



Africa Center of Excellence for Water Management
Addis Ababa University
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A thesis on
Enhancement of nonrevenue water management using integrated
model: A case of EXMO zone water distribution system, Addis Ababa

By
Yosan Legesse Galata

A thesis submitted to Africa center of excellence for water management
Addis Ababa University in partial fulfillment of the requirements for the
degree of Master of Science in water management (water supply and
sanitation)

Advisor:
Prof., Dr.-Ing Esayas Alemayehu (PhD, P.E.)

October, 2023

Addis Ababa, Ethiopia



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School of graduate studies

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Declaration

I, Yosan Legesse Galata (ID. GSR/4030/14), hereby declare that this MSc research titled *“Enhancement of nonrevenue water management using integrated model: A case of EXMO zone of water distribution system, Addis Ababa”* has been developed by me and has not been submitted to any other institution for award of any academic qualification. The content of the proposal has not been plagiarized and where works of other researchers have been used, they have been appropriately cited.

Candidate’s Name

Signature

Date

Yosan Legesse



7/11/2023



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Enhancement of nonrevenue water management using integrated
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By

YOSAN LEGESSE

A MASTER'S THESIS SUBMITTED

TO

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

ADDIS ABABA UNIVERSITY

Approval by board of examiners

This is to certify that we have read this MSc research and that in our opinion; it is fully adequate, in scope and quality, as a Master's thesis for the Degree of Master of Science in Water Management (water supply and sanitation)

Advisor:

Name **Prof., Dr.-Ing Esayas Alemayehu (PhD, P.E.)** Signature  Date 27/10/2023

Internal Examiner:

Name **Tamru Tesseme Aragaw (Ph.D)** Signature  Date 20/12/2023

External Examiner:

Name **Dr.-Ing Kinfu Kassa** Signature  Date 25/12/2023

Chairperson:

Name **Beteley Tekola Meshesha (Ph.D)** Signature  Date 25/12/23

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List of Abbreviation and Acronyms

AAWSA: Addis Ababa water and sewerage authority

AWWA: American water works association

BAC: Billed authorized consumptions

CARL: Current annual real loss

CIS: customer information system

DEM: Digital elevation model

DOH: Department of health

DMA: District metered area

EPA: Environmental protection agency

EPS: extended period simulation

ESRI: Environmental Systems Research Institute

EXMO: Ex main office

GIS: Geographical information system

ILI: infrastructure leakage index

INBO: International Network of Basin Organizations

IWA: international water association

MAAPL: minimum annual accepted physical loss

NRW: nonrevenue water

PMA; Pressure metered area

PRV: Pressure reducing valve

SIV: system input volume

SSS: steady state simulation

UAC: unbilled authorized consumptions

UAL: unavoidable level

UARL: Unavoidable real losses

UNESCO: United Nations Educational, Scientific and Cultural Organization

USAID: united state agency for international development

WDS: Water distribution system

Abstract

Nonrevenue water is one of the resisting problems for water utilities in developing countries. The lack of detail information on system condition is intensifying the challenges. To address the problems, understanding the condition of water distribution system is fundamental. Thus, the study focused on model based enhancement of nonrevenue water management and conducted in ex-main office (EXMO) hydraulic zone of Addis Ababa water distribution system. The integrated model of GIS and Water-GEMS was used to evaluate existing conditions. The water balance software used to analysis the nonrevenue water. As the result, the nonrevenue water of the zone was 44.58%, the hydraulic analysis showed 84.48% and 41% of the nodes received recommended pressure 15m to 60m while 4.81% and 27.18% of pipes experienced recommended velocity 0.6m/s to 2m/s during minimum and peak demand respectively. Similarly, the high water age 72 to 146 hours was simulated. Based on the assessment results, the potential vulnerable area in the zone was discovered and the improvement was done by redesigning the system and coupling it with leakage control practices. The improvement result showed 86% of nodes and 77.29% pipes achieved the pressure and velocity requirement during peak demand respectively while the water age was reduced to 56 to 78 hours. The improvement strategies used to decrease water loses by accelerating the procedures to fix and repair leakages. Thus, geospatial and hydraulic model integration approach is significant tool to enhance nonrevenue water management by diagnosing network, exploring and predicting the future challenges and solutions.

Keywords: - integrated model, hydraulic analysis, NRW management, water age, water distribution system

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1 Introduction

1.1 Background of the study

The nonrevenue water is one of the resisting problems for water utility in poorly planned and rapid growth of urbanization (USAID, 2015, Rajasekhar et al., 2018). Addis Ababa is one of the cities challenging with high nonrevenue water and water demands. The city was hosting a huge number of water demanding projects. The occurrence of high level nonrevenue water in water distribution system worsen the water demand and supply gap (Sardinha et al., 2017, water operators' partnerships, 2010, USAID, 2015). The level of water loss and nonrevenue water is at highest level and still showing the increasing trends in developing world (USAID, 2015). The reasons behind increasing tendency of nonrevenue water in African water utilities are due to lack of management systems to evaluate their own performance, inadequate strategy for infrastructures management, poor technical and financial performance, lack of integration work with stakeholders and development partners (Liemberger & Wyatt, 2019, Water Operators' Partnerships, 2010).

Globally, NRW costs estimated as 126 billion m³/ year and cost of USD 39 billion/year and the Sub-Saharan Africa 5.2 billion m³/year and cost of USD 1.4 billion/year (Liemberger & Wyatt, 2019). In Africa due to lack of proper water data it has remained stagnant over the period at 32 percent and become to 41percent (USAID, 2015). To address the management problems, mathematical modeling is interesting tools in analysis, prediction and optimization of the hydraulic performance (Bello et al., 2019).

Water distribution system is complex combination of physically, hydraulically and spatially interconnected components to deliver safe and adequate water for consumers at sufficient pressure without service disruptions (Mabrok et al., 2022, Ganesh et al., 2020, Patil et al., 2021, van Zyl, 2014, Desta & Befkadu, 2020). This interconnection can be failed due to physical factors, environmental factor, biochemical factors and hydraulic factors (Farmani et al., 2017). In order to handle the system failure, spatiotemporal vulnerability area identification is important (Filali-Meknassi et al., 2018). Based on the system vulnerability location, the water utility increase its preparedness to take either a reactive or a proactive measure (Berglund et al., 2020). Integrating GIS and hydraulic modeling is appropriate tool for water system data management due to its capability to

handle big data and analysis the system performance on the same interface (Kurepina & Rybkina, 2018, Berglund et al, 2021).

Usually, the operating level of NRW directly relates to the frequency of system integrity failures and duration of repair (Mesalie et al., 2021). Thus, having detail physical information such as age of pipe, size, spatial locations, network alignment; system performance information such as pressure, velocity and water quality conditions used to streamline leakage assessment and time taken to fix it (Karathanasi & Papageorgakopoulos, 2016, Ahopelto & Vahala, 2020). Also, the model based performance evaluation identify the potential vulnerability area of in the system to take rapid measure on failure either proactively or reactively (Bhatt & Paneria, 2017), Farmani et al., 2017). Generally, the model based approach can enhance NRW management by improving water system data management, diagnosing the hydraulic network, investigating and predicting the leakage problems and solution. Consequently, the study dedicated to enhance NRW management using GIS and hydraulic model integration approach.

1.2 Statements of the problems

Addis Ababa is one of cities fronting high level nonrevenue water. The lack of effective water system data handling method is one of the factors mounting the NRW challenges in Addis Ababa water distribution system. Thus, effective water distribution system data management is essential for nonrevenue water management. Without detail system information, it is difficult to localize, locate and pinpoint the leakage for immediate repairs (Hangan et al., 2022). Usually, due to lack of water distribution data management system Addis Ababa water and sewerage authority has been using its senior member of staff in order to find and locate underground infrastructures. This shows that, how the existing leakage control mechanisms are tedious and time intensive. On the other hand, the utility has no digital format to record the burst frequency and leakage cluster map that able to inform utility about the integrity of the system segments. Thus, the existing method of operation and maintenance is too poor to reduce NRW and ineffective for leakage assessment and control procedures.

In order to address these problems, the geospatial and hydraulic model integration method was selected and GIS and Water GEMS integrated software is the main data analysis tool for the study. It was used to provide the system performance condition on spatiotemporal

maps and graphs with attributable and flex tables. Effectively providing the water distribution data on maps, graphs and attributable inform the decision makers what, where, and how the system was existing. Having such data can speed up the decision making process by identifying potential susceptible segments, procedures and resources required to fix leakage (Tsitsifli et al., 2017, Candelieri et al., 2013, Karrani, 2020). Generally improving water data management, assessing the system performance condition and providing detail information using maps and graphs assisted to identify the potential vulnerable network segments. The GIS and hydraulic model integration method is the selected approach to improve water system data management, diagnose the network, explore and predict the leakage problems and solution. Consequently, the study focused on model based enhancement of NRW management using the Geospatial and hydraulic model integration method.

1.3 Objectives

1.3.1 General objective

The general objective of the study is to enhance nonrevenue water management using GIS and hydraulic model integration method.

1.3.2 Specific objectives

- To analysis the water balance of the study area using WB-easyCalc software
- To improve the water distribution system data management
- To enhance model based management system for nonrevenue water

1.4 Research questions

The study tried to answer the following questions:

1. What is the level of NRW and water coverage of the EXMO hydraulic zone?
2. Why the system data management is essential for NRW management?
3. How the model based system assessment can enhance NRW management?

1.5 Significance of the study

The main significance of the study is improving nonrevenue water management through providing spatiotemporal information on system vulnerability. Providing the vulnerability information can be used to accelerate decision making process and reduce the time to be wasted in leakage localization. Thus, actively controlling the leakage reduce the water

loses and improves the water distribution coverages as well as revenue. Generally, integrated model can improve the performance of water utility, water loss reduction, water quality and water distribution sustainability by providing detail spatiotemporal information on system condition that minimize time and costs. At utility level this can moderate the intermittent water supply, improves utility performance, recovers revenues, improve water quality, reduce energy consumption as well as operation and maintenance costs. Totally, model based water distribution management use to provide information on system vulnerability that upraising awareness and preparedness in order to tackle the causes and effects of system integrity failures either proactively or responsively.

1.6 The scope of the study

The study deals with the enhancement of overall nonrevenue water management by enhancing water data handling system, model based performance evaluation of the system and water balance analysis. Thus, it rounded mainly about the water balance analysis, database building and hydraulic modeling. It also explored the factors that mainly influence the quantity of water. The study used the primary and secondary data collection through interview, focus group, field survey and observations. The mixed research design was implemented for the study since it based on the qualitative and quantitative data. The study proposed the appropriate rationalize and realistic system management for nonrevenue water reduction activities based on the current situations of utility. The hydraulic modeling and GIS integration interface used as central tools for nonrevenue water. The study area was selected in Addis Ababa water distribution system in ex-main office (EXMO) hydraulic zone. Generally, the study focused on model based nonrevenue water management through improving data handling system and setting the appropriate water losses reduction intervention using GIS and hydraulic model integration method.

1.7 Limitations of the study

The study is limited to time and space. It was carried out in Addis Ababa water distribution system by selecting ex-main office (EXMO) distribution zone under current scenario. The hydraulic modeling part included only the pressure, velocity and water age as performance assessment parameters based on the research objectives and time.

2 Literature review

This section presented the reviews of different literatures that have relation with the objectives of the study. It focused on the concept of nonrevenue water and its management, factors causing nonrevenue water and water leakage, system integrity and causes of its failures, application of GIS and hydraulic modeling in water distribution system management.

2.1 The concept of nonrevenue water and water losses

2.1.1 Water loss

The external overload, internal load and age of infrastructures, quality materials and quality of work can be the main causes of water distribution system failures and leakage which lead to water losses (Farmani et al., 2017). Leakage can be categorized as background leakage and burst leakage. Background leakage resulted from infrastructures network elements such as fittings and potentially produces insignificant losses while burst leakage occurs from holes or breakages in the network (Chabe, 2018). Water loss can be defined as the difference between System Input Volume and Authorized Consumption that consists of Apparent Losses and Real Losses. Thus simply water loss is the summation of apparent losses and commercial losses (Jang, 2018).

1. **Commercial/apparent Losses:** This refers to the volumes of water that are successfully conveyed to tap of the end user but unregistered correctly due to metering inaccuracies, unauthorized consumption and poor consumption data handling system. In summary apparent losses occurred due to unauthorized consumption, errors in customer metering, errors in estimates of unmetered consumption, errors throughout the data acquisition Process. Thus controlling commercial loss is important to add the volume of revenue water but no effect on the system input volume (Jang, 2018, USAID & World bank, 2010,).
2. **Real/physical losses:** This refers to water losses that occurred in water supply system due to failures in system integrity. This can be the result of leaks, breaks, and overflows of reservoirs on the way to tap of consumers before successfully meet demand. This loss type primarily affects the demands by reducing the system input volume in the water supply system. Thus effectively managing this loss type reduces the production volume of water, narrow the gap of supply and demands and improves the utility performance (AWWA, 2009, Ociepa & Ociepa, 2019).

2.1.2 Non-revenue water (NRW)

Non-Revenue Water (NRW) is the difference between the system input volume and billed authorized consumption that contains unbilled authorized consumption (Liemberger & Wyatt, 2019). Nonrevenue water can be defined as any volume of water that neither meet the water demand nor generating revenue for water utility and the sum unbilled authorized consumption, apparent losses, and real losses (AWWA, 2009). The definition by IWA task forces Non-revenue water (NRW) is the volume of treated clean water released into distribution network in order to meet the demands and generate revenue but remains undelivered successfully to meet due to water loss and unauthorized consumptions on transient that is unbilled therefore does not generate any revenue for the water utility. Thus it is the difference between the system input volume and billed authorized consumption or as the sum of unbilled authorized consumption and water losses (Liemberger & Wyatt, 2019, Tsitsifli et al., 2017). Hence, NRW is the differences between systems input volume and the billed authorized consumption that unable to generate revenues.

2.2 Global and regional trends of nonrevenue water

Nonrevenue water is characterized by the system inefficiency and weak performance of water utility. Globally the amount nonrevenue water has been estimated as 346 million cubic meter per day and 126 billion cubic meters per day (Liemberger & Wyatt, 2019). Accordingly the Sub-Saharan Africa shared by 14.1million cubic meter per day. The considerable thing is that the lowest NRW result 1million m³ per day found in Australia in New Zealand due to extensive work on leakage reduction for 10 to 15 years (Liemberger & Wyatt, 2019). According to the second report on African utilities performance assessment and benchmarking (2006 to 2009) nonrevenue water (NRW) in Africa has remained stagnant over the period at 32 percent become to 41percent due to shortage of data (USAID, 2015).

2.3 Factors causing nonrevenue water (NRW)

Even though the primary target of the water supply system is to provide sufficient and reliable safe water to its users, due to the system integrity failures water supply components can lead to increased water loss and quality reduction (Mesalie et al., 2021). Nonrevenue water occurred due to water loss and unbilled authorized consumption (Sardinha et al., 2017).

The water loss is the result of system integrity failures due to physical factors, hydraulic factors and biochemical factors. Distribution system integrity maintenance is used as a primary barrier against the water losses (Salehi, 2022, DOH, 2020, National Academy of Sciences, 2007). Distribution system integrity is the capability of system components to maintain the operational sustainability of the system from the treatment plant to the tap of customers. System integrity includes the physical integrity that can be used physical barrier, hydraulic integrity that can be used as hydraulic barrier and water quality integrity that can be used as water quality barrier to protect the exposure of the system to physical, environmental, chemical and biological dynamics that can affect the sustainability of the system (van Zyl, 2014). These integrity failures facilitates the water losses, water contamination and intermittent water delivery (World Health, 2014, Mesalie et al., 2021).

2.3.1 Physical integrity failures

Physical integrity of the system refers to about correctly functioning of system components by resisting the internal and external hazards that possibly result in structural failure (Bouaziz et al., 2019). On the other hand, it is the capability of resisting external and internal stresses to be remain structurally and functionally interlinked without failing (Washington State Department of Health., 2017, World Health, 2014, National Academy of Sciences, 2007). Internal stresses include operating pressure variations, water hammer and internal corrosion, while external stresses include soil stresses, external loadings and external corrosion (van Zyl, 2014).

Generally, the physical system integrity can be affected by physical Factors, environmental dynamics, Chemical Dynamics such as Corrosion and Permeation (Clark et al., 2020) Thus, physical integrity is physical operational dependability of the system under different dynamic environment without service disruption.

2.3.2 Hydraulic integrity failures

Hydraulic integrity can be defined as the capability of water distribution system to provide water with the required pressure and velocity by resisting the factors that could cause a water distribution system to lose its hydraulic integrity (Washington State Department of Health., 2017). The factors may be one of the poor operational controls of valves, pumps, impacts of repairs, impacts of maintenance of aged materials, physical and environmental factors, biological and chemical processes in water system (Mohammed et al., 2021. World Health, 2014, van Zyl, 2014). Depressurization of a water line can lead to

contamination if the surrounding soil is saturated with environmental contaminants (Ghorbanian et al., 2015).

The length of distribution system is another critical hydraulic factor that decreases the flows in pipes that can increase travel times with a resulting loss of disinfectant residual as well as sediment accumulation. Such low flow and sediment accumulation cause the microbial development in system and hide them from disinfectants and reduce the hydraulic capacity. Long detention times can also greatly reduce corrosion control effectiveness by affecting phosphate inhibitors and pH management (Salehi, 2022, World Health, 2014, National Academy of Sciences, 2007).

Generally, hydraulic sustainability is hydraulically the functional consistency of the system under different hydraulic dynamics and can be affected by excessive demands, reduction in system capacity, negative pressures, pumping directly from the network, pressure transients, excessive pressures, low velocities, wrong operational settings and air in the system. Thus, using hydraulic modeling by integrating with Geospatial modeling can sustain the hydraulic integrity of the system through data analysis and interpreting preventive and proactive maintenance (Abdul Aziz et al., 2022).

2.3.3 Water quality integrity failures

Water quality integrity can be defined as the capability of water distribution system to provide water with acceptable quality by resisting to situation that could cause the loss of quality in water distribution system (Mohammed et al., 2021, Farmani et al., 2017). Water quality failures in distribution systems can include contaminant intrusion into the distribution network through failures of system components, biofilm formation and regrowth of microorganisms in a distribution network, water treatment breakthrough of bacteria and/or chemicals, formation of disinfection byproducts (DBPs), leaching of chemicals, release of corrosion byproducts, and permeation of organic compounds from the soil through system components (Sadiq et al., 2007, Abokifa et al., 2016).

Water quality affects the water distribution system by facilitating the regrowth of biofilms and microorganisms in pipe networks (Kanakoudis, 2017, Badr et al., 2022). The growths of microorganisms lead to decrease the velocity and pressure of the system (Ramos et al., 2020). Thus, as hydraulic integrity failed the system exposed to external factors that can cause leakage (Badr et al., 2022, Boulos et al., 2014).

2.4 The causes and effects of system integrity failures

Most of the water distribution infrastructures are underground and out of sight to get attention in priority in the management and financing (Adedeji & Hamam, 2020). Thus, this makes vulnerable to hazardous events of integrity failures (Christodoulou et al., 2010). Consequently, the water leaving the treatment plant with highest quality can seriously deteriorate on the way before reaching at the door of consumers due to many factors that can affect the sustainability of water distribution system. These factors can be clustered into three broad categories: hydraulic dynamics, biochemical dynamics and physical and environmental dynamics (Mazumder et al., 2018).

