ADDIS ABABA UNIVERSITY SCHOOL OF GRADUATE STUDIES
ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

DEVELOPMENT OF A MODEL FOR ESTIMATING NON REVENUE WATER IN ADDIS ABABA
(THE CASE OF BOLE SUB CITY)

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in partial Fulfillment of the Requirement for the Degree of Master Science in Hydraulic Engineering

By: Ephrem Mengistu

Advisor: Dr. Mebrate Tafesse

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ABSTRACT

One of the major bottleneck for the water utilities is a large number of water losses in the distribution network system and quantifying of this water loss. This is why this thesis focuses on the development of a model for estimating Non Revenue Water (NRW) in Addis Ababa, especially woreda-07 in the Bole sub city.

The method used for the model starts with component of real loss by applying Minimum Night Flow (MNF) data taken at a particular installed District Metered Area (DMA). Analysis of the network system is based on the background leakage and concept of Fixed and Variable Area Discharge (FAVAD) in addition with aggregated bill consumption of the study area.

Bentley Water GEMS hydraulic model is prepared to apply the procedure. Then, calculating network leakage at the minimum hour flow (MNF) and distribution of volumetric consumption at each junction for each time step is carried out. In doing so, for leakage plus volumetric, the model runs until the probable pressure and leakage coefficient is established.

Using the coefficient in regard with the demand factor for each hour, leakage at each node and pipes for the distribution network is estimated. Based on these information estimated value of real loss 21.04%, apparent loss 4.74 and NRW 131,522.2 m^3/year with 25.8% is found.

Finally, for a more representation of the network and to perform further analysis regarding of water losses a suitable model environment is created in Arc GIS environment; which can be used as an aid around the study area.

Key words: water supply network, water loss, leakage, real loss, apparent loss, MNF, NRW, Water GEMS, pressure.

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AAWSA	Addis Ababa Water and Sewerage Authority
ALC	Active leak control
APV	All-pipes valve
ALI	Apparent Loss Index
BABE	Bursts and Background Estimates
CSA	Central Statistics Agency
CAD	Computer Aid Drafting
CARL	Current annual real loss in the water balance
DEM	Digital Elevation Model
DMA	District Metered Area
EBCS	Ethiopian building code standard
FAVAD	Fixed and Variable Area Discharge
ILI	Infrastructure Leakage Index
NRW	Non Revenue Water
MNF	Minimum Night Flow
PLC	Passive Leakage Control
PI	Performance indicators
PVC	Polyvinyl chloride
RBP	Removing Branch Pipes
UARL	Unavoidable annual real loss

1. Introduction

1.1 Background

The major problem affecting water utilities in developing countries is a loss of large amount of water loss in a distribution system. The phenomena until the recent late nineties used to be referred as unaccounted water. Later after the year of 2000 Water Loss Task Force (WLTF) came up with a standard term known as Non Revenue Water (NRW). It is defined as the difference amount of water entered in to the supply system to the amount of water billed to consumers.

Each year large volume of treated water is being lost through background leakage, pipe bursts from the distribution systems and managing inefficiency, for this reason it is getting harder to fulfill the gaps in relation with the mounting number of urban population. Also, additional large amount of water form treatment plants is driven in to distribution systems and delivered to consumers but not invoiced because of poor metering, corruption, theft and diverse managing problems. As a result, the water yields no revenue and leads the water supply service unsatisfactory (AAWSA, 2011).

In recent years, situation of NRW has become a common problem especially in developing capitals like Addis Ababa, being aware of this problem some recommended measures are being implemented through the concerned authorities, however, the measures taken so far are not sufficient enough to address this issue. Currently in Addis Ababa City NRW reduction measures in terms of sub city to districts level can be considered as untouched, rather than upgrading in some old areas and expansion in newly established areas of the city.

Evidently loss of this large amount of potable water is characterized as a major challenge to meet the expected demand. Hence it is crucial to implement a sustainable water loss target as much as possible even though it requires large capital, efficient management and control mechanisms to reduce NRW to the least desired range (AAWSA, 2014).

Therefore, for a successful application of the reduction target estimating the quantity of loss in relation with locating the potential areas by the support of modern and simplified techniques shall be considered as a major first step.

1.2 Addis Ababa water supply and distribution system

1.2.1 Surface water sources

In earlier times city of Addis Ababa was originally served by a number of springs located at the foot of the Entoto mountain edge together with a series of hand-dug wells. Part of the spring water was treated at the Entoto plant, which was commissioned in 1938 (WWDSE, 2015).

The first dam to be built for the purpose of water supply was Gefersa dam situated on west of Addis Ababa. It was constructed in 1943 consisted of a masonry structure approximately 10m in height. At the first stage the supplied water was subjected to chlorination only as a treatment. Later an upgrade in capacity was initiated and the dam was raised to 16m crest height in 1955 providing an increased capacity of 6,200,000m^3 then the operation of the treatment plant was commissioned in 1960, with a capacity of 30,000 m^3/day (AAWSA Water and Sanitation Development Rehabilitation Project Office, 2015).

Further augmentation of the main Gefersa reservoir, Gefersa III earth fill dam with an impoundment capacity of 1,200,000m^3 and approximately 15m in height with a crest length of 220m was constructed in 1966 and later in 2009 the dam was fully rehabilitated and the reservoir capacity was increased to 7,390,000 m^3 (WWDSE, 2015).

Another main water supply scheme for the city is the Legedadi dam, located at the east side of Addis Ababa and has impounding capacity of 42,170,000 m^3. The dam consists a rock fill section 22m high and 600m long, in combination with a concrete buttress dam 44m high and 400m long with a spill way and hydraulic gates for controlling over flow. In 1970 the dam was commissioned together with a 50,000 m^3/day production capacity of treatment plant. The treatment plant then consequently upgraded to a level of 195,000 m^3/day in conjunction with the expansion project of Dire dam located at 10km north of Legedadi dam with impounding capacity of 19,540,000 m^3 (AAWSA, 2011).

1.2.2 Ground water sources

To overcome the shortages of water supply and rising of demand in the city, the utility has developed well fields in Akaki, Fenta and Legedadi areas. According to the report of Addis Ababa Water and Sewarage Authority (AAWSA) & Metaferia Consulting Engineers in association With FCG International Ltd. in 2015, these areas has current production capacity of 201,300 m^3/day and from other pocket wells and springs is 58,186.00 m^3/day.

1.2.3 Water supply network

Water distribution system of the city comprises; services reservoirs, pumping stations, appurtenances and pipe lines. Various pipe materials (Steel, DCI, CI, GS, uPVC and HDPE) and diameters (50mm - 900 mm) are used in the distribution system. The water supply network includes:-

- The Gefersa D700/ D500 DCI pipe transmission mains.
- The Legadadi D1400/D1200 and D900 Steel transmission mains.
- Akaki D800 DCI transmission mains, supplied by the Akaki Phase I and II well fields.
- Akaki D800 DCI transmission mains, supplied by the Akaki Phase IIIB well filed.
- 91 service reservoirs throughout the city.
- 100 pumps in 32 pumping stations.

1.2.4 Water tariff/price

The utility of Addis Ababa has different water tariff rates for different types of customers in the city and the current rate are:-

1. Public fountains at 1.75 birr / m^3
2. Residential up to 7 m^3 at 1.75 birr / m^3
3. Residential up to 7 m^3 to 20m3 at 3.15 birr / m^3
4. Residential above 20 m^3 at 3.80 birr / m^3
5. Non Residential at 3.8 birr / m^3 altogether

1.3 Description of the study area

Under the Addis Ababa City Administration classification there are ten sub cities and under the utility of AAWSA, eight branch offices and thirteen water supply systems are found. Among form those this study is based on the case of Bole sub city with on the area of Woreda-07 and the surroundings, which is administered by AAWSA Gurd Shola branch office.

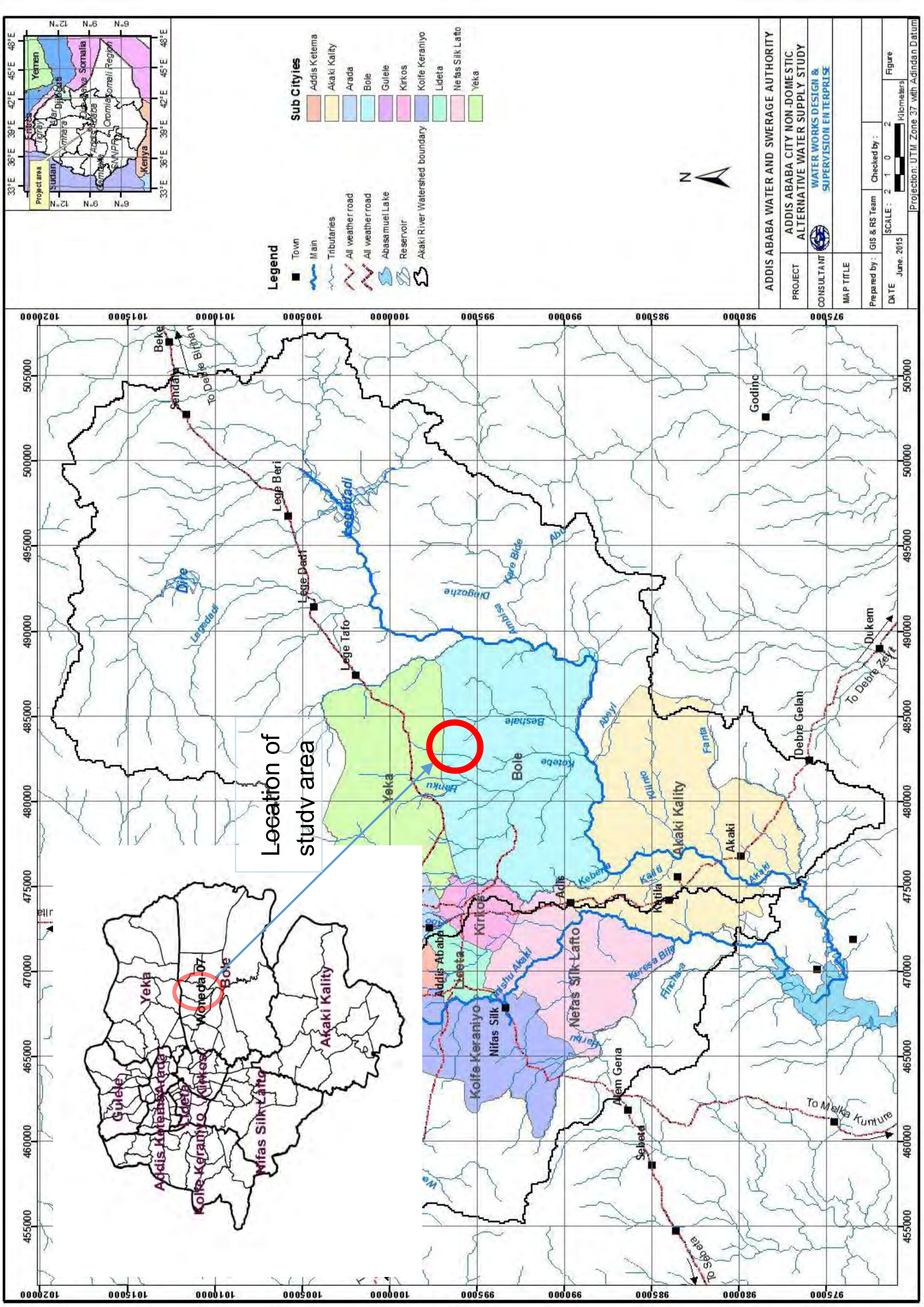


Figure 1-1: Map of study area

Figure 1-2: Location and feature of study area

The area is supplied form Terminal ground reservoir by gravity system, found at Yeka sub city, Woreda-09 which has two reservoirs with a storage capacity of 10,000m^3 each which receives form the Legedadi water treatment plant by main transmission lines.

Figure 1-3; Areal view of Terminal Reservoir

The study area distribution network contains different types of pipe materials with different size of diameter ranging from diameter 25mm – 900mm.

Table 1-1: Summary pipe lines in the study area

Pipe diameter	Length	Material type	Percentage
50	835	uPVC	5.72
50	1174	Galvanized Iron	8.04
63	3065	uPVC	20.99
63	166	GI	1.14
63	441	Ductile Iron	3.02
75	3126	uPVC	21.41
100	3489	uPVC	23.90
150	193	Ductile Iron	1.32
150	358	GI	2.45
150	590	uPVC	4.04
200	177	steel	1.21
900	987	steel	6.76
Total	**16,601**		**100.00**

1.4 Rationale of the Study

1.4.1 Water demand and its pattern

The daily water demand of the city changes with the season and days of the week. The ratio of the maximum daily consumption to the mean daily consumption is called the maximum day factor and usually varies between 1.0 and 1.3. According to the AAWSA the peak hour demand is the highest demand of anyone hour over the day. Such an event is likely to happen during morning hours when most people use water for bathing, washing, utensils and cooking. Moreover, it could also occur at the end of the day when people need water for the same purpose after working hours. The peak hour water demand is greatly influenced by the size of the city, mode of service used and social activity pattern. The ratio of the peak hour demand to the maximum day demand is called peak hour factor. The hourly water usage of the city varies according to the following pattern

Low usage	23.00 – 05:00 Hours
High Morning	05:00 – 11:00 Hours
Moderate	11:00 – 18:00 Hours
High Evening	18:00 – 23:00 Hours

1.4.2 NRW of Addis Ababa

NRW rate of Addis Ababa shows a decreasing rate, however, the reduction rate still not compromising. According to the report of AAWSA – Business Plan, 2011 it is worth noting that the daily volume of water loss in the system amounts to more than three times the production capacity of Gefersa treatment plant. Figure 1.4 shows the historical development of system, input Volume, billed authorized consumption and Non-Revenue Water over the period from 1986 to 2006 E.C. (AAWSA, 2014)

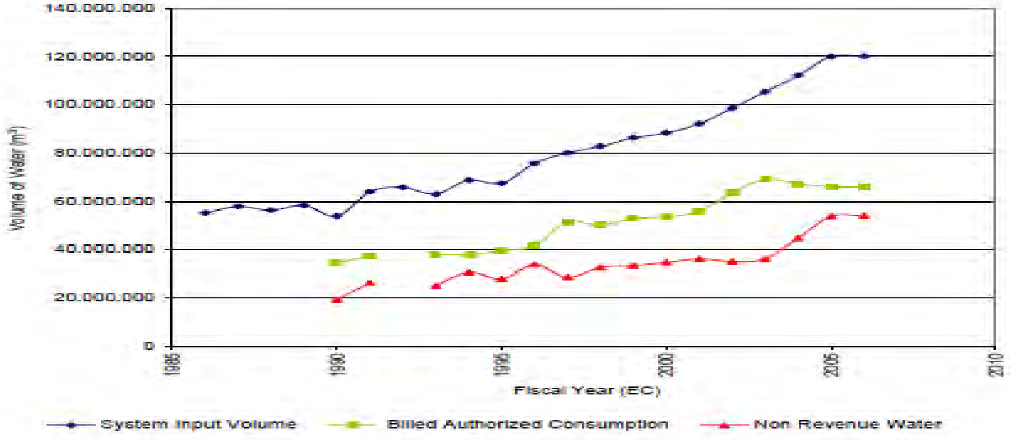


Figure 1-4: Non-Revenue Water over the period from 1986 - 2006 (EC)

1.4.3 Practice of estimating NRW

Most of the water utilities in different countries uses similar method for estimation of water loss by using the total water inflow put in the system and deducting the total amount consumed by the customers. Although, this method used as a simple and approximate estimation for the water loss and preferable to setting no targets at all, it does not fully express the different components of NRW or does not differentiate between real/physical losses and apparent/commercial losses as it is required.

It is also essential as a measure of the utility's year-on-year financial performance, as long as the measurement principles are consistent. In that case, it should be expressed as the value, not the volume of water lost. (Malcolm Farley, et al., 2008)

1.4.4 Challenges for determining amount of NRW

The main factors that contributes for the challenge of knowing the exact amount of water losses in the case of Addis Ababa city is most likely the same to other developing cities in the world. The following points can be indexed as the main challenges that makes it difficult for determination of NRW in general:

- Lack of finance and skilled technical staff
- Absence of public awareness & management focus
- Accountability and data handling errors
- Absence of comprehensive strategy to reduce NRW, successive evaluation and detailed study

With respect to the above mentioned points, unavailability of different improved methods for different areas in the city and developed model for estimation process in relation with up-to-date technological advancement can be considered as a major challenge for quantifying amount of water losses in the city (AAWSA, 2011).

1.4.5 Shortage of potable water supply

Due to the ever increasing population in the city with diverse water losses; the supply and the expected demand is not still satisfactory, even though, potential sources are available to cope up and resolve the scarcity issue of potable water supply for the city.

Most of areas in Addis Ababa city are characterized by intermittent supply, as a result the flow of water in the network is associated with irregular pressure profiles and wide pressure variations (AAWSA, 2014). Due to this it has laid a detrimental effect on the integrity of the networks in many parts of the sub cities including the area of study in Bole sub city.

1.5 Statement of the problem

It is visible that water supply distribution is not adequate in Addis Ababa and frequent cut offs for a longer days is a well-known problem, regardless of the availability of potential water sources with in and around the city. If the water supply distribution would appropriately utilized, it will enhance and satisfy the potential need of the consumers with in the city. According to the latest population census of 2007 from Central Statistics Agency (CSA), the population of the city is increasing with incremental rate of 3.7% per year and the demand should be fulfilled according to the rate of growth.

The problem arises not only in terms of shortage of water or limited network distribution, rather it's because of large amount of water loss. As a result, in some undetected leakage areas intermittent supply possess a significant health risk letting the sewerage entering to the leak pipes during supply interruptions time and at a very low pressure periods. So, evading of this public health risk can be enough to alleviate leakage and allow standard continuous supply.

According to the report of (AAWSA, 2014) most of the treated water supply that delivered to the demand is 60% from the total production, the remaining 40% considered as NRW. However, until the current period there is no specific quantified data for different location of city. Among those Bole sub city, which has the area of 122.08Km^2 and a population of 369,189 can be indexed.

1.6 The Research objectives

1.6.1 General objectives

The main objective of this study is to develop a model for estimating NRW for the water supply distribution network by selecting a specific study area in the Bole sub city in order to provide the means of systematical studying and better understanding of real and apparent water loss components based on district metered area (DMA) which has a similarity with other parts of the sub city; that helps to validate and examine the model based on the existing scenarios.

1.6.2 Specific objectives

Prior to the general objective, the paper address the following specific objectives:

- To elucidate hydraulic parameters which serve as a precursor of NRW
- To elucidate physical variables which pinpoint to leakage potential

- To develop a water balance model and perform scenario analysis to determine critical management scenarios using water balance model.
- To develop a multi-variable model to forecast NRW in Bole Sub City and which can be used as a management aid for the utility.
- To demonstrate the developed model.

1.7 Overview of the thesis

This thesis includes the following **six** chapters with a brief discussions under each section:

Chapter one: Contains general introduction of water supply of the city, description of the study area, rationale of the study, statement of the problem and research objectives.

Chapter two: Discuss literature review related to NRW components and basic aspects of general water losses and leakage parameter on water supply distribution system in relation with modeling practices and monitoring. In addition, it discusses regarding on minimum night flow analysis and its application, pressure and leakage relationship, computer modelling and assumption in leakage estimation.

Chapter three: Discussion about the process of study area selection, data collections, methodology for the model preparation and procedure of the study.

Chapter four: Elucidates the analysis and interprets the results of the model outputs and demonstrate the results with representation.

Chapter five: This chapter deals on the conclusion and recommendation.

2. Literature Review

2.1 Introduction

Until the early 90's there was no standard term to express and asses the water losses in the distribution system. The International Water Association (IWA) has acknowledged this problem and established the Water Loss Task Force (WLTF). The WLTF examined the international best practices and developed a standard terminology as "Non Revenue Water is the difference between the volume of water put in to the water distribution system and the volume that is billed to customers" (Rudolf & Liemberger, 2010).

As some literature shows that the worldwide NRW is estimated at 48.6 billion m^3/ year. The volume of real losses (45 million m^3/ daily) occurring in developing countries alone would be sufficient to supply 200 million people. Close to 30 million m^3 are delivered every day to consumers but are not invoiced because of theft, corruption and technical manipulation, poor metering, etc. (UNW-DPC, 2011).

In the distribution system of a water supply, processes of reducing and continuous control of NRW to some extent is complex but technically achievable. In order to get better understanding of the main issues involved on NRW, reviewing the existing literatures and different scientific views on the issue is necessary accordingly with the agreed international principles.

2.2 Components and definitions of Non Revenue Water

Various literatures were identified but the one which seemed to have dealt with the issue for the development of a model regarding of NRW and to which most researchers kept referring is the document which has been developed by the IWA water loss task force regarding concepts, methodologies for quantifying loss volume and definitions of the components of NRW.

According to the IWA (2003) NRW is "the difference between system input volume and billed authorized Consumption". System input is "the annual input to a defined part of the water supply system" and billed authorized consumption, is "billed metered consumption including water exported and billed unmetered consumption". (Rudolf & Liemberger, 2010)

The definitions and relevant technical terminologies regarding NRW are presented in the table 2-1 below.

Table 2-1: IWA best practice standard water balance

“IWA Best practice “ Water Balance and Terminology				
System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed metered consumption (including water exported)	**Revenue Water**
			Billed non-metered consumption	
		Unbilled Authorized Consumption	Unbilled metered consumption	**Non Revenue Water**
			Unbilled non- metered consumption	
	Water losses	Apparent Losses	Unauthorized consumption	
			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 customer’s meters	

According to this water balance NRW addresses three principal components; unbilled authorized consumption, apparent or commercial losses and physical or real losses.

2.3 Apparent losses

Unauthorized consumption, customer meter under registration, data-handling with transfer and processing errors associated with metering, are the main causes of apparent or commercial Losses.

The estimated customer water meter under registration in Addis Ababa for the year 2014 corresponds to 16% of the total billed metered consumption and the average annual volume of apparent losses from years 2003 (EC) to 2006 (EC) is 59,072,107 m^3 (AAWSA, 2014)

Table 2-2: Apparent annual volume losses of Addis Ababa 2003 E.C – 2006 E.C

Fiscal Year (EC)	Annual volume of apparent losses (m^3)	Number of service connections	Average volume of apparent losses (m^3/ service connection/ year)
2003	15,206,267	291,500	52.2
2004	14,807,165	298,900	49.5
2005	14,546,310	317,800	45.8
2006	14,512,365	331,400	43.8

Source: Consultancy service for NRW reduction, hydraulic modeling and GIS development for A.A, AAWSA, 2014.

The above tabulated values indicate the high loss and serious of financial impacts of NRW for the utility; and from different literature views it can be emphasized that reducing commercial losses requires a low level of investment with a short payback period, even though, it requires sustained management commitment, political will, and community support.

2.3.1 Authorized consumption

Authorized consumption is the volume consumption by the registered consumers; also it is referred as revenue water because of it produce revenue and depending on the country low it can be metered or unmetered for the items of firefighting, flushing of mains and sewers, street cleaning, watering of municipal gardens, public fountains, frost protection, building water, etc. (Simbeye & Ison, 2010)

2.3.2 Unbilled authorized consumption

Unbilled authorized consumption include water used by the utility for operational purposes like water that is used to flush the mains after fixing a break, water provided for free to certain consumer groups, water that is used for street cleaning, firefighting and fire flow tests. Unbilled authorized consumption consists metered and unmetered consumption and it can be assessed using the metering and billing output (Malcolm Farley, et al., 2008).

AAWSA Considers, the estimated percentage of unbilled authorized consumption for the fiscal year of 2006 E.C was 0.11% (AAWSA, 2014).

