pressure map of Southeast District at 12:00am showing the pressure distribution across the nodes.

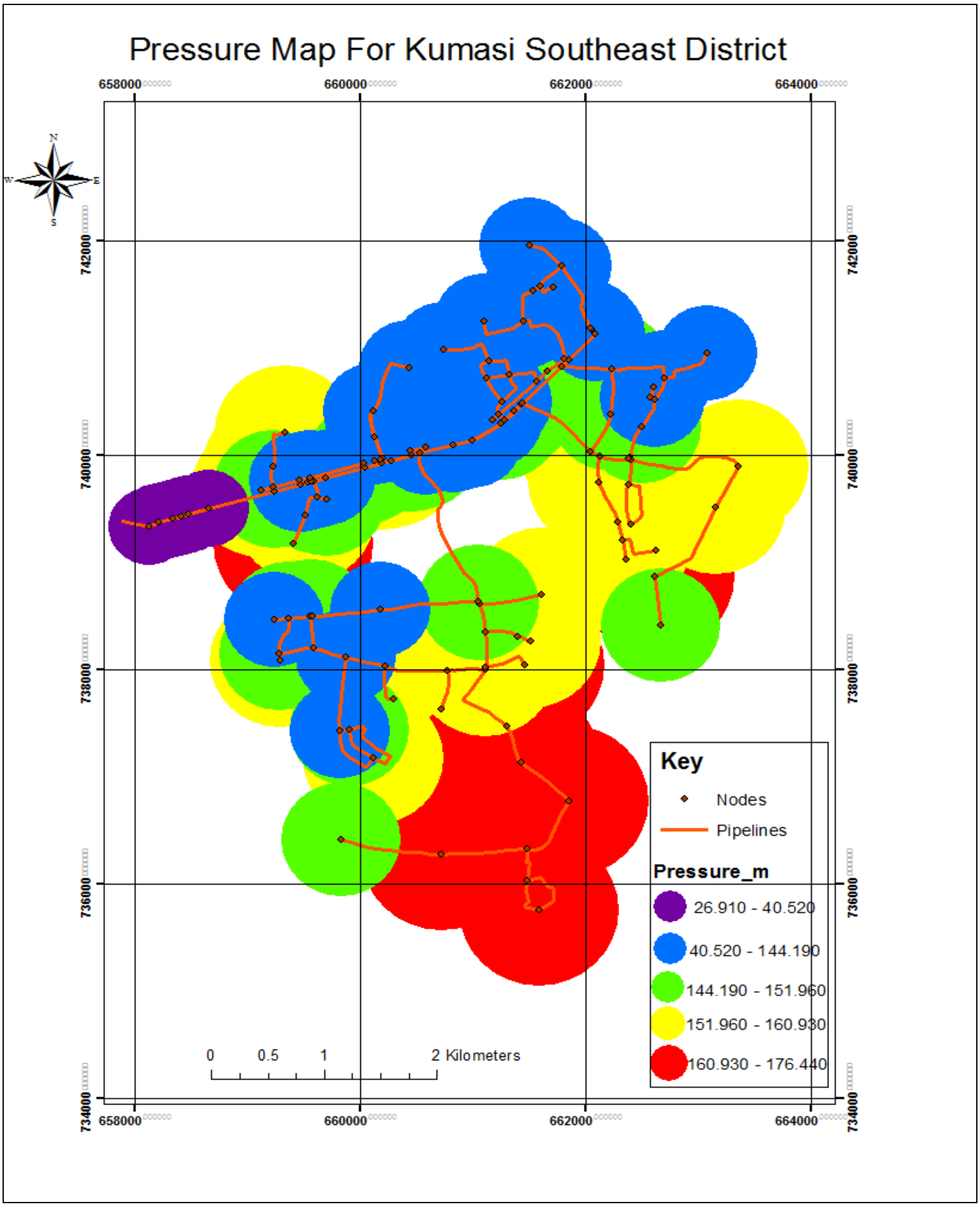

Figure 4-6 Pressure Distribution Map

Pressure distributions across the nodes were grouped into five classes. The lowest class had pressure values ranging from 29.910m – 40.520m. The highest class had pressure reading ranging from 160.930m – 176.440m. Figure 4-7 also represent the reported leakages for the Kumasi Southeast district.