2.4.1 Physical and environmental dynamics

The physical and environmental factors are the hazardous events directly affect the physical components of water distribution systems (Salehi, 2022). The soil type, backfills, climate conditions, floods, fire hazardous, water table and ground water movements and fluctuations, seismic activities and other hazardous events can be considered as an environmental dynamics while length, age, diameter and material of pipes are as physical dynamics (Młyński et al., 2021). These factors can be categorized as excessive load, environmental dynamics and design and construction factors.

2.4.2 Hydraulic dynamic

The major hydraulic dynamics affecting system integrity are pressure, water hammer (Pressure transients), change in flow direction (momentum), excessive demands, low velocities and reduction in system capacity (Salehi, 2022, van Zyl, 2014, World Health, 2014).

2.4.3 Biochemical dynamics

The biological and chemical dynamics in water distribution system include the discharge of hazards from materials and fittings, corrosion and scaling, biofilm growth, leaching, water age stagnation/high retention times (due to dead ends) and discoloration (WHO, 2019). Microbial growth in pipes wall in stagnation zones and scouring off the biofilm, scales, and corrosion products from the pipe surfaces due to the shear forces created by the sudden increase in water velocity which leads to hydraulic integrity failures (Salehi, 2022, Badr et al., 2022).

2.5 The concept of nonrevenue water management

2.5.1 The concept of Water balance

Water balance analysis is one of the nonrevenue water management strategies that used to assess the annual water status to know how much used and lost (AWWA, 2009). Obviously nonrevenue water is the summation of water loss and unbilled consumptions (Larbi et al., 2020). The water audit contain full of information about the annual volumes of water supplied, customer consumption, and water loss volumes (AWWA, 2016). Water Balance is a systematic procedure that provides detail information for managers on nonrevenue water and factors influencing to take reduction control measures by priority setting. The water balance procedures contain a key step to be followed in order to come up with effective strategic planning and management (Kamani et al., 2012). There are three approaches to water balance analysis (AWWA, 2009). These are top-down analysis, bottom up analysis and component analysis. Among these components analysis approach was selected for the study.

Component analysis: This technique that models leakage volumes based on the nature of leak occurrences and durations. This technique can also be used to model various occurrences of apparent losses by looking at the nature and duration of the occurrence.

Table 1 IWA Standard terminology for water balance analysis

System Input Volume (corrected for known errors)	Authorized Consumption	Billed authorized consumption	Billed Metered Consumption (including water exported)	Revenue Water
			Billed unmetered consumption	
		Unbilled authorized consumption	Unbilled metered consumption	Nonrevenue Water (NRW)
			Unbilled unmetered consumption	
	Water Losses	Apparent losses	Unauthorized consumption	
			Customer metering inaccuracies	
		Real losses	Leakage on transmission and/or distribution main	
			Leakage and overflows at utility's storage tanks	
			Leakage on service connections up to point of customer metering	

Source: Guidelines for water loss reduction a focus on pressure management (Oertlé & et al., 2012)

2.5.2 Management of real losses

In 2003, the IWA Water Loss Task Force arranged the four principal practical approaches to reduce the real water losses. A single strategy or a combination of different strategies should be used, to obtain the most efficient and economic instrument for water loss reduction in each situation. Accordingly this combatting water loss is starting by prioritizing among the four central NRW management pillars. These pillars of NRW management used to fight the real/physical loss (www.waterlossreduction.com). Pressure management, Active leak control, Speed and quality of repairs and water infrastructure management/ Pipeline and selection, installation, maintenance, renewal, replacement

2.5.3 Management of commercial water losses

Apparent (commercial) water loss management is one of the nonrevenue water management and has positive impact on revenue recovery. It can often result in a faster financial payback to the water utility recovering additional revenue into utility accounts (AWWA, 2016). Since Small volume of commercial loss will have a large financial impact on utility financial performance attention should be taken. The important commercial water loss intervention techniques are reduction of customer meter inaccuracies, reduction of unauthorized consumption, reduction of meter reading errors, improving meter data handling and accounting errors (USAID, 2015, Akdeniz, 2022).

2.6 Key performance indicators

Key performance indicators in water supply are designed to monitor and benchmark performance of water utility. Estimating of performance indicators used to support the evaluation of different utilities in different countries with varying dimension of management system (Sardinha et al., 2017).

2.6.1 Infrastructure Leakage Index (ILI)

The Infrastructure Leakage Index (ILI) is a dimensional performance indicator that takes into consideration the length of the network and its operational pressure. It is obtained by dividing the Current Annual Real Losses (CARL); which can be obtained by using a Water Balance methodology, by the Unavoidable Annual Real Losses refers to the lowest technically achievable reduction of the real losses. The lower the value of the ILI, the better is performing the system. It is the ratio of Current Annual Volume of Physical Losses (CAPL) to Minimum Achievable Annual Physical Losses (MAAPL)

$$ILI = CARL/MAAPL \dots \dots \dots 1$$

Where $MAAPL = (18 * Lm + 0.8 * Nc + 25 * Lp) * p \dots \dots \dots 2$

Lm=Mains length (km); Nc= number of service connectional=total length of private pipe property boundary to customer meter (km) and P= average pressure (m)

Table 2 Physical losses target matrix

Technical Performance Category		ILI	Physical Losses [liters/connection/day] (when the system is pressured) at an average pressure of				
			10	20	30	40	50
Developed Countries	A	1 – 2		<50	<75	<100	<125
	B	2-4		50 – 100	75 – 150	100 – 200	125 – 250
	C	4 – 8		100-200	150-300	200-400	250-500
	D	>8		>200	>300	>400	>500
Developing Countries	A	1-4	<50	<100	<150	<200	<250
	B	4-8	50-100	100-200	150-300	200-400	250-500
	C	8-16	100-200	200-400	300-600	400-800	500-1000
	D	>16	>200	>400	>600	>800	>1000

Source: The Manager's Non-Revenue Water Handbook by (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 intensifies NRW reduction efforts

Category D: - Bad. The utility is using resources inefficiently and NRW reduction programs are commanding.

2.6.2 Performance indicators for commercial losses

The IWA Water Loss Task Force is also developing a performance indicator for commercial losses similar to the ILI. The indicator uses a base value of 5% of water sales as a reference, and the actual commercial loss value is calculated against this benchmark. Currently, the best indicator is to measure commercial losses as a percentage of authorized consumption (Farley et al., 2008).

2.7 Experiences and techniques of water distribution data management

Commonly water system management based on huge amount of water assets data on paper record and small amount can be found in digital format likely transferred to a GIS system or excel spreadsheet as well as lot of utilities don't even know the importance of data and how it be and by whom managed (Handke et al., 2020). Technically failing to use

information system for efficient data handling and analysis is one of the highly influencing cases for nonrevenue water management. Efficient water resource management needs efficient access to necessary data and information as well as managing it (Filali-Meknassi et al., 2018). The information used in nonrevenue water management can be derived from data which has to be collected, processed and interpreted by means of hydraulic models, GIS data base, customer information systems (CIS), and water balance analysis software (Oertlé & et al., 2012) .

2.7.1 The concept of GIS application in water supply management

The main purpose of a GIS in nonrevenue water management is to combine diverse data from different sources in order to create new information and to provide a spatial framework for decision support(Oertlé & et al., 2012). A Geographic Information System (GIS) is type of information system composed of computer software, hardware, data and person that used to enter, manipulate, analyze, and present data related to geo-referenced data and information (Ali, 2020). GIS is able to show the spatial distribution of water supply data as thematic maps with different layers while using tables and data in the background. Also simplifying the reality of physical world, viewing, editing, updating, localization and data processing can be done everywhere that used to reduce the costs and time (Lateş et al., 2016).

The interpretation of the geospatial database with analytical tools allowed the water distribution network to be planned more economically and effectively (Hasan et al., 2020,Desta et al., 2022). Also GIS used to store about each infrastructures, including manufacturer year, year of installation, repair/burst history, size /volume, water quality data and type of information (Eljamassi & Abeaid, 2013). The Input data for setting up the GIS can be collected from different sources and the common forms of input data for water supply systems include paper network maps, as-built drawings, field measurement data, existing digital data from CAD and GIS systems, but also reports, spreadsheets and photographs (Oertlé & et al., 2012). In general, a GIS has a capability of locating the particular position of water infrastructures such as valves, hydrants, meters, pumps, pipe networks, manholes and meters by displaying them on a map.

2.7.2 Theory and the concept of hydraulic modeling

The concept of hydraulic analysis is based on conservation of mass and energy the fundamental fluid theory and laws. These are mass conservation and energy conservation (Hadush, 2004,Desta et al., 2022). There are two hydraulic analyses in water distribution,

these are steady state analysis and extended period analysis. Steady state analysis takes place under the occurrence of uniform flow when the cross-section of the flow remains constant at every section along the flow path (Swart, 2009). Fluid flow is governed by conservation of mass, conservation of energy and the friction head loss (Navin & Dohare, 2022).

Conservation of mass: The fluid mass entering any pipe will be equal to the mass leaving the pipe since the fluid is typically neither created nor destroyed in hydraulic systems. It is governed by the continuity equation that relates area and velocity (Walski et al., 2007)

$$A_1 V_1 = A_2 V_2 \dots \dots \dots 3$$

Where, V = average velocity and A = cross-sectional area

Conservation of energy: The difference in energy between two points must be the same regardless of the path that is taken. It is governed by Bernoulli's equation that consists of the pressure head, elevation head, and velocity head. Energy can be gained or lost from the system through hydraulic head. Thus the variation in energy is known as head gain or head loss (Walski et al., 2007).

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + Z_2 \dots \dots \dots 4$$

Where, P = Pressure, V = Velocity, z = Elevation, g = gravitational acceleration constant, γ = Specific weight of water

The pipe friction head loss: Governed by the most commonly used formulas of Hazen-Williams, Darcy-Weisbach formula and the Chezy-Manning formula. These equations solve for the friction slope (S), which is the head loss per unit length of pipe (Walski & Chase, 2001, Walski et al., 2007).

Table 3 pipe friction formulas

Hazen – Williams formula: $S_f = \frac{10.7}{D^{4.87}} \left(\frac{Q}{C} \right)^{1.852}$	used in the design and analysis of pressure pipe system	Where Q is for discharge in m ³ /s and D is for diameter in meter (m), S = Friction slope (m/m),
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Source: Advanced water distribution modeling and management (Walski et al., 2007)

Water age analysis:- Water age is the time taken by water to reach the end user or target place (Desta et al., 2022). The chemical processes that can affect distribution system water

quality are a function of water chemistry and the physical characteristics of the hydraulic system include pipe materials and age (Walski et al., 2007). Water age is the time spent by a parcel of water in the network. New water entering the network from reservoirs or source nodes enters with age of zero (Shamsaei et al., 2013).

2.7.3 Hydraulic modeling tools

Recently the open flow water GEMS update 4 the best modeling tools and incorporated with ArcMap. Water GEMS arc map interface is the integrated model which provides synchronized database connections, geospatial links, and advanced model-building modules that connect with virtually any digital data format (Bentley, 2018). Water GEMS is a multipurpose hydraulic modeling application for water distribution systems with advanced interoperability, optimization and asset management tools (Dhumal et al., 2018, Kadhim et al., 2021). Water-GEMS that provides full geodatabase integration so can create, display, edit, run, map, and analyze hydraulic models from geospatial environments (Patil et al., 2021).

The four tools used in Water GEMS are Model Builder used to transfer existing GIS data to construct new model or update an existing one, TRex Terrain Extractor used to assigns elevation data to the nodes, Load Builder used to facilitates the demand allocation and projection at nodes and Darwin Calibrator used to calibrate the model. During modeling practices the GIS data is important in model builder, TRex and load builder (Yuvaraj, 2017). Despite others application software of Bentley Water GEMS software is able to collect, analyze, and present large sets of data about water supply networks in large cities.

2.7.4 The concept of Integrating GIS and hydraulic modeling

There are three approaches to integrate GIS with hydraulic modeling (Shamsi, 2004, Walski et al., 2007).

Interchange method: - In the interchange approach both GIS hydraulic model run separately and independently. Data transfer carried out between them without direct link between GIS and hydraulic model. The GIS database is analyzed to extract model input parameters, which are manually copied into a model input file. Similarly, model output data are manually copied into the GIS to create a new layer for presentation mapping purposes.

Interface method:-The interface method provides a direct link to transfer information between the GIS and the model. The interface method consists of at least the following

two components. These are a preprocessor used to analyze and exports the GIS data to model input files and a postprocessor used to imports the model output and displays it as a GIS layer. The interface method basically automates the data interchange method. In this method, options for data editing and launching the model from within the GIS are not available.

Integration method:-Integration method is a combination of hydraulic model and a GIS such that the combined program offers both the GIS and the modeling functions. This method represents the closest relationship between GIS and hydraulic modeling. Water GEMS is a perfect example of such a system (Bentley, 2018). In modeling water supply system by GIS facilitate the interrogation process, shorten the working time, reduces the maintenance costs, modernizes and rehabilitation through textual data improvement with graphs (Lateş & Luca, 2017).

The three environments in which to work with Bentley Water GEMS V8i are Water GEMS V8i Stand-Alone Mode, AutoCAD Integrated Mode, and Arc Map Integrated Mode but Bentley Water GEMS V8i Stand-Alone mode may not be available when working in ArcMap Integrated mode, and vice-versa however, can use Arc-Catalog to perform actions on any Bentley Water GEMS V8i database (Manual, 2014). The hydraulic model can be created by importing the water network and the attribute data from the master geo-database to Water GEMS for Arc Map (Kadhim et al., 2021). All network elements will be imported and used to directly manage entities through their associate GIS geometry by searching and accessing their attribute and simulation results(Kuma & Abate, 2021).

2.8 Summary of the research gap

Numerous studies carried out on nonrevenue water management. Most of them mainly focused on assessment and quantification of nonrevenue water. Some of them pointed out the approaches to manage water loss while others introduce the technologies to find and repair leakages. Few of them were done on identification of causes for NRW. However, seldom of literatures indicated decision support system using integrated model. In addition rare literatures disclosed the dual impact of the hydraulic and water age on NRW and system integrity. Thus, model based analysis of hydraulic and water age dynamics in distribution system can enhance the NRW reduction by presenting the system vulnerable area on maps and graphs with background attributable and flex tables.

Model based approach used to show spatiotemporal relationship and effects of hydraulic parameters on NRW management. Water age modeling used to identify the potential location in pipe network to biofilm growth which is one of the internal factors for pipe failure. As biofilm growth developed in pipe the hydraulic capacity decreased and the pipe exposed to cracking by external factors. Accordingly, the study integrated the existing knowledge of water balance analysis, water loss reduction intervention techniques, geospatial modeling, hydraulic and water age modeling in order to add value on the existing intervention techniques in economic and realistic way. This can be done through providing effective system for water distribution data management, improving decision support system, integrating the water loss reduction intervention with model analysis. Mainly, the study focused on formulating approach that used to shorten the time and processes of decisions making for sustaining the system integrity and reduction of NRW.

2.9 Conceptual framework

System integrity failure is the main causes for nonrevenue water in distribution system. This can be due to physical, hydraulic and biochemical factors. Thus, the main focus of the study is to improve data management, evaluate system performance and investigate the options that enhancing nonrevenue water management in distribution system using GIS and hydraulic model integration approach.

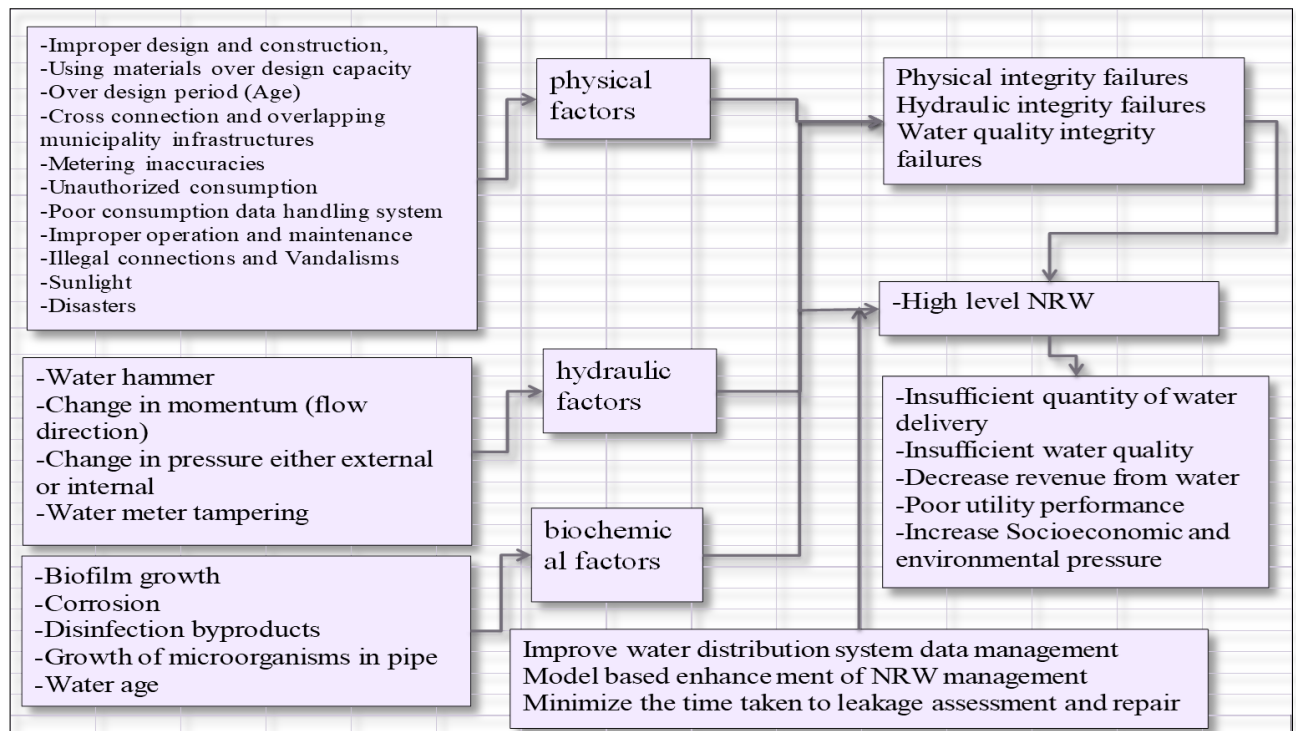


Figure 1 Conceptual framework of the research

3 Research methods and materials

This section clarified the selected study area, methodology and materials used to collect and analysis data.

3.1 Description of Study Area

The study area is found in Addis Ababa city of Ethiopia. Hydraulically it is known as ex-main office (EXMO) zone and served for Arada and Gulele branch offices of Addis Ababa water distribution system. Administratively found in Arada sub city and geographically located in between $9^{\circ} 1'30''$ to $9^{\circ} 2'30''$ northing and $38^{\circ} 45'00''\text{E}$ to $38^{\circ} 46'00''$ easting. The EXMO zone distribution system is one of the 70 distribution zones of Addis Ababa water and sewerage authority. The average elevation of the area approximately ranges from 2395m to 2495m above mean sea level. Commonly, the study area is covered 4 weredas that included wereda 1, wereda 2, wereda 9 and wereda10. The distribution zone is supplied by gravity from the Ex-main office service reservoir in addition to Janmeda pump system.