2.4 Real or Physical losses

Physical or real loss results from losses at mains, service reservoirs, and service connections (up to the point of customer metering) and the annual volume lost through all types of leaks, bursts, and overflows depends on their individual frequencies, flow rates, and duration.

Most of the time real losses are occurred due to poor operations and maintenance or active leak control (ALC). To estimate the real losses, according to Farley & Liemberger (2008), using bottom up approach there are three methods that should be compared with each other. These are:

Component analysis: - categorizes and concentrates on analyzing the volume of each component for every category of:

- Undetectable leakage: - small flow rate and that runs continuously.
- Reported breaks:- incidents of high flow rate at relatively short duration and
- Unreported breaks: - pipe disruption with moderate flow rates.

For those analysis, data must be available in water utilities, even though, average pressure to some extent is difficult to estimate but can be achieved with a good estimation in the analysis. Similarly, background losses are also difficult to define, because, leakage runs slowly and do not attract attention, as a result such losses are often unknown.

a) **24 hour zone measurement: -** inflow and pressure in recorded throughout the day. An accurate value of the real loss component can be determined using the logged measurements in an isolated network area to perform a 24 hour measurement and the area can only be supplied via one or two inflow points during the measurement (Puust, et al., 2010).

b) **Minimum night flow analysis:** - indicates the lowest water consumption level associated with the reduction of consumer activities and can only be performed in a district meter area. Also, the assumption is based on the minimum flow rate minus consumption rate that equals to the maximum real losses.

Real loss = Minimum flow rate - Consumption rate

Consumption rate = Total active population at the night x consumption during the night

Usually the pressure during the night is the largest and the pressure varies throughout the day. However, the real loss value of the whole day cannot be determined arbitrarily by extrapolating measured reading values of MNF, because it would lead to the overestimation of the daily leakage due to lower pressure during the day, therefore, considering the average pressure is necessary (Roland Liemberger & Malcolm Farley, 2004).

Table 2-3: Parameters required for calculation of components of annual real loss

Component according to water balance	**Component of the system**	**Background (undetectable) losses**	**Reported breaks**	**Unreported breaks**
Leakage on transmission/distribution mains	Mains	Length Pressure Min loss Rate/km	Number/year Pressure Average flow rate Average duration	Number/year Pressure Average flow rate Average duration
Leakage & overflows at utilizes storage tanks	Service reservoirs	Leakage through structure	Reported overflows: Flow rates Duration	unreported overflows: Flow Rates Duration
Leakage on connections up to the consumers' meters	Connections main to edge of street	Number Pressure Min loss Rate/conn.	Number/year Pressure Average flow rate Average duration	Number/year Pressure Average flow rate Average duration
	Connection after the edge of the street	Length Pressure Min loss Rate/km	Number/year Pressure Average flow rate Average duration	Number/year Pressure Average flow rate Average duration

*At some standard pressure, source (Thornton, et al., 2008).

Water Loss Task Force (2007) considers for determining the real loss value for the whole day, the night-day factor (NDF) should be estimated carefully, this factor varies with in the range of 18 – 24 hour, and the real loss value can be determined using equation of:

$$\text{Night- Day Factor (NDF)} = 24 * \left(\frac{\text{Average daily pressure}}{\text{Pmin}}\right)$$, then

$$\text{Real loss} = \text{NDF x real loses during the MNF}$$

2.4.1. Leakage in the distribution system

When referring leakage in the water distribution systems it is important to distinguish between total NRW and leakage. As the definition of NRW states the difference between the amount of water produced and the amount which is billed or consumed; were as leakage is taken as one of the components of the water loss in a distribution network and comprises the real losses from pipes, joints and fittings and overflowing from service reservoirs

Leakage, resulting from the distribution and transmission mains are usually has large in volume. Hence its result will affect not only supply interruption but it also leads the surrounding infrastructures to be damaged, sometimes causes a catastrophic event, even though the majority of such cases usually are not very severe because of the size and visibility, it can be reported and maintained as quickly as possible. Although, in the case of undetected leaks for a longer periods it leads the loss for larger range and may be undetected for months or even years (Farley, 2001).

2.4.2. Pressure in the distribution system

It has proved that pressure is directly proportional to leakage and it is one of the main contributing factors for a leakage, thus depending on the network profile reducing pressure might be an effective method in cost minimization, reduction of leakages and pipe cracks through effective measurement of flows and pressure values which supports to find average pressure.

However, without knowing the corresponding average pressure increasing the pressure even by a few meters can result in a large number of bursts occurring in a relatively short period of time such that a utility will not be able to understand the level of NRW and leaves no room for potential improvement, for example a utility that has an NRW level of 20% at an average pressure of 20 m is performing substantially better than a utility that also has an NRW level of 20% but an average pressure of only 10 m. (Rudolf & Liemberger, 2010)

In relation to these, according to the report of AAWSA (2014); a wide pressure fluctuation and irregular pressure profiles are widespread in the networks, intermittent water supply and the corresponding frequent emptying and filling of different parts of Addis Ababa is considered as a serious problem for the utility.

2.4.3. Water distribution pipes and materials

Water losses in a pipe system can be classified into two basic categories: losses due to pipe bursts and losses resulting from background leakage. Background leakages are characterized by a continual seeping of water from pipe fittings and from mains that are cracked or perforated through corrosion. To cope up these effects, providing the proper materials in a distribution system will ensure long service life, minimal service interruptions and high reliability.

Based on material type; pipes in a water supply distribution system can be divided in to three main categorizes:-

- Metallic pipes
- Plastic pipes and
- Cement pipes

Currently most water utilities uses cast iron pipes and polyvinyl chloride (PVC) pipe or metallic and plastic pipes in general for distribution and transmission systems. And regarding of iron pipe there are two divisions, grey cast iron and ductile iron, however, grey cast iron pipe is no longer used in water systems because, unlike the more modern ductile iron pipe, it is brittle and can be broken when hit or placed under stress due to this reason it is more subjective for leakage. In addition cast iron is also susceptible to corrosion when it comes in contact with corrosive water or with corrosive soils plus the manufacturing process of ductile iron is different and the process makes it less rigid, lighter, and it offers better corrosion resistance (Institute for Water Resources Support Center, U.S. Army Corps of Engineers, 1998).

Currently, ductile iron is lined on the inside with a cement mortar or epoxy lining to prevent the electrochemical corrosion that results in tuberculation and to provide a smoother pipe interior which will provide less friction to the water flowing through it. On the other hand the external part of the pipe has an extra bituminous coatings or a polyethylene cover placed during construction, also it sometimes used when the pipe is to be placed in corrosive soils. Prior to these the major disadvantage of ductile iron pipe is its weight (Institute for Water Resources Support Center, U.S. Army Corps of Engineers, 1998).

Plastic pipe types like PVC pipe, are being frequently used for many water supply applications with larger inches in diameter because of its distinct weight advantage. In some cases it is recommended to use ductile iron pipe in smaller sizes where extra protection is desired such as under pavement or parking areas where heavy loads are expected in order to minimize pipe burst and crack (WHO, 2006).

In relation to this steel pipe is lighter than ductile iron and has a high tensile strength, some flexibility, is easily installed and jointed, low in cost, readily welded together and easily assembled, handled and transported. However, its major disadvantage is that it is more subjected to corrosion and therefore must be coated in and outside.

In general, types of plastic pipe in use are PVC (polyvinyl chloride), un-plasticized polyvinylchloride (uPVC), PE (polyethylene), chlorinated polyvinylchloride (CPVC) and PB (polybutylene). Regarding of polybutylene pipe, it can be considered as a suitable material for the conveyance of drinking-water in domestic dwellings, but due to the problems with leaks at joints, it is banned and not accepted in some developed countries, like, USA (FRWA, 2005).

PVC pipes are non-corrosive, easy to handle and come in long lengths that lower installation and transportation costs, even though it is not strong enough for some applications.
According to WHO (2006) they are prone to physical damage, if exposed over ground they become brittle and easy to exposed for ultraviolet light (UV). In addition to the problems it is associated with the expansion and contraction, as a result the material can be soften and deform if exposed to the temperatures over 65 °C.

Chemical processes that can affect a distribution system water quality are a function of water chemistry and the physical characteristics like material and age of the distribution system itself. In addition, chemical deposition process that forms a material build-up along the pipe walls due to chemical conditions in the water for example, lime scaling is caused by the precipitation of calcium carbonate but when it occurs in an uncontrolled manner it can significantly reduce internal diameter of a pipe and promotes for problems related to corrosion especially on the materials like iron or steel pipes, although these processes occurs through the times (Haestad Methods, et al., 2003)

2.4.4. Purpose of Minimum Night Flow analysis

Minimum night flow occurs normally after midnight or in early morning hours at urban situations when the demand is low and the pressure is high when compared with other hour. It is used by utilities along with commercial or real losses to determine NRW in a district metered areas. As a result, for the purpose of estimation of the real loss component it is carried out by subtracting an assessed amount of legitimate night consumption for each of the customers connected to the mains at the specific area.

As MNF method uses the values of inflow and average pressure measured in DMA, such that by interpreting and analyzing the measured flow in to different models the leakage flow at MNF time, average daily and monthly leakage rates in relation with applying the Fixed and Variable Area Discharge (FAVAD) principles the daily and monthly level of real losses can also be calculated (Roland Liemberger & Malcolm Farley 2004, M. Tabesh, et al., 2008).

2.5 Performance indicators for water losses

For measuring the changes and evaluate water loss performance indicator (PI) is used test how well the network is managed in relation of comparing the achievement done in the reduction of NRW.

There are different types of standard PI which are wildly used in different countries and water utilities. The following PI can be indexed for the analyzing and comparison of NRW, real losses and apparent losses:

- Volume of NRW in percentages (% of system input volume)
- Liters/connection/day (m^3/km mains/day)
- Liters/connection/day/mWc (m^3/km mains/day/mWc) , and
- Infrastructure leakage index (ILI) for analyzing real losses
- Apparent loss index (ALI) for analyzing apparent losses

While most water utilities use percentage of NRW which is calculated by dividing the total water volume of NRW by the total system input. Even though, it is a traditional method and may hinder the NRW data like the cases of its suspicious, inaccurate or provide only partial information unless it is done perfectly (Rudolf & Liemberger, 2010).

It should be noted that expressing NRW in terms of percentage cannot be used to compare systems with each other and it cannot be used to compare figures of different months of the same system with each other (Farley, 2008).

When there are more than 20 connections per km main, the greater portion of the losses is associated with the connections, therefore liters/connection/day or Liters/ connection/ day/mWc should be used. With respect to this when the connections are less than 20 per km main, the greater portion of the losses is associated with the length of the mains and m^3/km, mains/day or

m^3/km mains/day/mwc should be used. The choice of using PI's liters/connection/day and m^3/km mains/day is based on the area in which more losses happens (Korevaar, 2013).

2.5.1. Performance indicators for real loss

IWA, regarding on PI also developed Infrastructure Leakage Index (ILI) as a quantitative method to compare performances between systems that are based upon the real losses. ILI is a measure of how well a distribution network is managed for the control of real losses, at a current operating pressure and the value is estimated by dividing the current annual real loss in the water balance (CARL) by the unavoidable annual real loss (UARL) for a system of the same size as the assessed system. i.e.

$$\mathrm{ILI} = \frac{\text{Current annual real loss (CARL)}}{\text{Unavoidable annual real loss (UARL)}}$$

Regarding UARL, it is determined by the length of the mains, the number of connections, the length of the supply pipe and the average operating pressure; a low ILI value is only likely to be economically justified when the marginal costs of the water supply is relatively high or the water is scarce (Lambert & McKenzie, 2002).

Real loss are always and must be related to the background losses of the distribution network system, because of this utilities uses a type of PI type of ILI for real loss to improve and evaluate the network development combining with the matrix guide to rank the level of leakage in the system by classifying the results in the category listed as in the table 2-4 below.

Table 2-4: Physical loss target matrix

Technical Performance Category		ILI	Physical Losses [litres/connection/day] (when the system is pressured) at an average pressure of:				
			10m	20m	30m	40m	50m
Developed country	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	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

The physical loss target matrix shows the expected level of ILI and physical losses in l/c/day from utilities in countries at differing levels of network pressure (Malcolm Farley, et al., 2008).

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

2.5.2 Performance indicators for apparent loss

The PI for apparent loss is expressed using the percentage of water supplied to the consumers, however "commonly used indicator that expresses commercial losses as a percentage of water supplied is misleading because it does not reflect the true value of lost revenue. Currently, the best indicator is to measure commercial losses as a percentage of authorized consumption" (Malcolm Farley, et al., 2008)

Also, recent and another way to express the performance indicator for apparent loss based on the IWA WLTF is using a base value of 5% of water sales as a reference and the actual apparent loss value is calculated with the benchmark of calculated loss value to the amount of 5% water sales value. i.e.

Apparent Loss Index (ALI) = Apparent loss value ÷ 5% of water sales

2.6 Modeling practices and use for NRW

2.6.1 Modeling practices

According to U.S. Army Corps of Engineers definition modeling is the process of selecting variables for analysis and determining their significance for a specific study. Water resources modeling applications normally focus on either water quality or water quantity and address the areas such as: groundwater, water distribution, demand forecasting, balancing supply and demand, watershed runoff, stream hydraulics, river and reservoir quality, multipurpose management and operation and environmental protection (Institute for Water Resources Support Center, U.S. Army Corps of Engineers, 1998).

Development of models is often an evolutionary process through several agencies, universities, consulting firms' and personnel making contributions at various fields depending on the purposes. With respect to this, in the field of water technologies there are different types of modeling based on assumption and application types. These are;

- Predictive and estimating models: - it is intended for explaining the real-world phenomena and patterns that may be expected over time. Regularly used in planning as standard curves fitted to the appropriate data.
- Linear models: - which can be simple or complex and it assumes that the future is an extension of the past, and used for mainly for planning analysis.
- Non-linear models: - it is used for solving different parameters, like polynomial and logistic and especially used at the time when linearity does not adequately explain the relationships between variables.
- Optimizing models: - based on the given constraints, estimates the best solution utilizing a group of methods using classical calculus, linear, nonlinear programming, and dynamic programming.
- Stochastic or probabilistic models: - it deals with expressions in which it includes terms of uncertainty and used for when the terms of different problems are probabilistic.

However, it should be considered that each type of model has a specific goal and related characteristics and their application depends on the importance of study or intended use.

2.6.2 Use of modeling application

Modeling of water supply schemes is an excellent tool for qualifying a real world crucial problems, emergency response, planning, estimation and understanding of different types of water losses. Also a model is important for water supply distribution systems due to its complex topology, frequent maintenances and changes.

As a result, the way to develop a model is to break it down into its components and work through each step. Some tasks can be done in parallel while others must be done in series. The undertaking of any modeling project is to develop a consensus within the water utility regarding the need for the model and intended purpose for which the model will be used for both short- and long-term periods.

Prior to these, there is no single correct way to use models on the case of how a model application used to last. For example, for a design purposes it differs depending on whether the model is being used for master planning, preliminary design, subdivision development, or system rehabilitation (Haestad Methods, et al., 2003).

In addition, every type of model has a specific goal, characteristics and modeling purposes interims of diverse application, therefore, it should not be viewed as an isolated endeavor by a single modeler but rather a utility wide effort with the modeler as the key worker.

2.6.3 Bentley Water CAD application

Due to the rise of advanced computing techniques and applications. There are various computer software's developed for the purpose of design and analysis of models for a water distribution networks like EPANET, WaterCAD, WaterGEMS, etc. Among these application software's Bentley WaterGEMS/CAD at the current time is a well-known throughout the world due to its availability, functionality, user interference, compatibility, etc.

The advantages of WaterGEMS V8i over other software's its tools for a simplified model building with geospatial modules like water quality modeling, fire flow analysis, optimization and scenario management, etc. WaterGEMS V8i is thus easy to use as a multipurpose water distribution schemes as well as quality modeling. In addition the main advantage of WaterGEEMS application is its various tools like darwin designer for analyzing cost of pipes and pipe catalogue tools which are found to be very effective for modeling, design and optimization of water distribution network with respect to strong data management and integration along with AutoCAD, ArcGIS and other related software packages (Bentley Systems, Incorporated, 2014).

Moreover, the choice of software's for modeling distribution network is based on the overall cost of project, data required by software's, specificity of the software related to types of distribution networks it can handle as well as its computational requirements.

2.6.4 GIS application

Currently application of Geographical Information System (GIS) is much more than mapping the capital asset, it offers extensive tools for spatial analysis and data management. Prior to these, when integrated with hydraulic modeling it gives a tremendous operational advantages for the utility (ESRI, 2016). ArcGIS integration with hydraulic modeling software's like Bentley Water GEEMs, can eliminates the need of importing and exporting a model data back and forth between a models and GIS. For carrying out water demand allocation, it involves special allocation according to the existing and future demands. Such that, level of water demand should be derived from data's of metered billing records in relation to per-acre or area estimation of land use, therefore, the information with spatial component for making the demand allocation for a specific model containing node or pipe, is it is a powerful tool.

Regarding of demand allocation, GIS uses two methods these are point methods and area methods:

- Point methods: - customer billing data is linked to each meter points either by using X, Y coordinate system or using related address such that designation of total water demand will be geocoded model node.
- Area methods: - the demand will be derived indirectly by estimating on the population and land use data for the estimation of future water usage especially in a more growing areas (ESRI, 2016).

2.6.5 Comparison of modeling software

Prior to the primitive technique of hydraulic analysis methods which was manual; like Hardy Cross which is full of iteration, accountable for error and very time consuming; were used to be applicable for the purpose of modeling, design of water supply and other distribution networks. Also, EPANET which has the ability to model some basic elements, however for a real system that has various types of elements, it lacks various features like isolation of valves, hydrants. In addition the inability to convert data into pipes, nodes, etc. nor does it allow to bring tabular data such as in excel format.

WaterGEMS unlike the others it includes different additional features maintaining its easiness for converting a data and maintaining a constant connection between the source and the model. Also for exporting a data back to the source in different formats and linking of the preference directly with CAD or GIS and running the models inside the microstation of AutoCAD or ArcGIS is applicable.

2.6.6 Integration of models and between software's

Integration of GIS and modeling is a process by which new, updated or abandoned elements are synchronized. The integration enables feeding of the up-to-date information, minimizes response time and accessibility of modeling elements, functionality and data interpretation of various features. Integration approach eliminates the need to manually update different data sets for the models and data bases.

The data which can be available in linking or integrating with GIS data base, such as pipe leakage and burst or break history, operational data and customer complaints in the supply system can be easily done for a model.

In this regard, in GIS for the purpose of water supply distribution parameters includes different modeling structures, like all-pipes valve model and all- pipe model:

All-pipes valve (APV) model: - preserves the level of detail data maintaining of the GIS. The relationships between GIS elements and their counterparts in the modeling process which reduces or eliminates the effort of skeletonization and enables it to integrate directly with the models.

APV models also provides a better representation of a system for analysis and gives cost-effective option for the process of identifying water loss, quality and maintenance problem.

However, APV models tends to take a longer process, slower scenario processing and demand allocation; most of a time it requires more data storage.

All-pipes (AP) model: - it eliminates significant valves, fittings and nods but the total length of the pipe is schematically represented such that pipes that has similar types of diameter, materials and installation are merged. Therefore, a model of pipe segment may consists multiple GIS pipe segment and enables the number of pipes and nodes to be reduced by 50% or more. But, using a distribution network as a layer, connectivity features can be maintained by editing tools (Haestad Methods, et al., 2003)

2.7 Aspects for water losses

Successful access to water supply and sanitation services is a prominent concern for most of developing countries but still these services does not reached for a significant achievement. Every year, this becomes a more challengeable issue due to rapid population growth and speed of urbanization. Relating to this, water industries suffers major challenges due to high level of water loss through the distribution networks throughout worldwide (Josephat Alexander Saria, 2015).

In general water losses openly affects the level of income from water billings, service level and consumer satisfaction to meet the water demand from consumers. Which in turn affects service sustainability of water sectors with respect to a combined gaps of unknowing the precise figure. Especially in developing countries this cases are high due to lack of strong understanding of the magnitude and absence of reduction measures.

2.8 Consequence of NRW

The current water supply problems observed in Addis Ababa can be related to sources and use of raw water, frequent cutoffs for longer days, intermittent supply and the quality of tap water at the consumer’s end. Yet, millions of cubic meters of treated water will continue to be lost and utilities will continue to lose a substantial amount of revenues.

Beyond the financial impact; customer complaints regarding to pressure drops, quality of water, billing expenses, etc… can be indexed as a major criticism for the water services unless each type of loss is addressed from smaller to larger scale and sub city to district levels of the city.

2.8.1 Potable water scarcity / shortage

Many definitions of water shortage/scarcity is available in a border sense but in this context it seems agreeable with a definition which had been given by the report of FAO (2012) “water scarcity/shortage is a gap between available supply and demand of fresh water in a specified domain” i.e.

Water scarcity = an excess water demand over available supply

It can also be signaled by unsatisfied demand tensions between users and competition for a potable water in most of Sub-Saharan Africa is categorized as an economic scarcity due to lack of capacity to satisfy the public demand.

Different international organizations explained the water is becoming as a scarce resource in terms of the growing number of industries and cities. A limited water supply is already constraining development efforts of many countries especially in the developing ones, however, water development could do so much to reduce losses and scarcity in the case of building additional projects.

Despite water shortages, misuse of water is also widespread phenomena. Small communities and large cities, farmers and industries, developing countries and industrialized economies - all are mismanaging water resources. Surface water quality is deteriorating in key basins due to urban and industrial wastes. Groundwater is polluted from surface sources and irreversibly damaged by the intrusion of salt water. In spite of this, cities become unable to provide adequate potable and forced to find other alternatives.

Even though plenty of water sources are available to supply billions of peoples throughout the globe, the availability of sources doesn’t necessary mean it will lead to eradicate the scarcity of drinking water supply. Rather it is managing to reduce water loss that expedites and mitigates this wide phenomena of - scarcity and shortage (FAO, 2012).

Prior to this, unsatisfied demand of potable water in Addis Ababa city seems to be a common and but a forgotten issue. The availability of potable water supply time is not 24/7 and many parts of the city can be categorized as in a worst conditions plus it is putting a major effect on the living conditions of many poor peoples.

As AWWSA (2014) report indicated the daily demand of potable water in Addis Ababa city is estimated to reach 640,000 m3/day, but while the production rate is not more than 400,000 m^3/day. This number signifies how much the shortage is available within the city.

Also, in the case of Bole sub city still it does not fulfill the full supply demand especially in a day time due to the limitations of pressure and head. Due to this, the interruption can even extend for several days even in some areas it can last a week. As a result, households, institutions and many organizations had supposed to use roof and elevated water tanks in order to avert intermittent supply and to cope up the low level of pressure and quality.

2.9 Leakage management and monitoring

Management of NRW is the process of ensuring the availability of freshwater to users at the right time, place, quantity and quality as needed. And also simply leakage monitoring is a process of measuring flows of water into zones or districts, then perform leakage detection activities. It is the most cost effective strategy and widely used by utilities throughout the world.

Leakage management and monitoring is a broad tool with different approaches that could be undertaken in achieving major loss, even though to implement in a large networks it requires a big commitment, public awareness, qualified professionals and above all short term but long term return of finance.

There are two groups of leakage management; Passive Leakage Control (PLC) and Active Leakage Control (ALC).