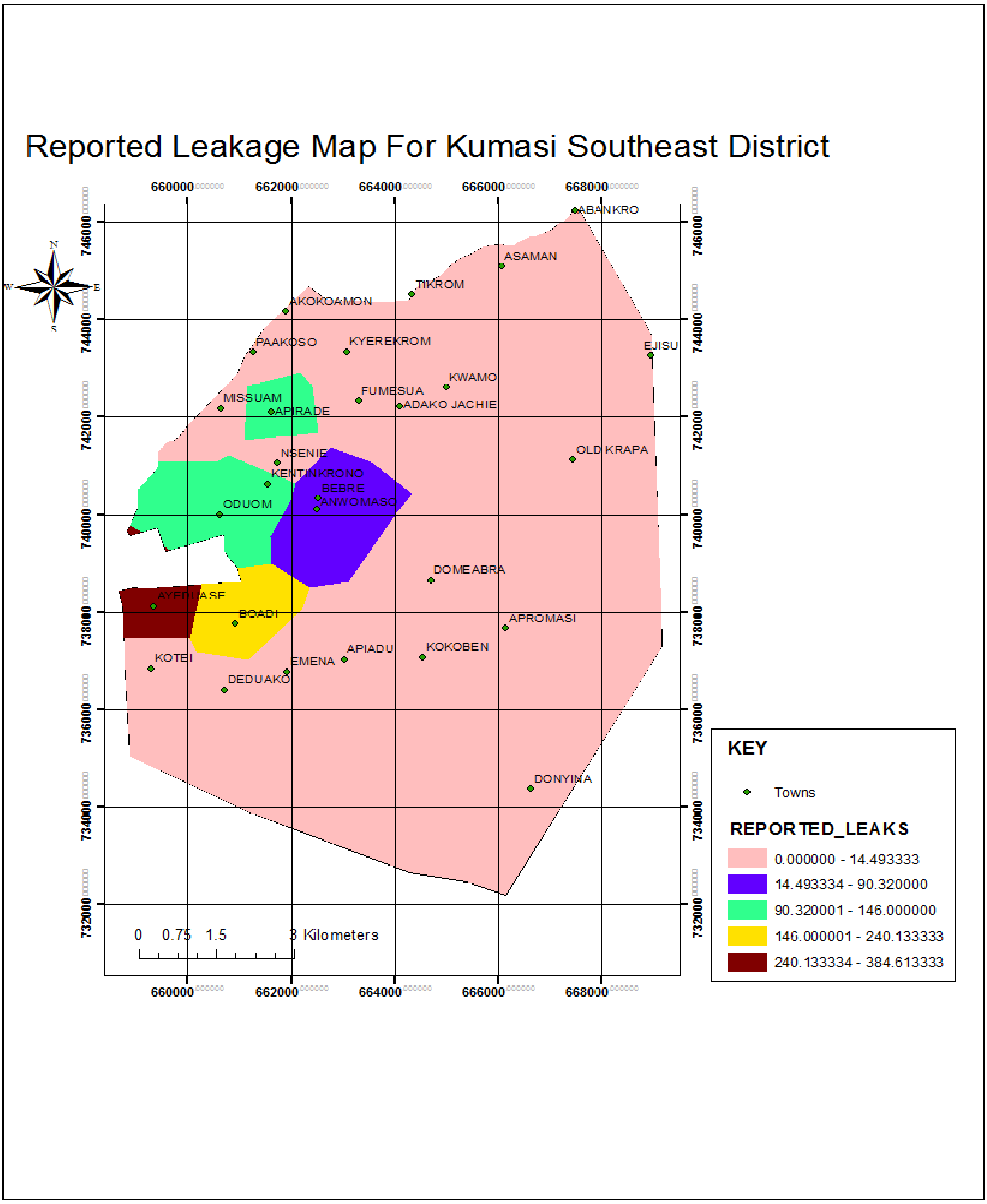

Figure 4-7 Reported Leakage Map

From the map Ayeduase recorded the highest reported leaks. It can also be observed from the map that most of the towns reported low levels of reported leaks. This is because most of the pipelines in those communities were disconnected from the GWCL WDS due to low patronage.

4.5 DISCUSSIONS

4.5.1 Pressure and Leakage Reduction

The four basic methods of managing leakage as shown in Figure 2-9 shows that real losses in WDSs can be driven down by reducing pressure in the system, improving the speed of detection, location and repair of burst. Pressure at the nodes and pump of the distribution network contribute directly to leakages in the WDS. From the hydraulic and the GIS models used in this study, high pressured nodes (160.930m – 176.440m.) will be prone to leakage. Although this should be the case, however the leakage maps produced in Figure 4-4 proves otherwise. The reason for this might be as a result of the numerous over aged pipes in the district. These over aged pipes are prone to leakages irrespective of nodal and pump pressure. However identifying these nodal and pump pressure and a management of them can be used to reduce background leakage and the incidence of pipe bursts in the district. According to AbdelMeguid (2011), operational pressure management is a cost-effective method for leakage reduction over entire DMAs, and for minimizing the risk of further leaks by smoothing pressure variations. Managing these pressure values offers one of the best tools for system optimization which serves as one of the best strategies for water loss reduction and efficient management of water distribution systems.

4.5.2 Water Consumption and Losses

The GIS models generated show that nodes with higher consumption (demand) had higher levels of background leakages; this confirms the standard hydraulic equations 3.10 and 3.11. The model aided in identifying the level of reported leakages at various communities and the background leakages at the nodes. Direct detection and repair of these bursts is one of the most effective means that can be used to prevent the high level leakage in the district. This will help decision makers to know where exactly to tackle what type of water loss.

According to the American Water Works Association (AWWA) free water audit, 1.25% of the system input volume (SIV) should be assumed as the volume of water consumed under unbilled unmetered consumption. However the IWA methodology used in this study show an unbilled unmetered consumption to be 0.02%. This might be as a result of the absence of a fire hydrant in the Kumasi Southeast District. 41.6% of the water supplied was metered and billed, while 5.54% of water supplied was billed but unmetered. From the above, 47.14% of the water distributed was by authorized usage. Out of total authorized usage, 47.12% of it generated revenue for GWCL.

The American Water Works Association (AWWA) free water audit also estimates 0.25% of SIV to be the volume of water lost to unauthorized consumption. But this research shows unauthorized consumption to be as high as 11.84%. The main reason for the high unauthorized consumption is because the district has not been divided into zone. This has resulted in inefficiency on the part of the managers of the utility company in detecting those illegally connected to the distribution network. 37.48% of the water supplied to the district was lost to real losses (leakages). This percentage is very high and it is mainly caused by worn-out (old) pipes. A systematic approach of replacing these worn-out pipes will help reduce the high level of real loss.

Also the computed ILI of 3.9 falls in Category B of the real loss assessment matrix shown in Appendix 11. This means that the water distribution network has potential for improvements.

The total volume of water lost in the district was 49% of the total treated water supplied. NRW at a rate of GHc 1.3 per cubic meter result in a revenue loss of GHc 368,089.80. This is clear evidence that GWCL can increase their revenue significantly by reducing NRW.