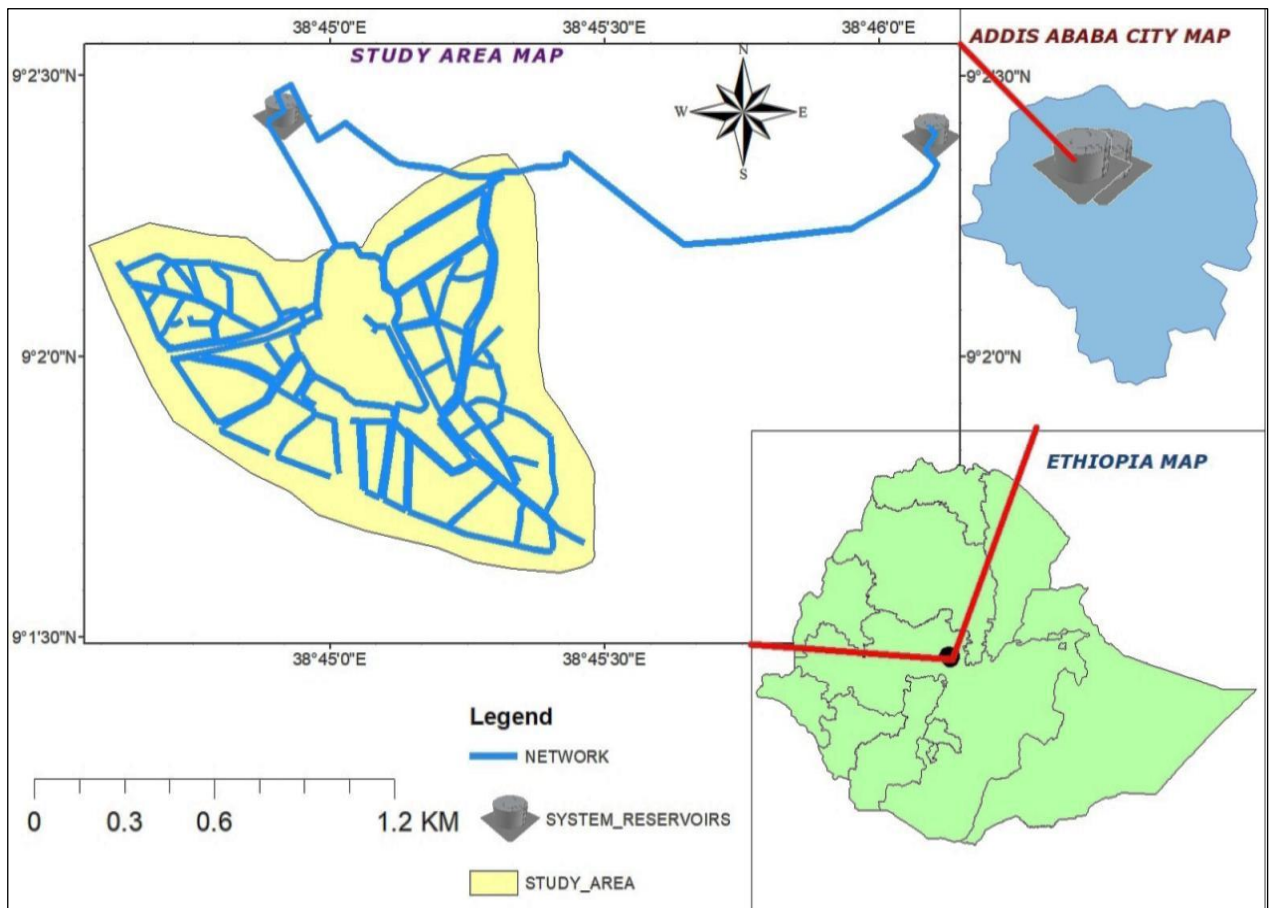


Figure 2 the map of the EXMO hydraulic zone

3.1.1 Existing water distribution system components in EXMO zone

The EXMO zone water distribution system constructed by different type of pie including ductile iron, JISPVC, ISOPVC, HDPE and steel pipes with about 25km total in length.

Table 4 types of pipe in EXMO zone

Material type	Diameter (mm)	Length (m)
HDPE	110	1566
	90	299
	75	684
	64	632
	Subtotal	3181
ISOPVC	250	409
	100	385
	90	1699
	75	393
	63	4966
	Subtotal	7852
JISPVC	100	1588
	75	1256
	63	5345
	Subtotal	8189
DCI	200	1045
	250	559
	350	548
	400	301
	500	2804
		5257
STEEL	400	268
	100	217
	Subtotal	485
Total length		24964

3.1.2 Service life of the EXMO water distribution system

Most of the existing water infrastructures in EXMO zone water distribution system were longstanding over design period. According to the water supply design and construction the design period is up to 30 years (MoWR, 2006). But, for the case of EXMO hydraulic zone most of the pipe was longstanding more than 30 years. Because of the different installation years the pipes in the network experienced different design period starting from 68 years to 4years. So, different pipe materials had different design period and service life. The existing service life of the EXMO zone water distribution system was listed in the following table 5.

Table 5 service life of pipe in EXMO zone

Pipe Materials	Service life	Existing age (years)	Length (m)	Percentage	Total length	Percentage
Ductile iron	40	age >40	3653	29.78%	5257	21.06%
PVC	25	age>25	8127	66.26%	16041	64.26%
Steel pipes:	30	age>30	485	3.95%	485	1.94%
HDPE	50	Age>50	0	0.00%	3181	12.74%
			12265	100.00%	24964	100.00%
Total	Service life			49.13%		

3.1.3 Sources of water for the study area

The source of water for the EXMO water distribution system is Lega Dadi treatment plant. The zone is supplied by pumping system from Janmeda while Janmeda supplied by pumping system from Terminal reservoir. The terminal service reservoir supplied by gravity from Laga dadi clear water tank.

Table 6 capacity of pumping station

Pumping Station	Terminal S/R	Jan Meda S/R
Destination	Lega Dadi through 1200mm and Jan Meda through D900mm	EXMO S/R through D500mm
Pumps	3 parallel	3 parallel
Flow Q (m ³ /h)	1125	360
Lift H (m)	76	32
Status	Operational	Operational

3.2 Method of data collection

The data required for the study were the annual and monthly water production, consumption data, base population data, demand data, water infrastructures data, management practices, existing strategy, topographic data, pressure data, leakage or burst data, water balance components data, customer category and water distribution condition. Based on the required data type the study used qualitative and quantitative data. This led to qualitative and quantitative research methods. Hence, the research used mixed type of research design. The data collection procedures included the primary and secondary data collection procedures.

Thus, the data collection procedures used interview, field survey (observation), focus group or participatory approaches with relevant professionals in the area of water distribution and nonrevenue water management, department manager, networks engineer, technicians, general services departments, facilitators, technicians, customers and

operators. The data collection was carried out for five months starting from early February 2023 to early July 2023.

3.2.1 Sample size for model calibration

The systematic sampling methods were applied to pressure sampling data for calibration. In the sampling procedures members of a sample were chosen at regular intervals of nodes and used to collect pressure and chlorine residual data collection. Thus, to determine the sample size for model calibration and validation the minimum sample size should be 2% of entire junction (AWWA, 2012, Walski et al., 2007, WSDOH, 2009, Walski et al., 2007, Bentley, 2017). Accordingly, the AWWA M32 guideline adopted to determine the sample size and so, 12% of nodes were used for calibration purposes.

3.2.2 Materials used for data collection and analysis

GPS and digital phones: - used to collect the required elevation data, Northing and Easting of junction, tanks, pumps and valves.

Ultrasonic Flow meter and water meter: used to measure the system inflow by connecting it to water line at location of inflow to the hydraulic zone.

Pressure logger: used to measure pressure of the system by connecting it on customer faucets at selected locations. This pressure logger provided the information in the form of graphs and numerical values.

Integrated model (Water GEMS for ArcMap): - used for building hydraulic model and geospatial database. Model builder wizard used to input data prepared in the shapefile format. The TRex Wizard used to input the elevation data prepared in the shapefile format to the nodes. Thiesen polygon wizard used to create proximity polygon to nodal demand. Based on created proximity polygon the nodal demand transferred to nodes using load builder. The model control center wizard used to adjust the demand. Commonly, the integrated model was selected due to its significance over others in such way that modeling the full functionality from within the GIS, without the need for data import, export, or transformation, the ability to view and edit multiple scenarios in the same geodatabase, minimizes data replication, building models from scratch using practically any existing data source and utilize the powerful reporting and presentation capabilities of GIS.

Microsoft Excel sheet: - used to compute and organize the quantitative data

Water balance softer: used to analysis the NRW components and performance indicators

3.2.3 Primary Data collection:

It includes the water distribution network, zonal inflow, zonal outflow, zonal consumptions and zonal distribution coverage and quality status and pressure data. The collection was carried out using field survey and observation. Tools such as digital phones (camera), GPS, flow meter and pressure logger were used. The following figure showed that how the ultrasonic flow meter and pressure logger installed and measured the primary flow and pressure data.



Figure 3 ultrasonic flow meter and Pressure logger

3.2.4 Secondary Data collection:

Secondary data collection includes the printed materials such rule and regulation of operation and maintenance, documents on the study issue such as monthly customers' consumption documents, NRW reports, network maps, work standards and templates. The collection was carried using interviews supported by official letter of support from ACEWM to the AAWSA officials.

3.3 Methods of data analysis

Data analysis includes the qualitative and quantitative data analysis. The data presented or gathered in the form of verbal and narrative form was analyzed under qualitative data analysis. Mostly the qualitative data analysis was carried out using GIS and Water GEMS integrated. The data with numerical value that is measurable in a systematic way of investigation of phenomena and their relationships analyzed under quantitative data analysis. The quantitative data analysis carried out using water balance software and Microsoft excel based on the given formula.

3.3.1 Population projection

The latest population data was found from Arada sub city administration. The 2007 population data was found from CSA published Addis Ababa census document of 2007 the annual growth rate of the study area adjusted based on the Arada sub city population growth rate from CSA 2007 and population in 2021.

$$(P_t|P_o)^{1/t} - 1 = r \dots \dots \dots 5$$

Where P_t is latest population of Arada sub city, P_o is the population of Arada sub city at 2007, t is the time between two population census year (2007 to 2021) and r is sub city annual growth rate in percentage. Based on the gathered information from CSA and sub city, the population of the sub city in 2007 was 211,501 and the 2021 was totaled as 291,401 respectively. Thus, growth rate become 2.3% and the projected population was 40487 in 2023 and 55664 in 2037.

The population projection per mode of services determined based on the consumption data from AAWSA and AWWSA service delivery standards. Accordingly the mode of service of house connection (HC) and yard private connection (YPC) in study area annually increasing while the yard connection shared (YCS) and public fountain (PF) annually decreasing (AAWSA 2016). Hence, in 2023 the coverage of house connection (HC), yard connection (YCP), yard connection shared (YCS) and public fountain (PF) become to 32, 57, 10 and respectively. In 2037 yard connection private (HC), yard connection private (YCP), yard connection shared (YCS) and public fountain (PF) become to 40, 60 and 0 respectively.

The population served by each nodal service were computed and in 2023 house connection (HC), yard connection (YCP), yard connection shared (YCS) and public fountain (PF) become 12956, 23078, 4049 and 405 respectively while In 2037 only house connection (HC) and yard connection (YCP) become 22266 and 33398 respectively. The yard connection shared (YCS) and public fountain (PF) become zero and total population started using house connection and yard private connection.

3.3.2 Demand projection

Domestic demand: - projected based on the population and nodal services per capita demand the daily domestic demand for the study area from 2023 to 2037 was figured as follows in table and all the demand projection process can be found on Annex G.

Table 7 average domestic daily demand

Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Average domestic demand	l/d		4310141	4592036	4893620	5239729	5506325	0	6420692	6794659	7265595	7461649
	m3/d		4310	4592	4894	5240	5506	0	6421	6795	7266	7462
	l/s		50	53	57	61	64	0	74	79	84	86

Nondomestic demand: - water demand includes the commercial water demand, institutional water demand and industrial water demand. This demand covers about 40% of domestic water demand (MoWR, 2006). The demand for firefighting was also underlined under the design and modeling guidelines and covers the 10% of domestic demand. The demand category recommended adding about 15% of total domestic demand assuming reducing the NRW.

Average total demand:-Average total demand includes the domestic demand nondomestic demand which includes the demand for firefighting, commercial, institutional and unaccounted for water.

Table 8 average total demand

Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Total daily demand	m3/d		7823	8335	8882	9510	9994	0	11654	12332	13187	13543
	l/s		91	96	103	110	116	0	135	143	153	157

Thus, based on the total average demand and maximum daily demand 1.2 and peak factor 1.6 the average daily demand, maximum daily demand and peak hour demand computed as 91l/s,109l/s and 145l/s for the year 2023 and 157l/s,188l/s and 251 l/s for the year 2037.

Base demand:-The required demand for each node (nodal demand) calculated by the following formula based on the number of beneficiaries from each nod and time of suppling water at peak hour.

$$\text{Nodal base demand} = \frac{\text{Total beneficiaries at the node}}{\text{Total population of the area}} * \text{peak hour demand} \dots\dots\dots 6$$

3.3.1 System input volume

Normally the system input volume was controlled through six (6) inlet points that of five inlets are measured by ultra-sonic electronic flow meter and one measured by mechanical flow meter. The ultrasonic flow meter measure the flow of water per hour by tying it with

pipe. Accordingly, the average annual input volume was quantified as 1141470.1m³ or 36.2l/s.

3.3.2 Water Consumption

The total annual consumption of the study area was computed as 632553 m³ from the collected the data. The total population of the area in is 40487 in 2023 persons and projected to be 55664 persons 2037. Thus, the per capita consumption was computed as the following formula.

$$\text{Per capita consumption } \frac{l}{c/d} = \frac{\text{total consumption m}^3 * 1000l/m^3}{\text{total population of the area} * 365} \dots\dots\dots 7$$

Accordingly, the domestic per capita consumption of the study area for 2023 GC is computed as 42.8 l/c/d including NRW rate whereas the WHO recommends about 110 l/c/d. Based on this value, the average daily consumption of the study area is computed by per capita consumption multiply by total population. Thus, the average daily consumption is 20.06 l/s.

3.3.3 Water coverage

The average total average daily demand of the study area was computed as 91 l/s whereas the average daily consumption of the study area is 36.2 l/s that have the difference of 54.8 l/s. the water supply coverage of the can be evaluated as follows.

$$\text{water supply coverage} = \frac{\text{Annual input volume} * 100\%}{\text{Annual demand}} \dots\dots\dots 8$$

3.3.4 Building Geospatial database

The unavailability of water data handling system was one of the problems to reduce NRW in AAWSA. So, the utility need efficient data handling system that can enhance the decision making process. For such problems the preferable data handling system is integrated water data management system which incorporated geospatial database with hydraulic modeling. The geospatial database handles and provides the geospatial referenced data while the hydraulic model handle and provide the spatiotemporal system performance. The developed data handling system for EXMO zone can simplify the operation and maintenance management system through mapping by identifying the spatiotemporal system performance on map, showing the system behaviors and existing assets age, type and size in attribute tables.

For the EXMO zone water distribution system geospatial database built to store mainly network (pipe) data, valve data, customers' meter data, pump data and service reservoirs data. It obvious that the first steps to build geospatial database is defining the spatial reference. Thus, in order to build EXMO geospatial database the study adopted projected coordinate system. Water infrastructures data is stored in the form of lines, points, polygons, annotations and texts. Polylines/lines represents for water distribution network, points represents valves, water meters, reservoirs and pump stations. The EXMO zone geospatial data base stores the geographical information for water distribution system that governed under the zone pressure regime. Storing water system information in the form of graphical presentation with background attribute table that provide the decision makers and workers to simply visualize and pass decision in short period of time.

There are three steps to develop geospatial database. These are conceptual design phase, logical design phase and physical design phase.

Conceptual design phase: - Under this stage all the required data for water information such as pipeline, valves, reservoirs, customer meters and pump stations were identified, classified and geographically defined. The data required for database development were decoded and the spatial representation of the geographic data entities decided. The EXMO zone geospatial data entities required for geospatial database development in GIS categorized as feature class. The spatial representation of defined feature class subdivided into line feature, point feature and polygon features based on the existing data and project purposes.

Table 9 spatial representation of feature classes

Water distribution system	Geographic data set	Spatial representation Feature class
Pipelines	Feature class	Line feature
Valves	Feature class	Point feature
Service reservoirs	Feature class	Point feature
Pump stations	Feature class	Point feature
Customers' meters	Feature class	Point feature

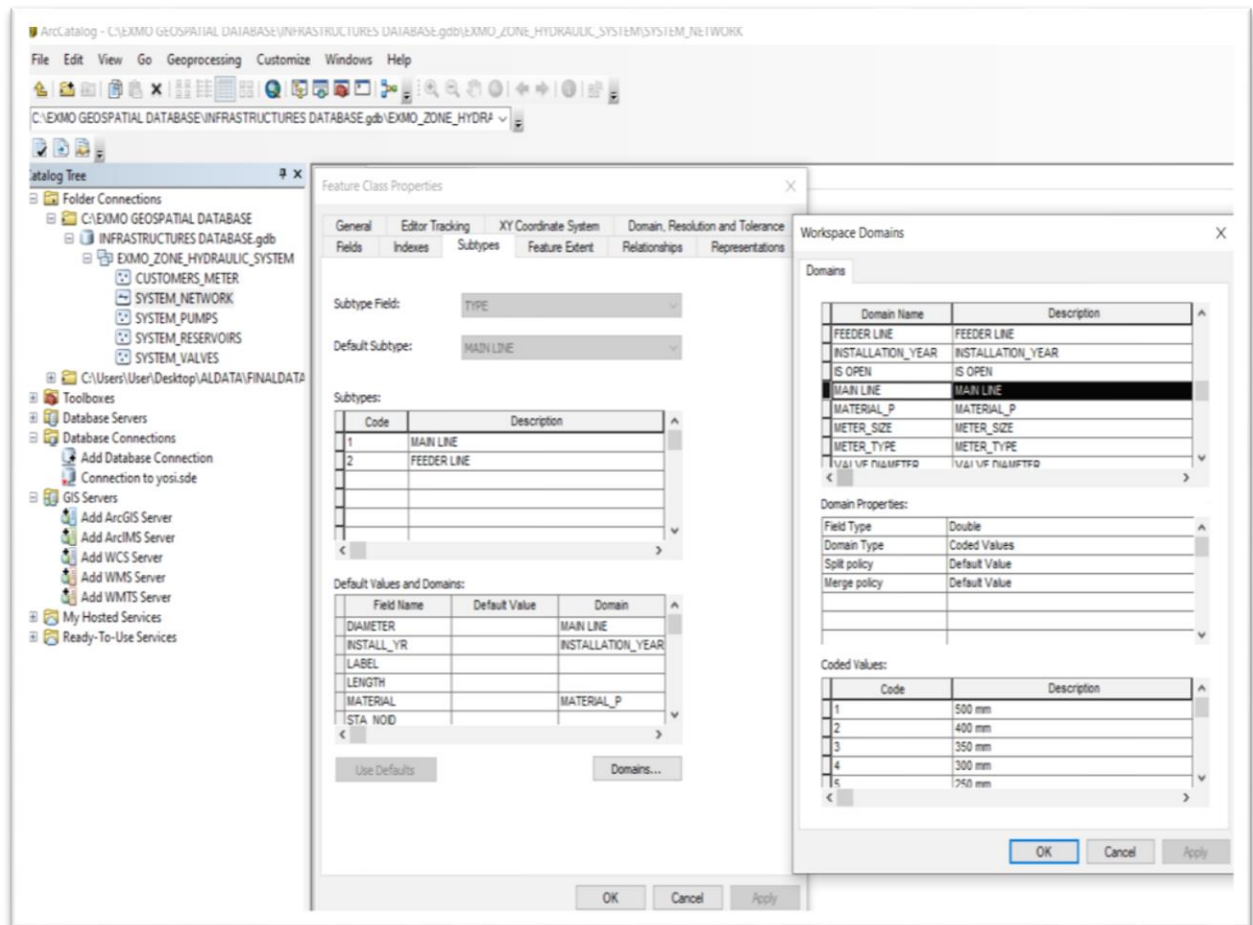
Logical design: - Organizing and structuring the data in geospatial data base format, attribute table field, data type, character size, domains and field description were identified depending on the existing features in the study area. The feature data set organized to be created in EXMO zone infrastructures database in the name of EXMO Zone hydraulic system. Under this EXMO Zone hydraulic system feature data set about five feature

classes were identified with their respective domains. These geospatial feature class are system network, valves, service reservoirs, pumps stations and customers' meters. All feature classes included in feature data set. The geographic reference defined during creating feature dataset is used in order to make the same geospatial reference for all the feature classes. The feature classes included in to feature dataset contain their respective Attribute tables and domain. Generally, logical design phase is important to define data base structures, behaviors, define spatial properties and propose geodatabase design. The following figure illustrated that logical design phase for EXMO zone water distribution system.