ALC is the policy that a water utility implements; if it decides to pro-actively search for hidden leaks and its most basic form consists of regular sounding (e.g. listening to leak noise on fire hydrants, valves and curb stops with listening sticks or electronic devices. Whereas PLC is responding to reported bursts or pressure drops, usually reported by customers or noted by the utility’s own staff while carrying out other duties. However, this method can only be justified in areas with plentiful and very low cost supplies, but using this method leads the overall level of leakage continue and rise (Malcolm Farley, et al., 2008).

In most of the developing countries; NRW cases are not appropriately estimated and well understood from least to highest management staff, this situation makes it unable to know the exact figure or estimated volume of NRW and this delays the true financial cost and drawback on the utilities. In spite of this, NRW reduction neither receive essential attention nor successful implantation.

These conditions can be taken as an answer for why most of the utilities in developing countries struggle with NRW reduction, although, its management is not technically difficult but it is complexity and proper understanding of the baseline situation as a critical step in moving toward an effective reduction program by the utility's (Bill Kingdom, et al., 2006).

2.9.1 Basic concepts of leakage management and monitoring

When leakage management and monitoring is raised the concepts of Bursts and Background Estimates (BABE) and Fixed and Variable Area Discharge (FAVAD) concept are also raised to gather.

BABE concepts were developed by the UK National Leakage Initiative between 1991 and 1993. The concepts were the first to model physical leakage objectively, rather than empirically, thus permitting rational planning management and operational control of strategies for their reduction (Lambert A, et al., Dec 1999).

Important aspects of BABE is that all leakage management studies for a particular supply system; whether for planning, economics or operations, draw on the same concepts and the same data and parameter values. This ensures that the results of all calculations are compatible and there are no 'loose ends' or 'black holes'. Each advance in knowledge is integrated into the concepts and for the reliability of the calculations.

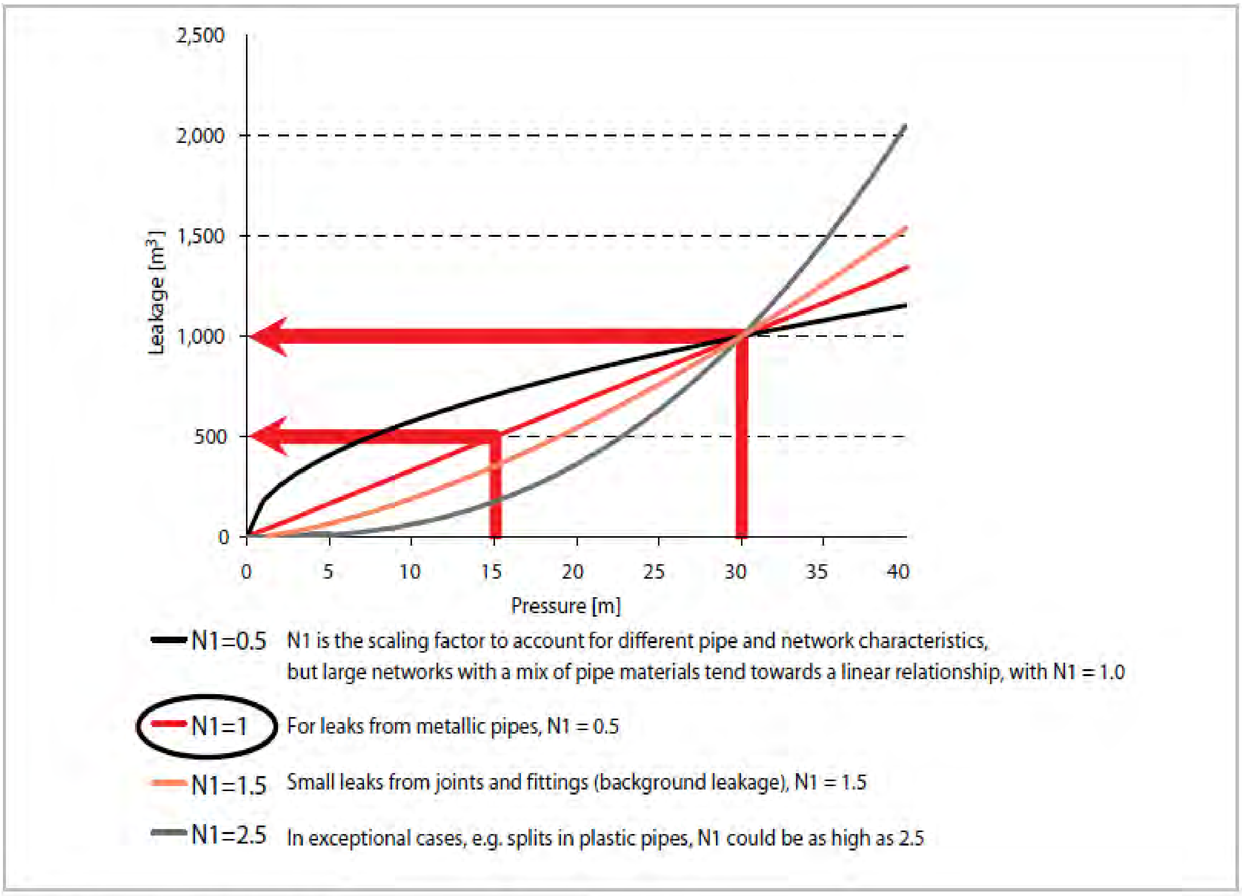
Basically the concept of BABE, is designed for international application and used for evaluation of leakage values. Also the components values are calculated with combination of different appropriate parameters such as MNF- night usage by customers that are mainly influenced by pressure.

In MNF analysis, presence of unreported burst in DMA is investigated in detail based on the flow rate in m^3/hour for calculation purposes. Then for calculating losses from bursts, the number of reported and unreported bursts are determined. In addition the numbers, pressure-corrected typical flow rates and average durations are also used to calculate the annual losses (Farley, 2001).

Another excellent concept regarding leakage monitoring and management is Fixed and Variable Area Discharge (FAVAD) concept. This concept is used to forecast the increasing or decreasing rate of real losses using a change in pressure. The simplest versions of the FAVAD concepts are leakage rate L (Volume/unit time) varies with pressure exponent N1, as:

$$L1/L0 = (P1/P0)^{N1}$$

N1 values might be in the order of 1 to 1.15 in the distribution system which contains different pipe materials. The higher the N1 value, the more sensitive existing leakage flow rates will be (Malcolm Farley, et al., 2008). As a result a linear relationship of leakage flow rate and pressure can be assumed as shown below in the figure 2.1.



Source: World Bank Institute

Figure 2-1: Pressure and leakage relationship

In general, pressure Management is best undertaken in conjunction with DMA and it does not necessarily require dramatic pressure reduction, sometimes good results can be achieved with alleviating the pressures at slightly lower levels or reducing excessive night pressures. Plus

Pressure Reducing Valves (PRV) are also should be understood as control devices used to reduce, regulate and manage operating pressures (Malcolm Farley, et al., 2008).

2.9.2 Miscarrying of NRW management and monitoring

Different studies and researches were carried out in the past decades, however, "decades of work on the subject has not delivered much improvement in the public sector in many countries" (Paul Fanner, 2008) even though benefits of NRW reduction are clear and the methodologies and technologies for reducing NRW are well developed. For this inadequacy many reasons can be indexed; according to Paul Fanner (2008) some of the bold ones are:

- The volume and causes of NRW are often not properly quantified or understood by senior management.
- NRW reduction is not simple to implement, because it is necessary to adopt new technical methodologies to correctly quantify NRW volumes and develop the correct NRW reduction strategy.
- NRW reduction is also not politically attractive.
- NRW reduction program will be self-financing in the longer term but funding is required in the short term to implement.

2.9.3 Purpose of estimating NRW

Estimating NRW can help water utilities to ensure their financial viability in terms of:

- Avoiding a spiral of financial decline and expediting the economic level of utility
- Minimizes the water loss volume of water supplied to customers that is not paid
- Maximizes revenues, at the same time it reduces the overall operation costs
- Preserves the network capacity of service
- Saves the budget for upgrading and construction of new projects, etc...

In addition, it helps the utility to improve the levels of services provided to customers and helps the utility staff to develop a better understanding of the operation of the distribution system as well as it minimizes consecutive complains of the consumers (Paul Fanner, 2008).

2.10 Theoretical Background

2.10.1 Minimum night flow (MNF)

MNF technically refers the flow in to a distribution system at a specific district metered area with a minimum quantity of flow and high pressure when compared to the other hours. And, usually occurs after mid night form 1 – 4 hour GMT and used for real loss with a background leakage estimation when the flow is minimum at the DMA through these time interval.

Based on MNF different types analysis, models and strategies can be built like pressure reduction for minimizing water loss and optimizing distribution networks in to a best performance in relation with setting of night-day factor.

2.10.2 Daily real loss volume

Based on the MNF or average minimum leakage flow rate, hourly and daily real loss volume can be determined using the equation:-

$$\text{Daily real loss volume} = \text{NDF} \times \text{Q}_{\text{min}}$$

Where NDF is night day factor and

Q_{min} is minimum night leak flow

NDF is computed by the sum of 24 hour pressure values collected from DMA installed at a representative point in the network area, that is :-

$$\text{NDF} = \sum_{t=0}^{24} \left(\frac{\text{Pt}}{\text{Pmnf}}\right)^{\text{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{2-1}$$

Where: P_t is pressure value at a time *t;*

P_{mnf} is pressure value at minimum flow time and N is orifice exponent or pressure exponent determined based on FAVAD concept with the equation of

$$\frac{Q1}{Qo} = \left(\frac{P1}{Po}\right)^{N1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{2-2}$$

Q_o is the flow rate in association with P_o pressure; Q_1 is the flow rate in association with P_1 pressure and N1 is obtained by closing the valve usually situated at the system inlet point. Experiences and different experiments performed in several countries have determined N1 values of 0.5 for metallic pipes and 1.5-2.5 for plastic pipes, however, if there is no satisfactory data is available the pressure exponent can be considered as 1 (Roland Liemberger & Malcolm Farley, 2004).

2.10.3 Pressure and leakage relationship

Pressure is one of the most important parameter influencing leakage as highlighted earlier in the literature review section 2.9.1. The increasing rate of pressure leads to increase the rate of leakage in pipes and junctions. This shows that the increasing rate of pressure in the distribution main is directly proportional with leakage. The relationship between pressure and leakage can be approximated by orifice classical formulation as:

$$Q = C_e H^{N1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{2-3}$$

Where C_e is the discharge coefficient of the orifice that is subjected on the shape and the diameter of the pipe; H is the nodal head and N1 was as explained previously. Therefore, based on from various literature it is generally accepted that flow from a hole or crack in a pipe will react to pressure with a hydraulic theory in agreement.

2.10.4 Computer modeling

Basically modeling of water supply distribution systems are mainly based on the hydraulic equations or parameters. Prior to this all computer modeling conveys mathematical equations to describe network system and uses principle of conservation of mass to answer the network properties.

Water distribution computer modeling and simulations were primarily used to solve design problems. In addition to this, recent advances in software technology have made models more powerful and easier to use. As a result, computer modeling and simulations now a days had become as a tool to aid and give a full range of possible alternative for the performance of water supply systems (Haestad Methods, et al., 2003).

2.10.5 Leakage assessment methods

There are two type of leakage assessment methods:

a) top-down leakage assessment methods
b) bottom-up leakage assessment methods

Top-down assessment method is used to estimate the leakage in a particular system and for different consumption purposes and uses different components of the overall water balance which can be evaluated. To reallocate the components into the IWA standard approach the procedure follows the simple steps of:

1. system input data collection
2. approve the Authorized Consumption

3. estimate Apparent Losses
4. finally, the remainder will be real loss

Even though the method is simple, it does not provide more information regarding the volume of real losses (Puust, et al., 2010).

Whereas bottom-up assessment method is carried out by using the minimum night flow in which in the case of urban areas the minimum flow occurs after mid night and in the early morning because of few customers uses the water such that this varying water consumption can reflect the real leakage (Kunlun Xin, et al., 2014).

2.10.6 Assumptions in leakage estimation

As mentioned in the literature review; there are different types of leakage models that tends to estimate the quantity and correlations with other parameters for a particular water supply distribution systems. Most likely for the process of estimating real loss based on the hydraulic modeling, the following assumption shall be considered:-

- Continuous flow data records for the modeled network area, usually readings from DMA's appropriate point;
- Number of population in the area and night users with special nodal demand allocation using house hold count, area or ground occupation and number of connections;
- Leakage is an exclusive function of pressure
- Leakage coefficient *C* is independent from cross-section of the pipe and it is the same for all the pipes in the DMA;
- Leakage coefficient shall be optimized in anticipation of measured inflow.
- Pressures of all orifices in each half part of the pipe are the same and are equal to pressure of the nearest node.
- The total flow at each time step shall be split in to effective demand or volumetric consumption and nodal leakage consumption.

For real simulation of modeled distribution network or schemes the effort of molding starts form recorded flow measurement at the inlet of the network and an estimation of the spatial distribution of this total demand across the network. Although, the location of the demand at the nodes might be known but how the total inflow into the network is allocated among nodes can only be estimated because at most domestic metering at each point is not available. Therefore, the technique used will be more consistent in terms of description of demands and to assign part of the total metered inflow to leakage by in consideration of pressure dependent demand. Most of the time leakage is modeled based on the equation of flow through the orifice as explained earlier. (Araujo LS, et al., 2003)

3. Methodology

3.1 Process of study area selection

The study of this research paper is conducted on Addis Ababa, Bole sub city water supply mains and distribution system based on the current operational and performance characteristics. In order to model and estimate NRW from its components, the starting point was mainly based on the availability of data's, documentations and some studies which had been undertaken by the utility of AAWSA and from different studies that seems more relevant for the study.

This is mainly because, concerning on the task for minimization of water loss and its derivatives has not been given that much attention, in spite of this there are not more work done or performed studies and actions in a detail scientific ways for each branch offices under the utility, especially in the newest distribution network zones. Therefore, based on the availability of the data's and some investigations in relation with selecting the relevance areas which has more susceptible for water loss and which can assist for the study, pilot areas were selected that has a probable similarity with other provinces in the Bole sub city.

3.2 Selected study area

Consideration of the availability of the data's was among the major issue during the selection process of the pilot/study area to carry out the study for the estimation of water loss parameters. Therefore, based on the preeminent available data's found form different sources, the selected study area in the Bole sub city is; woreda-07; situated north east of the Bole sub city at an elevation range of 2330-2450 m.a.s.l. and a total population of 43,637 is selected.

With respect to the above mentioned parameters, the processes of selecting this area is mainly depends on the available minimum night flow data, inflow volume of water in to the system, clear aggregated billed consumption for monthly and annually, updated water supply network map and average number of population per household.

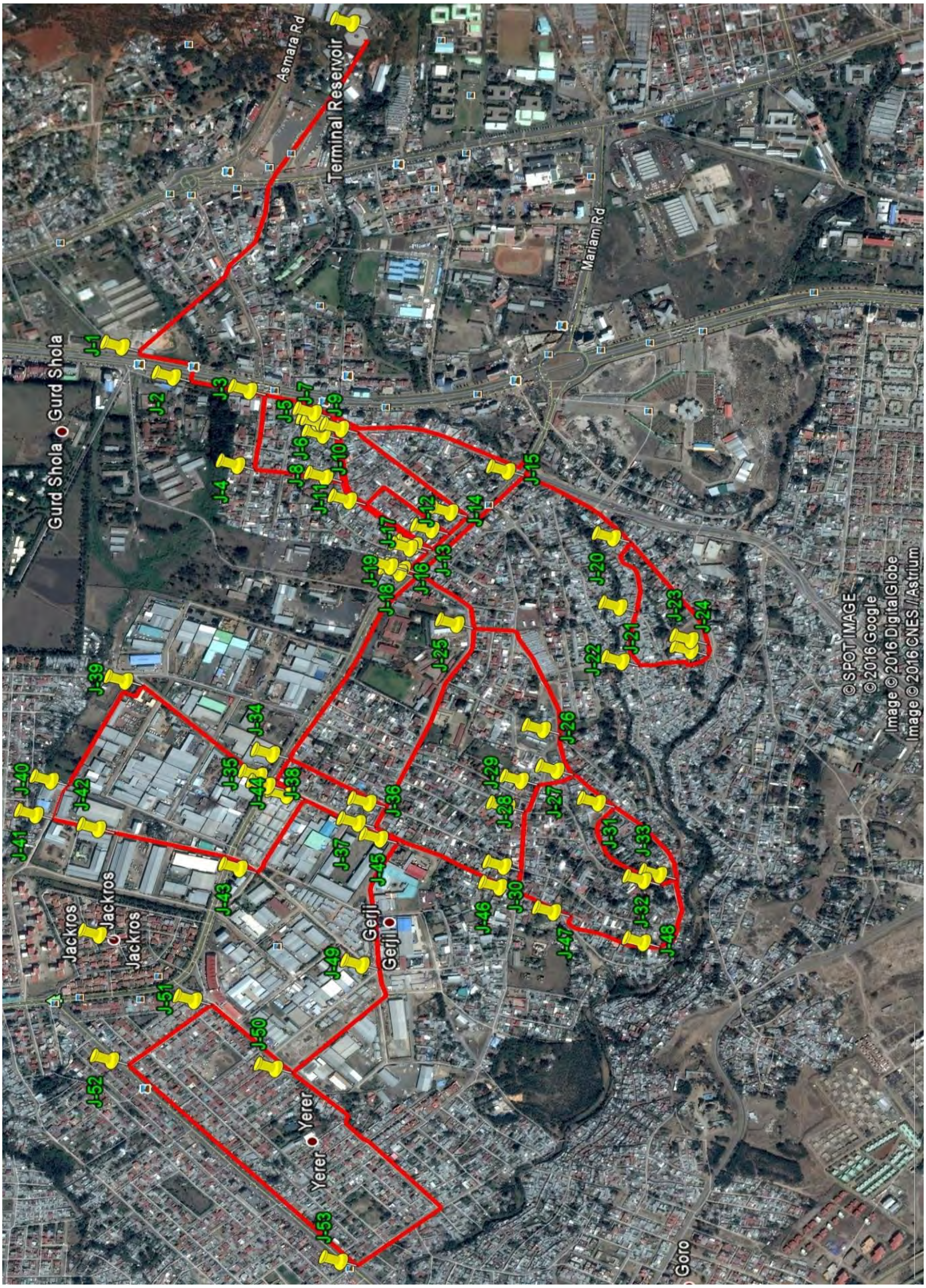


Figure 3-1: Aerial view of study area and distribution mains

3.2 Data collections

The data's for this research paper is collected based on primary and mainly on secondary datas which are viable for the study as a starting point. Also, it was aimed to collect through a formal request from AAWSA, as well as other related organization through physical communication, discussions and form online sources.

In order to clarify the collected data with respect the current situation and to obtain data's which were not found at the utilities, site visit and certain measurement had been taken place for a detail investigation on a selected study area and its surroundings.

As per the request, most of the data's had been gathered form AAWSA and its branch offices plus, it has been also tried to fill some gaps of gathered data through personal communications and meeting with the experts of the authority as much as possible.

To quantify the components of NRW or water losses, the total water production volume and water that are put in to the distribution network systems of the sub city in collaboration with different types of major incidents like pipe break and burst, monthly amount of water consumption or billed amount form the customer meter reading form AAWSA Gurd Shola branch and some design documents regarding the network lay out / profile and study parameters were collected form Water Works Design and Supervision Enterprise (WWDSE).

For the analysis of real losses; some reported leakage, minimum night flow of the study area at Bole sub city, number of connections per km and junctions, demand, pressure profile and some background loses considering district metered areas has been studied. However, regarding the minimum night flow data for other location has been tried to find but due to the inevitability and unavailability at the utility office only the twelve hour measured flow is found as a result it is rejected and concentrated only at the selected area.

While concerning for apparent losses, meter inaccuracies and theft or illegal connections of water use are studied. Meter inaccuracies are estimated based on AAWSA recommendations; whereas unauthorized consumption which is water theft and illegal connection is not a big problem and it is considered based on previous study report of AAWSA, 2014 and as per report it is taken as approximately as 1 %. Regarding apparent loss components errors like meter reading data, data transfer and billing process related studies had not been found through the utility departments and in order to asses it requires a considerable personals and time, in addition to carry out a detail investigation it requires testing of water meters installed to each of customers in the area with closing and opening of valves, therefore, based on from the AAWSA executive summary report in 2014 it assumed as 5% error margin of the total billed metered consumption.

Prior to these, different data were organized and processed for the analysis. Some missing data were filled with regression methods to fit the data's and to meet the expected range.

3.3 Sub City network data

Regarding the Bole sub city digital mapping and network data for water distribution network in Auto CAD format incorporating material types and size was mainly collected from the Gurd Shola branch office of AAWSA. Updating, isolation of valves, checking and transforming network data to the WaterGEMS software and integration with other user interference programs like ArcGIS were performed to get an information on the selected study area is based on the current actual state and for enabling different scenarios and alternatives in to the model by isolating the selected study form other region, also branching and looping selotonization process is also performed.

Basically the bole sub city is comprised of 14 Woreda's, has an area of 122.08 km^2, population density of 2605.291 peoples/ km^2 and an estimated population of 368.19. Most of the pipe networks along the edge of the sub city are interconnected to other sub cities. All the districts has the water consumption or bill data, however, most of the water supply data; for example volume of inflow, pressure, bulk meter readings, DMA data and major related performance parameters like operating pressure and minimum night flow data is not available for the most of the areas in the utility. Therefore, in order to fill some of this gaps, based on different demand patterns of a more alike areas within the city from previous studies had been carried out by approximation and interpolation and checked in collaboration with the utility's experts.

3.3.1 Reservoirs

When collecting distribution network one has to look for necessary baseline data's and information's regarding reservoirs that fed the supply in to the systems. Then after, reservoir data's with in the sub city is collected in terms of capacity, location and elevation, material of construction, supply area and flow.

Based on location, supply area and the water supply route; there are seven reservoirs; among form these three of reservoirs serves as service reservoir and boosting station with in the Gurd shola branch, in addition some of them serves as directly for the sub city and as a transfer plug for the other sub citys like Terminal Reservoirs; it consists two hexagonal concrete type reservoirs with a storage capacity of 10,000m^3 each.

3.4 Source of existing water supply

The main sources of water supply of the Bole sub city are from surface water of Legedadi treatment plant, deep ground water sources and Legedadi wells. The area of Bole sub city water supply network is administered by joint offices; Gurd Shola and Megenagna branch offices, in which the capacity form only borehole source has a potential of supplying 17,496 m^3/day. For storage and transferring to other systems there are seven reservoirs with a storage capacity of each 5000 m^3 and other larger capacity under construction. Prior to this there are 144 water points/bono water with in the sub city.

3.5 Water demand consumption and population data

3.5.1 Water demand consumption

Aggregation of the water demand for different zones with in the sub city is assessed based on the socio economic condition of the current state, even though there is no up to date detail study that had been performed for all the districts with in the sub city.

As there is no specific data for annual water supplied and consumption volume at the area, the overall inflow data is used to estimate the annual system input volume to the area. Also, using the aggregated bill consumption data’s and number of population the per capital consumption amount is estimated for different types of house holdings based on the physical situations and with referencing section 9 of Ethiopian building code standard for plumbing services of buildings (EBCS).

$$\text{Capital consumption}(\text{l/person/day}) = \frac{\text{Annual consumption (m3)}\times 1000\text{l/m3}}{\text{Population number of Town}\times 365} \qquad \text{...............3-1}$$

Table 3-1: Residential water requirements

Type of building occupancy	Consumption (l/day)
a) Dwellings with house connections	
i) Low consumption	80-120
ii) Medium Consumption	120 – 200
iii) High consumption	200 - 300
(b) Dwellings with yard connection	40 – 60
(c) Public fountain (standard pipes)	15-20

Source: Ministry of Urban Development and Construction, 2013

3.5.2 Population data

Population projection value under the sub city level which is published in August 2013 has gathered from the Ethiopian Central Statistical Agency (CSA) which is based on at zonal and woreda levels by urban and rural residence. According to this document the total projected value for the Bole sub city on the year of 2016 is taken as 378,104 with a projection rate of 3.7% per year. Prior to this as per the data of woreda 07 administration, the selected study area has a total population of 34,497 with average number of occupants per house hold 4.5 for the year 2007 E.C.