4.5.3 Integrated Hydraulic and GIS Models for NRW Reduction

Water loss in a distribution network is inevitable. A quick identification of real and apparent losses is key in NRW reduction. The integration of the hydraulic and GIS models provided access to more reliable, up-to-date information and reduces response time to tackle water losses. Also the integration of the hydraulic and GIS models makes water loss auditing and modeling easier. This is because water losses can be monitored within the distribution network with knowledge of the nodal pressure. The model can be used to estimate water losses when the distribution network is under high pressure and the level of water losses when the pressure is reduced.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMENDATION

5.1 INTRODUCTIONS

This chapter presents the conclusions drawn from the research questions in the light of the research findings as well as the other findings made by the research. The chapter also includes recommendations for future research.

5.2 CONCLUSIONS

The research was set out in order to answer the research questions. The conclusions are presented with respect to the research questions.

What strategies are used for identifying and managing NRW in Kumasi Southeast District?

Water demand in Kumasi Southeast District is increasing with increase in population. This makes NRW reduction in Kumasi Southeast District water distribution system (WDS) an important issue to the water industry. The managers of the KWSS undertake periodic meter inspection and active leakage control management. These are done to identify illegal connections and background leakages in the district. They also keep a record of reported leakages to identify areas prone to leakages. These steps being taken by the managers of the water distribution network are highly commendable but the absence of the computation of NRW and its components and the modeling of water losses makes these steps being taken yield very little result.

The approach of determining NRW is based on a percentage of volume of water billed to the volume of water supplied to the district. This approach is not comprehensive enough to deal with rising levels of NRW. The figures quoted by GWCL are highly inaccurate and too simplistic. It is actually insufficient to use the ratio of billed authorized consumption to water supplied as a measure of NRW. These values quoted by GWCL do not categorize NRW into its main components. The current approach adopted by management to determine NRW levels in the water distribution network does not enable the drawing of a water balance table for the district. Such an approach certainly cannot achieve much in NRW reduction.

How is the pressure distributed along the water distribution network in the district?

The standard hydraulic equation as described earlier in the literature review shows that pressure management has an effect on leakages in a water distribution network. The integrated hydraulic model and GIS generated nodal pressure values across the WDS. Pressures along the nodes were categorized into five main classes. The lowest range of pressure was 26.910m-40.520m while the highest range was between 160.930m-176.440m. The pressure values generated at each node was a key tool in monitoring leakages. An increase in pressure will cause an increase in leakages and vice versa. Proper pressure management will be key in reducing real loss in Kumasi Southeast District.

How can the application of hydraulic and GIS models be used to evaluate non-revenue water levels in Kumasi Southeast District?

GIS and hydraulic models are complementary technologies. Therefore combining the two technologies in evaluating non-revenue water (NRW) in water distribution networks yields greater dividend. The integration of the hydraulic and GIS models provided access to more reliable, up-to-date information and reduced response time to tackle water losses. Also the integration of the hydraulic and GIS models makes water loss auditing and modeling easier. The methodology used in this report involves the use of a hydraulic modeling software to determine the nodal pressure, nodal and pipe leakages by using a hydraulic simulation model. Also for a better representation of the results and management of the system, the outputs are exported to a GIS model. The GIS model aided in the visualization and the analysis of the results obtained. Using the capabilities of the GIS model, the network map and attribute data are linked and leakages identified. This process aids decision makers in identifying areas prone to leakages in the District. Also since leakages are dependent on pressure, the nodal pressure generated by the model when managed will result in decrease in leakages in the District.

5.3 RECOMMENDATION

There were several drawbacks to the study. Nevertheless, the methodology employed ensured that these limitations did not affect the outcome of the study. In order to improve the findings in the study, the following recommendation were made.

- The standard water balance table should be drawn yearly to assess NRW. To effectively do this, it is highly recommended that a thorough study be conducted on an in-depth approach of using GIS to estimating unauthorized consumption and zoning of the districts into district meter area (DMA). This will help the utility managers manage and monitor the water distribution system (WDS) efficiently.

- Since a larger percentage of NRW was in the area of real loss, a further investigation into pipe age, pressure and meter age on NRW should be conducted help fully understand their effect on water losses.

- A study on night flow analysis in each district should be conducted. It is important for the utility company to consider monitoring MNF for each district when real losses are at their maximum percentages of the total flow during that period.

- Managers of the Kumasi water supply system should consider pressure management, better active leakage control, and better maintenance to reduce real loss further more.