Physical design: - under physical design the overall conceptual and logical design incorporated to develop the actual database design. The feature dataset, feature classes with respective domain had been identified in conceptual and logical phase were established and the spatial reference described in above portion defined for the dataset. This design phase is the final design implementation phase and used to develop database and maintaining work flows and documentation the database design.

The geospatial database design developed using Arc Catalog in GIS software. In order to start database design the first step is creating the folder containing database name called EXMO geospatial database in Arc Catalog. After that file geodatabase was created with the name of infrastructures database in the folder of EXMO geospatial database. Then the feature data set created with the name of EXMO zone hydraulic system in infrastructures database. After creating the feature data set the feature classes previously described under conceptual design was created one by one in feature data set holding the name of system network with line feature, system valves with point feature, system customers Meter with point feature, system service reservoirs with point feature and system pumps with point feature in EXMO zone hydraulic system feature data set.

Table 10 Building geospatial database



3.3.5 Building hydraulic Modeling and simulations

Based on the objective of the study modeling and simulation was carried out using GIS and hydraulic model integration method. Water GEMS connect edition version 10.04.00.106 was the appropriate tool to proceed the integration procedures. The hydraulic model created by importing the water network and the attribute data from the master geodatabase from Arc Catalog to Water GEMS for ArcMap interface. After that the material characteristics such as diameter of pipe, type of material, size, year of installations and Hazen Williams's coefficient(C) added to the point data to make full hydraulic model. Elevation data introduced to model through TRex. The following figure showed the integrated model interface and the calibration free running model.

Basically, the study focused on the existing situation of study area network under present conditions. The consumer demands introduced in distribution network models are the year 2023 consumer consumptions. The total consumption allocated is 3127 m³/day or 36.21/s including NRW. The non-domestic demand diurnal pattern is shown in figure 7 and

reflects industry and commercial establishment working hours. The main assumption for the network hydraulic modeling is that of a pressurized system providing a continuous supply of water and aiming to satisfy the consumer demand for year 2023.

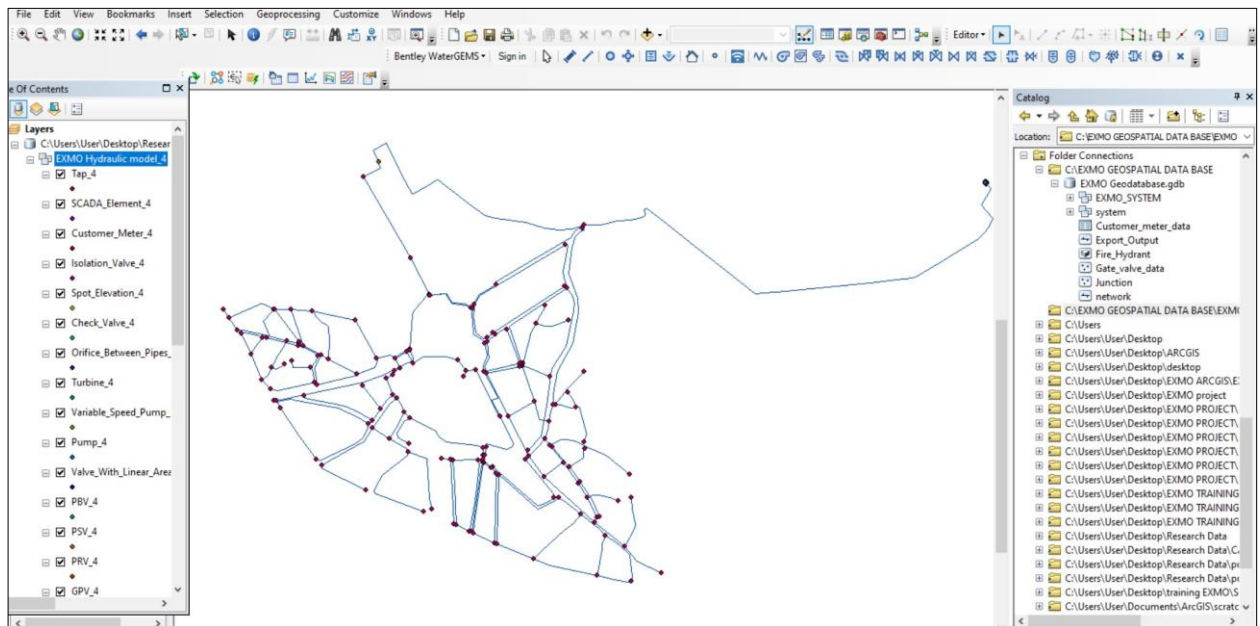


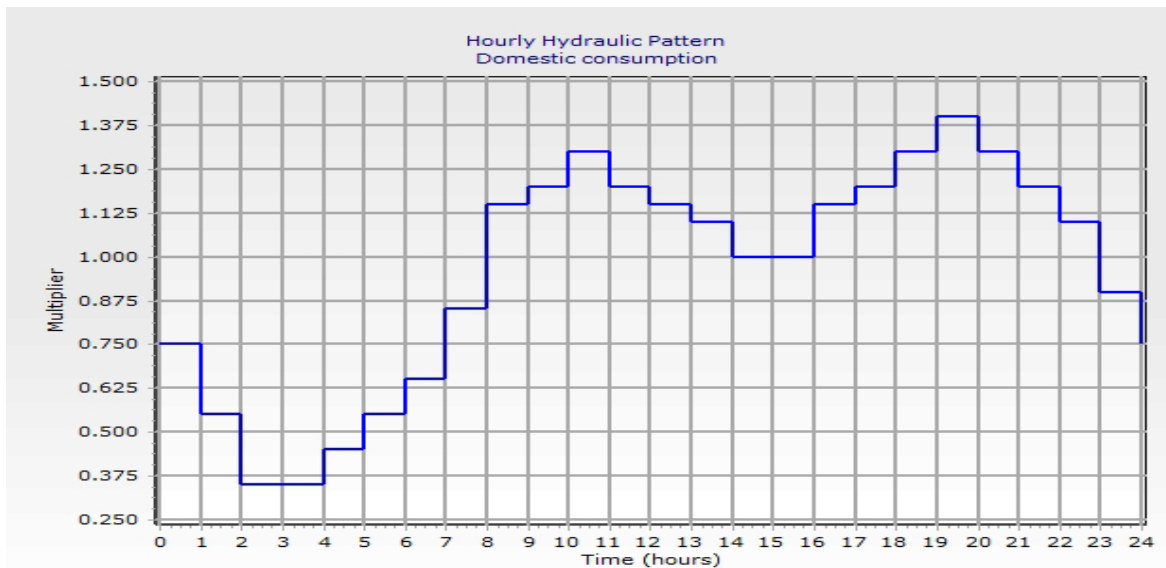
Figure 4 model running pre calibration in Water-GEMS for ArcMap interface

Simulations: On the other hand, one of the processes in modeling water distribution system is simulation. Either it can be steady state simulation which the flow regime is unchanged with time due to variation in consumption or extended period simulation which is the flow regime is changed due to variation in consumptions with time. The flow in water distribution system is depending on the demand at nodes. If the nodal demand of the system constant across the junction the steady state simulation would be performed otherwise the extended period simulation employed. Normally the steady state simulation (SSS) was employed for running the average daily demand assuming the nodal demand at junctions constant throughout 24 hours of a day and the extended period simulation (EPS) employed depending on hourly hydraulic pattern for the peak hour and minimum hour demand analysis. The simulation started performing at 12:00 AM to 5:00AM for minimum hour demand and 6:00 PM to 8:00 PM for the peak hour demand as shown on the following diurnal curve.

Diurnal Curve: - diurnal curves are patterns that used to represent the hourly variation of demands and the amount of water consumption than average daily demand. Relatively, the minimum demand and consumption occurs at midnight since most of the consumers are sleeping and emerging increase at early morning when the consumers wake up. Then

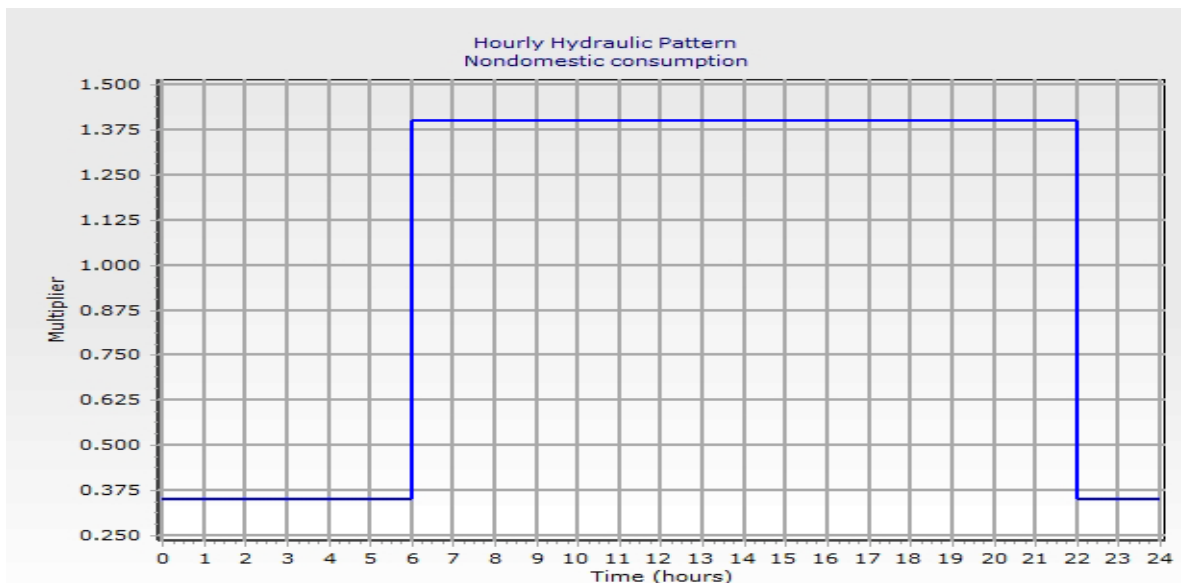
again the consumption relatively to be decreased at midday during the consumers leave home and more amplified at early evening during the consumers back home. Hourly hydraulic pattern was founded from AAWSA developed based on the system inflow variation respect to time in 24 hours. Hydraulic pattern started with monitoring system input volume at hourly intervals since it is the relation between the time and demand variation factor of daily demand.

$$Pf = \frac{\text{peak hourly demand}}{\text{Average day demand}}$$



Source: AAWSA, 2016

Figure5: hourly hydraulic pattern for domestic



Source (AAWSA 2016)

Figure 6: hourly hydraulic pattern for nondomestic consumption

Loading demand: - after that the demand data loaded to the model through load builder wizard using Thiessen polygon method and the elevation of the area loaded through TRex wizard. The following figure showed that the loaded customers meter data.

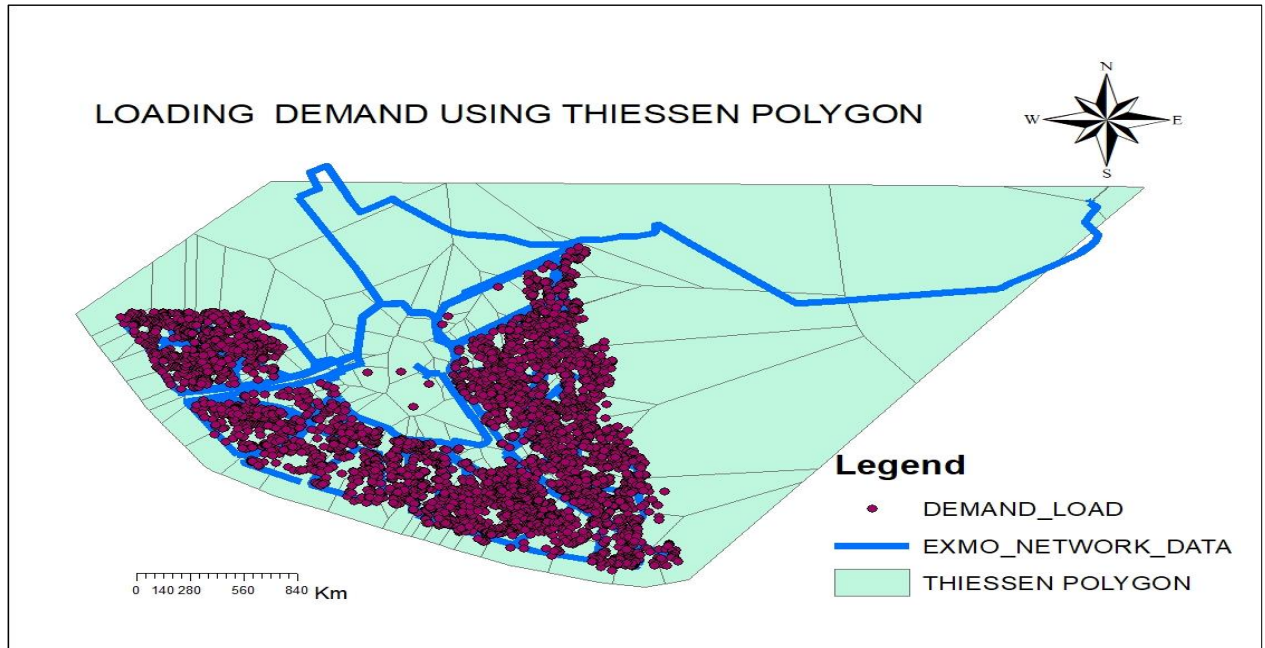


Figure 7 Loading Demand through model builder using Thiessen polygon method

3.3.6 Model calibration

Calibrating the model is the process used to make better reflection of the behavior of the model with actual system on the ground. Hydraulic model calibration is an iterative process of comparing the simulation outcomes with field measured data in order to make corrections to model parameters until reach the required level of agreement between values.

The hydraulic model calibration was undergone by comparing the observed pressure on the field and simulated pressure and hydraulic grade lines. However, for appropriate hydraulic calibration process HGL is the best fit when compare to pressure as calibration parameter. Thus, the overall calibration objective is to minimize the average of root mean square error (RMSE) values between the field observed and the simulated HGL at the different pressure controlling locations. The HGL data was measured at different specified locations in-terms of pressure using Metro logs (Data logger) by installing it at selected customer faucets. The data logger stayed for 7 days onsite to measure the pressure for both high and low demand durations. Accordingly, ten metro logs (data loggers) were used for measuring pressure in two phases for twenty samples. After that the calibration process was done using Darwin calibration method. All observed data transferred to Darwin

calibrator and run for optimal solution. Thus, the twenty selected samples for calibration processed under Darwin calibrator resulted with minimal (RMSE) =0.94 as shown below. The size of water distribution system and the quantity of samples can be determining the degree of model accuracy. Even though there was no constant nationwide calibration criterion, the American water works association manual of water supply practices (M32) tried to provide guidelines for water distribution system modeling. Thus, if the model constructed with good data the average error variance of ± 1.5 m to ± 5 m while ± 3 m to 10 m far bad data set (AWWA, 2012, Walski et al., 2007). Accordingly, the calibration process result value is 1.58 befallen in intervals of good data set (± 1.5 m to ± 5 m) and the model is acceptable.

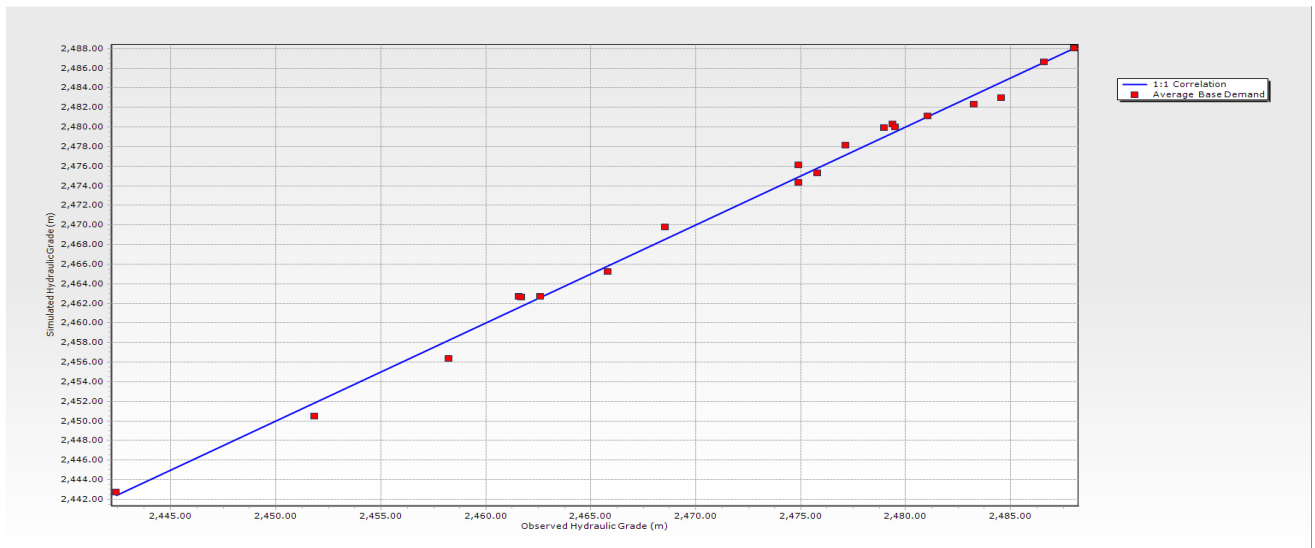


Figure 8 calibration result

Generally the calibration process was performed and concluded by adjusting roughness coefficients of pipes in such that DCI pipe to 150%, steel to 70% and while all plastic materials (HDPE, JIS PVC, ISOPVC) are adjusted to 50% original roughness from guide lines.

3.3.7 Model Validation

After calibration preceded model validation started using coefficient of determination by observing the linearity between observed and simulated data based on the coefficient of determination R^2 . The coefficient of determination is normally set between 0 and 1. when the value of R^2 equal to one ($R^2=1$) the observed and simulated data has no variation and the model is 100% accurate and valid while as it defect or decreased from 1 to zero the model accuracy goes to inaccurate. Accordingly, the R^2 for hydraulic modeling was about 99.8% (0.9977) and for water quality 95.51% (0.9551). The observed and simulated data correlation was look like more linear and the model is valid.