3.6 Verification of data’s

Before using all the collected data’s for different levels of the studies, checking and comparisons with timely basis and up to date situation is carried out.

For the distribution network data reviewing as it is received in the original AutoCAD format in conjunction with the contour map, cadastral map and road network map is checked and updated by using Google earth delineation and generating a digital elevation model by a global mapper.

Regarding to the water consumption and different incidents which is collected form the utilities in Microsoft excel and word format is arranged and evaluated as per the respective time range, expected consumption usage and ordered according to the use of study as much as possible. In addition, filling some parameters in the data’s like meter reading and recording error with other related gaps are analyzed based on regression technique and discussion with the utility experts. But, regarding on the burst and incident data is rejected because it lacks exact reference, volume and location.

3.7 Hydraulic Modeling

The model contains different elements, which are very fundamental for purpose of study and excluded some elements depending on their significance like valves and smaller diameter pipes.

To visualize the existing distribution network system and simulation according to the actual flow parameters, building of hydraulic model is crucial. Such that artificial network model is done to guide the test and validation processes for the estimation of real loss in conjunction with different scenarios and alternatives for determining the pressure and demand output for each time step.

3.7.1 Assembling of the Model

The most useful document for the overall representation and understanding of the distribution system used are:

- **Distribution network maps**: - which gives information of the pipe length, material type, alignment, and connectivity.
- **Topographic maps**: - to indicate the ground surface elevation and points, the contour maps with respect to the Digital Elevation Model (DEM) are used.
- **Electronic map records**: - to identify the number and types of house holdings with the reference of infrastructures recorded and recent updated Computer Aid Drafting (CAD) drawings, GIS shape files and other data formats are used.

Based on these data with other supporting application software like Global mapper 10 and Goggle earth transformation in to the WaterGEEMS is executed.

3.7.2 Model skeletonization

The simplest skeletonization type performed is called Removing Branch Pipes (RBP); it is the process of removing the dead end branches because the removal has no effect on the carrying capacity of the remainder of the system and it used to preserve the pressure loss in system (Haestad Methods, et al., 2003).

Pipes whose diameter 50 mm and above are considered to reduce tremendous amounts of data and only the main parts of network elements that have a significant impact on the behavior of the system are included in the hydraulic model.

3.7.3 Friction factors

The model mainly concentrates on the analysis of pressure systems throughout the network, the friction method used is based on Hazen-Williams C-factor according to pipe material type.

3.7.4 Demand allocation

The first procedure after the setting up of all the required information is allocation of estimated base demand to each node area using categories of residential and non-residential consumption and population coverage in each junctions by using a thiessen polygon tool in the WaterGEMS software.

Parameters used in hydraulic modeling and schematic network system are listed in the table and figure below respectively. Also spatial reference of the nodes/ junctions are listed in appendices A.

Table 3-2: Parameters used in hydraulic modelling using WaterGEMS

Units	Head loss	Trials	Accuracy	Demand Multiplier	Tolerance	Scale
System international (SI)	Hazen Williams	40	0.0001	1	0..01	1cm:0.005Km

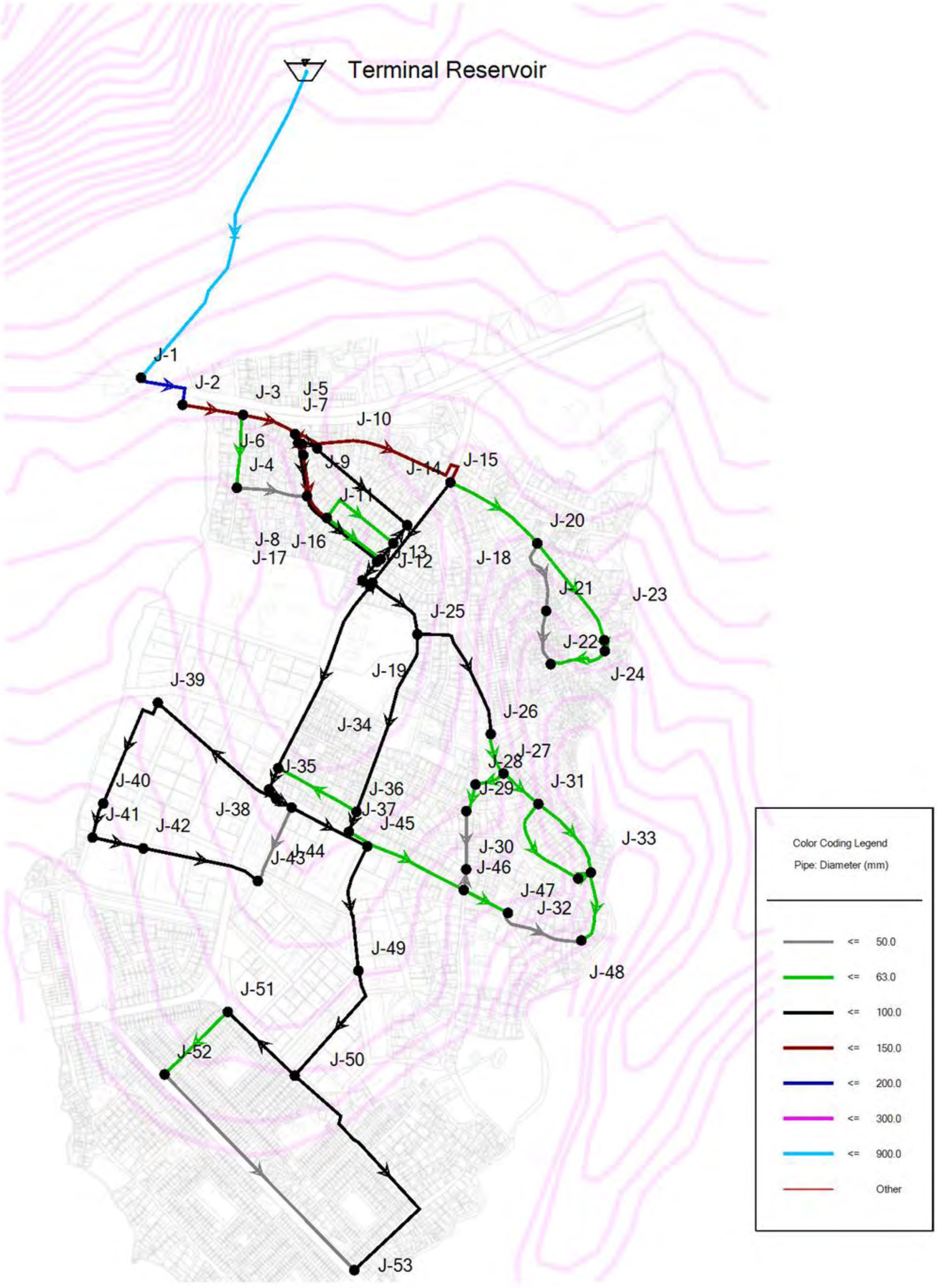


Figure 3-2: Schematics of modeled network of selected study area (Bole SC, Woreda-07)

3.8 Procedure of the study

All the modeling and data's were in terms of SI unit and based on the latest definitions adopted by the IWA. The processes involved in the study work are presented and described schematically below on figure.

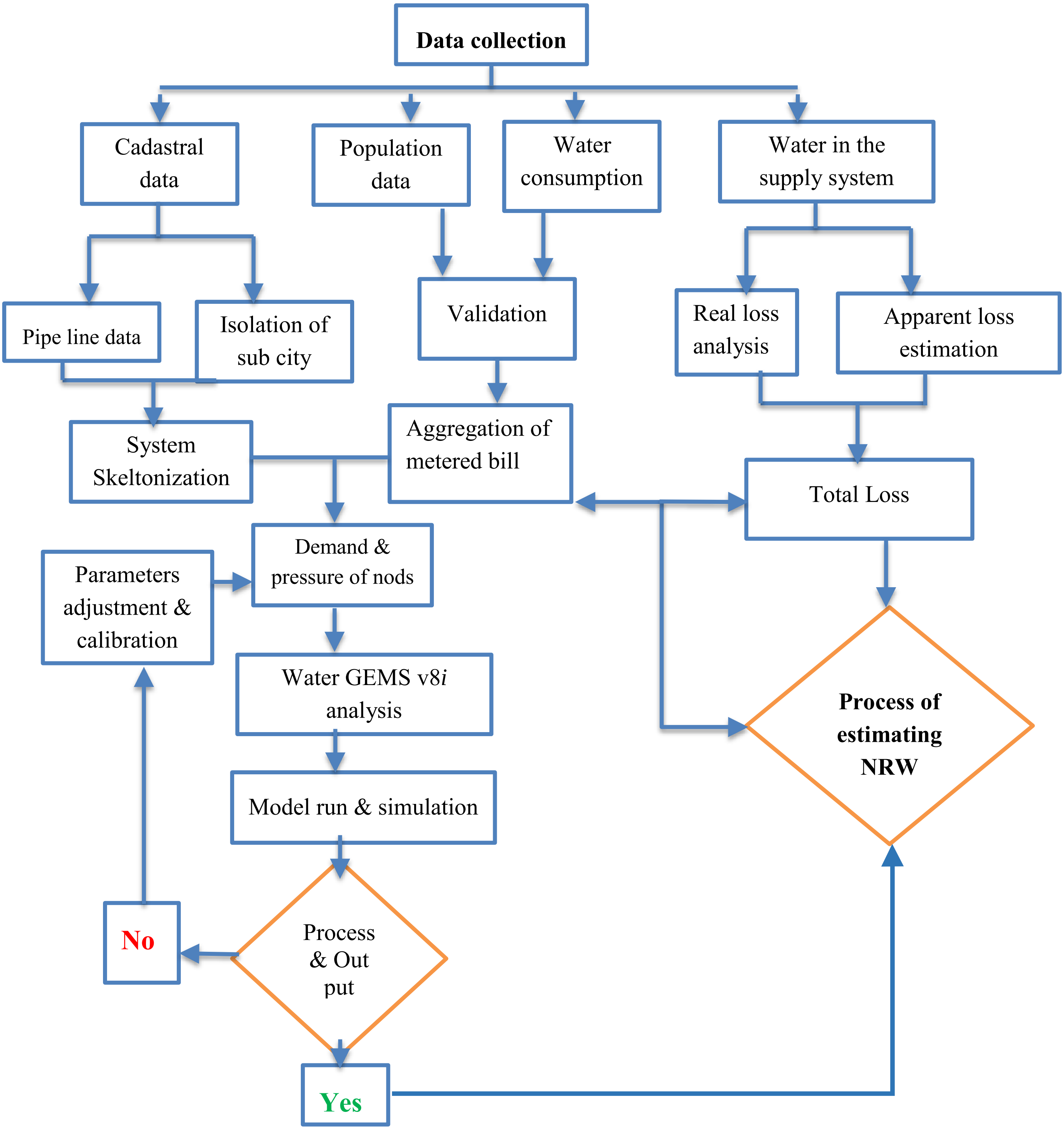


Figure 3-3: Diagram of study process

3.9.1 Estimation of real loss

As explained in the theoretical background, continuous flow measured data records for the selected area is taken as a starting point. The data is collected form the utility office which is taken from DMA's installed for the distribution system of the selected study area in 2007 E.C. According to the data, system input volume is 1398.06 m^3/day and the minimum flow occurred at 2:00 AM - 3:00 AM with a flow rate of 38 m^3/hr and at pressure of 4 bar.

Table 3-3: Inflow rate and pressure in 24 hours

Hour	Flow (m^3/hr.)	Pressure(bar)
6:00 PM - 7:00 PM	66	2
7:00 PM - 8:00 PM	64	2.8
8:00 PM - 9:00 PM	50	2.8
9:00 PM - 10:00 PM	50	3
10:00 PM - 11:00 PM	44	3
11:00 PM - 12:00 AM	50	3
12:00 AM - 1:00 AM	40	3.5
1:00 AM - 2:00 AM	52	4
2:00 AM - 3:00 AM	38	4
3:00 AM - 4:00 AM	50	4
4:00 AM - 5:00 AM	44	4
5:00 AM - 6:00 AM	52	4
6:00 AM - 7:00 AM	88	3.2
7:00 AM - 8:00 AM	85	3
8:00 AM - 9:00 AM	67	2.6
9:00 AM - 10:00 AM	67	2.3
10:00 AM - 11:00 AM	59	2
11:00 AM - 12:00 AM	67	2.6
12:00 AM - 1:00 PM	53	2.2
1:00 PM - 2:00 PM	69	2
2:00 PM - 3:00 PM	51	2.1
3:00 PM - 4:00 PM	67	2
4:00 PM - 5:00 PM	59	2
5:00 PM - 6:00 PM	69	2

After getting, average inflow data, calculation of network leakage at MNF time ($Q_{L,\ MNF}$) is performed.

$$Q_{L,\ MNF} = MNF - NightUses \text{ .... } 3\text{-}2$$

$$Q_{L,t} = Q_{L,MNF} \times (Pt/P_{MNF})^N \text{ .... } 3\text{-}3$$

Where: - P_t is pressure value at times

P_{MNF} is pressure values a minimum night flow and

N is pressure exponent

Using FAVAD concept and the network's burst and incident data the pressure exponent (N) can be determined, however, if there is no satisfactory data available the pressure exponent can be considered as 1 (Roland Liemberger & Malcolm Farley, 2004), and for a large systems with mixed pipe materials, the overall N1 value is often quite close to 1.0 (Paul V. Fanner, et al., 2007).

In the next stage, volume of consumption is determined by deducting the network leakage from the total inflow at MNF time.

Values of inflow at each hour is planted in the hydraulic model and volume of consumption is set to each node based on the estimated population covered in each node area, then the hydraulic model (WaterGEEMS) is run to obtain the pressure for each nodes.

After obtaining the output pressure from the hydraulic model, estimation of the coefficient "C" is calculated using the equation of:

$$\mathrm{C} = \frac{\mathrm{Q_{L,MNF}}}{\sum_{\mathrm{i=1}}^{\mathrm{NJ}}\left(\sum_{\mathrm{j=1}}^{\mathrm{NK}}\frac{\mathrm{L_{li}}}{2}\times \mathrm{P_i^N}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{3-4}$$

Where: - NK is number of pipes connected to node i

P_i is the pressure at node i

N is pressure exponent

Using the estimated coefficient "C" nodal dependent consumption or nodal leakage is carried out as a first scenario using the following equation:

$$\mathrm{Q_{L,i}} = \sum_{\mathrm{j=1}}^{\mathrm{NK}}\frac{\mathrm{L_{ij}}}{2}\,\mathrm{C.P_i^N} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{3-5}$$

After allocating the nodal dependent or leakage which is free from the consumption volume, by creating a new or second scenario in the hydraulic model updating of the nodal consumption value is performed, that is adding the nodal leakage values with the volumetric consumption on the created new scenario and running of the model is performed which is used to produce the new nodal pressure.

Pressure at the first scenario (volumetric consumption only) and pressure at the second scenario (volumetric consumption and leakage) is cheeked if they are equal in relation with the total measured inflow at the MNF time. However, if the values are not equal, producing another nodal dependent consumption and changing of the coefficient is performed until the model develops the equivalency of both scenarios.

Finally, after finding the reliable final coefficient "C" calculation of nodal leakage rate at each hour with respect to the hourly pattern and inflow volume at each hour is carried out.

To determine the leakage flow in each pipe at each time step, the following equation is used:

$$Q_{L,ij} = Q_{L,i} \times \frac{L_{ij}}{\sum L_i} + Q_{L,j} \frac{L_{ij}}{\sum L_j} \text{ .... 3-6}$$

Where: - $Q_{L,ij}$ is the leakage of pipe ij.

$Q_{L,i}$ and $Q_{L,\, j}$ are the nodal leakage rates and

L_i and L_j are the total pipe lengths connected to nodes i and j

3.9.2 Estimation of Apparent Loss

Collection of aggregated bill for each month in 2007 E.C is done in collaboration with the AAWSA meter readers based on the number of house hold in the study area.

According to the bill data, the total volume is 378,769.70 m^3/year. Using this data as an authorized consumption and adding it with the volume apart from the estimated real loss, total annual consumption is determined.

Then apparent loss components; unauthorized consumption and losses due meter inaccuracies and data handling error is estimated as:

a) Unauthorised consumption value is obtained multiplying annual water consumption with total percentage of illegal consumption volume.
b) Customer meter inaccuracies and data handling error value is estimated by multiplying the annual water consumption with total data handling errors.

3.10 Performance Indicator (PI)

One of the traditional method of expressing performance indicator is NRW as a percentage of input volume. Although, expressing NRW in terms of percentage is misrepresentative as a PI because it does not differentiate between real losses and apparent losses it is useful for knowing the high result and take an action in addition it also enables monthly and yearly financial performance. The Manager's Non-Revenue Water Handbook, Farley 2008

3.10.1 Real Loss Performance Indicator

From different performance indicator as indicated in the literature review for real loss other than percentage expression the Infrastructure Leakage Index (ILI) is used after CARL and UARL values are known.

3.10.2 Apparent Loss Performance Indicator

The method used for expressing performance indicator for the apparent loss is based on the IWA Water Loss Task Force for apparent losses in which the indicator uses a base value of 5% of water sales as a reference.
The actual apparent loss value is calculated with respect to the benchmark of calculated loss value to the amount of 5% water sales value (Malcolm Farley, et al., 2008). i.e.

Apparent Loss Index (ALI) = Apparent loss value ÷ 5% of water sales

3.11 Limitations to the Study

The model requires as a priority using of a reliable measured inflow data for a specific DMA at a bulk meter station. But, most of the bulk meter during the study were not functional and the installed numbers are small when compared to the network size.

For best estimation the model lacks pipe burst and incident documented data, even though, their effect is not that much significant due to the frequency of occurrence and maintenance period. Also, inevitability of recorded intermittent supply times may hinder the pressure and volume of consumption to some extent.

In addition, difficulty of isolating supply pipe lines of the distribution network form district level to sub city boundary and lack of data makes the study to be constrained at a specific area.

4. Results and Discussion

4.1 Analysis of water loss components

Water loss in the distribution system is estimated through NRW components of real and apparent loss. Annual water consumption from aggregated bill data is used to estimate apparent loss and for estimation of real loss minimum night flow data is used for calculating background leakages at the nodes and pipes for different hours.

Besides the annual water balance method, the model estimates daily, monthly and annual leakage rates based on FAVAD concept.

4.2 Water consumption

Average water consumption per person is the basis and an essential element for assigning the required demand to each of the junction in the distribution network using the hydraulic model. Therefore, to catch out the average per capital demand the annual domestic water consumption form the aggregated bill is converted to average l/capital/day using the total number of population in the distribution network area.

Based on the inflow measured data and in order to allocate the flow at each hour step, the demand pattern is used as shown in the figure below:

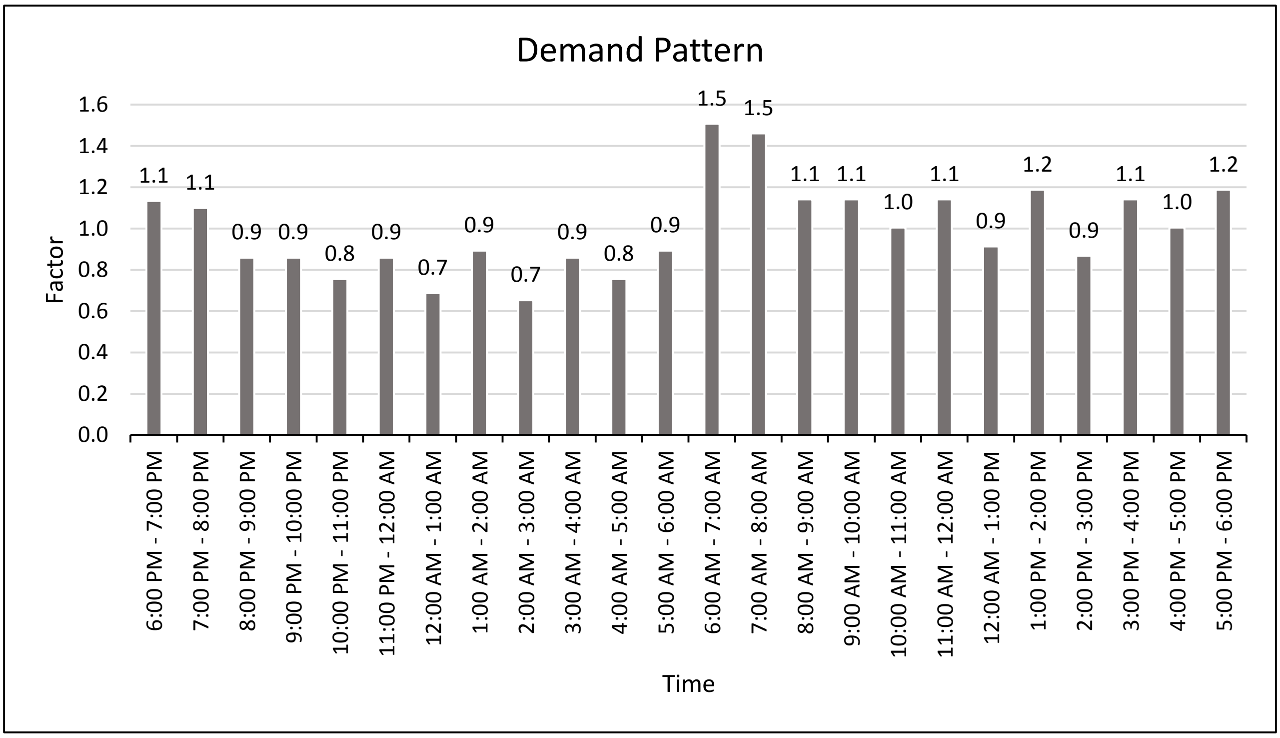


Figure 4-1: Demand pattern of the area

4.3 Model performance and evaluation criteria

In order to use the hydraulic model for the work evaluation performed through calculating the squared relative difference between observed and simulated pressure for each test. The evaluation criteria used was statically method using correlation coefficient (R^2).

$$R^2 = \frac{\text{Sum(X-X mean)(Y-Y mean)}}{\text{(SQUR(Sum(X-X mean)}^2\text{) x Sum(Y-Y mean)}^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{4-1}$$

Where R^2 is Correlation coefficient, X and Y are measured and simulated values, X mean and Y mean are average value of measured and simulated data respectively.

4.3.1 Pressure calibration and validation

The acceptable level or criteria of calibration for a water supply model shall have an average pressure difference of ± 15.2 kPa (± 0.15 bars) with a maximum difference of ± 50.3 kPa (± 0.5 bars) represents a "Good" data set and an average pressure difference of ± 29.6 kPa (± 0.29 bars) with a maximum difference of ± 97.9 kPa (± 0.98 bar) represents a "Poor" data set (ATSDR, 2000).