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APPENDICES

Appendix 1: Properties of Nodes

Node	X	Y	Elevation (m)	Demand (CMH)	Head (m)	Pressure (m)	Bi	Ki	li
N1	658482.1	739451.8	265.05	0.07	298.87	33.82	0.000551	3.85E-05	0.001854
N2	658660.4	739502.1	258.32	0.07	298.84	40.52	0.000451	3.16E-05	0.001854
N5	659834.7	736419.4	268.7	0.07	417.95	149.25	0.000108	7.53E-06	0.001854
N7	659291.6	738090.3	263.33	0.07	417.96	154.63	0.000103	7.24E-06	0.001854
N9	660721	736275.3	254.51	0.07	417.95	163.44	9.73E-05	6.81E-06	0.001854
N11	661407.8	738309.1	261.77	0.22	417.97	156.2	0.000102	2.25E-05	0.005827
N13	661516.3	738264.8	257.03	0.22	417.96	160.93	9.9E-05	2.18E-05	0.005827
N14	660202.6	739969.2	265.85	0.14	418.08	152.23	0.000105	1.47E-05	0.003708
N15	660439.7	740823.4	282.37	1.26	417.82	135.45	0.00012	0.000151	0.033372
N16	660203.3	739969.4	265.84	0.14	418.08	152.24	0.000105	1.47E-05	0.003708
N17	660121.1	740414.1	277.85	3.31	417.74	139.89	0.000116	0.000382	0.087669
N18	661601.1	741582.3	275.54	0.09	418.02	142.48	0.000113	1.02E-05	0.002384
N19	661723.9	741568.6	280.86	0.1	418.02	137.16	0.000118	1.18E-05	0.002649
N21	659238.7	738474.4	276.07	0.07	417.96	141.89	0.000114	7.96E-06	0.001854
N23	661615.8	738700	259.89	0.28	417.98	158.09	0.000101	2.83E-05	0.007416
N25	662630.6	739118.2	251.46	0.31	417.96	166.5	9.54E-05	2.96E-05	0.008211
N26	659521.6	739446.5	265.94	0.07	418.16	152.22	0.000105	7.37E-06	0.001854
N30	661429.8	737138.8	241.52	0.31	417.96	176.44	8.95E-05	2.77E-05	0.008211
N31	661862.5	736780.8	250.5	0.09	417.96	167.46	9.48E-05	8.53E-06	0.002384
N32	662399.1	739988.5	259.08	0.17	417.98	158.9	0.0001	1.71E-05	0.004503
N33	662615.2	740522.6	275.78	0.11	417.98	142.2	0.000113	1.25E-05	0.002913
N34	658220.1	739376.7	272.01	0.07	298.92	26.91	0.000708	4.96E-05	0.001854
N35	658338.6	739411	270.11	0.07	298.89	28.78	0.000658	4.6E-05	0.001854
N36	658412.8	739432.2	268.07	0.07	298.88	30.81	0.00061	4.27E-05	0.001854
N37	659825.5	737435.4	274.6	0.08	417.96	143.36	0.000112	9E-06	0.002119
N38	660121.2	737176.4	265.66	0.07	417.96	152.3	0.000105	7.36E-06	0.001854
N39	659287.2	738153.2	266.73	0.07	417.96	151.23	0.000106	7.42E-06	0.001854
N40	659480.6	739733.7	276.06	0.07	418.17	142.11	0.000114	7.95E-06	0.001854
N41	659535.7	739748.7	276.1	0.07	418.16	142.06	0.000114	7.95E-06	0.001854
N42	659246.6	739670.1	266.23	0.28	418.19	151.96	0.000105	2.95E-05	0.007416
N43	659594.4	739765.1	276.14	0.18	418.16	142.02	0.000114	2.05E-05	0.004767
N45	659621.3	739610.3	271.45	0.07	418.16	146.71	0.00011	7.67E-06	0.001854
N46	659576	739760	276.13	0.32	418.16	142.03	0.000114	3.64E-05	0.008476
N48	659564.1	739795.9	275.3	1.29	418.16	142.86	0.000113	0.000146	0.034167
N49	659565.5	738496.8	272.65	0.07	417.96	145.31	0.000111	7.76E-06	0.001854
N51	659592.1	738203.9	264.93	0.09	417.96	153.03	0.000105	9.42E-06	0.002384
N57	660189	738560.3	274.67	0.23	417.97	143.3	0.000112	2.59E-05	0.006092
N59	662091.1	741139.2	275.75	0.07	418.03	142.28	0.000113	7.94E-06	0.001854
N60	662061.4	741176.8	278.22	0.07	418.03	139.81	0.000116	8.09E-06	0.001854