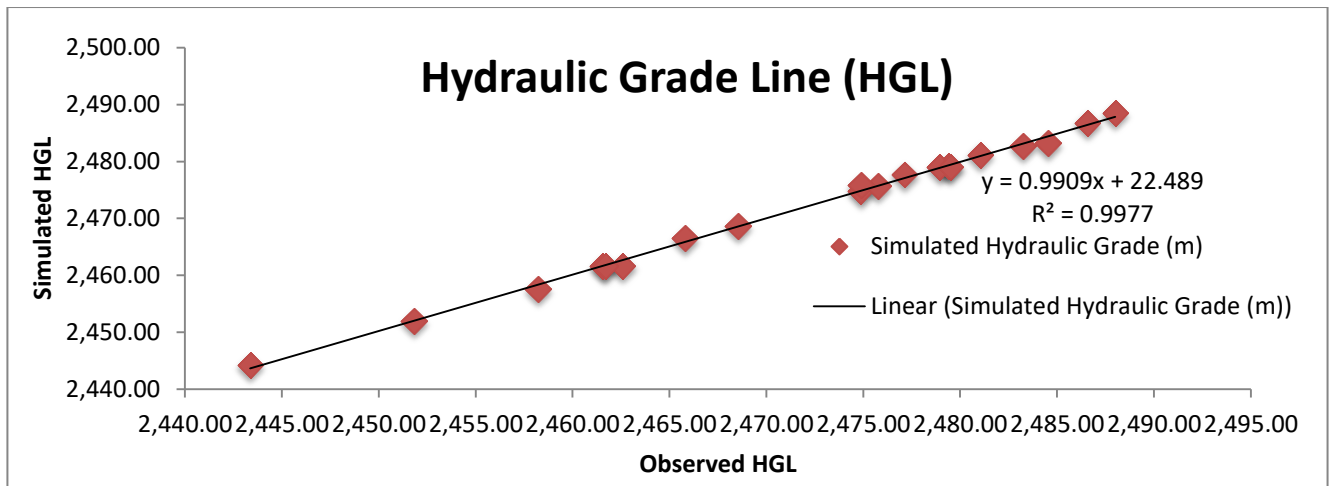


Figure 9 Model validation

3.4 Research design

The overall research design steps concluded in the following flow chart

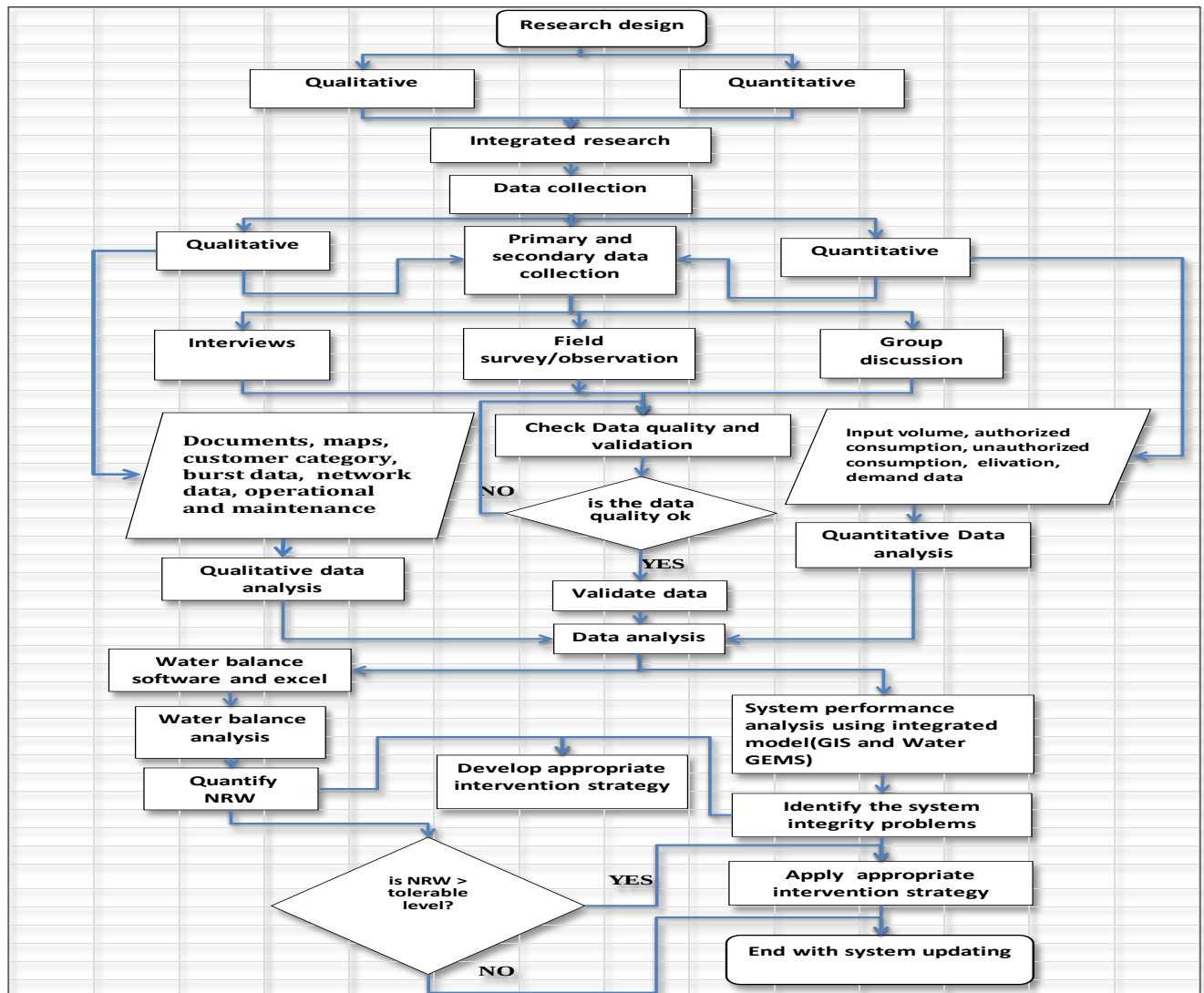


Figure 10: Flow chart for research design

4 Results and discussions

4.1 Water balance analysis

The water balance analysis carried out based on the input volume and consumptions to explore the amount of NRW and water coverage condition of the study area. This is to investigate the amount of water demand and supply gap. Thus, existing water service performance evaluation was undertaken through NRW components analysis and water coverage analysis including surplus and deficits analysis.

4.1.1 NRW components analysis

As shown from the following table 11 of water balance software result the billed unmetered consumption, unbilled metered consumption and an authorized consumption is zero that indicate nonexistence of the components in study area. So, these three components of NRW are not problematic for the study area while the physical losses and customer meter inaccuracies with data handling errors are the agendas need care full attention.

Table 11 NRW components analysis

Water Balance in m3/year				
System Input Volume 1,141,475 m3/year Error Margin [+/-]: 1.0%	Authorized Consumption 641,685 m3/year Error Margin [+/-]: 0.0%	Billed Authorized Consumption 632,553 m3/year	Billed Metered Consumption 632,553 m3/year	Revenue Water 632,553 m3/year
			Billed Unmetered Consumption 0 m3/year	
		Unbilled Authorized Consumption 9,132 m3/year Error Margin [+/-]: 0.0%	Unbilled Metered Consumption 0 m3/year	Non-Revenue Water 508,922 m3/year Error Margin [+/-]: 2.2%
	Water Losses 499,790 m3/year Error Margin [+/-]: 2.3%		Unbilled Unmetered Consumption 9,132 m3/year Error Margin [+/-]: 0.0%	
		Commercial Losses 65,297 m3/year Error Margin [+/-]: 0.0%	Unauthorized Consumption 0 m3/year Error Margin [+/-]: 0.0%	
			Customer Meter Inaccuracies and Data Handling Errors 65,297 m3/year Error Margin [+/-]: 0.0%	
		Physical Losses 434,493 m3/year Error Margin [+/-]: 2.6%		

As shown from the water balance software result the physical losses of zone was 434493m3/year, commercial losses was 65297m3/year, unbilled authorized consumption was 9132m3/year and total NRW of the area was 508922m3/year. The billed unmetered consumption, unbilled metered consumption and an authorized consumption were zero that indicating nonexistence of the components in EXMO zone. So, these three

components of NRW were not problematic for the study area while the physical losses and customer meter inaccuracies with data handling errors are the agendas need careful attention.

4.1.2 NRW analysis using performance indicators

The performance indicators and group used to evaluate the changes of performance over time to determine the improvement required (Tsitsifli et al., 2017). The following table shows that the level of NRW of the study area figured as about 44.58% of total input volume and the performance group fallen in C standard and B category. The standard “C” indicated as on table 2 that Poor NRW record; tolerable only if water is plentiful and cheap; even then, analyze level and causes of NRW and intensify NRW reduction efforts while the “B” indicated that Potential for marked improvements; establish a water balance to quantify the components of NRW; consider pressure management, better active leakage control practices, and better network maintenance; improve customer meter management, review meter reading, data handling and billing processes and identify improvement potentials. Based on the NRW target matrix, the EXMO zone water distribution system required further improvements and model based improvements were essential to meet the target.

1. Physical losses performance

According to the physical losses performance the CAPL value was 1190m³/day. Based on the service level of the study area the physical losses of the area computed as the following table. The minimum achievable volume of physical lose is 198m³/day or 72270m³/year. The best result of infrastructural index (ILI) was 6 and the performance group of the system fallen in C and B of leakage matrix.

2. Commercial losses performance

According to the commercial losses performance indicators the commercial losses expressed in percentage authorized consumption was 10%, the litter per connection per day was 30 and liters per customers per day was 33 l/customer/day.

Accordingly, appropriate strategy is essential to minimize the NRW in EXMO zone water distribution system based on the causes behind losses. The performance group showed that the EXMO zone found in poor NRW record need critical attention to improve the performance. Thus, the study tried to improve the performance through enhancing water

data management and model based hydraulic analysis. Then based on the analysis the reason behind NRW identified and the improvement mechanisms were forwarded.

4.1.3 Existing Water coverage

According to the collected data, annual input volume was 1141475 m³ (36.2l/s) and the annual consumption was 632553 m³ (20.06 l/s). The total population of the area was 40487 in 2023 and going to be 55664 in 2037. Based on the data, the domestic per capita consumption of the study area for 2023 GC was computed as 42.8 l/c/d including NRW whereas the average daily demand was projected as 91 l/s and the peak hour demand was 145 l/s. The average total average daily demand 91l/s and the average daily consumption of the study area is (36.2 l/s) have the gap of 54.8 l/s. The water supply coverage of the area is 39.97% of target demand of 2023 for current scenario while 23% of target demand for 2037 for feature scenario. Thus, the area is under water deficit. Additionally, adding the nonrevenue water on existing condition worsen the water shortage of the area. But, reducing NRW can narrow the supply and consumption gap. Under current scenario, reducing the current NRW to 15% can increase the water coverage of the area to 69.55% and reduce the deficit to 29.45%.

Generally, the water balance analysis result showed that the study area was operating under high water deficit. Taking the 15% water loss as bench mark about 30% the water shortage of the area resulted from high water loses. So, working on NRW control management mechanisms are imperative and mandatory accomplishments.

4.2 Geospatial analysis of the EXMO hydraulic zone

The geospatial analysis of the EXMO hydraulic zone included the investigation of spatial relationship of water infrastructures with their respective size, service life and type of pipe materials. Geospatial database is best tool to reduce water loss by shortening the time required for finding infrastructures location and conditions (Bhatt & Paneria, 2017). All of required water infrastructures data in EXMO hydraulic zone were collected and transferred to geospatial database. These data included the geospatial locations, size, type of materials and installation years. The main importance of geospatial database is the capability of storing assets features with their respective geographical location (Kadhim et al., 2021, Yeung, 2019). Location is the most important to manage the underground assets. Due to lack of data, in Addis Ababa water distribution system leakage assessment and localization needs long time weeks or months to repair. Thus building geospatial

database can reduce the time required to assess and repair of leakage by providing all necessary data.

4.2.1 Geospatial relations of pipe materials and valves

As tried to show on the above table 10 geospatial database can store and provide all types of important data including geographical and non-geographical data that can assist as communication and decision tool for operation and maintenance workers and management. The EXMO hydraulic zone Geospatial database included information on the infrastructures' location, sizes and ages as well as materials type in the system. The following figure showed that the spatial locations of water infrastructure in the EXMO hydraulic zone including flow control valves and pressure reducing valves, type of pipe materials in different colors. This is assisting the utility operators to control the leakage in short period of time; the spatial understanding the infrastructures on site informed what type of materials should have to be in stock for accelerating the maintenance procedures of failures might be occurred.

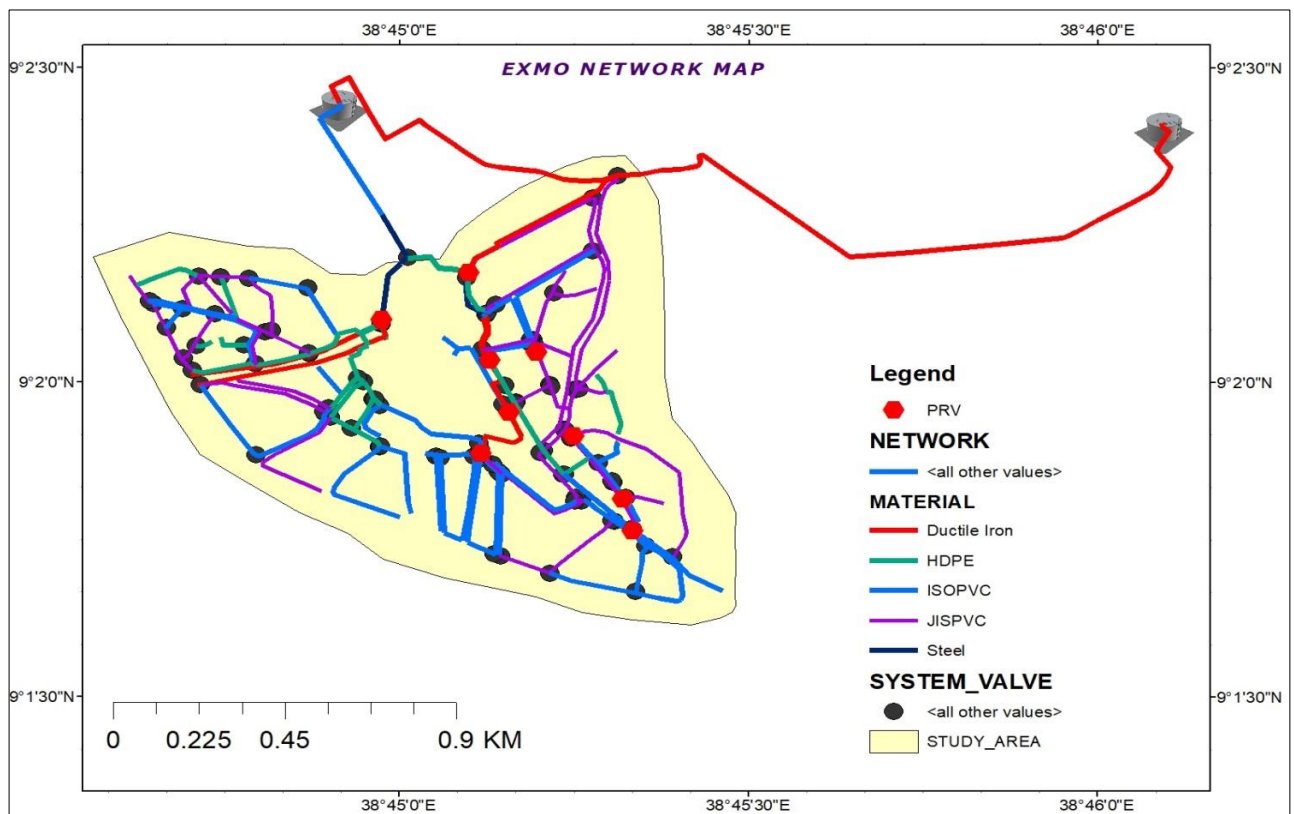


Figure 11:-type of pipe materials and valve locations in the EXMO zone

As shown above figure 11 the map demonstrated the types of pipe materials and valves including locations of pipe network with different colors. Based on the valves and pipe

information, responsible person can simply stop the leakage by closing the valves around the affected area. Also, the materials and fittings used to maintenance purposes could be easily identified and arranged. Accordingly, the ductile iron pipe demonstrated in red color, HDPE pipe in green, ISOPVC in deep blue, JISPV in pink and steel pipe in black color while the flow control valves in black circled point and the pressure reducing valves (PRV) in red circled point. Valves are the main flow control and the immediate tools to stop leakage during system failure and maintenance. If all important information was arranged, implementing leakage control practices could be easy. Consequently, this assisted to improve the leakage control techniques especially the speed and quality of repairs by shortening the time taken to find materials type and valve location to stop leaks.

4.2.2 Geospatial relation of size and service life of infrastructures

According to the specifications of materials different pipes have different service life. according to the ministry of water resources of Ethiopia the economic life of ductile iron is 40 years, PVC pipe is 25 years and Steel pipe is 30 years (MoWR, 2006). According literatures the service life of HDPE pipe is 50 years (<https://usfusion.com>).

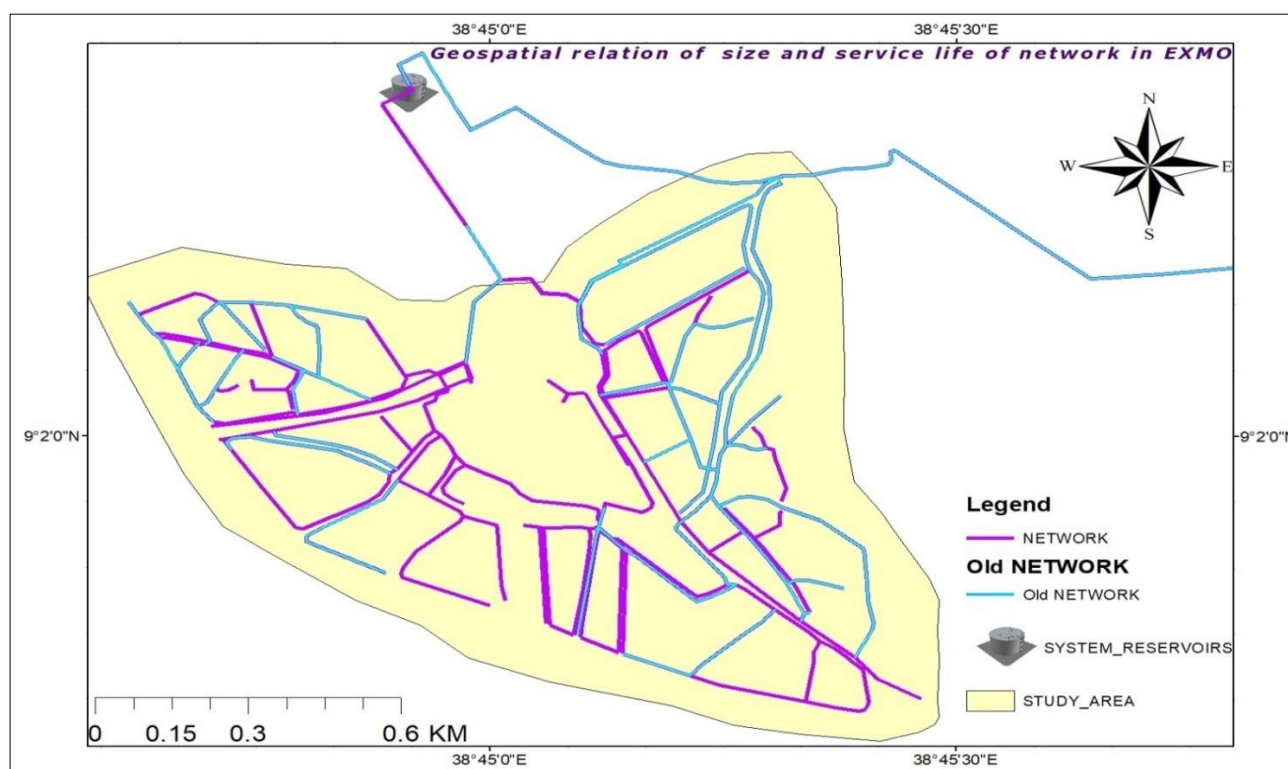


Figure 12 geospatial locations of old pipes

As shown on above figure 12 above the pipe displayed in blue color had been servicing for above 40 years and most of them were installed in 1955 and 1975. The total lengths of the

old pipes were about 49.13% of existing pipe network 24964m with different diameters starting from 50mm to 500mm. thus, this already simplified leakage control practices such as replacement, repairs, material selection, preparation of bill of quantity and other process already simplified without any ground surveying. The diameters of the new pipes determined based on the water demand of the zone and implemented according to the masterplan of the area. Arranging all important information such as type of pipes, size of pipes and service life of pipes improved the pipe replacements and upgrading practices to control leakage.