Table 4-1: Arrangement of pressure readings for calibration at the selected junctions

S/N	Sample Location pints	Measured Pressure(m)	Computed Pressure (bars)	Difference	Measured Time	Sample Location		
						X(m)	y(m)	Elevation
1	J-1	3.22	3.19	-0.03	7:45:00 AM	479,841.72	996,839.60	2,381.66
2	J-3	3.40	3.60	0.20	8:15:00 AM	480,128.59	996,737.48	2,375.52
3	J-10	3.21	3.33	0.12	11:25:00 AM	480,337.41	996,645.19	2,376.91
4	J-15	4.47	4.54	0.07	12:00:00 PM	480,711.57	996,551.67	2,365.10
5	J-16	3.34	3.64	0.30	9:40:00 AM	480,504.89	996,333.10	2,373.97
6	J-20	4.50	4.72	0.22	2:00:00 PM	480,955.81	996,384.20	2,359.54
7	J-25	3.90	3.95	0.05	4:35:00 PM	480,618.64	996,134.31	2,370.79
8	J-41	5.30	5.30	0.00	2:00:00 AM	479,705.82	995,575.72	2,347.81
9	J-43	4.30	4.67	0.37	3:15:00 PM	480,170.11	995,456.16	2,361.90
10	J-46	6.05	5.91	-0.14	11:35:00 AM	480,748.93	995,431.31	2,348.94
11	J-51	4.73	5.10	0.37	1:10:00 AM	480,085.81	995,096.38	2,353.53

The calibration result of pressures as shown in the Figure 4.2 displays that the statistical correlation between the measured and the computed during the calibration process. The result shows that R^2=96.73% this implies that the computed pressure are within the acceptable limit.

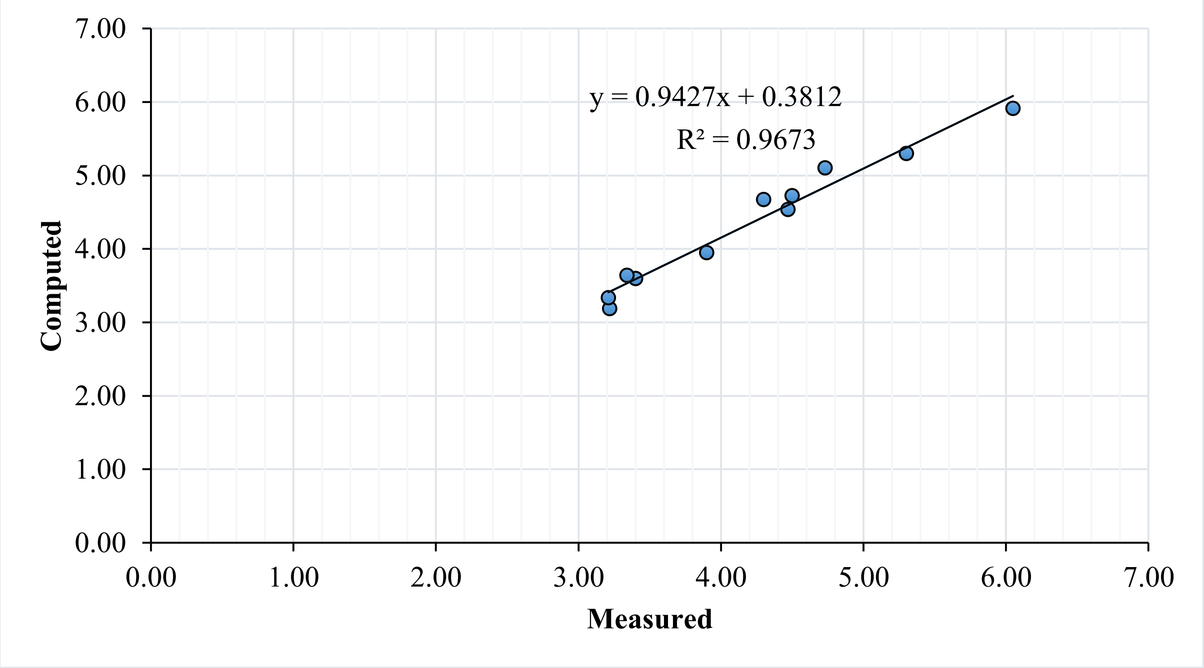


Figure 4-2: Correlated plot of measured and computed pressure in bars

4.3 Real loss analysis

After calculating the network leakage at each hour, the total real loss for the area from the model output is 294.1 m^3 / day and 107,345.41 m^3 / year.

4.3.1 Network leakage

In order to obtain the network leakage, calculation of leakage rate at MNF time should be examined. From the data gathered, taking the total population number of the consumers in the modeled study area is 34,497 and considering 6% active population during night time out of the total population with consumption rate of 10 l/head/h (McKenzie 1999) night use can be estimated.

Based on these basic assumptions; the minimum flow occurred is at 2:00 AM - 3:00 AM which is $38m^3$/hr with a pressure of 4 bar as shown in the table 3.3.

Therefore: - the estimated night use is calculated as

$$\text{Night use} = 6\% \text{ x number of population x } 10 \ \text{l/head/hr.}$$

$$= 6\% \text{ x } 34{,}497 \text{ x } 10 \text{ l/head/ hr.} = 20.7 \text{ m}^3\text{/hr.}$$

Therefore, the leakage rate MNF time is:-

$Q_{L,\,MNF}$ = MNF − Night uses = 38-20.7 = 17.3 m^3/hr.

The hourly leakage rate is determined by multiplying leakage rate at MNF time with the pressure values at a time t and MNF time with the pressure exponent N. It is necessary to indicate that when N is not exactly known, a linear relationship (N=1) can be used based on the FAVAD concept. (Roland Liemberger & Malcolm Farley, 2004).

$$Q_{lt} = Q_{L,MNF} \times \left(\frac{P_t}{P_{MNF}}\right)^N \quad \text{.................. 4-2}$$

Where: - Q_{lt} is network leakage at a time (t) and P_t and P_{MNF} is pressure values at a time t and MNF respectively. Using this equation the network leakage at MNF time is:

$$Q_{lt} = 17.3 \text{ m}^3\text{/hr.} \times 4 \text{ bar} / 4 \text{ bar} \quad = 17.3 \text{ m}^3\text{/hr.}$$

4.3.1.1 Determination of leakage coefficient "C"

Using the thiessen polygon tool in Water GEMS the total consumption is distributed and assigned at each node based on the surrounding population and household coverage. This is used for obtaining the nodal pressure at MNF time and to estimate coefficient 'C' and calculate the nodal leakage consumption to each nods. In doing so, the final coefficient C by trial and error is found as 0.24392159.

Prior to these, the nodal consumption values shall be updated by adding the nodal leakage values to the volumetric consumption to each node and running of the model shall be carried out again to produce newly pressure to each node based on each time step interval by assigning the scenario and alternative analysis in the hydraulic model.

Then, the newly updated and the first pressure values to each node which is after and before adding the nodal leakage to the volumetric consumption respectively, then the pressure values in both scenarios attained approximately the same pressure values as shown in figure below and the values at the appendices B.

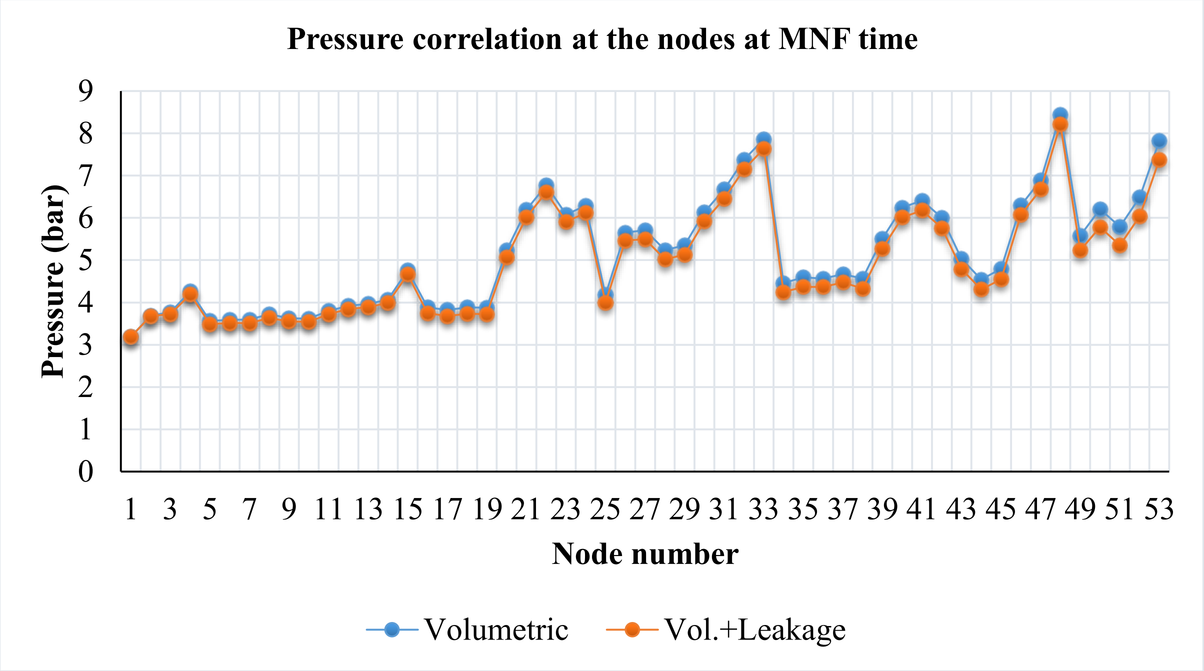


Figure 4-3: Correlation of pressure between volumetric and total consumption at nodes

After checking the correlation of pressures at MNF time, applying the same procedures the coefficient-C for the rest of the hour is determined as shown in the table below to produce the pressure and leakage values at each node based on the inflow at each time intervals or demand pattern.

Table 4-2: Estimated C values for each time interval

Time	1	2	3	4	5	6	7	8	9	10	11	12
C	0.13	0.18	0.18	0.19	0.19	0.19	0.21	0.25	0.24	0.25	0.25	0.25
Time	13	14	15	16	17	18	19	20	21	22	23	24
C	0.23	0.22	0.17	0.15	0.13	0.17	0.14	0.14	0.13	0.13	0.13	0.14

4.3.1.2 Nodal Leakage rate

For each successive time step based on the demand factor and recorded inflow, consumer demand at each nodes is reallocated to adjust total demand of the area according to the metered inflow.

Using the estimated coefficient results at each our nodal leakage rate is estimated by the following equation:

$$Q_{L,i} = \sum_{j=1}^{NK} \frac{Lij}{2} \times \boldsymbol{C}P_i^N \qquad \text{..................} \; 4\text{-}3$$

Where: - Pi is the pressure at node i

L_{ij} pipe length connected to nodes ij

N is pressure exponent

NK is number of pipes connected to node i

C is the coefficient

The total leakage rate at each hour is shown in the table below and the results of each nodal leakage rate and pressure values at each hour time step is can be shown in the appendices C. From the analysis the estimated result of total real loss volume is 294.1 m^3/day and 107,345.41 m^3/year. This shows that from the system input volume there is a 21.04% of real loss.

Table 4-3: Total leakage volume of nodes at each time interval

Time (hour)	1	2	3	4	5	6	7	8	9	10	11	12
Leakage (m^3)	8.64	12.09	12.09	12.95	12.95	12.95	15.11	17.27	17.30	17.27	17.27	17.27
Time (hour)	13	14	15	16	17	18	19	20	21	22	23	24
Leakage (m^3)	13.83	12.96	11.23	9.93	8.64	11.23	9.50	8.64	9.07	8.64	8.64	8.64

4.3.2 Leakage flow in the pipe

Pipe leakage flow in each hour is evaluated after the analysis of distributing the total network leakage to each nodes based on the assumption that pressures of all orifices in each half part of the pipe are the same and are equivalent to pressure of the adjacent node. The leakage flow in each of the pipes for each hour is determined in the table 5.3 below and the detail output result from the model can be shown in appendices D.

Table 4-4: Total leakage of pipe at each hour

Time (hour)	1	2	3	4	5	6	7	8	9	10	11	12
Leakage (m^3)	4.87	6.69	6.68	7.16	7.15	7.16	8.34	9.54	9.60	9.54	9.54	9.54
Time (hour)	13	14	15	16	17	18	19	20	21	22	23	24
Leakage (m^3)	7.67	7.19	6.21	5.50	4.78	6.21	5.25	7.78	5.01	4.78	4.78	4.78

For a more representation and to perform further analysis and leakage management of these pipe leakage results and nodal/junction leakage with respect to pipe data like material, diameter, pressure, flow, length and other required information with respect to special geographic references is exported to ArcGIS environment as shown figure below.

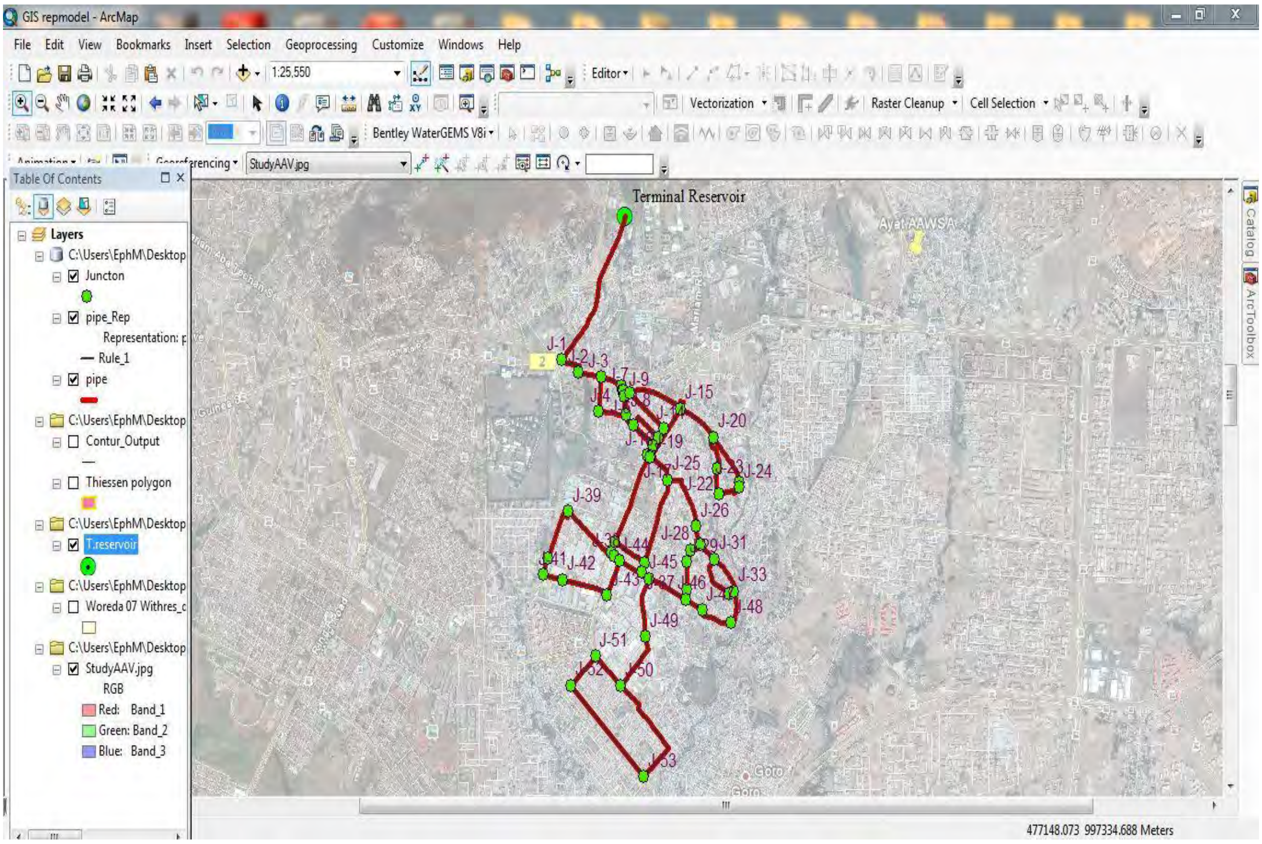


Figure 4-4: Representation of the model on GIS environment for farther analysis

4.3.3 Calculation of real loss performance indicator (PI)

Performance indicators for a real loss is known as Infrastructure Leakage Index (ILI) and it is used for monitoring leakage or measuring the progress of reducing NRW with respect to developing the standards and prioritize investments. (Farly M., 2008). Prior to this, as stated in the literature review part section 2.5.1 the minimum achievable annual physical losses which is known as Unavoidable Annual Real Losses (UARL) shall be determined.

So based on IWA specified assumptions and formula for practical use of calculating UARL depends on total pipe lengths, number of service connection and most likely on existing pressure in the system is : -

$$\text{UARL} = (18 \times \text{Lm} + 0.8 \times \text{Nc} + 25 \times \text{Lp}) \times \text{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{4-4}$$

Where, UARL = unavoidable annual real losses (l/d)

Lm= length of mains (km)

Nc= Number of service connections (main to meter)

Lp= length of unmetered underground pipe form street edge to customer meter (km)

P= average operating pressure (m)

Hence, for the study area UARL is considered as

Lm=14.61, Nc = 6,123 Lp= 4.5m x 6,123 = 27.55 km P_{avg} = 28.93 m

UARL = (18×14.61+0.8×6123 +25×27.55) × 28.93 = 169,246.8 lit/day

=169.25 m^3/day

= 61,775.08 m^3/year

$$\text{Therefore: - } \mathrm{ILI} = \frac{CARL}{UARL} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4\text{-}5$$

$$= \frac{107{,}345.41}{61{,}775.08} = 1.74$$

This illustrates, the current annual real losses are approximately two times as high as the unavoidable annual real losses for the system in the study area and according to physical/real loss target matrix of World Bank Institute for developing countries the ILI value lays in the technical performance category of A as highlighted in the literature review of table 2.4, however, for further real loss reduction careful analysis is needed to identify and for implementation of cost-effective improvements (Malcolm Farley, et al., 2008) .

4.4 Quantification of Apparent Loss

According to Farley M. (2008), to estimate an unauthorised consumption is always a difficult task and should at least be done in a transparent, component based way so that the assumptions can be easily checked or modified later. Due to this, for the purpose of estimation process form the earliest study report of AAWSA; unauthorised consumption considered and taken as approximately 1% due to the fact that illegal connection and theft is not a big problem. In addition for data handling errors like meter reading, data transfer and billing process 5% error margin of the total billed metered consumption is assumed.

4.4.1 Losses due to unauthorised consumption

As indicated previously, number of water theft or illegal consumption is insignificant in the case of the city. Based on this the total value of consumption for the year is multiplied with a percentage value of 1 for the study area on the year 2007 E.C is calculated as:

Unauthorised consumption = water consumption x 1% ………………. 4-6

= 402,946.49x 1%

= 4,029.46 m^3/year

4.4.2 Losses due to data errors

As per the study from the utility, total combined error margin of customer meter inaccuracy, meter reading errors, data transfer and billing errors for correspond to 5% of the total billed metered consumption (AAWSA, 2014, Malcolm Farley, et al., 2008). Based on this the value for this loss is calculated as:

Customer meter inaccuracies and data handling errors = water consumption x 5%

= 402,946.49x 5%

= 20,147.32 m^3/year

Therefore, the total apparent loss form the above components value is:

Apparent losses = 4,029.46 + 20,147.32

= 24,176.79 m^3/year

4.5 Apparent Loss Index (ALI) calculation

According to IWA Water Loss Task Force the performance indicator for apparent water loss is similar to ILI in which the indicator uses a base value of 5% of water sales as a reference, and the actual apparent loss volume is calculated against this benchmark

Apparent Loss Index (ALI) = Apparent loss value ÷ 5% of water sales ………………. 4-7

= 24,176.79 / (5% x 378,769.70)

= 1.28

4.6 Water balance

Using the above estimated data the water balance for the years 2007 E.C IWA water balance components are summarized in table 5-4 below.

Table 4-5: Water balance (m^3) for the year 2007 E.C

“IWA Best practice “ Water Balance and Terminology				
System Input Volume 510,291.9 100 %	Authorized Consumption 378,769.70 74.23 %	Billed Authorized Consumption 378,769.70 74.23 %	Billed metered consumption 378,769.70 74.23 %	Revenue Water 378,769.70 74.23 %
			Billed non-metered consumption 0 0.00 %	
		Unbilled Authorized Consumption 0 0.00 %	Unbilled metered consumption 0 0.00 %	Non Revenue Water 131,522.20 25.8%
			Unbilled non- metered consumption 0 0.00 %	
	Water losses 131,522.20 25.8 %	Apparent Losses 24,176.79 4.74 %	Unauthorized consumption 4,029.46 0.79 %	
			Metering inaccuracies 20,147.32 3.95 %	
		Real Losses 107,345.41 21.04 %		

5. Conclusion and Recommendation

5.1 General

Water loss is not just only an engineering problem but also reflects a social situation that requires changes through authorities, community behavior and attitudes towards the water usage. When the water is lost the consequential effect leads the loss of capital, assets, raising the expense of maintenance, in general a loss of revenue. As a result when a large amount of water supplied is lost, meeting consumer demands is difficult especially in areas where water shortage level is high.

To alleviate NRW form the initial stage, quantifying and locating the potential leakage areas plays a significant role for managing and monitoring of distribution networks as well as for the reduction target of NRW level under the authorities.

5.2 Conclusion

Recent applications in computing software's plays a big role for design, simulation and for other various purposes of the water distribution network and schemes specially in building or developing a model for different scenarios. The use of Water GEEMS and Arc GIS has a greater acceptance interims of simplified model building with geospatial modules and tools like hydraulic and water quality modeling, fire flow analysis, for the assessment of leakage, pipe burst and other related water loss tasks and operational optimization and scenario management due to their user interference and integration capability with other related software's.

Based on these, the model used in this study is comprised of the city network maps, updated water supply distribution network systems, 24 hour inflow data and annual aggregated bill consumption for the selected study area of woreda-07 at Bole Sub city. Using these data in collaboration with the parameters required by the modeling software and the developed methodology, development of a model for estimation of NRW with its components according to the objective is made.

Appling the model on the selected study area the following output and estimated results are found:

- ✓ Annual NRW volume form the water balance 131,522.20 m^3 with a percentage 25.8% form the total water input.

- ✓ Annual water consumption or delivered for the customers 402,946.49 m^3 and apparent loss of 24,176.79 at a rate of 4.74 %.
- ✓ Volume of real loss 107,345.41 m^3/year
- ✓ Daily pipe leakage rate of 162.66 m^3
- ✓ Nodal and pipe leakage estimation at each individual element and through 24-hours as shown in the appendices C and D.
- ✓ Using the results a performance indicator is established for real loss as 1.74 and for apparent loss as 1.28.

Finally for a more representation of the network and for conducting further analysis regarding the network behavior and water loss related schemes a suitable environment is created in the Arc GIS as displayed in the figure 4.4; which can be used as an aid for the utility around the study area and can be used for identifying susceptible pipe leakage analysis, level of leakage demonstration, silt accumulation analysis, linking of reported or detected leak reports, etc… Also, by applying house reference number and other required elements water billing database and other records can be collaborated for best management practices.

5.3 Recommendation

Successful NRW reduction is not about solving an isolated technical problem, instead it is tied to overall asset management, operations, customer support, financial allocations and devotion of the government. Also, in another perspective poor construction, quality of material and ageing of the system are the main causes of NRW. Therefore, with strong control mechanism it is necessary to upgrade the system with proper construction technology and material quality, otherwise it would be easy for unscrupulous manufacturers and contractors to use inferior materials to be installed.

Thus to achieve the maximum range of unavoidable water loss, attention from the higher authorities and good management practices at the utility level is required. Furthermore, for quantifying different types of water losses and for other related scenarios the following facts shall be applied in water utilities.

5.3.1 Data handling system

Documentation of data's with simple and reliable method is another way of creating a well-organized management and a key for conducting various tasks at a time, otherwise it hinders lot of activities through time, cost and quality. This is due to in different utilities finding the important data for specifics locations would not be easy, even though various types of studies is already done. Therefore, every piece evident shall be recorded and documented for setting out different target plans and performance comparison.