N61	661456.5	741251	273.83	0.11	418.02	144.19	0.000112	1.23E-05	0.002913
N62	661103.5	741253.4	285.15	0.07	418.02	132.87	0.000122	8.56E-06	0.001854
N63	661540	741540.6	274.93	0.07	418.02	143.09	0.000113	7.89E-06	0.001854
N65	659905.4	737439.4	273.27	0.07	417.96	144.69	0.000111	7.79E-06	0.001854
N67	658129.6	739335.7	269.26	0.07	298.94	29.68	0.000636	4.45E-05	0.001854
N70	659228.7	739705.7	267.26	0.23	418.19	150.93	0.000106	2.44E-05	0.006092
N71	659236.9	739708.2	267.78	0.47	418.18	150.4	0.000107	5.01E-05	0.012448
N73	659583.9	738499.2	273.09	0.07	417.96	144.87	0.000111	7.78E-06	0.001854
N74	659878.1	738119.9	274.41	0.07	417.96	143.55	0.000112	7.86E-06	0.001854
N75	660224.9	738033.5	260.91	0.08	417.96	157.05	0.000102	8.14E-06	0.002119
N76	660049.6	739892.7	267.96	0.52	418.1	150.14	0.000107	5.56E-05	0.013773
N77	660193.5	739933.2	264.77	0.07	418.08	153.31	0.000104	7.31E-06	0.001854
N78	660183.2	739964.4	266.23	0.14	418.08	151.85	0.000106	1.48E-05	0.003708
N80	660276.3	739956.4	263.25	0.07	418.08	154.83	0.000103	7.23E-06	0.001854
N81	660463.7	740006	269.63	0.07	418.06	148.43	0.000108	7.58E-06	0.001854
N82	660532	740022.4	273.37	0.57	418.06	144.69	0.000111	6.34E-05	0.015097
N83	660836.2	740098.5	277.24	1.56	418.05	140.81	0.000115	0.000179	0.041318
N86	661060.1	738616.9	266.96	0.15	417.98	151.02	0.000106	1.59E-05	0.003973
N87	661049.9	738641.2	266.52	0.22	417.98	151.46	0.000106	2.33E-05	0.005827
N88	661118.6	738008.1	258.26	0.64	417.96	159.7	9.99E-05	6.39E-05	0.016951
N89	661118.8	738029.1	258.65	0.19	417.96	159.31	0.0001	1.9E-05	0.005032
N90	661114.1	738357.4	264.71	0.14	417.97	153.26	0.000104	1.46E-05	0.003708
N92	661237.9	740381.2	272.54	0.34	418.03	145.49	0.000111	3.76E-05	0.009005
N93	661255.1	740305.1	272.43	0.15	418.04	145.61	0.000111	1.66E-05	0.003973
N94	661284.7	740333.2	270.98	0.36	418.03	147.05	0.000109	3.94E-05	0.009535
N95	661485.9	736329.7	243.96	0.07	417.96	174	9.09E-05	6.36E-06	0.001854
N97	661570.3	740692.1	271.11	0.4	418.03	146.92	0.000109	4.38E-05	0.010594
N99	661791.4	741773.8	280.32	0.07	418.02	137.7	0.000118	8.23E-06	0.001854
N108	660306.7	737726.3	253.01	0.07	417.96	164.95	9.64E-05	6.75E-06	0.001854
N109	660783.4	737997.3	250.47	0.16	417.96	167.49	9.48E-05	1.52E-05	0.004238
N111	660725.4	737637.9	247.56	0.1	417.96	170.4	9.3E-05	9.3E-06	0.002649
N114	661000.6	740145.6	275.88	0.55	418.04	142.16	0.000113	6.24E-05	0.014567
N115	661437.2	740478.8	271.77	0.2	418.04	146.27	0.00011	2.2E-05	0.005297
N124	661462.2	738042.2	255.16	0.3	417.96	162.8	9.78E-05	2.93E-05	0.007946
N133	659695.3	739793.4	276.67	0.07	418.14	141.47	0.000114	7.99E-06	0.001854
N138	660454.3	740043.3	268.57	1.2	418.06	149.49	0.000107	0.000129	0.031783
N140	661369.9	740414.4	271.42	0.07	418.03	146.61	0.00011	7.68E-06	0.001854
N141	661447.4	740491.1	271.67	0.22	418.03	146.36	0.00011	2.42E-05	0.005827
N143	662051.7	740041	259.1	0.42	418	158.9	0.0001	4.22E-05	0.011124
N144	662137.9	739992.6	261.58	0.26	417.99	156.41	0.000102	2.66E-05	0.006886
N146	662337.1	739209.8	260.95	0.53	417.96	157.01	0.000102	5.39E-05	0.014038
N148	662407.8	739961.2	259.63	0.29	417.98	158.35	0.000101	2.92E-05	0.007681
N151	662576.5	740539.8	277.19	0.07	417.98	140.79	0.000115	8.03E-06	0.001854
N153	662612.8	740636.6	280.26	0.28	417.98	137.72	0.000118	3.29E-05	0.007416

N156	661853.1	740895.8	266.18	0.07	418.03	151.85	0.000106	7.39E-06	0.001854
N160	659468.7	739769.9	275.09	0.07	418.17	143.08	0.000113	7.89E-06	0.001854
N164	661176.4	740329.2	274.13	0.11	418.03	143.9	0.000112	1.23E-05	0.002913
N168	661332.5	740751.7	271.62	0.19	418.03	146.41	0.00011	2.09E-05	0.005032
N169	661144.8	740879.1	276.13	0.17	418.03	141.9	0.000114	1.93E-05	0.004503
N170	661128.6	740722	280.21	0.21	418.03	137.82	0.000117	2.47E-05	0.005562
N176	662368.5	739035.7	252.59	0.31	417.96	165.37	9.61E-05	2.98E-05	0.008211
N179	661485.7	736031.2	249.97	0.07	417.96	167.99	9.45E-05	6.61E-06	0.001854
N180	661269.8	740503	275.59	0.26	418.03	142.44	0.000113	2.94E-05	0.006886
N181	660747.9	740994.1	279.43	0.11	418.03	138.6	0.000117	1.28E-05	0.002913
N183	661794	740835.7	262.89	0.16	418.03	155.14	0.000103	1.65E-05	0.004238
N184	662700	740729.7	279.7	0.07	417.99	138.29	0.000117	8.19E-06	0.001854
N185	663090.6	740955.9	281.02	0.64	417.98	136.96	0.000118	7.57E-05	0.016951
N186	662669.2	738418.1	267.1	0.13	417.91	150.81	0.000106	1.38E-05	0.003443
N187	662392.4	739728.5	265.63	0.63	417.97	152.34	0.000105	6.63E-05	0.016686
N195	659713.4	739593.3	270.95	0.07	418.16	147.21	0.000109	7.65E-06	0.001854
N196	659366.7	738482.5	273.12	0.07	417.96	144.84	0.000111	7.78E-06	0.001854
N197	659411.3	739180.3	255.88	0.07	418.16	162.28	9.81E-05	6.87E-06	0.001854
N198	659333.4	740215.5	261.37	1.88	418.14	156.77	0.000102	0.000192	0.049794
N203	661667.2	740790.6	268.03	0.35	418.03	150	0.000107	3.74E-05	0.00927
N204	662392.3	739971.4	259.61	0.65	417.99	158.38	0.000101	6.55E-05	0.017216
N206	659126.6	739678.2	261.8	0.33	418.19	156.39	0.000102	3.37E-05	0.00874
N207	660036.4	739929.5	269.6	0.9	418.16	148.56	0.000108	9.73E-05	0.023837
N208	660127.7	739950.5	267.31	0.15	418.08	150.77	0.000106	1.6E-05	0.003973
N209	660592.5	740080	276.94	0.07	418.06	141.12	0.000114	8.01E-06	0.001854
N210	661814.1	740907.6	265.24	0.14	418.03	152.79	0.000105	1.47E-05	0.003708
N211	661509	741965.1	295.44	0.08	418.02	122.58	0.000134	1.07E-05	0.002119
N212	662049.9	741187.3	278.71	0.07	418.02	139.31	0.000116	8.12E-06	0.001854
N213	659233.1	739902.3	259.7	0.66	418.16	158.46	0.000101	6.65E-05	0.017481
N214	660130.7	740173.6	274.49	2.01	417.93	143.44	0.000112	0.000226	0.053237
N215	662236.2	740807.2	267.04	0.64	418.01	150.97	0.000106	6.8E-05	0.016951
N216	662127.3	739753.6	259.87	0.47	417.98	158.11	0.000101	4.75E-05	0.012448
N217	662288.6	739384.2	264.24	0.2	417.97	153.73	0.000104	2.08E-05	0.005297
N218	662405.7	739363.5	263.23	0.52	417.97	154.74	0.000103	5.38E-05	0.013773
N219	663356.7	739899.7	263.16	0.67	417.92	154.76	0.000103	6.93E-05	0.017746
N220	663163.7	739519.3	264.46	0.65	417.91	153.45	0.000104	6.78E-05	0.017216
N221	662615.2	738874.3	254.07	0.28	417.91	163.84	9.71E-05	2.72E-05	0.007416
N222	661588.8	735758.9	249.4	0.07	417.96	168.56	9.41E-05	6.59E-06	0.001854
N223	662503.4	740273.4	272.58	0.12	417.98	145.4	0.000111	1.33E-05	0.003178
N224	662226.3	740386.1	266.78	0.41	418	151.22	0.000106	4.35E-05	0.010859
N225	661303.5	737478.9	254.2	0.42	417.96	163.76	9.71E-05	4.08E-05	0.011124