4.3 Hydraulic analysis of the EXMO hydraulic zone

4.3.1 Pressure condition

Pressure fluctuation is one of the usually occurring leakage problems and it is one of the hydraulic dynamic conditions and main cause for hydraulic integrity failure in water distribution system (Mabrok et al., 2022, Desta et al., 2022). Both negative pressure and high pressure are the main causes for system failure and leakages (Tsitsifli et al., 2017). On the other way, pressure is exponentially related to leakage (Tsitsifli et al., 2017, Mohammed et al., 2021). Thus, Pressure management is one of the NRW reduction approaches. The study used to reduce the NRW through providing spatiotemporal variability of pressure and vulnerability of system that assist the decision making. Based on the result decision maker decided how, when and which intervention method to be implemented to reduce the pressure. Based on the model assumption and the Ethiopian ministry of water resources guideline on water supply design, the minimum and maximum pressure condition in system analyzed as below during minimum and at peak hour demand. It is obvious that, pressure fluctuation depend on the demand fluctuation. EXMO water distribution zone was experienced low pressure during peak hour demand especially in between 6:00 PM to 8:00 PM in 24 hour as shown in the following pressure contour.

Table 12 pressure analysis

S.N	Pressure at low demand	Minimum hourly demand		Peak hour demand	
		Junction Nodes No.	Coverage percentage	Junction Nodes No.	Coverage percentage
1	≤ 0	0	0.00%	47	28%
2	0-14	14	8.48%	49	30%
3	15-60	139	84.24%	67	41%
4	> 60	12	7.27%	2	1%
	Total	165	100%	165	100%

As shown on above table 13 most of the area had been receiving water with pressure in between recommended standard 15m to 60m while about 16% and 59% of the node out of recommended pressure value during minimum and peak hour demand respectively. Accordingly, during minimum hourly demand 14 nodes (8.48%) and during peak hour demand 96 nodes (58%) exposed to pressure below 15m whereas 12 nodes (7.27%) and 2 nodes (1%) above the recommended standard 60m respectively. As shown above table the system only met 41% of target pressure demand during peak hour demand. Based on the simulation result most of the nodes were experienced minimum including negative pressure which is one of the causes for leakage occurrences. Thus, an area under low pressure exposed to failure and has high probability for occurrence of the water losses (Ghobadian & Mohammadi, 2023). The following figure showed that the spatiotemporal variability of pressure and vulnerability of the system.

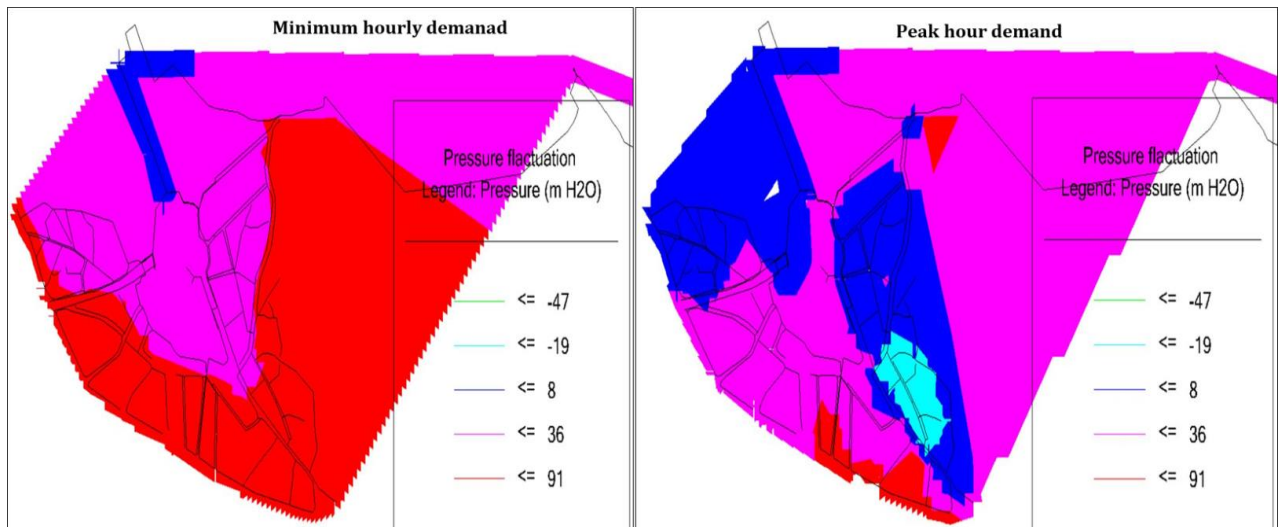


Figure 13 pressure analysis

Accordingly, the red color showed the area under high pressure, the pink color showed the area under normal pressure from 15m to 60m; the blue color showed the minimum positive pressure that less than 15m, the sky blue and green color showed the area under negative pressure. Based on the pressure data the vulnerable area was identified for pressure improvements.

4.3.2 Velocity condition

Velocity is one of the parameters of water supply system design. It also fluctuates as pressure during a day based on consumption patterns. Velocity is the main causes for

physical and biochemical dynamics in water distribution system that causes for water quality integrity failure (Adhav et al., 2022)

Table 13 velocity analysis

		Minimum hourly demand		Peak hour demand	
	Velocity range	Pipe No.	Coverage percentage	Pipe No.	Coverage percentage
1	0-0.6	198	95.19%	150	72.82%
2	0.6-2	10	4.81%	56	27.18%
3	above 2	0	0.00%	2	0.97%
	Total	208	100.00%	208	100.00%

As shown above table 14 the different velocity values were enumerated from the EXMO system including zero velocity. Zero velocity is obvious in loop configuration pipe system and the occurred zero velocities are around isolated valves and higher elevation pipes with dead end as well as higher diameter pipes with dead ends at low elevations. But, 95.19% and 72.82% of the velocity found below minimum acceptable range while only 4.81% and 27.18% of pipe found to be in allowable range during minimum and peak hour demand respectively.



Figure 14 velocity analysis

The effect of velocity fluctuation is that high velocity erodes pipe material and low velocity facilitates the sediment accumulation and growth of microorganisms (Joseph Terlumun et al., 2019). The high velocity resulted in high head losses that exposed the system to failure. The spatiotemporal mapping of velocity used to forecast the vulnerable site to sedimentation and to prevent it (Paneria & Bhatt, 2017, Pothof & Blokker, 2012). According to the simulation result most of the pipes experienced low velocity and has the probability to expose to sedimentations. Consequently, the spatiotemporal pipes mapping with green color showed that the minimum velocity less than standard value 0.6m/s while

the red color showed the pipe with in standard velocity range 0.6m/s to 2m/s and the pink color showed the velocity greater than 2m/s. Based on the velocity result the vulnerable area for sedimentations and biofilm growth was identified for improvement.

4.3.3 Water age condition

Water age is one of the biochemical dynamics affect water quality integrity through facilitating biofilm growth. Water age analysis of EXMO distribution system was performed under calibrated extended period simulation for 120 hours and compared with international and local water quality standards. Usually water age depends on the rate of water production and consumption, residence time in pipes and storage time in tanks as well as length of network from source to target point (Junaid & Izinyon, 2022 , Shamsaei et al., 2013). An average best recommended water age in water supply distribution ranges from 1.3 days and a maximum of 3.0 days (World Health, 2014). The area under high water was exposed to low water quality and high probability to growth of microorganisms in pipes (Mabrok et al., 2022). Thus, this degrades the hydraulic capacity of the system and exposes system to failure. So, water age contributed to water losses through facilitating the growth of microorganisms by decreasing the internal pressure. The following figure showed that how the distance and storage tanks influenced the water quality from Lega Dadi water treatment to end of EXMO distribution network.

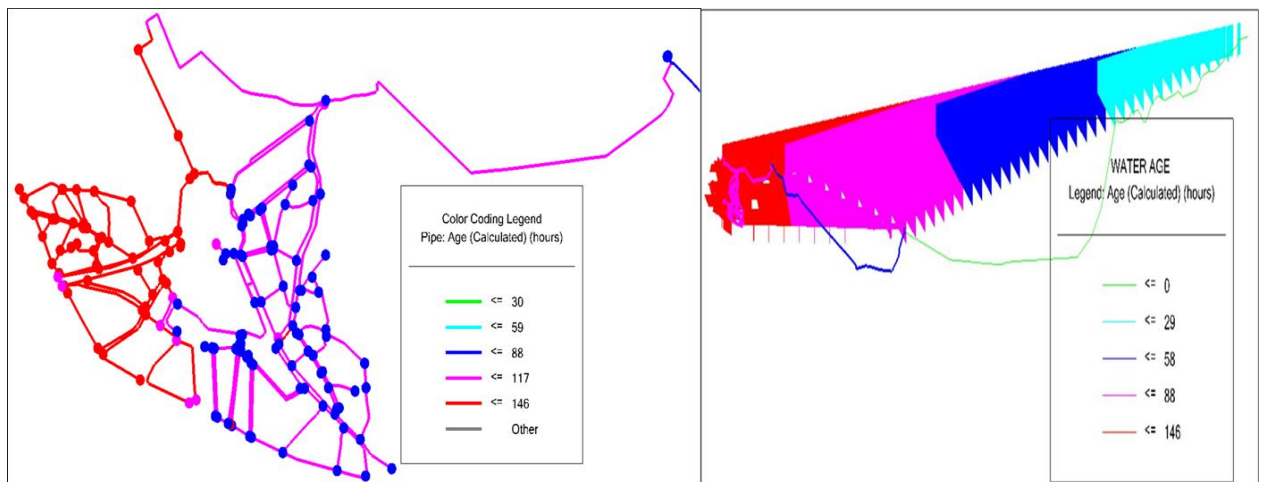


Figure 15: water age analysis

As shown in above figure 15 the age of water was increased as the length of pipe far from source. The water inter to reservoir was zero age and at outlet of the reservoir the age of water simulated as 4hour and 146hour at the end nodes of distribution system. The nodes presented the average water age in pipe networks. The simulation identified the potential area for recontamination. Accordingly, EXMO reservoir and its direct mouthpiece pipe

networks were more vulnerable to water age problems as observed from the above figure 18 in red color.

In general, the maximum water age 72 hours to 146 hours was observed around isolation valve, large pipe with dead end and in the network exposed to minimum velocity or zero in EXMO system. Thus, the consumers using water from such network has high probability to use unsafe water and frequently exposed to water contamination problems. During high demand the velocity of water in pipe increased, pressure decreased, water age also decreased while during low demand minimum velocity and maximum pressure and long water age occurred in the system. Thus, these situations revealed that water age is a function of water demand, system design, operation and maintenance. Water age problems can be solved by pressure management, pipe replacement, injecting disinfectant and flushing the network (Mabrok et al., 2022). Thus, model based spatiotemporal mapping of water age used to announce the location and area affected by high water age in order to select the intervention techniques to maintain water quality integrity.

4.4 Identified Causes for system integrity failures and NRW

Depending on the model based system conditions assessment result, the EXMO water distribution system was highly vulnerable to system integrity failure and NRW. The physical integrity was endangered by system design problem and long standing, the hydraulic integrity of the system exposed to high fluctuation of demand and pressure whereas the quality integrity of the system threatened by high water age. As the result, the hydraulic performance of the system was satisfied only 40% of the target demand under sufficient water in reservoirs. Thus, model based operation and maintenance strategy is essential to tackle problems of infrastructural water scarcity and effect of NRW.

The EXMO zone water distribution system is operating under high water loss and water deficit. Also the hydraulic and water quality analysis result of the systems inferred that the integrity of system is under pressure. The main dynamics behind system integrity failures are physical dynamics were pipe age, quality of materials, city rehabilitation, overlapping parallel infrastructures such as electric infrastructures, telecommunication infrastructure, road construction, quality of repairs, hydraulic dynamic such low pressure, high pressure , low velocity and biochemical dynamics such as water age, high chlorine residual and low chlorine residual in water distribution system. According to burst data collected from Arada branch most of the reasons behind system failure was the speed and quality of

repairs followed by age of infrastructures. Pressure and overlapping infrastructures covers about 39 percent as shown following table.

Table 14 reasons for pipe breakage and leakage

Reasons of network failures	Failures (Burst)	Percentage
Speed and quality of repairs	2630	39%
Overlapping parallel infrastructures	1416	21%
Age of materials	1484	22%
Pressure	1215	18%
Total failures (burst)	6745	100%

It is obvious that, the old pipe is one of the main causes for system sustainability failures and NRW. As shown on table about 49.13% of the pipe network working over the service life and being the reason for 22% of the occurred burst. Especially most of pipes installed before 1975 needs replacement to sustain system integrity and reduce physical water losses. According to the hint and information gathered during field observation and worker interview the third party involvement of system integrity failure is the lack of perfect water distribution system data and usage as well as sectorial integration on common activities.

The other root causes of system integrity failures were pressure fluctuations due to demand fluctuations in the study area. During high consumption the pressure in the system reduced to below minimum acceptable level and negative pressure occurred in many parts of network. Conversely, moderate and high pressure was occurred during low demand. This negative pressure occurrence can be resulted in hydraulic integrity failures and pipe breakage. Pipe breakage during low pressure facilitates the pollutant intrusion and water losses (Ghadai et al., 2020). The high pressure during low demand can be resulted in new leaks especially at old age pipe network which can intensify the water losses. The other hydraulic dynamics in the system was velocity fluctuations that lead to high water age. Most of the pipe networks were exposed to low velocity less than minimum acceptable level. Thus, the low velocity is the main causes for sedimentation and biofilm growth in pipe network (Desta et al., 2022).

4.5 Improvement strategies

Depending on the results of model based assessment of system condition, the improvement was undergone by redesigning the system depending on design guidelines and coupling it with leakage control practices such as system flushing and gradual pipe replacement. The system redesigned for 15 years and the implementation is carried out depending on the utility performance and financial capacity. But, the best way is gradual implementation by setting the priority depending on the degree of the system vulnerability. So, the design used as operation and maintenance masterplan and should be implemented gradually according to the design assumptions. Under current scenario the system operation and maintenance implemented by installing pressure reducing valves (PRV), replacing highly vulnerable old pipes and making simple connections at required locations based on the assumption of redesigned system. As the result, the zone pressure was improved and 99% of the nodes started operating in-between recommended pressure ranges. Almost 24.79 % of the pipes were operating with standard velocity while the water age never changed. This is because the objective of the redesigned system is to meet peak hour demand of 2037. So, to address the velocity and water age problems the leakage control practices should be implemented based on redesign assumption. However, at 2037 almost 86% of the nodes will operate with standard pressure and 77.29% pipes meet the recommended velocity at peak hour demand. The remaining 22.71% of pipes simulated to operate less than minimum acceptable velocity was observed around dead ends and isolation valves. These minimum velocity problems can be resolved by periodical flushing and cleaning pipes after operation and maintenance practices.

4.5.1 Improved pressures

The following table 16 showed that pressure of existing system and the pressure after the system optimized through redesigning and coupling with leakage control practices.

Table 15 comparison of pressure at low demand before and after improvement

S.N	Pressure range at peak hour demand	Existing condition		Improved condition	
		Nodes No.	Coverage	Nodes	Coverage
1	≤ 0	0	0.00%	0	0.00%
2	0-14	14	8.48%	1	0.59%
3	15-60	139	84.24%	168	98.82%
6	> 60	12	7.27%	1	0.59%
	Total	165	100.00%	170	100.00%

As shown on above table 16 about 98.82% of the nodes start operating with in recommended pressure(15m to 60 m) pressure while 1.8% of nodes out of the standard. there were two nodes operated out of recommended standard in which one node had been operating with pressure 13m while the other with 61m that had no significant pressure on system integrity.

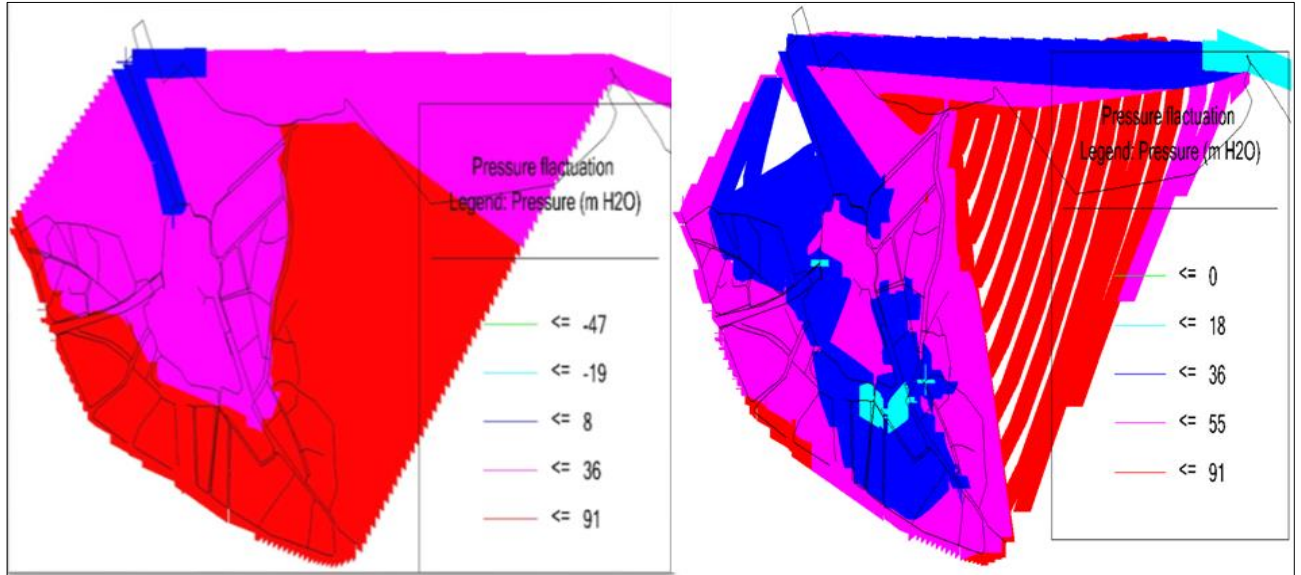


Figure 16 comparison of pressure at low demand before and after improvement

As shown on the figure 16 above the red color represented high pressure greater and the pink color represented the moderate pressure in between recommended pressure while the deep blue color and the sky blue color presented the minimum pressure.