5.3.2 Flow measurement

To evaluate the performance and service of water supply in a distribution network in general and to quantify amount of water losses in particular, a successive measurement of inflow and outflow from larger elements to the least ones shall be carried out. This is used to easily identify the probable locations of leakage and other related aspects are taking place.

5.3.3 Zoning and establishing DMAs

Active NRW management is only possible using zones, dividing the open networks in to smaller and more manageable areas called district metered areas (DMAs) (Malcolm Farley, et al., 2008). Establishment of DMAs has a great importance and improves:

- Capacity of pressure management
- detection of potential leak areas and maintenance service
- safeguards water quality and customer services
- minimizes complains due to intermittent supply

Above all establishment of DMAs is the main operational tool for the utility managers for monitoring NRW components through installation of bulk meters and data logging devices for measuring different flow parameters.

5.3.4 Upgrading of meter reading database

Water meter readings are the main section for several purposes especially for gathering information regarding water consumption and finding out apparent loss errors. Most of the time meter readings are handled with simple data base formats like spread sheets in the utilities, however, this kind of data base does not compromise or assist other users of the data like managers and staffs. Also, it is difficult to identify locations of the customers or connection points unless meter readers are fully participated such that, considering other users in mind, linking and use of software that are specifically designed for this purpose has a great importance for the utility plus it gives the potential and functionality in determining of metering and other associated errors.

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APPENDICES A: - Reference location of junctions

Label	X (m)	Y (m)	Elevation (m)	Label	X (m)	Y (m)	Elevation (m)
J-1	479,841.72	996,839.60	2,381.66	J-38	480,221.64	995,681.83	2,366.75
J-2	479,958.82	996,765.11	2,376.57	J-39	479,889.23	995,945.96	2,357.02
J-3	480,128.59	996,737.48	2,375.52	J-40	479,736.04	995,669.27	2,349.50
J-4	480,111.34	996,536.79	2,370.40	J-41	479,705.82	995,575.72	2,347.81
J-5	480,275.05	996,684.51	2,377.46	J-42	479,848.41	995,545.70	2,351.99
J-6	480,283.45	996,660.27	2,377.20	J-43	480,170.11	995,456.16	2,361.90
J-7	480,293.34	996,657.95	2,377.15	J-44	480,265.10	995,658.10	2,366.91
J-8	480,308.53	996,513.52	2,375.70	J-45	480,477.69	995,551.27	2,364.23
J-9	480,297.93	996,626.63	2,376.84	J-46	480,748.93	995,431.31	2,348.94
J-10	480,337.41	996,645.19	2,376.91	J-47	480,873.07	995,368.33	2,342.78
J-11	480,364.27	996,454.31	2,375.00	J-48	481,079.62	995,292.64	2,327.02
J-12	480,515.80	996,340.69	2,373.79	J-49	480,453.03	995,209.46	2,355.96
J-13	480,550.84	996,384.46	2,373.30	J-50	480,274.03	994,920.92	2,349.28
J-14	480,590.33	996,433.89	2,372.31	J-51	480,085.81	995,096.38	2,353.53
J-15	480,711.57	996,551.67	2,365.10	J-52	479,908.25	994,924.33	2,346.39
J-16	480,504.89	996,333.10	2,373.97	J-53	480,441.53	994,386.23	2,332.73
J-17	480,464.00	996,282.37	2,374.55				
J-18	480,492.34	996,276.23	2,373.92				
J-19	480,485.56	996,265.72	2,374.02				
J-20	480,955.81	996,384.20	2,359.54				
J-21	480,980.44	996,198.70	2,349.53				
J-22	480,993.36	996,052.13	2,343.52				
J-23	481,143.68	996,117.74	2,350.68				
J-24	481,145.50	996,088.30	2,348.57				
J-25	480,618.64	996,134.31	2,370.79				
J-26	480,824.87	995,860.26	2,355.61				
J-27	480,860.48	995,751.57	2,355.00				
J-28	480,782.20	995,721.37	2,359.77				
J-29	480,755.97	995,648.35	2,358.62				
J-30	480,755.82	995,488.11	2,350.55				
J-31	480,958.63	995,667.97	2,345.06				
J-32	481,070.50	995,462.75	2,337.90				
J-33	481,105.93	995,478.98	2,332.91				
J-34	480,227.52	995,766.35	2,367.83				
J-35	480,202.05	995,707.69	2,366.46				
J-36	480,447.36	995,646.40	2,366.74				
J-37	480,426.23	995,591.13	2,365.65				

APPENDICES B: - Pressure (bars) values of volumetric consumption and volumetric consumption with leakage at minimum flow hour.

Label	Volumetric	Volumetric + Leakage
J-1	3.189	3.189
J-2	3.683	3.676
J-3	3.767	3.721
J-4	4.258	4.197
J-5	3.563	3.487
J-6	3.588	3.511
J-7	3.593	3.516
J-8	3.728	3.632
J-9	3.624	3.547
J-10	3.616	3.539
J-11	3.803	3.726
J-12	3.922	3.844
J-13	3.969	3.892
J-14	4.066	3.988
J-15	4.762	4.663
J-16	3.882	3.745
J-17	3.822	3.677
J-18	3.882	3.733
J-19	3.873	3.723
J-20	5.23	5.071
J-21	6.191	6.02
J-22	6.778	6.605
J-23	6.081	5.91
J-24	6.287	6.116
J-25	4.178	3.999
J-26	5.658	5.467
J-27	5.707	5.492
J-28	5.238	5.021
J-29	5.349	5.131
J-30	6.139	5.919
J-31	6.678	6.454
J-32	7.378	7.152
J-33	7.866	7.64
J-34	4.459	4.243
J-35	4.591	4.365
J-36	4.567	4.368
J-37	4.674	4.474
J-38	4.561	4.328
J-39	5.513	5.278
J-40	6.248	6.009
J-41	6.413	6.174
J-42	6.004	5.764
J-43	5.034	4.794
J-44	4.544	4.307
J-45	4.801	4.546
J-46	6.298	6.077
J-47	6.899	6.676
J-48	8.441	8.215
J-49	5.579	5.228
J-50	6.208	5.78
J-51	5.789	5.353
J-52	6.486	6.041
J-53	7.821	7.372

APPENDICES C: - Analysis of leakage at the junctions

NK : is the number of pipes connected to node i.
Pi : pressure at the i th node
Lij : pipe length connected to nodes ij
N : pressure exponent determined by FAVAD concept
C : coefficient
Qli : the nodal leakage flow

Node (i)	Pressure (Pi)	pipe number	Length of each pipe /km	Demand (m3/hr)	Total length of connected pipe (Lij)	No. of pipe connected to *i* (NK)	Pressure exponent (N)	$\frac{Lij}{2} \times P_i^N$	$\sum_{i=1}^{NK} \frac{Lij}{2} \times P_i^N$	$\mathbf{Q_{L,i} = \sum_{j=1}^{NK} \frac{Lij}{2} \times CP_i^N}$	Updated demand ($Q_{L,i}$)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**

Time – 2:00 AM - 3:00 AM (MNF time) for C =0.24392159

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
J-1	3.189	P- 1	0.987	0	1.164	2	1	1.574		0.453	0.000
	3.189	P- 2	0.177				1	0.282	1.856		
J-2	3.683	P- 2	0.177	0	0.349	2	1	0.326		0.157	0.000
	3.683	P- 3	0.172				1	0.317	0.643		
J-3	3.767	P- 3	0.172	0.2941	0.533	3	1	0.324		0.245	0.551
	3.767	P- 4	0.203				1	0.382			
	3.767	P- 5	0.158				1	0.298	1.004		
J-4	4.258	P- 4	0.203	0.8687	0.402	2	1	0.432		0.209	1.089
	4.258	P- 12	0.199				1	0.424	0.856		
J-5	3.563	P- 5	0.158	0.1521	0.734	3	1	0.281		0.319	0.483
	3.563	P- 6	0.028				1	0.050			
	3.563	P- 15	0.548				1	0.976	1.308		
J-6	3.588	P- 6	0.028	0.1183	0.187	3	1	0.050		0.082	0.212
	3.588	P- 7	0.01				1	0.018			
	3.588	P- 8	0.149				1	0.267	0.335		
J-7	3.593	P- 7	0.01	0.0304	0.09	3	1	0.018		0.039	0.082
	3.593	P- 9	0.032				1	0.057			
	3.593	P- 10	0.048				1	0.086	0.162		
J-8	3.728	P- 8	0.149	0.4022	0.62	3	1	0.278		0.282	0.696
	3.728	P- 12	0.199				1	0.371			
	3.728	P- 17	0.272				1	0.507	1.156		
J-9	3.624	P- 9	0.032	0.2366	0.225	2	1	0.058		0.099	0.348

1	2	3	4	5	6	7	8	9	10	11	12
	3.624	P- 11	0.193				1	0.350	0.408		
J-10	3.616	P- 10	0.048	0.2535	0.378	2	1	0.087		0.167	0.432
	3.616	P- 14	0.33				1	0.597	0.683		
J-11	3.803	P- 11	0.193	0.6051	0.634	3	1	0.367		0.294	0.911
	3.803	P- 13	0.252				1	0.479			
	3.803	P- 16	0.189				1	0.359	1.206		
J-12	3.922	P- 16	0.189	0.098	0.245	2	1	0.371		0.117	0.227
	3.922	P- 19	0.056				1	0.110	0.480		
J-13	3.969	P- 13	0.252	0.2163	0.371	3	1	0.500		0.180	0.408
	3.969	P- 18	0.063				1	0.125			
	3.969	P- 19	0.056				1	0.111	0.736		
J-14	4.066	P- 14	0.33	0.5746	0.393	2	1	0.671		0.195	0.781
	4.066	P- 18	0.063				1	0.128	0.799		
J-15	4.762	P-15	0.548	0.8924	0.848	2	1	1.305		0.492	1.397
	4.762	P- 24	0.3				1	0.714	2.019		
J-16	3.882	P- 17	0.272	0.2265	0.337	2	1	0.528		0.160	0.398
	3.882	P- 20	0.065				1	0.126	0.654		
J-17	3.822	P- 20	0.065	0.1859	0.092	2	1	0.124		0.043	0.241
	3.822	P- 21	0.027				1	0.052	0.176		
J-18	3.882	P- 22	0.013	0.1521	0.568	3	1	0.025		0.269	0.433
	3.882	P- 23	0.353				1	0.685			
	3.882	P- 30	0.202				1	0.392	1.102		
J-19	3.873	P- 21	0.027	0.1623	0.04	2	1	0.052		0.019	0.193
	3.873	P- 22	0.013				1	0.025	0.077		
J-20	5.23	P- 24	0.3	1.1831	0.839	3	1	0.785		0.535	1.730
	5.23	P- 25	0.329				1	0.860			
	5.23	P- 26	0.21				1	0.549	2.194		
J-21	6.191	P- 26	0.21	0.9803	0.364	2	1	0.650		0.275	1.267
	6.191	P- 27	0.154				1	0.477	1.127		
J-22	6.778	P- 27	0.154	1.3183	0.326	2	1	0.522		0.269	1.600
	6.778	P- 28	0.172				1	0.583	1.105		
J-23	6.081	P- 25	0.329	0.3177	0.359	2	1	1.000		0.266	0.596
	6.081	P- 29	0.03				1	0.091	1.092		
J-24	6.287	P- 28	0.172	0.3887	0.202	2	1	0.541		0.155	0.556
	6.287	P- 29	0.03				1	0.094	0.635		
J-25	4.178	P- 30	0.202	0.5882	1.116	3	1	0.422		0.569	1.169
	4.178	P- 32	0.522				1	1.090			
	4.178	P- 33	0.392				1	0.819	2.331		
J-26	5.658	P- 33	0.392	0.6422	0.51	2	1	1.109		0.352	1.006
	5.658	P- 34	0.118				1	0.334	1.443		
J-27	5.707	P- 34	0.118	0.4259	0.333	3	1	0.337		0.232	0.670
	5.707	P- 35	0.129				1	0.368			
	5.707	P- 50	0.086				1	0.245	0.950		
J-28	5.238	P- 50	0.086	0.3549	0.166	2	1	0.225		0.106	0.473
	5.238	P- 51	0.08				1	0.210	0.435		
J-29	5.349	P- 51	0.08	0.5003	0.24	2	1	0.214		0.157	0.669
	5.349	P- 52	0.16				1	0.428	0.642		
J-30	6.139	P- 52	0.16	0.4327	0.217	2	1	0.491		0.162	0.607

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	6.139	P- 53	0.057				1	0.175	0.666		
J-31	6.678	P- 35	0.129	0.2028	0.672	3	1	0.431		0.547	0.762
	6.678	P- 36	0.249				1	0.831			
	6.678	P- 57	0.294				1	0.982	2.244		
J-32	7.378	P- 57	0.294	0.2772	0.333	2	1	1.085		0.300	0.589
	7.378	P- 58	0.039				1	0.144	1.228		
J-33	7.866	P- 36	0.249	0.2299	0.288	2	1	0.979		0.276	0.518
	7.866	P- 58	0.039				1	0.153	1.133		
J-34	4.459	P- 31	0.565	0.4293	0.879	3	1	1.260		0.478	0.919
	4.459	P- 37	0.25				1	0.557			
	4.459	P- 38	0.064				1	0.143	1.960		
J-35	4.591	P- 38	0.064	0.1014	0.108	2	1	0.147		0.060	0.174
	4.591	P- 39	0.044				1	0.101	0.248		
J-36	4.567	P- 32	0.522	0.6084	0.831	3	1	1.192		0.463	1.083
	4.567	P- 37	0.25				1	0.571			
	4.567	P- 48	0.059				1	0.135	1.898		
J-37	4.674	P- 48	0.059	0.0676	0.42	1	1	0.138		0.239	0.319
	4.674	P- 49	0.361				1	0.844	0.982		
J-38	4.561	P- 39	0.044	0.0507	0.52	3	1	0.100		0.289	0.352
	4.561	P- 40	0.05				1	0.114			
	4.561	P- 41	0.426				1	0.971	1.186		
J-39	5.513	P- 41	0.426	0.1453	0.77	2	1	1.174		0.518	0.675
	5.513	P- 42	0.344				1	0.948	2.123		
J-40	6.248	P- 42	0.344	0.0575	0.443	2	1	1.075		0.338	0.407
	6.248	P- 43	0.099				1	0.309	1.384		
J-41	6.413	P- 43	0.099	0.098	0.245	2	1	0.317		0.192	0.302
	6.413	P- 44	0.146				1	0.468	0.786		
J-42	6.004	P- 44	0.146	0.213	0.484	2	1	0.438		0.354	0.579
	6.004	P- 45	0.338				1	1.015	1.453		
J-43	5.034	P- 45	0.338	0.1555	0.562	2	1	0.851		0.345	0.512
	5.034	P- 46	0.224				1	0.564	1.415		
J-44	4.544	P- 40	0.05	0.1487	0.512	3	1	0.114		0.284	0.444
	4.544	P- 46	0.224				1	0.509			
	4.544	P- 47	0.238				1	0.541	1.163		
J-45	4.801	P- 47	0.238	0.2028	0.595	2	1	0.571		0.348	0.563
	4.801	P- 59	0.357				1	0.857	1.428		
J-46	6.298	P- 49	0.361	0.3887	0.557	3	1	1.137		0.428	0.828
	6.298	P- 53	0.057				1	0.179			
	6.298	P- 54	0.139				1	0.438	1.754		
J-47	6.899	P- 54	0.139	0.5577	0.386	2	1	0.479		0.325	0.894
	6.899	P- 55	0.247				1	0.852	1.332		
J-48	8.441	P- 55	0.247	0.3887	0.452	2	1	1.042		0.465	0.866
	8.441	P- 56	0.205				1	0.865	1.908		
J-49	5.579	P- 59	0.357	0.578	0.726	2	1	0.996		0.494	1.084
	5.579	P- 60	0.369				1	1.029	2.025		
J-50	6.208	P- 60	0.369	0.9803	1.393	3	1	1.145		1.055	2.047
	6.208	P- 61	0.257				1	0.798			

1	2	3	4	5	6	7	8	9	10	11	12
	6.208	P- 64	0.767				1	2.381	4.324		
J-51	5.789	P- 61	0.257	0.507	0.504	2	1	0.744		0.356	0.875
	5.789	P- 62	0.247				1	0.715	1.459		
J-52	6.486	P- 62	0.247	0.5746	1.005	2	1	0.801		0.795	1.382
	6.486	P- 63	0.758				1	2.458	3.259		
J-53	7.821	P- 63	0.758	1.1324	1.525	2	1	2.964		1.455	2.599
	7.821	P- 64	0.767				1	2.999	5.964		

- Using the same analysis but changing only the parameters of pressure and demand output form the hydraulic model, for each time steps with respect to the estimated coefficients as listed below the rest output results of the leakage from the model are summarized.

Time – 6:00 PM - 7:00 PM C = 0.134356255
Time – 7:00 PM - 8:00 PM C = 0.184379057
Time – 8:00 PM - 9:00 PM C =0.176759794
Time – 9:00 PM - 10:00 PM C = 0.188969689
Time – 10:00 PM - 11:00 PM C =0.186370493
Time – 11:00 PM - 12:00 AM C =0.188969689
Time – 12:00 AM - 1:00 AM C = 0.214865544
Time – 1:00 AM - 2:00 AM C =0.250544135
Time – 2:00 AM - 3:00 AM (MNF time) C =0.24392159
Time – 3:00 AM - 4:00 AM C =0.249402811
Time – 4:00 AM - 5:00 AM C = 0.246370188
Time – 5:00 AM - 6:00 AM C = 0.250544135
Time – 6:00 AM - 7:00 AM C = 0.231683506
Time – 7:00 AM - 8:00 AM C = 0.215219653
Time – 8:00 AM - 9:00 AM C = 0.173299554
Time – 9:00 AM - 10:00 AM C = 0.154053527
Time – 10:00 AM - 11:00 AM C = 0.130794833
Time – 11:00 AM - 12:00 AM C = 0.173299554
Time – 12:00 AM - 1:00 PM C = 0.141111951
Time – 1:00 PM - 2:00 PM C = 0.136071387
Time – 2:00 PM - 3:00 PM C = 0.133836547
Time – 3:00 PM - 4:00 PM C = 0.134629458
Time – 4:00 PM - 5:00 PM C = 0.130794833
Time – 5:00 PM - 6:00 PM C = 0.13607138

Nodal Pressure & Leakage output

	6:00 PM - 7:00 PM		7:00 PM - 8:00 PM		8:00 PM - 9:00 PM		9:00 PM - 10:00 PM		10:00 PM - 11:00 PM		11:00 PM - 12:00 AM		12:00 AM - 1:00 AM		1:00 AM - 2:00 AM		3:00 AM - 4:00 AM		4:00 AM - 5:00 AM	
Label	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)	Pressure (bars)	Nodal Leakage (m^3/h)
J-1	3.188	0.249	3.188	0.342	3.189	0.328	3.189	0.351	3.189	0.346	3.189	0.351	3.189	0.399	3.189	0.465	3.189	0.463	3.189	0.457
J-2	3.663	0.249	3.667	0.342	3.676	0.328	3.676	0.351	3.679	0.346	3.676	0.351	3.681	0.399	3.677	0.465	3.678	0.463	3.681	0.457
J-3	3.643	0.130	3.668	0.180	3.721	0.175	3.724	0.188	3.742	0.186	3.724	0.188	3.758	0.215	3.731	0.249	3.737	0.248	3.754	0.246
J-4	4.080	0.110	4.115	0.153	4.192	0.149	4.197	0.159	4.223	0.158	4.197	0.159	4.245	0.183	4.207	0.212	4.216	0.211	4.239	0.210
J-5	3.361	0.166	3.401	0.230	3.488	0.226	3.493	0.242	3.523	0.241	3.493	0.242	3.548	0.280	3.505	0.322	3.515	0.322	3.541	0.320
J-6	3.383	0.042	3.424	0.059	3.512	0.058	3.517	0.062	3.547	0.062	3.517	0.062	3.573	0.072	3.529	0.083	3.539	0.083	3.566	0.082
J-7	3.387	0.020	3.428	0.028	3.517	0.028	3.522	0.030	3.552	0.030	3.522	0.030	3.578	0.035	3.534	0.040	3.544	0.040	3.571	0.040
J-8	3.482	0.145	3.531	0.202	3.637	0.199	3.643	0.213	3.679	0.213	3.643	0.213	3.710	0.247	3.657	0.284	3.669	0.284	3.701	0.283
J-9	3.418	0.052	3.459	0.072	3.548	0.071	3.553	0.076	3.583	0.075	3.553	0.076	3.609	0.087	3.565	0.100	3.575	0.100	3.602	0.100
J-10	3.410	0.087	3.451	0.120	3.540	0.118	3.545	0.127	3.575	0.126	3.545	0.127	3.601	0.146	3.557	0.168	3.567	0.168	3.594	0.167
J-11	3.597	0.153	3.639	0.213	3.728	0.209	3.732	0.224	3.762	0.222	3.732	0.224	3.789	0.258	3.744	0.297	3.754	0.297	3.781	0.295
J-12	3.714	0.061	3.755	0.085	3.845	0.083	3.850	0.089	3.880	0.089	3.850	0.089	3.907	0.103	3.862	0.119	3.872	0.118	3.899	0.118
J-13	3.761	0.094	3.803	0.130	3.893	0.128	3.897	0.137	3.928	0.136	3.897	0.137	3.954	0.158	3.910	0.182	3.920	0.181	3.947	0.180
J-14	3.858	0.102	3.899	0.141	3.989	0.139	3.994	0.148	4.024	0.147	3.994	0.148	4.051	0.171	4.006	0.197	4.016	0.197	4.043	0.196
J-15	4.495	0.080	4.549	0.112	4.664	0.112	4.670	0.120	4.709	0.120	4.670	0.120	4.743	0.140	4.686	0.160	4.698	0.160	4.733	0.160
J-16	3.552	0.080	3.618	0.112	3.760	0.112	3.768	0.120	3.816	0.120	3.768	0.120	3.858	0.140	3.787	0.160	3.803	0.160	3.846	0.160
J-17	3.474	0.021	3.544	0.030	3.694	0.030	3.702	0.032	3.753	0.032	3.702	0.032	3.797	0.038	3.723	0.043	3.740	0.043	3.785	0.043
J-18	3.527	0.135	3.597	0.188	3.751	0.188	3.759	0.202	3.811	0.202	3.759	0.202	3.857	0.235	3.780	0.269	3.798	0.269	3.844	0.269
J-19	3.517	0.009	3.588	0.013	3.742	0.013	3.750	0.014	3.802	0.014	3.750	0.014	3.847	0.017	3.771	0.019	3.788	0.019	3.834	0.019
J-20	4.539	0.256	4.677	0.362	4.975	0.369	4.991	0.396	5.092	0.398	4.991	0.396	5.180	0.467	5.032	0.529	5.065	0.530	5.155	0.533
J-21	5.395	0.132	5.554	0.186	5.898	0.190	5.916	0.203	6.032	0.205	5.916	0.203	6.134	0.240	5.963	0.272	6.002	0.272	6.105	0.274
J-22	5.976	0.131	6.136	0.184	6.482	0.187	6.501	0.200	6.618	0.201	6.501	0.200	6.720	0.235	6.548	0.267	6.587	0.268	6.691	0.269
J-23	5.302	0.128	5.457	0.181	5.794	0.184	5.812	0.197	5.926	0.198	5.812	0.197	6.025	0.232	5.858	0.263	5.896	0.264	5.997	0.265
J-24	5.503	0.075	5.659	0.105	5.998	0.107	6.016	0.115	6.131	0.115	6.016	0.115	6.231	0.135	6.063	0.153	6.101	0.154	6.203	0.154
J-25	3.759	0.282	3.842	0.395	4.023	0.397	4.033	0.425	4.094	0.426	4.033	0.425	4.148	0.497	4.058	0.567	4.078	0.568	4.133	0.568
J-26	5.207	0.178	5.297	0.249	5.492	0.248	5.502	0.265	5.568	0.265	5.502	0.265	5.625	0.308	5.529	0.353	5.550	0.353	5.609	0.352
J-27	5.198	0.116	5.300	0.163	5.519	0.162	5.531	0.174	5.605	0.174	5.531	0.174	5.670	0.203	5.561	0.232	5.586	0.232	5.652	0.232
J-28	4.718	0.053	4.821	0.074	5.046	0.074	5.058	0.079	5.134	0.079	5.058	0.079	5.200	0.093	5.089	0.106	5.114	0.106	5.182	0.106
J-29	4.825	0.078	4.929	0.109	5.156	0.109	5.168	0.117	5.245	0.117	5.168	0.117	5.311	0.137	5.199	0.156	5.225	0.156	5.293	0.156
J-30	5.614	0.082	5.719	0.114	5.946	0.114	5.958	0.122	6.035	0.122	5.958	0.122	6.101	0.142	5.989	0.163	6.014	0.163	6.083	0.163
J-31	6.156	0.278	6.260	0.388	6.485	0.385	6.497	0.413	6.574	0.412	6.497	0.413	6.640	0.479	6.528	0.550	6.554	0.549	6.621	0.548
J-32	6.851	0.153	6.956	0.214	7.184	0.211	7.196	0.226	7.273	0.226	7.196	0.226	7.340	0.263	7.227	0.301	7.252	0.301	7.321	0.300
J-33	7.340	0.142	7.444	0.198	7.672	0.195	7.684	0.209	7.761	0.208	7.684	0.209	7.828	0.242	7.715	0.278	7.741	0.278	7.809	0.277