Appendix 2: Properties of Pipelines

PIPE_ID	Length	Diameter	Roughness	Flow	Velocity	Unit Headloss	Friction Factor	Status
P1	99.42	250	150	37.39	0.21	0.18	0.02	Open
P2	123.3	250	150	37.32	0.21	0.18	0.02	Open
P3	77.2	250	150	37.25	0.21	0.18	0.02	Open
P4	72.01	250	150	37.18	0.21	0.18	0.02	Open
P5	185.3	250	150	37.11	0.21	0.18	0.02	Open
P6	609.73	250	150	37.04	0.21	0.18	0.02	Open
P7	39.9	150	150	9.57	0.15	0.17	0.023	Open
P8	105.69	150	150	0.33	0.01	0	0.039	Open
P9	8.63	150	150	9.01	0.14	0.16	0.023	Open
P10	202.68	100	150	2.54	0.09	0.11	0.026	Open
P11	400.49	100	150	1.88	0.07	0.06	0.027	Open
P12	242.48	250	150	27.19	0.15	0.1	0.021	Open
P13	239.86	150	150	6	0.09	0.07	0.024	Open
P14	98.85	150	150	5.93	0.09	0.07	0.024	Open
P15	57.18	250	150	27.12	0.15	0.1	0.021	Open
P16	41.77	250	150	27.05	0.15	0.1	0.021	Open
P17	19.18	250	150	30.47	0.17	0.12	0.02	Open
P18	159.36	150	150	0.28	0	0	0.035	Open
P19	93.64	100	150	0.07	0	0	0.064	Open
P20	231.11	100	150	0.14	0	0	0.039	Open
P21	288.17	100	150	0.07	0	0	0.041	Open
P22	104.77	250	150	30.01	0.17	0.12	0.02	Open
P23	490.87	150	150	0.9	0.01	0	0.032	Open
P24	367.91	250	150	29.94	0.17	0.12	0.02	Open
P25	57.25	150	150	0.15	0	0	0	Open
P26	149.52	250	150	29.42	0.17	0.12	0.021	Open
P27	32.88	150	150	7.15	0.11	0.1	0.024	Open
P28	19.91	150	150	6.86	0.11	0.09	0.024	Open
P29	0.8	150	150	3.45	0.05	0.02	0.023	Open
P33	37.86	150	150	-3.74	0.06	0.03	0.026	Open
P34	85.96	250	150	22.2	0.13	0.07	0.021	Open
P35	193.85	250	150	22.13	0.13	0.07	0.021	Open
P36	38.44	150	150	1.27	0.02	0	0.032	Open
P37	143.04	150	150	0.07	0	0	0	Open
P38	70.23	250	150	20.79	0.12	0.06	0.022	Open
P39	313.59	250	150	15.25	0.09	0.03	0.023	Open
P41	80.57	150	150	0.11	0	0	0	Open
P42	67.03	150	150	2.28	0.04	0.01	0.028	Open