On the other hand during peak hour consumption about 99.41% of the nodes observed operating within the recommended pressure ranges while 0.59% or 1 node was out of the standards. The node had no significance pressure on system integrity and operated with 12m to13m

Table 16 comparison of pressure at peak demand before and after improvement

S. N	Pressure range	Existing peak demand		Optimized peak demand	
		Nodes No.	Coverage	Nodes No	Coverage
1	<=0	47	28%	0	0.00%
2	0-14	49	30%	1	0.59%
3	15-60	67	41%	169	99.41%
4	>60	2	1%	0	0.00%
	Total	165	100%	170	100.00%

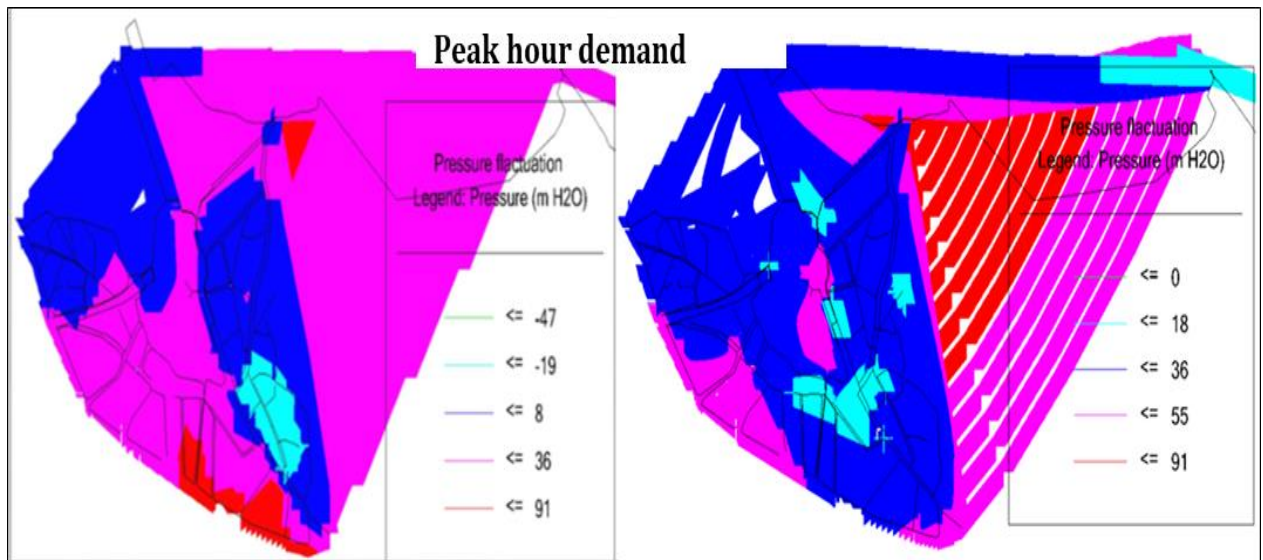


Figure 17 comparison of pressure at peak demand before and after improvement

As demonstrated on above figures 17 the blue shade represented the minimum pressure while the red color shade represented the high pressure. Accordingly the light blue colored shade in existing system showed the negative pressure while in modified system minimum in standard pressure range in between 15 to 18m, deep blue color showed the positive minimum less than minimum requirement 15m in existing system while moderate pressure from 18m to 36m. The pink color showed that the pressure head between 36m to 60m in both system. Normally in modified system all colors represented pressure within recommended pressure range.

4.5.2 Improved velocity

On the other hand the velocity and water age problems could not be addressed as pressure since it depends on pipe cross sectional. Usually the necessary pipe is not found on the market to implement the design. So, system redesign and coupling it with leakage control practices can solve the problems. As shown on the table 18 below the velocity of the system designed to meet the 2037 peak hour demand. So, perhaps it is not the immediate solution for current velocity problem but gradually meet the target depending on demand of the area. But, based on the assumptions of redesigned system the continuous operation and maintenance can be done to improve the system integrity. The pipes with minimum velocity were observed from simulation and quantified as 22.71% of the pipes due to the low demand with respect to the pipes found on markets, pipes that found with dead ends and with isolation valves. At dead ends and isolation valves movements for water is difficult and periodical flushing is essential.

Table 17 comparison of velocity at peak demand for 2023 and 2037

Before improvement hourly demand				After improvement Peak hour demand	
	Velocity range	Pipe No.	percentage	Pipe No.	percentage
1	0-0.6	150	72.12%	52	22.71%
2	0.6-2	56	26.92%	177	77.29%
3	above 2	2	0.96%	0	0.00%
	Total	208	100.00%	229	100.00%

The spatiotemporal variation of velocity for current at 2023 and futur at 2037 presented as follwing graph. This graphs showed the degree of potential vulnerability area. This used to identify which area was higly vurneable or which area was less vulnerable. So based on the degree of vurnerability the solution sellected and priteriorized according to the redesigned system.

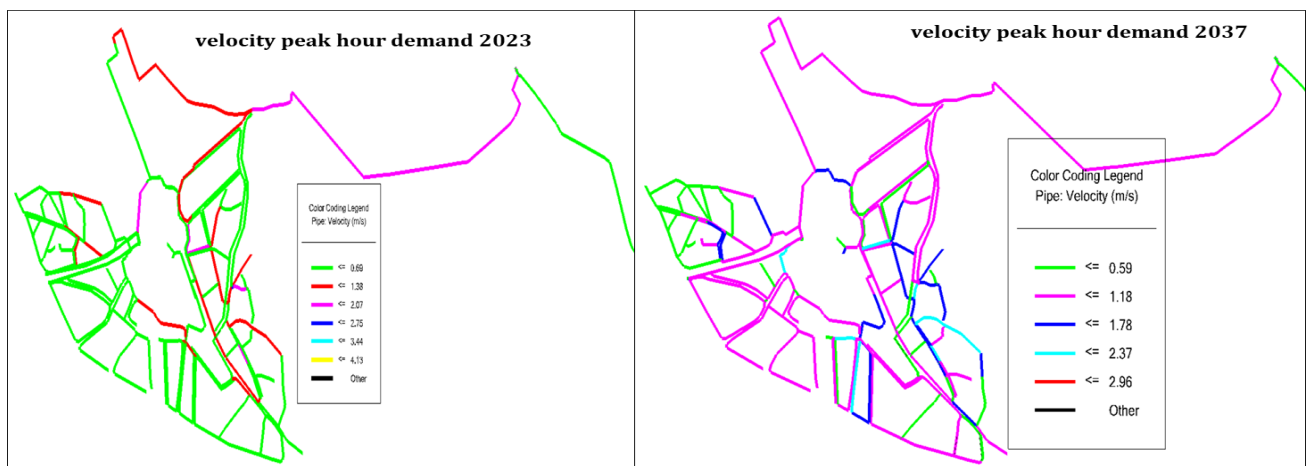


Figure 18 comparison of velocity at peak demand for 2023 and 2037

4.5.3 Improved water age

Water age depends on flow velocity in the system. The water age of the redesigned system oscillated in-between 56 hours to 78 hours. The following figure showed that the maximum water age determination for selected node. Different nodes characterized by its own different water age. High water age was observed at dead ends and isolation valves.

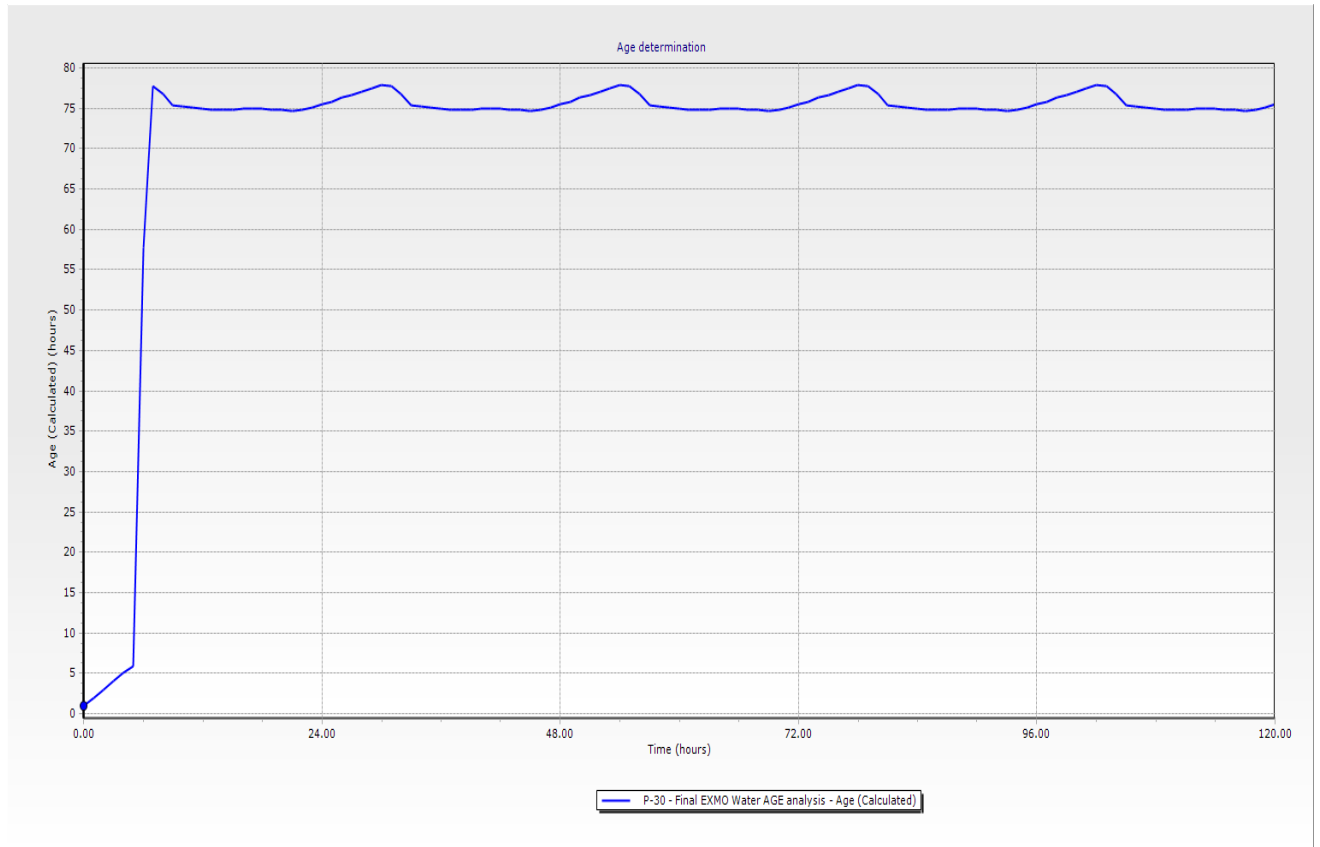


Figure 19 water age at selected node

Generally any water supply projects are designed considering the coming demand at least for 10 to 15 years (MoWR, 2006). So, full pipe flow occurrence is rare and this decrease the velocity and increases water age especially during minimum consumption hours. The water age and velocity depend on the pipe cross section and demands. Modeling results of velocity and water age analysis strengthen this idea. On the other hand leakage can be the result of internal or external factors. When hydraulic integrity failed the system would be exposed to external factors that can cause leakage (Badr et al., 2022, Boulos et al., 2014). Thus, in order to fight the internal hydraulic and biochemical dynamics such as sedimentation and biofilm growth as well as pressure and velocity fluctuations in pipes, periodical flushing is best approach. Generally water age modeling played great role in NRW management by identifying the area exposed to internal hydraulic dynamics.

5 Conclusion and recommendations

5.1 Conclusion

Typically, the study aimed to enhance the management of nonrevenue water using geospatial and hydraulic model integration method. The GIS and Water-GEMS integration model and water balance software were used for data analysis. Based on the data analysis result, the current NRW level was 44.58%. Under current scenario, reducing the current NRW to 15% can increase the water coverage of the area to 69.55% and reduce the deficit to 29.45%. Thus, reducing NRW was mandatory endeavors.

Most of the physical dynamics identified behind leakage in EXMO hydraulic zone was the speed and quality of repairs due to lack of system data, overlapping parallel infrastructures and age of materials. These all cases were related to lack of perfect infrastructural data. So, arranging and handling the system geospatial and hydraulic performance data improved the leakage control practices by reducing time and process to aware the potential vulnerable area. Hydraulically, now only 41% of nodes fulfilled the minimum pressure requirement 15m to 60m at peak hour consumption and 9% of the nodes operated above maximum recommended value during minimum consumption while only 4.81% and 27.18% of pipes found to be in allowable velocity requirement 0.6m/s to 2m/s during minimum and peak hour demand respectively. On the other hand, High water age 72 to 146 hours was observed. Thus, the EXMO hydraulic zone exposed to system integrity failure and high nonrevenue water.

Based on the nature of identified problems, the system integrity improvement was done through redesigning the system and coupling it with leakage control practices. As the result, in 2037 almost 86% of the nodes simulated to operate with standard pressure and 77.29% pipes achieved the recommended velocity (0.6m/s to 2m/s) at peak hour demand. The maximum water age was reduced to 56 hours to 78 hours. For current scenario, the zone pressure was improved and 99% of the nodes started operating recommended pressure ranges by installing pressure reducing valves (PRV), replacing old pipes and laying new pipes at proposed locations based on the redesign assumption. Therefore, integrating the Geospatial and hydraulic modeling is essential decision support tool to enhance nonrevenue water management. Generally, the technical and managerial problems in NRW water management can be addressed by integrating the geospatial and hydraulic modelling approach and leakage control practices.

5.2 Recommendations

The hydraulic modeling result showed that EXMO reservoir had significant contribution to water age. So, the utility should have to periodically cleaning the reservoir and respective pipe lines.

According to site survey of pipe line layout, many of the pipes passed through the private compounds or very attached to the private compounds. This can be the problematic to find leakage and repair. So, the utility should have to think how to own its right of way and space near the high way and roads.

The reported burst showed that overlapping infrastructures such as electric infrastructures, telecommunication infrastructures and road infrastructures have critical impact on water system integrity and NRW. Hence, AAWSA should try to solve through sectorial communication and common understanding for immediate solution while the city and federal government should sustain the solution through policy provision.

Periodical flushing and disinfecting should be employed for new installed and rehabilitated parts of network especially in loop system to reduce biofilm growth.

Smarting and digitalizing water system is important for system performance sustainability and NRW management. Water utility should have to be ready and exercise to overcome the water management challenges and water losses through intelligent water system management.

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Annex A: - Existing NRW trends in Addis Ababa water utility

Years	water production	Consumption	NRW	
	m3/year	m3/year	m3/year	%
2011	105440998	69262863	36178135	34.31%
2012	112174751	67469189	44705562	39.85%
2013	119972725	66283391	53689334	44.75%
2014	120088391	65637111	54451280	45.34%
2015	131205622	75335697.5	55869924.5	42.58%
2016	157211768	84664234.43	72547533.57	46.15%
2017	159255704	84524344	74731360	46.93%
2019	176288670	100274846	76013824	43.12%
2020	177288670	98074817	79213853	44.68%
2021	168647632	98394666	70252966	41.66%
2022	167861437	98000514	69860923	41.62%
2023	167503768	97757040	69746728	41.64%

Source: AAWSA annual report from 2011-2023

Annex B: - Annual population Growth Rates

Consumer Category	Unit	2022	2024	2026	2028	2030	2032	2034	2036	2038
House connection (HC)	l/c/d	141	146	152	159	165	171	176	182	189
Yard Connection Private (YCP)	l/c/d	96	100	104	108	110	112	114	116	1018
Yard Connection Shared (YCS)	l/c/d	59	60	63	66	70	73	76	79	82
Public Fountain (PF)	l/c/d	28	29	30	30	30	30	30	30	30

Source (AAWSA, 2016)

Annex C:- Seasonal variation and Peak Day Factor

Factors		Value	
Peak day factor		1-1.3	
Seasonal factor		1-1.2	
Socioeconomic factor	Group A towns	1.1	high living standards and with very high potential for development
	Group B towns	1.05	very high potential for development but now lower living standards
	Group C towns	1	under normal Ethiopian conditions
Population range			Peak hour factor
<20000			2
20001-50000			1.9
50001-100000			1.8
>100000			1.6

Sources (MoWR, 2006)

Annex D:- Standard pressure and velocity

Conditions	Normal conditions	Exceptional Conditions	Normal Velocity	Exceptional Conditions
Minimum	15 mH ₂ O	10 mH ₂ O	0.6	in loop system 0 may exist
Maximum	60 mH ₂ O	70 mH ₂ O	2.	2.5 for pump system

source (MoWR, 2006)

Annex E: - Hazen-Williams (C-value)

Materials	For new conditions	For existing conditions	Recommended Service life for pipe materials
UPVC	130	100-110	25 years
Steel	110	90-110	30 years
DCI/GI	120	100-110	40 years

source (MoWR, 2006)

Annex F:- Monthly input volume and consumption

Months of the year 2023		Monthly input volume (M ³)	Monthly consumption (m ³)
July		95633	49833
August		95633	49504
September		95633	56097
October		95633	52680
November		95633	51514
December		95633	56095
January		95633	49292
February		95633	56505
March		95633	54762
April		93677	53319
May		93506	51952
June		93595	51000
Average	M3	1141475	632553
	l/s	36.2	20.06

Annex G: - population and demand projection

			population									
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Growth rate (%)			2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
projected pop			40487	41418	43345	45362	47473	48565	49682	51993	54413	55664
			Modal coverage									
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
HC	%		32	33	34	36	36		37	38	40	40
YCP	%		57	57	58	59	59		59	59	60	60
YCPS	%		10	9	8	5	5		4	3	0	0
PF	%		1	1	0	0	0	0	0	0	0	0
Population served with each modal			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
HC			12956	13668	14737	16330	17090	0	18382	19757	21765	22266
YCP			23078	23608	25140	26764	28009	0	29312	30676	32648	33398
YCPS			4049	3728	3468	2268	2374	0	1987	1560	0	0
PF			405	414	0	0	0	0	0	0	0	0
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
HC	l/c/d	141	141	146	146	147	147	165	165	166	166	167
YCP	l/c/d	96	97	100	101	101	102	110	111	111	112	112
YCPS	l/c/d	59	59	60	60	60	60	70	70	70	70	70
PF	l/c/d	28	28	29	29	29	29	30	30	30	30	30
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
HC	l/c/d		1830919	1995529	2156674	2395667	2513287	0	3039868	3274799	3616256	3708336
YCP	l/c/d		2228603	2360837	2528612	2707681	2850192	0	3241635	3410564	3649339	3753313
YCPS	l/c/d		239278	223658	208335	136381	142846	0	139188	109295	0	0
PF	l/c/d		11340	12011	0	0	0	0	0	0	0	0
Average domestic demand	l/d		4310141	4592036	4893620	5239729	5506325	0	6420692	6794659	7265595	7461649
	m3/d		4310	4592	4894	5240	5506	0	6421	6795	7266	7462
	l/s		50	53	57	61	64	0	74	79	84	86
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Average demand	l/d		4310141	4592036	4893620	5239729	5506325	0	6420692	6794659	7265595	7461649
	m3/d		4310	4592	4894	5240	5506	0	6421	6795	7266	7462
Climatic factors			1	1	1	1	1	1	1	1	1	1
Socioeconomic factors			1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
climatic and socioeconomic adjusted demand	l/d		4741155	5051240	5382983	5763702	6056957	0	7062761	7474125	7992154	8207814
	m3/d		4741	5051	5383	5764	6057	0	7063	7474	7992	8208
	l/s		55	58	62	67	70	0	82	87	93	95
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Nondomestic demand (40%)	m3/d		1896	2020	2153	2305	2423	0	2825	2990	3197	3283
Firefighting demand(10%)	m3/d		474	505	538	576	606	0	706	747	799	821
Unaccounted for water(15%)	m3/d		711	758	807	865	909	0	1059	1121	1199	1231
Total daily demand	m3/d		7823	8335	8882	9510	9994	0	11654	12332	13187	13543
	l/s		91	96	103	110	116	0	135	143	153	157
Period			2023	2024	2026	2028	2030	2031	2032	2034	2036	2037
Day factor			1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Maximum day demand	m3/d		9387	10001	10658	11412	11993	0	13984	14799	15824	16251
Peak hour factor			1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Peak hour demand	m3/d		12517	13335	14211	15216	15990	0	18646	19732	21099	21669
			145	154	164	176	185	0	216	228	244	251