	6:00 PM - 7:00 PM		**7:00 PM - 8:00 PM**		**8:00 PM - 9:00 PM**		**9:00 PM - 10:00 PM**		**10:00 PM - 11:00 PM**		**11:00 PM - 12:00 AM**		**12:00 AM - 1:00 AM**		**1:00 AM - 2:00 AM**		**3:00 AM - 4:00 AM**		**4:00 AM - 5:00 AM**	
Label	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)
J-34	3.997	0.236	4.089	0.331	4.289	0.333	4.300	0.357	4.367	0.358	4.300	0.357	4.426	0.418	4.327	0.476	4.349	0.477	4.410	0.478
J-35	4.115	0.030	4.210	0.042	4.416	0.042	4.427	0.045	4.496	0.045	4.427	0.045	4.557	0.053	4.455	0.060	4.478	0.060	4.540	0.060
J-36	4.114	0.230	4.205	0.322	4.401	0.323	4.411	0.346	4.477	0.347	4.411	0.346	4.535	0.405	4.438	0.462	4.460	0.462	4.519	0.463
J-37	4.219	0.119	4.310	0.167	4.506	0.167	4.517	0.179	4.583	0.179	4.517	0.179	4.641	0.209	4.544	0.239	4.566	0.239	4.625	0.239
J-38	4.076	0.142	4.173	0.200	4.383	0.201	4.394	0.216	4.464	0.216	4.394	0.216	4.526	0.253	4.422	0.288	4.446	0.288	4.509	0.289
J-39	5.026	0.260	5.123	0.364	5.334	0.363	5.345	0.389	5.416	0.389	5.345	0.389	5.478	0.453	5.374	0.518	5.397	0.518	5.461	0.518
J-40	5.758	0.171	5.855	0.239	6.067	0.238	6.078	0.254	6.150	0.254	6.078	0.254	6.212	0.296	6.108	0.339	6.131	0.339	6.195	0.338
J-41	5.922	0.097	6.020	0.136	6.232	0.135	6.244	0.145	6.316	0.144	6.244	0.145	6.378	0.168	6.273	0.193	6.297	0.192	6.361	0.192
J-42	5.512	0.179	5.610	0.250	5.823	0.249	5.834	0.267	5.906	0.266	5.834	0.267	5.968	0.310	5.863	0.355	5.887	0.355	5.951	0.355
J-43	4.542	0.171	4.640	0.240	4.853	0.241	4.864	0.258	4.936	0.258	4.864	0.258	4.999	0.302	4.893	0.344	4.917	0.345	4.981	0.345
J-44	4.052	0.139	4.150	0.196	4.363	0.197	4.374	0.212	4.446	0.212	4.374	0.212	4.508	0.248	4.403	0.282	4.427	0.283	4.491	0.283
J-45	4.277	0.171	4.381	0.240	4.608	0.242	4.620	0.260	4.697	0.260	4.620	0.260	4.763	0.304	4.651	0.347	4.676	0.347	4.745	0.348
J-46	5.777	0.216	5.880	0.302	6.106	0.301	6.118	0.322	6.194	0.321	6.118	0.322	6.260	0.375	6.149	0.429	6.174	0.429	6.242	0.428
J-47	6.372	0.165	6.477	0.230	6.705	0.229	6.717	0.245	6.794	0.244	6.717	0.245	6.861	0.285	6.748	0.326	6.774	0.326	6.843	0.325
J-48	7.913	0.240	8.018	0.334	8.246	0.329	8.259	0.353	8.336	0.351	8.259	0.353	8.403	0.408	8.290	0.469	8.315	0.469	8.384	0.467
J-49	4.876	0.238	5.016	0.336	5.320	0.341	5.336	0.366	5.439	0.368	5.336	0.366	5.528	0.431	5.378	0.489	5.412	0.490	5.503	0.492
J-50	5.370	0.503	5.537	0.711	5.899	0.726	5.918	0.779	6.041	0.784	5.918	0.779	6.147	0.920	5.968	1.041	6.008	1.044	6.118	1.050
J-51	4.936	0.167	5.106	0.237	5.474	0.244	5.494	0.262	5.619	0.264	5.494	0.262	5.727	0.310	5.545	0.350	5.586	0.351	5.697	0.354
J-52	5.620	0.379	5.793	0.537	6.167	0.548	6.187	0.588	6.313	0.591	6.187	0.588	6.423	0.693	6.238	0.785	6.280	0.787	6.393	0.791
J-53	6.949	0.712	7.123	1.001	7.500	1.011	7.520	1.084	7.648	1.087	7.520	1.084	7.758	1.271	7.572	1.447	7.614	1.448	7.727	1.452
SUM		**8.638**		**12.092**		**12.088**		**12.952**		**12.950**		**12.952**		**15.107**		**17.268**		**17.268**		**17.266**

	5:00 AM - 6:00 AM		**6:00 AM - 7:00 AM**		**7:00 AM - 8:00 AM**		**8:00 AM - 9:00 AM**		**9:00 AM - 10:00 AM**		**10:00 AM - 11:00 AM**		**11:00 AM - 12:00 AM**		**12:00 AM - 1:00 PM**		**1:00 PM - 2:00 PM**		**2:00 PM - 3:00 PM**		**3:00 PM - 4:00 PM**		**4:00 PM - 5:00 PM**		**5:00 PM - 6:00 PM**	
Label	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)
J-1	3.189	0.465	3.188	0.430	3.188	0.399	3.188	0.322	3.188	0.286	3.188	0.243	3.188	0.322	3.188	0.262	3.188	0.252	3.189	0.248	3.188	0.250	3.188	0.243	3.188	0.252
J-2	3.677	0.465	3.649	0.430	3.651	0.399	3.665	0.322	3.664	0.286	3.668	0.243	3.665	0.322	3.672	0.262	3.661	0.252	3.674	0.248	3.663	0.250	3.668	0.243	3.661	0.252
J-3	3.731	0.249	3.556	0.220	3.566	0.205	3.653	0.169	3.647	0.150	3.676	0.128	3.653	0.169	3.701	0.139	3.628	0.132	3.709	0.132	3.641	0.131	3.676	0.128	3.628	0.132
J-4	4.207	0.212	3.954	0.184	3.969	0.172	4.094	0.143	4.085	0.126	4.128	0.109	4.094	0.143	4.163	0.118	4.058	0.111	4.175	0.112	4.077	0.110	4.128	0.109	4.058	0.111
J-5	3.505	0.322	3.217	0.274	3.234	0.255	3.376	0.215	3.367	0.190	3.415	0.164	3.376	0.215	3.455	0.179	3.336	0.167	3.468	0.170	3.357	0.166	3.415	0.164	3.336	0.167
J-6	3.529	0.083	3.237	0.070	3.254	0.065	3.399	0.055	3.389	0.049	3.438	0.042	3.399	0.055	3.478	0.046	3.357	0.043	3.492	0.044	3.379	0.043	3.438	0.042	3.357	0.043
J-7	3.534	0.040	3.242	0.034	3.259	0.032	3.403	0.027	3.393	0.024	3.442	0.020	3.403	0.027	3.483	0.022	3.362	0.021	3.497	0.021	3.383	0.020	3.442	0.020	3.362	0.021
J-8	3.657	0.284	3.308	0.238	3.329	0.222	3.502	0.188	3.490	0.167	3.548	0.144	3.502	0.188	3.597	0.157	3.452	0.146	3.613	0.150	3.478	0.145	3.548	0.144	3.452	0.146
J-9	3.565	0.100	3.273	0.085	3.290	0.080	3.434	0.067	3.424	0.059	3.474	0.051	3.434	0.067	3.514	0.056	3.393	0.052	3.528	0.053	3.414	0.052	3.474	0.051	3.393	0.052
J-10	3.557	0.168	3.265	0.143	3.282	0.134	3.427	0.112	3.417	0.099	3.466	0.086	3.427	0.112	3.506	0.094	3.385	0.087	3.520	0.089	3.406	0.087	3.466	0.086	3.385	0.087
J-11	3.744	0.297	3.452	0.254	3.469	0.237	3.614	0.199	3.604	0.176	3.653	0.151	3.614	0.199	3.694	0.165	3.572	0.154	3.707	0.157	3.593	0.153	3.653	0.151	3.572	0.154
J-12	3.862	0.119	3.566	0.101	3.584	0.094	3.730	0.079	3.720	0.070	3.769	0.060	3.730	0.079	3.811	0.066	3.688	0.061	3.824	0.063	3.710	0.061	3.769	0.060	3.688	0.061
J-13	3.910	0.182	3.614	0.155	3.631	0.145	3.778	0.121	3.768	0.108	3.817	0.093	3.778	0.121	3.858	0.101	3.736	0.094	3.872	0.096	3.757	0.094	3.817	0.093	3.736	0.094
J-14	4.006	0.197	3.710	0.169	3.728	0.158	3.874	0.132	3.864	0.117	3.914	0.101	3.874	0.132	3.955	0.110	3.832	0.102	3.969	0.104	3.854	0.102	3.914	0.101	3.832	0.102
J-15	4.686	0.160	4.307	0.130	4.329	0.121	4.516	0.104	4.503	0.092	4.567	0.080	4.516	0.104	4.620	0.088	4.463	0.081	4.637	0.084	4.490	0.080	4.567	0.080	4.463	0.081
J-16	3.787	0.160	3.319	0.130	3.347	0.121	3.578	0.104	3.562	0.092	3.641	0.080	3.578	0.104	3.706	0.088	3.512	0.081	3.728	0.084	3.546	0.080	3.641	0.080	3.512	0.081
J-17	3.723	0.043	3.228	0.034	3.257	0.032	3.501	0.028	3.485	0.025	3.568	0.021	3.501	0.028	3.637	0.024	3.431	0.021	3.660	0.023	3.467	0.021	3.568	0.021	3.431	0.021
J-18	3.780	0.269	3.275	0.215	3.305	0.202	3.554	0.175	3.537	0.155	3.622	0.135	3.554	0.175	3.692	0.148	3.483	0.135	3.716	0.141	3.520	0.135	3.622	0.135	3.483	0.135
J-19	3.771	0.019	3.265	0.015	3.295	0.014	3.545	0.012	3.528	0.011	3.613	0.009	3.545	0.012	3.683	0.010	3.473	0.009	3.706	0.010	3.510	0.009	3.613	0.009	3.473	0.009
J-20	5.032	0.529	4.050	0.394	4.108	0.371	4.593	0.334	4.560	0.295	4.724	0.259	4.593	0.334	4.861	0.288	4.454	0.254	4.907	0.276	4.526	0.256	4.724	0.259	4.454	0.254
J-21	5.963	0.272	4.831	0.204	4.898	0.192	5.458	0.172	5.419	0.152	5.609	0.134	5.458	0.172	5.766	0.148	5.297	0.131	5.819	0.142	5.380	0.132	5.609	0.134	5.297	0.131
J-22	6.548	0.267	5.408	0.204	5.475	0.192	6.039	0.171	6.000	0.151	6.191	0.132	6.039	0.171	6.350	0.146	5.877	0.130	6.403	0.140	5.961	0.131	6.191	0.132	5.877	0.130
J-23	5.858	0.263	4.750	0.198	4.816	0.186	5.363	0.167	5.325	0.147	5.511	0.129	5.363	0.167	5.665	0.143	5.206	0.127	5.717	0.137	5.287	0.128	5.511	0.129	5.206	0.127
J-24	6.063	0.153	4.947	0.116	5.013	0.109	5.564	0.097	5.526	0.086	5.713	0.075	5.564	0.097	5.869	0.084	5.406	0.074	5.920	0.080	5.488	0.075	5.713	0.075	5.406	0.074
J-25	4.058	0.567	3.462	0.448	3.497	0.420	3.791	0.367	3.771	0.324	3.871	0.283	3.791	0.367	3.954	0.311	3.707	0.281	3.982	0.297	3.751	0.282	3.871	0.283	3.707	0.281
J-26	5.529	0.353	4.888	0.289	4.925	0.270	5.242	0.232	5.220	0.205	5.328	0.178	5.242	0.232	5.417	0.195	5.151	0.179	5.447	0.186	5.198	0.178	5.328	0.178	5.151	0.179
J-27	5.561	0.232	4.838	0.187	4.881	0.175	5.238	0.151	5.214	0.134	5.335	0.116	5.238	0.151	5.436	0.128	5.136	0.116	5.469	0.122	5.189	0.116	5.335	0.116	5.136	0.116

	5:00 AM – 6:00 AM		**6:00 AM – 7:00 AM**		**7:00 AM – 8:00 AM**		**8:00 AM – 9:00 AM**		**9:00 AM – 10:00 AM**		**10:00 AM – 11:00 AM**		**11:00 AM – 12:00 AM**		**12:00 AM – 1:00 PM**		**1:00 PM – 2:00 PM**		**2:00 PM – 3:00 PM**		**3:00 PM – 4:00 PM**		**4:00 PM – 5:00 PM**		**5:00 PM – 6:00 PM**	
Label	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)	Pressure (bars)	Nodal Leakage (m³/h)
J-28	5.089	0.106	4.350	0.084	4.393	0.078	4.759	0.068	4.733	0.061	4.857	0.053	4.759	0.068	4.960	0.058	4.654	0.053	4.995	0.055	4.708	0.053	4.857	0.053	4.654	0.053
J-29	5.199	0.156	4.454	0.124	4.498	0.116	4.866	0.101	4.841	0.089	4.966	0.078	4.866	0.101	5.069	0.086	4.760	0.078	5.104	0.082	4.815	0.078	4.966	0.078	4.760	0.078
J-30	5.989	0.163	5.242	0.132	5.287	0.123	5.655	0.106	5.630	0.094	5.755	0.082	5.655	0.106	5.859	0.090	5.550	0.082	5.894	0.086	5.604	0.082	5.755	0.082	5.550	0.082
J-31	6.528	0.550	5.787	0.450	5.831	0.422	6.197	0.361	6.172	0.319	6.296	0.277	6.197	0.361	6.399	0.303	6.092	0.279	6.434	0.289	6.146	0.278	6.296	0.277	6.092	0.279
J-32	7.227	0.301	6.479	0.250	6.523	0.234	6.893	0.199	6.867	0.176	6.993	0.152	6.893	0.199	7.097	0.167	6.787	0.154	7.131	0.159	6.841	0.153	6.993	0.152	6.787	0.154
J-33	7.715	0.278	6.967	0.232	7.011	0.217	7.381	0.184	7.355	0.163	7.481	0.141	7.381	0.184	7.585	0.154	7.275	0.143	7.620	0.147	7.329	0.142	7.481	0.141	7.275	0.143
J-34	4.327	0.476	3.669	0.374	3.707	0.351	4.033	0.307	4.010	0.272	4.121	0.237	4.033	0.307	4.212	0.261	3.940	0.236	4.243	0.250	3.988	0.236	4.121	0.237	3.940	0.236
J-35	4.455	0.060	3.778	0.047	3.818	0.044	4.153	0.039	4.130	0.034	4.243	0.030	4.153	0.039	4.337	0.033	4.057	0.030	4.369	0.032	4.106	0.030	4.243	0.030	4.057	0.030
J-36	4.438	0.462	3.793	0.365	3.831	0.343	4.150	0.299	4.128	0.264	4.236	0.230	4.150	0.299	4.326	0.254	4.059	0.229	4.356	0.242	4.106	0.230	4.236	0.230	4.059	0.229
J-37	4.544	0.239	3.898	0.190	3.936	0.178	4.255	0.155	4.233	0.137	4.341	0.119	4.255	0.155	4.431	0.131	4.163	0.119	4.461	0.125	4.211	0.119	4.341	0.119	4.163	0.119
J-38	4.422	0.288	3.733	0.225	3.774	0.211	4.114	0.185	4.091	0.164	4.207	0.143	4.114	0.185	4.302	0.158	4.017	0.142	4.334	0.151	4.067	0.142	4.207	0.143	4.017	0.142
J-39	5.374	0.518	4.682	0.418	4.723	0.391	5.065	0.338	5.041	0.299	5.157	0.260	5.065	0.338	5.253	0.285	4.967	0.260	5.285	0.272	5.017	0.260	5.157	0.260	4.967	0.260
J-40	6.108	0.339	5.410	0.278	5.451	0.260	5.796	0.222	5.772	0.197	5.889	0.171	5.796	0.222	5.986	0.187	5.697	0.172	6.019	0.178	5.748	0.171	5.889	0.171	5.697	0.172
J-41	6.273	0.193	5.574	0.158	5.616	0.148	5.961	0.127	5.937	0.112	6.054	0.097	5.961	0.127	6.151	0.106	5.862	0.098	6.184	0.101	5.913	0.098	6.054	0.097	5.862	0.098
J-42	5.863	0.355	5.164	0.290	5.205	0.271	5.551	0.233	5.527	0.206	5.644	0.179	5.551	0.233	5.741	0.196	5.451	0.179	5.774	0.187	5.503	0.179	5.644	0.179	5.451	0.179
J-43	4.893	0.344	4.193	0.273	4.235	0.256	4.581	0.223	4.557	0.197	4.674	0.172	4.581	0.223	4.772	0.189	4.481	0.171	4.804	0.181	4.533	0.171	4.674	0.172	4.481	0.171
J-44	4.403	0.282	3.703	0.220	3.745	0.206	4.090	0.181	4.067	0.160	4.184	0.140	4.090	0.181	4.281	0.155	3.991	0.139	4.314	0.148	4.042	0.139	4.184	0.140	3.991	0.139
J-45	4.651	0.347	3.906	0.269	3.950	0.253	4.318	0.223	4.293	0.197	4.418	0.172	4.318	0.223	4.521	0.190	4.212	0.171	4.556	0.181	4.267	0.171	4.418	0.172	4.212	0.171
J-46	6.149	0.429	5.407	0.349	5.451	0.327	5.817	0.281	5.792	0.248	5.917	0.216	5.817	0.281	6.020	0.237	5.712	0.216	6.054	0.226	5.767	0.216	5.917	0.216	5.712	0.216
J-47	6.748	0.326	5.998	0.268	6.043	0.251	6.413	0.214	6.388	0.190	6.514	0.164	6.413	0.214	6.618	0.180	6.307	0.166	6.653	0.172	6.362	0.165	6.514	0.164	6.307	0.166
J-48	8.290	0.469	7.538	0.395	7.583	0.369	7.954	0.312	7.929	0.276	8.055	0.238	7.954	0.312	8.159	0.260	7.848	0.241	8.194	0.248	7.903	0.240	8.055	0.238	7.848	0.241
J-49	5.378	0.489	4.379	0.368	4.438	0.347	4.931	0.310	4.897	0.274	5.065	0.240	4.931	0.310	5.204	0.267	4.790	0.237	5.250	0.255	4.863	0.238	5.065	0.240	4.790	0.237
J-50	5.968	1.041	4.776	0.771	4.847	0.727	5.435	0.656	5.395	0.579	5.595	0.510	5.435	0.656	5.761	0.566	5.267	0.499	5.816	0.542	5.354	0.502	5.595	0.510	5.267	0.499
J-51	5.545	0.350	4.331	0.253	4.403	0.239	5.002	0.218	4.961	0.193	5.165	0.170	5.002	0.218	5.334	0.190	4.831	0.166	5.390	0.182	4.919	0.167	5.165	0.170	4.831	0.166
J-52	6.238	0.785	5.007	0.583	5.080	0.549	5.688	0.495	5.646	0.437	5.853	0.385	5.688	0.495	6.024	0.427	5.514	0.377	6.081	0.409	5.603	0.379	5.853	0.385	5.514	0.377
J-53	7.572	1.447	6.332	1.119	6.405	1.051	7.018	0.927	6.976	0.819	7.184	0.716	7.018	0.927	7.356	0.791	6.842	0.710	7.414	0.757	6.933	0.712	7.184	0.716	6.842	0.710
SUM		**17.268**		**13.830**		**12.965**		**11.230**		**9.934**		**8.637**		**11.230**		**9.499**		**8.639**		**9.067**		**8.639**		**8.637**		**8.639**

APPENDICES D: - Analysis of leakage at the pipes

QL,ij is the leakage of pipe ij.