P43	40.81	250	150	12.79	0.07	0.03	0.023	Open
P45	117.76	250	150	10.15	0.06	0.02	0.024	Open
P46	171.06	250	150	13.69	0.08	0.03	0.023	Open
P47	300.3	250	150	12.94	0.07	0.03	0.023	Open
P48	558.84	150	150	0.2	0	0	0.04	Open
P49	109.05	250	150	10.08	0.06	0.02	0.024	Open
P50	146.21	100	150	0.67	0.02	0.01	0.032	Open
P51	262.52	100	150	0.22	0.01	0	0.038	Open
P52	215.2	100	150	0.15	0.01	0	0.041	Open
P53	514.3	100	150	0.11	0	0	0.038	Open
P54	312.45	100	150	0.2	0.01	0	0.038	Open
P55	206.07	250	150	0.15	0	0	0	Open
P56	304.93	100	150	0.13	0	0	0.041	Open
P57	455.08	150	150	1.16	0.02	0	0.031	Open
P58	307.02	150	150	0.27	0	0	0.041	Open
P59	138.2	100	150	0.49	0.02	0.01	0.033	Open
P60	190.14	75	150	0.14	0.01	0	0.039	Open
P61	84.25	250	150	0.87	0	0	0.045	Open
P62	488.78	250	150	5.53	0.03	0.01	0.026	Open
P63	651.25	100	150	0.66	0.02	0.01	0.032	Open
P64	484.9	100	150	0.07	0	0	0.049	Open
P65	469.61	75	150	3.31	0.21	0.71	0.024	Open
P66	216.68	75	150	3.27	0.21	0.7	0.024	Open
P67	905.22	75	150	1.26	0.08	0.12	0.028	Open
P68	661.62	100	150	-0.07	0	0	0.045	Open
P69	351.66	100	150	0.08	0	0	0.039	Open
P70	290.11	100	150	-0.22	0.01	0	0.037	Open
P71	166.39	75	150	0.1	0.01	0	0.042	Open
P72	73.95	100	150	-0.41	0.01	0	0.035	Open
P73	349.14	100	150	0.48	0.02	0	0.033	Open
P74	47.96	100	150	0.07	0	0	0.124	Open
P75	340.73	250	150	0.14	0	0	0	Open
P77	230.58	100	150	-0.79	0.03	0.01	0.031	Open
P78	42.27	100	150	0.35	0.01	0	0.034	Open
P79	103.4	100	150	0.28	0.01	0	0.04	Open
P80	512.26	100	150	0.64	0.02	0.01	0.032	Open
P81	443.08	150	150	4.5	0.07	0.04	0.025	Open
P82	567.46	100	150	1.5	0.05	0.04	0.028	Open
P83	764.89	150	150	4.33	0.07	0.04	0.026	Open
P84	98.84	150	150	5.86	0.09	0.07	0.024	Open
P86	18.46	100	150	3.13	0.11	0.16	0.025	Open
P87	28.72	100	150	3.17	0.11	0.16	0.025	Open

P88	259.78	150	150	3.78	0.06	0.03	0.026	Open
P89	243.87	100	150	1.82	0.06	0.06	0.028	Open
P90	233.58	100	150	1.15	0.04	0.02	0.029	Open
P94	411.77	100	150	0.31	0.01	0	0.035	Open
P95	176.91	100	150	0.31	0.01	0	0.034	Open
P96	404.04	100	150	1.35	0.05	0.03	0.029	Open
P97	181.08	100	150	1.15	0.04	0.02	0.03	Open
P98	377.71	100	150	0.28	0.01	0	0.034	Open
P99	493.67	100	150	-0.24	0.01	0	0.034	Open
P102	1040.83	100	150	1.73	0.06	0.05	0.028	Open
P103	426.53	100	150	1.06	0.04	0.02	0.03	Open
P104	890.22	100	150	0.41	0.01	0	0.034	Open
P105	459.38	100	150	0.13	0	0	0.041	Open
P107	1551.19	150	150	4.97	0.08	0.05	0.025	Open
P108	26.32	150	150	3.89	0.06	0.03	0.026	Open
P109	563.25	100	150	0.28	0.01	0	0.036	Open
P110	267.18	150	150	3.46	0.05	0.03	0.026	Open
P111	305.64	75	150	0.44	0.03	0.02	0.033	Open
P112	119.64	75	150	0.22	0.01	0	0.036	Open
P113	331.1	150	150	2.88	0.05	0.02	0.027	Open
P114	411.15	100	150	0.3	0.01	0	0.036	Open
P115	21.07	150	150	2.39	0.04	0.01	0.028	Open
P116	337.13	100	150	0.58	0.02	0.01	0.033	Open
P117	369.65	100	150	0.1	0	0	0.039	Open
P119	562.67	100	150	0.44	0.02	0	0.034	Open
P120	647.16	100	150	0.35	0.01	0	0.035	Open
P121	324.89	100	150	0.14	0	0	0.041	Open
P124	560.9	100	150	0.11	0	0	0.014	Open
P125	393.25	100	150	0.04	0	0	0.166	Open
P126	767.17	75	150	0.14	0.01	0	0.039	Open
P127	902.58	100	150	0.07	0	0	0.046	Open
P128	128.21	100	150	0.07	0	0	0.046	Open
P129	353.34	100	150	0.11	0	0	0.04	Open
P130	63.06	100	150	0.07	0	0	0.094	Open
P131	199.41	100	150	0.25	0.01	0	0.037	Open
P132	294.09	100	150	0.24	0.01	0	0.037	Open
P133	311.38	100	150	0.03	0	0	0	Open
P134	18.52	100	150	0.56	0.02	0.01	0.035	Open
P135	300.26	100	150	-0.12	0	0	0.038	Open
P136	688	150	150	0.22	0	0	0.04	Open
P137	79.95	100	150	0.1	0	0	0.039	Open
P138	364.93	100	150	-0.01	0	0	1.22	Open