QL,i and QL, j are the nodal leakage rates

Li and Lj are the total pipe lengths connected to nodes i and j

Pipe Label	Length of pipe (Lij)	QL,i	Junction i	Total length of pipe connected to junction (∑Li)	Nodal Leakage (QL, i)	Junction j	Total length of pipe connected to junction(∑Lj)	Leakage of pipe(QL,ij)
A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**

Time – 2:00 AM - 3:00 AM (MNF time)

A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
P-1	0.987		TR.		0.453	J-1	1.164	0.384
P-2	0.177	0.45	J-1	1.164	0.157	J-2	0.349	0.080
P-3	0.172	0.157	J-2	0.349	0.245	J-3	0.533	0.079
P-4	0.203	0.245	J-3	0.533	0.209	J-4	0.402	0.105
P-5	0.158	0.245	J-3	0.533	0.319	J-5	0.734	0.069
P-6	0.028	0.319	J-5	0.734	0.082	J-6	0.187	0.012
P-7	0.01	0.082	J-6	0.187	0.039	J-7	0.09	0.004
P-8	0.149	0.082	J-6	0.187	0.282	J-8	0.62	0.068
P-9	0.032	0.039	J-7	0.09	0.099	J-9	0.225	0.014
P-10	0.048	0.039	J-7	0.09	0.167	J-10	0.378	0.021
P-11	0.193	0.099	J-9	0.225	0.294	J-11	0.634	0.090
P-12	0.199	0.282	J-8	0.62	0.209	J-4	0.402	0.103
P-13	0.252	0.294	J-11	0.634	0.180	J-13	0.371	0.122
P-14	0.33	0.167	J-10	0.378	0.195	J-14	0.393	0.164
P-15	0.548	0.319	J-5	0.734	0.492	J-15	0.848	0.318
P-16	0.189	0.29	J-11	0.634	0.180	J-12	0.245	0.139
P-17	0.272	0.282	J-8	0.62	0.160	J-16	0.337	0.129
P-18	0.063	0.180	J-13	0.371	0.195	J-14	0.393	0.031
P-19	0.056	0.180	J-12	0.245	0.180	J-13	0.371	0.027
P-20	0.065	0.160	J-16	0.337	0.043	J-17	0.092	0.030

A	B	C	D	E	F	G	H	I
P-21	0.027	0.043	J-17	0.092	0.019	J-19	0.04	0.013
P-22	0.013	0.269	J-18	0.568	0.019	J-19	0.04	0.006
P-23	0.353	0.492	J-15	0.848	0.269	J-18	0.568	0.167
P-24	0.3	0.492	J-15	0.848	0.535	J-20	0.839	0.191
P-25	0.329	0.535	J-20	0.839	0.266	J-23	0.359	0.244
P-26	0.21	0.535	J-20	0.839	0.275	J-21	0.364	0.159
P-27	0.154	0.275	J-21	0.364	0.269	J-22	0.326	0.127
P-28	0.172	0.269	J-22	0.326	0.155	J-24	0.202	0.132
P-29	0.03	0.155	J-24	0.202	0.266	J-23	0.359	0.022
P-30	0.202	0.269	J-18	0.568	0.569	J-25	1.116	0.103
P-31	0.565	0.019	J-19	0.04	0.478	J-34	0.879	0.307
P-32	0.522	0.569	J-25	1.116	0.463	J-36	0.831	0.291
P-33	0.392	0.569	J-25	1.116	0.352	J-26	0.51	0.271
P-34	0.118	0.352	J-26	0.51	0.232	J-27	0.333	0.082
P-35	0.129	0.232	J-27	0.333	0.547	J-31	0.672	0.105
P-36	0.249	0.547	J-31	0.672	0.276	J-33	0.288	0.239
P-37	0.25	0.478	J-34	0.879	0.463	J-36	0.831	0.139
P-38	0.064	0.478	J-34	0.879	0.060	J-35	0.108	0.036
P-39	0.044	0.060	J-35	0.108	0.289	J-38	0.52	0.024
P-40	0.05	0.289	J-38	0.52	0.284	J-44	0.512	0.028
P-41	0.426	0.289	J-38	0.52	0.518	J-39	0.77	0.286
P-42	0.344	0.518	J-39	0.77	0.338	J-40	0.443	0.262
P-43	0.099	0.192	J-41	0.245	0.338	J-40	0.443	0.075
P-44	0.146	0.354	J-42	0.484	0.192	J-41	0.245	0.114
P-45	0.338	0.345	J-43	0.562	0.354	J-42	0.484	0.248
P-46	0.224	0.284	J-44	0.512	0.345	J-43	0.562	0.138
P-47	0.238	0.284	J-44	0.831	0.348	J-45	0.595	0.139
P-48	0.059	0.463	J-36	0.831	0.239	J-37	0.42	0.034

A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
P-49	0.361	0.239	J-37	0.42	0.428	J-46	0.557	0.277
P-50	0.086	0.106	J-28	0.166	0.232	J-27	0.333	0.060
P-51	0.08	0.157	J-29	0.24	0.106	J-28	0.166	0.051
P-52	0.16	0.162	J-30	0.217	0.157	J-29	0.24	0.104
P-53	0.057	0.428	J-46	0.557	0.162	J-30	0.217	0.043
P-54	0.139	0.428	J-46	0.557	0.325	J-47	0.386	0.117
P-55	0.247	0.325	J-47	0.386	0.465	J-48	0.452	0.254
P-56	0.205	0.465	J-48	0.452	0.276	J-33	0.288	0.197
P-57	0.294	0.547	J-31	0.672	0.300	J-32	0.333	0.265
P-58	0.039	0.276	J-33	0.288	0.300	J-32	0.333	0.035
P-59	0.357	0.348	J-45	0.595	0.494	J-49	0.726	0.243
P-60	0.369	0.494	J-49	0.726	1.055	J-50	1.393	0.279
P-61	0.257	0.356	J-51	0.504	1.055	J-50	1.393	0.195
P-62	0.247	0.795	J-52	1.005	0.356	J-51	0.504	0.174
P-63	0.758	1.455	J-53	1.525	0.795	J-52	1.005	0.600
P-64	0.767	1.055	J-50	1.393	1.455	J-53	1.525	0.732

Pipe Leakage rate output (m^3/hr)

Pipe Label	Length of pipe (Lij)	6:00 PM - 7:00 PM	7:00 PM - 8:00 PM	8:00 PM - 9:00 PM	9:00 PM - 10:00 PM	10:00 PM - 11:00 PM	11:00 PM - 12:00 AM	12:00 AM - 1:00 AM	1:00 AM - 2:00 AM	2:00 AM - 3:00 AM	3:00 AM - 4:00 AM	4:00 AM - 5:00 AM	5:00 AM - 6:00 AM	6:00 AM - 7:00 AM	7:00 AM - 8:00 AM	8:00 AM - 9:00 AM	9:00 AM - 10:00 AM	10:00 AM - 11:00 AM	11:00 AM - 12:00 AM	12:00 AM - 1:00 PM	1:00 PM - 2:00 PM	2:00 PM - 3:00 PM	3:00 PM - 4:00 PM	4:00 PM - 5:00 PM	5:00 PM - 6:00 PM
P-1	0.987	0.211	0.290	0.278	0.297	0.293	0.297	0.338	0.394	0.384	0.393	0.388	0.394	0.365	0.339	0.273	0.242	0.206	0.273	0.222	0.214	0.211	0.212	0.206	0.214
P-2	0.177	0.126	0.174	0.166	0.178	0.175	0.178	0.202	0.236	0.080	0.235	0.232	0.236	0.218	0.203	0.163	0.145	0.123	0.163	0.133	0.128	0.126	0.127	0.123	0.128
P-3	0.172	0.042	0.058	0.057	0.061	0.060	0.061	0.069	0.080	0.079	0.080	0.080	0.080	0.071	0.066	0.054	0.048	0.041	0.054	0.045	0.042	0.043	0.042	0.041	0.042
P-4	0.203	0.056	0.077	0.075	0.081	0.080	0.081	0.093	0.107	0.105	0.107	0.106	0.107	0.093	0.087	0.072	0.064	0.055	0.072	0.060	0.056	0.057	0.056	0.055	0.056
P-5	0.158	0.036	0.050	0.049	0.052	0.052	0.052	0.060	0.069	0.069	0.069	0.069	0.069	0.059	0.055	0.046	0.041	0.035	0.046	0.039	0.036	0.037	0.036	0.035	0.036
P-6	0.028	0.006	0.009	0.009	0.009	0.009	0.009	0.011	0.012	0.012	0.012	0.012	0.012	0.010	0.010	0.008	0.007	0.006	0.008	0.007	0.006	0.007	0.006	0.006	0.006
P-7	0.010	0.002	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.002
P-8	0.149	0.035	0.049	0.048	0.051	0.051	0.051	0.059	0.068	0.068	0.068	0.068	0.068	0.057	0.053	0.045	0.040	0.035	0.045	0.038	0.035	0.036	0.035	0.035	0.035
P-9	0.032	0.007	0.010	0.010	0.011	0.011	0.011	0.012	0.014	0.014	0.014	0.014	0.014	0.012	0.011	0.010	0.008	0.007	0.010	0.008	0.007	0.008	0.007	0.007	0.007
P-10	0.048	0.011	0.015	0.015	0.016	0.016	0.016	0.019	0.021	0.021	0.021	0.021	0.021	0.018	0.017	0.014	0.013	0.011	0.014	0.012	0.011	0.011	0.011	0.011	0.011
P-11	0.193	0.047	0.065	0.064	0.068	0.068	0.068	0.079	0.091	0.090	0.090	0.090	0.091	0.077	0.072	0.060	0.054	0.046	0.060	0.050	0.047	0.048	0.047	0.046	0.047
P-12	0.199	0.055	0.075	0.074	0.079	0.078	0.079	0.091	0.105	0.103	0.105	0.104	0.105	0.091	0.085	0.071	0.063	0.054	0.071	0.058	0.055	0.056	0.055	0.054	0.055
P-13	0.252	0.064	0.088	0.087	0.093	0.092	0.093	0.107	0.123	0.122	0.123	0.123	0.123	0.106	0.098	0.082	0.073	0.063	0.082	0.069	0.064	0.065	0.064	0.063	0.064
P-14	0.330	0.086	0.119	0.116	0.125	0.124	0.125	0.144	0.166	0.164	0.165	0.164	0.166	0.142	0.132	0.111	0.098	0.084	0.111	0.092	0.086	0.088	0.086	0.084	0.086
P-15	0.548	0.052	0.073	0.072	0.078	0.077	0.078	0.090	0.103	0.318	0.103	0.103	0.103	0.084	0.078	0.068	0.060	0.052	0.068	0.057	0.052	0.054	0.052	0.052	0.052
P-16	0.189	0.072	0.100	0.098	0.105	0.105	0.105	0.122	0.140	0.139	0.140	0.139	0.140	0.120	0.112	0.094	0.083	0.071	0.094	0.078	0.073	0.074	0.072	0.071	0.073
P-17	0.272	0.065	0.091	0.090	0.097	0.097	0.097	0.113	0.129	0.129	0.129	0.129	0.129	0.105	0.098	0.084	0.075	0.065	0.084	0.071	0.065	0.068	0.065	0.065	0.065
P-18	0.063	0.016	0.023	0.022	0.024	0.024	0.024	0.027	0.032	0.031	0.032	0.031	0.032	0.027	0.025	0.021	0.019	0.016	0.021	0.018	0.016	0.017	0.016	0.016	0.016
P-19	0.056	0.014	0.020	0.019	0.021	0.020	0.021	0.024	0.027	0.027	0.027	0.027	0.027	0.023	0.022	0.018	0.016	0.014	0.018	0.015	0.014	0.015	0.014	0.014	0.014
P-20	0.065	0.015	0.021	0.021	0.023	0.023	0.023	0.027	0.030	0.030	0.030	0.030	0.030	0.024	0.023	0.020	0.017	0.015	0.020	0.017	0.015	0.016	0.015	0.015	0.015
P-21	0.027	0.006	0.009	0.009	0.010	0.010	0.010	0.011	0.013	0.013	0.013	0.013	0.013	0.010	0.010	0.008	0.007	0.006	0.008	0.007	0.006	0.007	0.006	0.006	0.006
P-22	0.013	0.003	0.004	0.004	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.004	0.004	0.003	0.004	0.003	0.003	0.003	0.003	0.003	0.003
P-23	0.353	0.084	0.117	0.117	0.125	0.125	0.125	0.146	0.167	0.167	0.167	0.167	0.167	0.134	0.126	0.109	0.096	0.084	0.109	0.092	0.084	0.088	0.084	0.084	0.084
P-24	0.300	0.091	0.129	0.132	0.141	0.142	0.141	0.167	0.189	0.191	0.189	0.191	0.189	0.141	0.133	0.119	0.105	0.093	0.119	0.103	0.091	0.099	0.091	0.093	0.091
P-25	0.329	0.117	0.166	0.168	0.181	0.182	0.181	0.213	0.241	0.244	0.242	0.243	0.241	0.181	0.171	0.153	0.135	0.119	0.153	0.132	0.117	0.126	0.117	0.119	0.117
P-26	0.210	0.076	0.108	0.109	0.117	0.118	0.117	0.138	0.157	0.159	0.157	0.158	0.157	0.118	0.111	0.099	0.088	0.077	0.099	0.085	0.076	0.082	0.076	0.077	0.076
P-27	0.154	0.062	0.087	0.088	0.095	0.095	0.095	0.111	0.126	0.127	0.126	0.127	0.126	0.096	0.091	0.081	0.071	0.062	0.081	0.069	0.062	0.066	0.062	0.062	0.062
P-28	0.172	0.064	0.090	0.091	0.098	0.098	0.098	0.115	0.131	0.132	0.131	0.131	0.131	0.099	0.093	0.083	0.073	0.064	0.083	0.071	0.063	0.068	0.064	0.064	0.063
P-29	0.030	0.011	0.015	0.015	0.016	0.017	0.016	0.019	0.022	0.022	0.022	0.022	0.022	0.017	0.016	0.014	0.012	0.011	0.014	0.012	0.011	0.011	0.011	0.011	0.011

Pipe Label	Length of pipe (Lij)	6:00 PM - 7:00 PM	7:00 PM - 8:00 PM	8:00 PM - 9:00 PM	9:00 PM - 10:00 PM	10:00 PM - 11:00 PM	11:00 PM - 12:00 AM	12:00 AM - 1:00 AM	1:00 AM - 2:00 AM	2:00 AM - 3:00 AM	3:00 AM - 4:00 AM	4:00 AM - 5:00 AM	5:00 AM - 6:00 AM	6:00 AM - 7:00 AM	7:00 AM - 8:00 AM	8:00 AM - 9:00 AM	9:00 AM - 10:00 AM	10:00 AM - 11:00 AM	11:00 AM - 12:00 AM	12:00 AM - 1:00 PM	1:00 PM - 2:00 PM	2:00 PM - 3:00 PM	3:00 PM - 4:00 PM	4:00 PM - 5:00 PM	5:00 PM - 6:00 PM
P-30	0.202	0.051	0.072	0.072	0.077	0.077	0.077	0.090	0.103	0.103	0.103	0.103	0.103	0.081	0.076	0.066	0.059	0.051	0.066	0.056	0.051	0.054	0.051	0.051	0.051
P-31	0.565	0.152	0.213	0.214	0.230	0.230	0.230	0.269	0.306	0.307	0.306	0.307	0.306	0.240	0.225	0.197	0.175	0.152	0.197	0.168	0.151	0.160	0.152	0.152	0.151
P-32	0.522	0.144	0.202	0.203	0.218	0.218	0.218	0.254	0.290	0.291	0.290	0.291	0.290	0.229	0.215	0.188	0.166	0.145	0.188	0.159	0.144	0.152	0.144	0.145	0.144
P-33	0.392	0.137	0.191	0.190	0.204	0.203	0.204	0.237	0.272	0.271	0.271	0.271	0.272	0.222	0.208	0.178	0.158	0.137	0.178	0.150	0.137	0.143	0.137	0.137	0.137
P-34	0.118	0.041	0.058	0.058	0.062	0.062	0.062	0.072	0.082	0.082	0.082	0.082	0.082	0.066	0.062	0.054	0.047	0.041	0.054	0.045	0.041	0.043	0.041	0.041	0.041
P-35	0.129	0.053	0.074	0.074	0.079	0.079	0.079	0.092	0.105	0.105	0.105	0.105	0.105	0.086	0.081	0.069	0.061	0.053	0.069	0.058	0.053	0.056	0.053	0.053	0.053
P-36	0.249	0.123	0.171	0.169	0.181	0.180	0.181	0.209	0.241	0.239	0.240	0.240	0.241	0.201	0.188	0.159	0.141	0.122	0.159	0.133	0.123	0.127	0.123	0.122	0.123
P-37	0.250	0.069	0.097	0.097	0.104	0.104	0.104	0.122	0.139	0.139	0.139	0.139	0.139	0.110	0.103	0.090	0.079	0.069	0.090	0.076	0.069	0.073	0.069	0.069	0.069
P-38	0.064	0.018	0.025	0.025	0.027	0.027	0.027	0.031	0.036	0.036	0.036	0.036	0.036	0.028	0.026	0.023	0.020	0.018	0.023	0.020	0.018	0.019	0.018	0.018	0.018
P-39	0.044	0.012	0.017	0.017	0.018	0.018	0.018	0.021	0.024	0.024	0.024	0.024	0.024	0.019	0.018	0.016	0.014	0.012	0.016	0.013	0.012	0.013	0.012	0.012	0.012
P-40	0.050	0.014	0.019	0.019	0.021	0.021	0.021	0.024	0.028	0.028	0.028	0.028	0.028	0.021	0.020	0.018	0.016	0.014	0.018	0.015	0.014	0.014	0.014	0.014	0.014
P-41	0.426	0.144	0.201	0.201	0.215	0.215	0.215	0.251	0.287	0.286	0.287	0.287	0.287	0.231	0.217	0.187	0.165	0.144	0.187	0.158	0.144	0.151	0.144	0.144	0.144
P-42	0.344	0.133	0.186	0.184	0.198	0.197	0.198	0.230	0.263	0.262	0.263	0.263	0.263	0.216	0.202	0.173	0.153	0.132	0.173	0.145	0.133	0.139	0.133	0.132	0.133
P-43	0.099	0.038	0.053	0.053	0.057	0.057	0.057	0.066	0.076	0.075	0.076	0.076	0.076	0.062	0.058	0.050	0.044	0.038	0.050	0.042	0.038	0.040	0.038	0.038	0.038
P-44	0.146	0.058	0.081	0.080	0.086	0.086	0.086	0.100	0.115	0.114	0.115	0.114	0.115	0.094	0.088	0.075	0.067	0.058	0.075	0.063	0.058	0.060	0.058	0.058	0.058
P-45	0.338	0.125	0.175	0.174	0.186	0.186	0.186	0.217	0.248	0.248	0.248	0.248	0.248	0.202	0.189	0.163	0.144	0.125	0.163	0.137	0.125	0.131	0.125	0.125	0.125
P-46	0.224	0.068	0.096	0.096	0.103	0.103	0.103	0.120	0.137	0.138	0.137	0.137	0.137	0.109	0.102	0.089	0.079	0.068	0.089	0.075	0.068	0.072	0.068	0.068	0.068
P-47	0.238	0.068	0.096	0.097	0.104	0.104	0.104	0.122	0.139	0.139	0.139	0.139	0.139	0.108	0.101	0.089	0.079	0.069	0.089	0.076	0.068	0.073	0.068	0.069	0.068
P-48	0.059	0.017	0.023	0.023	0.025	0.025	0.025	0.029	0.034	0.034	0.034	0.034	0.034	0.027	0.025	0.022	0.019	0.017	0.022	0.018	0.017	0.018	0.017	0.017	0.017
P-49	0.361	0.140	0.196	0.195	0.209	0.208	0.209	0.243	0.278	0.277	0.278	0.278	0.278	0.226	0.212	0.182	0.161	0.140	0.182	0.153	0.140	0.146	0.140	0.140	0.140
P-50	0.086	0.030	0.042	0.042	0.045	0.045	0.045	0.052	0.060	0.060	0.060	0.060	0.060	0.048	0.045	0.039	0.035	0.030	0.039	0.033	0.030	0.031	0.030	0.030	0.030
P-51	0.080	0.025	0.036	0.036	0.038	0.038	0.038	0.045	0.051	0.051	0.051	0.051	0.051	0.040	0.038	0.033	0.029	0.025	0.033	0.028	0.025	0.027	0.025	0.025	0.025
P-52	0.160	0.052	0.073	0.073	0.078	0.078	0.078	0.091	0.104	0.104	0.104	0.104	0.104	0.083	0.077	0.067	0.060	0.052	0.067	0.057	0.052	0.055	0.052	0.052	0.052
P-53	0.057	0.021	0.030	0.030	0.032	0.032	0.032	0.037	0.043	0.043	0.043	0.043	0.043	0.035	0.032	0.028	0.025	0.021	0.028	0.024	0.022	0.022	0.022	0.021	0.022
P-54	0.139	0.060	0.083	0.082	0.088	0.088	0.088	0.102	0.118	0.117	0.117	0.117	0.118	0.097	0.090	0.077	0.068	0.059	0.077	0.065	0.060	0.062	0.060	0.059	0.060
P-55	0.247	0.131	0.183	0.180	0.193	0.192	0.193	0.223	0.257	0.254	0.256	0.255	0.257	0.216	0.202	0.170	0.151	0.130	0.170	0.142	0.132	0.135	0.131	0.130	0.132
P-56	0.205	0.101	0.141	0.139	0.149	0.148	0.149	0.172	0.198	0.197	0.198	0.197	0.198	0.165	0.155	0.131	0.116	0.100	0.131	0.110	0.101	0.105	0.101	0.100	0.101
P-57	0.294	0.135	0.189	0.187	0.200	0.199	0.200	0.232	0.266	0.265	0.266	0.265	0.266	0.221	0.206	0.176	0.156	0.134	0.176	0.147	0.136	0.140	0.135	0.134	0.136

Pipe Label	**Length of pipe (Lij)**	**6:00 PM - 7:00 PM**	**7:00 PM - 8:00 PM**	**8:00 PM - 9:00 PM**	**9:00 PM - 10:00 PM**	**10:00 PM - 11:00 PM**	**11:00 PM - 12:00 AM**	**12:00 AM - 1:00 AM**	**1:00 AM - 2:00 AM**	**2:00 AM - 3:00 AM**	**3:00 AM - 4:00 AM**	**4:00 AM - 5:00 AM**	**5:00 AM - 6:00 AM**	**6:00 AM - 7:00 AM**	**7:00 AM - 8:00 AM**	**8:00 AM - 9:00 AM**	**9:00 AM - 10:00 AM**	**10:00 AM - 11:00 AM**	**11:00 AM - 12:00 AM**	**12:00 AM - 1:00 PM**	**1:00 PM - 2:00 PM**	**2:00 PM - 3:00 PM**	**3:00 PM - 4:00 PM**	**4:00 PM - 5:00 PM**	**5:00 PM - 6:00 PM**
P-58	0.039	0.018	0.025	0.025	0.027	0.026	0.027	0.031	0.035	0.035	0.035	0.035	0.035	0.029	0.027	0.023	0.021	0.018	0.023	0.020	0.018	0.019	0.018	0.018	0.018
P-59	0.357	0.117	0.165	0.168	0.180	0.181	0.180	0.212	0.241	0.243	0.241	0.242	0.241	0.181	0.170	0.153	0.135	0.118	0.153	0.131	0.116	0.125	0.117	0.118	0.116
P-60	0.369	0.133	0.188	0.192	0.206	0.208	0.206	0.244	0.276	0.279	0.276	0.278	0.276	0.204	0.192	0.174	0.153	0.135	0.174	0.150	0.132	0.144	0.133	0.135	0.132
P-61	0.257	0.093	0.131	0.134	0.144	0.145	0.144	0.170	0.192	0.195	0.193	0.194	0.192	0.142	0.134	0.121	0.107	0.094	0.121	0.104	0.092	0.100	0.093	0.094	0.092
P-62	0.247	0.082	0.116	0.119	0.128	0.129	0.128	0.152	0.172	0.174	0.172	0.173	0.172	0.124	0.117	0.107	0.094	0.083	0.107	0.093	0.081	0.089	0.082	0.083	0.081
P-63	0.758	0.286	0.405	0.413	0.443	0.446	0.443	0.523	0.592	0.600	0.594	0.597	0.592	0.440	0.414	0.374	0.330	0.290	0.374	0.322	0.284	0.308	0.286	0.290	0.284
P-64	0.767	0.358	0.504	0.508	0.545	0.547	0.545	0.639	0.728	0.732	0.728	0.730	0.728	0.563	0.529	0.466	0.412	0.360	0.466	0.398	0.357	0.381	0.358	0.360	0.357
SUM		**4.781**	**6.689**	**6.680**	**7.156**	**7.153**	**7.156**	**8.342**	**9.540**	**9.597**	**9.539**	**9.535**	**9.540**	**7.671**	**7.189**	**6.214**	**5.498**	**4.777**	**6.214**	**5.251**	**4.783**	**5.011**	**4.782**	**4.777**	**4.783**