P139	558.95	100	150	0.04	0	0	0.056	Open
P140	733.49	100	150	0.03	0	0	0.033	Open
P141	359.85	100	150	0.07	0	0	0.05	Open
P142	357.52	100	150	0.17	0.01	0	0.038	Open
P143	566.68	100	150	0.32	0.01	0	0.035	Open
P144	866.22	100	150	0.86	0.03	0.01	0.031	Open
P145	608.74	100	150	0.63	0.02	0.01	0.032	Open
P146	247.6	250	150	37.46	0.21	0.18	0.02	Open
P30	307.97	100	150	-0.21	0.01	0	0.038	Open
P31	279.99	100	150	-0.33	0.01	0	0.036	Open
P32	389.72	150	150	-1.95	0.03	0.01	0.029	Open
P40	422.79	150	150	-2.36	0.04	0.01	0.028	Open
P44	813.39	150	150	1.17	0.02	0	0.031	Open
P76	365.26	150	150	0.75	0.01	0	0.033	Open

Appendix 3: Summary of Leakage Repair Data

Months	Main Line		Service Line		Total No. of Burst
	No. of Bursts	Avg. Duration	No. of Burst	Avg. Duration	
January			3	1.72	3
February	2	1.49	8	2.22	10
March	1	5.18	2	2.07	3
April	2	3.00	1	0.50	3
May	13	5.13	7	2.67	20
June	8	2.67	6	3.13	14
July	1	2.88	6	1.25	6
August	8	2.53	5	1.59	13
September	2	3.50	3	1.95	5
October	3	5.44	5	2.48	8
November	4	2.30	4	1.41	8
December			6	1.89	6
Grand Total	44	3.59	56	2.08	99

Appendix 4: Summary of Leakage Data

	UNITS	MAIN PIPELINES	SERVICE PIPELINES
Average Pressure	m	30	25
No. of Reported Leaks	No.	54	72
Leak Duration	hr	562	358
Pipe Length	km	39	148
Invisible Leaks/km	No.	0.3	0.3
Supply Hours	hr	2260	2260
No. of Service Connections	No.	-	2047
Pipe Length	-	-	-
to main property boundary	km	-	172
property boundary to meter	km	-	25
Mains	km	39	197

Appendix 5: Unavoidable Background Leakage Flow Rates

Infrastructure Component	Background Leakage at ICF=1.0	Units
Mains	9.6	Liters per km of mains per day per meter of pressure
Service Connection – main to property boundary	0.6	Liters per service connection per day per meter of pressure
Service Connection – property boundary to customer meter	16.0	Liters per km of service connection per day per meter of pressure

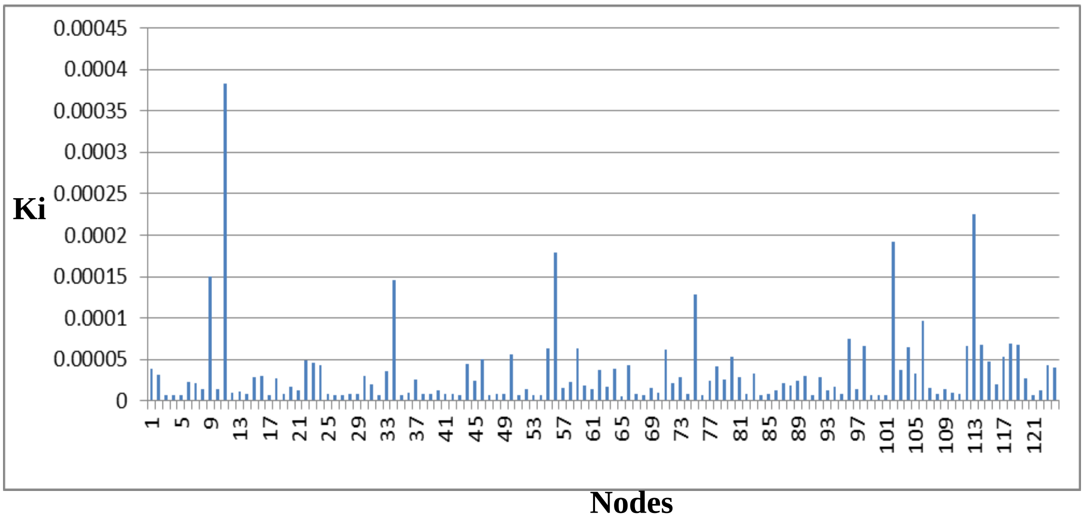
Source: IWA Water Loss Task Force

Appendix 6: Flow Rates for Reported and Unreported Bursts

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

Source: IWA Water Loss Task Force

Appendix 7: Computed Ki among Nodes



Appendix 8: GWCL Offices Water Demand

Water Demand	Vol (l)
Toilet/day	20
Hand washing 3/day	6
Dish-washing 2/day	4
Bathing	12
Misc. (Car washing, etc.)	100

Appendix 9: Unauthorized Consumption for Southeast District

Southeast District	
Random Sample Conn.	100
No. of illegal Conn.	8
No. of Conn.	2047
Est. no. of Illegal Conn. per District	164
Average Consumption per month (m^3)	35
Unauthorized Usage (m^3)	68,880

Appendix 10: Domestic Meter Adjustments

Meter Reading (m^3)	238,683.00
Meter Error %	-0.39
Standard Deviation	0.76
Meter Inaccuracies (m^3)	931.73
% NRW	-0.3%

Appendix 11: Real Loss Assessment Matrix

	Technical Perfomance Category	ILI	Liters/Connection/Day (when system is pressurized) at an average of:				
			10 m	20 m	30 m	40 m	50 m
Developed Country Situation	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 Country Situation	A	1 - 4	< 50	< 100	< 150	< 200	< 250
	B	4 - 8	50 - 100	100 - 200	150 - 300	200 - 400	250 - 500
	C	8 - 16	100 - 200	200 - 400	300 - 600	400 - 800	500 - 1000
	D	> 16	> 200	> 400	> 600	> 800	> 1000

Source: Ranhill Utilities Berhad and the United States Agency for International Development, (2008)