Annex H:-site data for calibration

S.N	LABEL	X	Y	ELEV_Z_	NAME	CONTRACT	DEMAND CAT	METER SIZE	METER TYPE	Observed Pressure (m H2O)
1	J-7	471970.2	998663.4	2450.64	SHEMESU G/MEDEHEN	101373	DOM	15	BAY-10769194	12
2	J-14	471921.2	998617.4	2446.05	ARADA K/K WORDA 2 N/A	525825	DOM	15	BAY-10719783	16
3	J-19	472136.2	998757.4	2462.61	ATO MUSSA ADEM	10534	DOM	15	MET-7371919	6
4	J-22	472297.2	998551.4	2454.51	ATO MESFIN ABRHAM	508287	DOM	15	SIN-6196387	26
5	J-30	472515.2	998084.4	2431.9	RENTED HOUSES N/A	306485	DOM	15	SIN-6211001	46
6	J-33	472321.2	998500.4	2452.3	TESEMA FELEKE	43850	NON-DOM	15	APA-34101562	27
7	J-37	472407.2	998476.4	2456.3	RETED HOUSESADM N/A	134283	NON-DOM	15	PRE-28176229	23
8	J-55	472084	998695	2451	ARADA K.KW-2 N/A	519178	DOM	15	A&M-09030025	13
9	J-65	473214.2	998099.4	2420.25	ADANE BELAY	322230	DOM	15	APA-34062002	23
10	J-75	473125.2	998047.4	2431.49	ATO AGONAFER F/MEDHEN	318919	NON-DOM	25	APA-34161675	22
11	J-82	473081.2	998550.4	2439.78	ARADA K/K N/A	325306	DOM	15	BAY-10758359	19
12	J-86	472993.2	998424.4	2448.82	ADDIS FANA TEKLALA SHEKET N/A	33347	NON-DOM	25	MET-7408338	17
13	J-96	473165.2	997843.4	2414.52	ARADA K/K N/A	324141	DOM	15	APR-34078218	60
14	J-98	472908.2	997892.4	2428.44	ALEMU TAFESSE	56576	NON-DOM	15	SIN-6191023	47
15	J-100	472823.2	998403.4	2460.54	GERMAN GARAGE GARAGE	23383	NON-DOM	25	BAY-10684687	15
16	J-107	472987.2	998115.4	2446.66	RENTED HOUSES N/A	307639	NON-DOM	15	SIN-6216510	37
17	J-111	472868.2	998588.4	2465.06	WOIZERO ERUKIA SHEK BESHIR	68273	DOM	15	MET-3451633	17
18	J-123	473015.2	998975.4	2451.02	KF 2 KB 9 HU.NO 1084 N/A	3753	NON-DOM	15	APA-34078181	36
19	J-132	472636.2	998035.4	2431.6	ETHIOPIAORTODOCSMOUSES N/A	311138	NON-DOM	25	SIN-6245224	58
20	J-140	472838.2	998703.4	2469.7	HOUSING ADIMINSTERATION N/A	135003	DOM	15	MET-3461908	14

Annex I: - pressure Analysis report

ID	Label	X (m)	Y (m)	Elevation (m)	Pressure at peak hour		Pressure at low demand	
					optimized Pressure	existing Pressure	optimized Pressure	existing Pressure
					(m H2O)	(m H2O)	(m H2O)	(m H2O)
31	J-89	473089.7	999050.7	2450.1	22	-3	40	38
32	J-34	472371.7	998419.6	2450.17	35	20	42	39
33	J-37	472414.7	998468.6	2456.55	29	14	35	33
34	J-35	472429.7	998457.6	2456.78	28	13	35	33
35	J-39	472455.7	998409.6	2455.62	29	15	36	34
36	J-45	472475.7	998388.6	2456.05	29	14	36	34
37	J-41	472393.7	998528.6	2458.29	30	15	34	31
40	J-42	472442.7	998561.6	2464.66	25	10	27	25
41	J-44	472423.7	998597.6	2465.62	25	10	26	24
42	J-118	473034.7	998841.6	2451.17	35	29	54	41
44	J-48	472476.7	998626.6	2475.63	16	1	17	14
45	J-51	472487.7	998578.6	2473.67	18	2	18	16
46	J-58	472637.7	998587.2	2474.74	38	15	46	18
47	J-74	472676.7	998554.6	2470.26	42	20	50	22
48	J-73	472666.7	998534.6	2469.45	43	20	51	23
49	J-76	472710.7	998555.6	2469.16	43	21	51	24
50	J-140	472798.7	998393.6	2460.39	52	29	60	32
51	J-24	472357.7	998596.6	2461.66	28	12	30	28
52	J-22	472288.7	998540.6	2453.44	35	19	38	36
53	J-114	473024.7	998848.7	2452.01	34	16	53	39
54	J-21	472146.7	998505.6	2449.23	38	23	42	40
55	J-17	471980.7	998489.6	2446.12	41	26	45	43
56	J-16	471950.7	998522.6	2445.4	34	2	45	41
57	J-14	471911.7	998612.6	2445.59	34	1	45	41
58	J-13	471876.7	998684.6	2446.76	33	0	44	40
59	J-12	471863.7	998694.6	2446.65	33	0	44	40
60	J-5	471833.7	998739.6	2446.49	33	1	44	40
61	J-11	471814.7	998768.6	2446.87	33	0	44	40
62	J-6	471992.7	998767.6	2455.9	23	-9	35	31
63	J-8	471952.7	998669.6	2449.4	30	-2	41	37
64	J-84	473041.7	998730.6	2448.58	33	-7	53	39
65	J-7	471965.7	998670.6	2450.61	29	-3	40	36
66	J-10	472039.7	998656.6	2455.36	25	-8	35	31
67	J-4	472083.7	998655.6	2457.27	22	-11	33	30
69	J-9	472053.7	998766.6	2460.04	21	-11	31	27
70	J-15	472148.2	998605.6	2454.74	28	-7	36	32
71	J-18	472159.7	998608.6	2454.93	28	4	36	33
72	J-20	472187.7	998593.6	2455.01	28	5	36	33
73	J-19	472127.7	998761.6	2462.55	20	-5	28	25
74	J-23	472281.7	998728.6	2465.46	23	7	26	24
75	J-106	472972.7	998532.6	2450.64	26	18	47	40
76	J-101	472917.7	998447.6	2454.19	25	4	37	35
77	J-116	472895.7	998276.6	2456.83	16	23	33	35
78	J-100	472825.7	998395.6	2459.93	17	0	30	30
79	J-112	472747.7	998545.6	2468.12	44	5	52	23
80	J-142	472740.4	998550.8	2468.31	44	22	52	24
82	J-143	472743.7	998647.6	2472.17	40	18	48	21
83	J-122	472749.7	998655.6	2472.69	39	2	48	19
84	J-127	472750.1	998668.6	2473.73	36	8	46	18

ID	Label	X (m)	Y (m)	Elevation (m)	Pressure at peak hour		Pressure at low demand	
					optimized Pressure	existing Pressure	optimized Pressure	existing Pressure
					(m H2O)	(m H2O)	(m H2O)	(m H2O)
86	J-120	472780.7	998680.6	2473.25	35	1	46	18
87	J-117	472819.7	998699.6	2471.26	33	3	47	20
88	J-115	472865.7	998579.6	2464.97	31	8	52	26
89	J-113	472871.7	998579.6	2464.55	31	7	52	26
90	J-109	472877.7	998579.6	2464.23	30	7	52	27
91	J-110	472866.7	998567.6	2464.68	30	6	52	26
93	J-111	472875.7	998569.6	2464.08	30	7	52	27
94	J-88	472925.7	998717.6	2462.21	24	-16	53	26
95	J-87	472957.7	998782.6	2458.64	28	-12	57	30
96	J-94	472969.7	998377.6	2451.16	21	-1	39	38
97	J-90	472985.7	998433.6	2450.08	22	-3	40	38
98	J-82	473094.7	998550.6	2439.25	15	-16	49	47
99	J-78	473038.7	998477.6	2440.99	29	-20	49	45
100	J-79	473065.7	998427.6	2437.19	33	-16	53	48
101	J-77	473095.7	998303.6	2431.84	34	-16	58	53
102	J-92	472957.7	998316.6	2452.56	18	-3	37	36
103	J-150	472478.7	998945.6	2484	25	6	36	7
104	J-85	472972.7	998292.6	2450.04	20	-4	40	38
105	J-59	472983.7	998287.6	2447.75	18	-47	41	36
106	J-81	473021.7	998232.6	2443.42	27	3	46	45
107	J-62	473042.2	998218.6	2440.76	18	-39	48	43
108	J-60	473097.7	998281.6	2431.21	27	-30	57	53
109	J-66	473081.7	998164.6	2436.73	20	-32	52	47
110	J-68	473075.7	998160.6	2437.44	20	-32	51	47
111	J-67	473106.7	998111.6	2435.08	18	-33	53	49
112	J-65	473217.7	998100.6	2419.42	28	-22	54	64
113	J-64	473263.7	998111.6	2410.35	31	-1	42	74
115	J-80	473257.7	998192.6	2410.55	31	0	43	74
116	J-70	473239.7	997940.6	2414.44	29	-5	37	70
117	J-75	473133.7	998024.6	2429.87	27	-19	59	55
118	J-71	473140.7	998042.6	2430.35	26	-24	58	54
119	J-69	473371	997844	2395.2	48	14	57	89
120	J-83	472953.7	998184.6	2450.94	20	-3	38	38
121	J-91	472899.7	998256.6	2456.22	16	-4	33	33
122	J-93	472886.7	998242.6	2456.46	7	20	13	35
123	J-107	472988.7	998109.6	2446.32	17	31	23	45
124	J-105	473006.6	998109.6	2445.01	17	29	24	46
125	J-146	472699.3	998767	2477.47	35	13	43	15
126	J-99	473083.7	998051.6	2434.5	22	34	34	56
127	J-95	473170.7	997978.6	2424.03	31	42	44	66
128	J-97	473261.7	997819.6	2406.55	48	59	61	83
129	J-96	473142.7	997837.6	2414.99	40	51	53	75
130	J-98	472915.7	997897.6	2428.87	28	38	39	61
131	J-102	472784.7	997947.6	2430.57	32	41	38	60
132	J-128	472776.7	997951.6	2430.46	39	56	39	62
133	J-134	472702.7	997986.6	2430.85	39	58	39	62
134	J-144	472695.5	997991.3	2431.02	39	59	39	62
135	J-132	472633.4	998018.2	2430.13	37	56	39	62
137	J-129	472589.7	998247.6	2450.98	17	36	19	41
138	J-130	472620.7	998243.6	2451.46	16	35	18	41
139	J-131	472629.7	998241.6	2451.54	16	36	18	41
140	J-135	472718.7	998240.6	2454.42	15	34	15	38
141	J-137	472732.7	998240.6	2454.34	15	35	16	38
142	J-139	472735.7	998233.6	2453.96	16	36	16	39

ID	Label	X (m)	Y (m)	Elevation (m)	Pressure at peak hour		Pressure at low demand	
					optimized Pressure	existing Pressure	optimized Pressure	existing Pressure
					(m H2O)	(m H2O)	(m H2O)	(m H2O)
143	J-136	472740.7	998233.6	2454.01	15	35	16	39
144	J-125	472764.7	998213.6	2452.84	16	32	17	39
145	J-124	472771.7	998218.6	2453.36	16	31	16	39
146	J-126	472782.7	998193.6	2452.19	17	33	18	40
148	J-108	472791.7	998187.6	2452.22	16	23	17	39
149	J-133	472735.7	998257.6	2455.29	42	34	42	37
150	J-119	472736.7	998284.6	2456.35	40	31	41	36
151	J-138	472747.7	998287.6	2456.55	41	33	41	36
152	J-27	472553.7	998071.6	2431.9	48	34	59	57
153	J-30	472524.7	998061.6	2431.23	51	36	60	58
154	J-26	472319.7	998137.6	2431.92	42	28	59	56
155	J-29	472471.7	998268.6	2447.47	34	20	44	42
156	J-43	472473.7	998297.6	2449.5	34	20	42	40
157	J-31	472403.7	998317.6	2446.84	36	22	45	42
158	J-123	473027.7	998994.7	2450.65	37	32	54	41
159	J-32	472342.7	998353.6	2445.59	38	23	46	44
160	J-38	472327.7	998368.6	2445.46	40	25	46	44
161	J-36	472341.7	998378.6	2446.72	39	24	45	43
162	J-40	472142.7	998242.6	2435.2	51	36	57	54
163	J-25	472164.7	998222.6	2433.9	42	28	57	55
164	J-46	472016.7	998424.6	2445.39	45	30	47	44
165	J-49	472000.7	998448.6	2446.03	46	30	46	44
166	J-50	471992.7	998448.6	2445.7	46	30	46	44
167	J-28	472099.7	998465.6	2446.31	26	11	44	42
168	J-33	472309.7	998501.6	2452	34	19	40	38
1211	J-147	473151.7	998045.1	2429.71	26	-23	59	55
1243	J-159	472737.7	998242.8	2454.59	15	35	15	38
1249	J-157	472687.7	997993.4	2430.78	38	57	39	62
1251	J-156	472641.5	998014.4	2430.47	38	57	39	62
1257	J-160	472740.9	998257.6	2455.46	42	34	42	37
1274	J-163	472546.2	998819.4	2483.79	25	6	36	8
1318	J-103	472476.9	998629.1	2475.79	16	0	16	14
1353	J-53	471995.9	998767.5	2456.16	23	-9	34	31
1367	J-72	472138	998512.5	2449.73	37	22	42	40
1371	J-63	472124	998564.8	2453.06	32	-5	38	34
1376	J-61	472055.7	998587.5	2453.19	31	-6	38	34
1378	J-55	471985.4	998566.1	2448.72	31	-2	42	38
1387	J-54	472030.5	998576.1	2451.54	28	-5	39	35
1398	J-56	472081.5	998647.7	2456.98	24	-9	34	30
1401	J-57	472080.2	998641.7	2456.76	24	-9	34	30
1416	J-158	472737.8	998233.7	2453.98	16	36	16	39
1424	J-52	472097.3	998640.3	2456.86	24	-8	34	30
1430	J-145	472696.6	998752.8	2477.91	35	12	43	15
1439	J-153	474522	999206.5	2471	47	27	50	28
1480	J-151	472312	999229.4	2484.9	24	6	35	6
1497	J-86	472993.8	998433.7	2448.84	23	42	42	43
1528	J-104	471975.9	998478.4	2445.93	46	-7	46	39
1582	J-114	472527.3	998803.5	2484	25	30	36	44
1589	J-115	472698.3	998768.6	2477.5	35	6	43	7
1592	J-116	472700.7	998766.4	2477.41	35	13	43	15
1780	J-139	472489	998588.7	2474.14	18	12	18	15
1796	J-140	472829.5	998706.2	2470.56	21	8	42	8
1847	J-143	472475.1	998625.7	2475.36	17	2	17	16
1853	J-144	472700.2	998768.3	2477.4	35	4	43	21
1899	J-149	472137	998517.8	2450.16	37	1	41	15
1996	J-151	473072.8	998752.3	2450.09	22	13	40	15
2174	J-184	472840.4	998293.9	2458.48	39	-3	39	37
2178	J-185	473095.5	998291.5	2433.84	21	-3	26	38
2183	J-186	472977.9	998295.1	2449.34	17	82	40	82
2187	J-187	473049.8	998728.8	2452.29	29	82	49	82
2198	J-190	472746.2	998551.6	2468.36	43	6	52	6

Annex J: - Velocity and pipe inventory report

ID	Label	Start Node	Stop Node	Length (Scaled) (m)	Diameter (mm)	Material	Installation	Hazen-Will	existing at low Velocity (m/s)	existing Velocity at peak (m/s)	optimized at low Velocity (m/s)	optimized Velocity (m/s)
2358	P-1	J-201	J-199	22	110	HDPE	0	55			0.3	0.73
2357	P-10	J-116	J-201	183	75	JISPV	1975	52.5			0.23	0.22
1354	P-100	J-9	J-53	58	50	JISPV	1975	52.5	0.23	0.72	0.12	0.52
1216	P-101	J-66	J-147	139	63	ISOPV	2010	52.5	0.24	0.74	0.02	0.77
1349	P-102	J-19	J-9	74	50	JISPV	1975	52.5	0.01	0.05	0.12	0.54
1307	P-103	J-32	J-25	226	50	JISPV	1975	52.5	0.04	0.15	0.14	0.71
1168	P-104	J-121	J-114	301	50	JISPV	1975	52.5	0.08	0.24	0.55	0.75
1256	P-105	J-130	J-132	226	90	ISOPV	1998	52.5	0.04	0.13	0.05	0.78
1403	P-106	J-57	J-7	118	63	ISOPV	2009	52.5	0.26	0.8	0.09	0.73
1253	P-107	J-156	J-131	228	90	ISOPV	1998	52.5	0.15	0.45	0.05	0.03
1167	P-108	J-127	J-121	28	50	JISPV	1975	52.5	0.11	0.35	0.35	0.57
2292	P-109	J-116	J-127	124	64	HDPE	2019	55			0.21	0.57
1295	P-11	J-38	J-36	17	90	ISOPV	2009	52.5	0.05	0.14	0.02	0.75
1425	P-110	J-18	J-52	70	50	JISPV	1975	52.5	0.09	0.28	0.14	0.88
1209	P-111	J-71	J-67	77	50	JISPV	1975	52.5	0.1	0.32	0.18	0.54
2274	P-112	J-106	J-194	3	64	HDPE	0	55	0.52	1.22	0.61	0.96
1164	P-113	J-109	J-88	147	50	JISPV	1975	52.5	1.33	4.13	0.19	1.31
1348	P-114	J-23	J-19	157	50	ISOPV	1975	52.5	0.12	0.37	0.16	1.03
1252	P-115	J-157	J-156	51	90	ISOPV	1998	52.5	0.03	0.09	0.06	1.02
2326	P-116	PRV-9	J-65	111	50	JISPV	1975	52.5			0.17	0.87
2325	P-117	J-67	PRV-9	4	50	JISPV	1975	52.5			0.17	0.87
1337	P-118	J-22	J-20	114	50	JISPV	1975	52.5	0.18	0.58	0.17	1.13
2315	P-119	J-75	PRV-6	5	63	ISOPV	1989	52.5			0	1.27
1215	P-12	J-62	J-66	67	63	ISOPV	2010	52.5	0.12	0.38	0.13	1
2316	P-120	PRV-6	J-70	130	63	ISOPV	1989	52.5			0	1.27
1200	P-121	J-99	J-95	114	63	ISOPV	1994	52.5	0.04	0.12	0.11	1
1250	P-122	J-135	J-157	250	90	ISOPV	1998	52.5	0.06	0.19	0.06	0.74
1400	P-123	J-56	J-10	43	63	ISOPV	2009	52.5	0.29	0.89	0.11	1.03
1304	P-124	J-36	J-28	262	50	JISPV	1975	52.5	0.24	0.7	0.18	0.94
1347	P-125	J-24	J-23	152	90	ISOPV	1990	52.5	0.04	0.14	0.06	1.26
1191	P-126	J-94	J-90	59	100	JISPV	1975	52.5	0.12	0.37	0.13	1.3
1227	P-127	J-108	J-102	240	63	ISOPV	1998	52.5	0.18	0.55	0.13	1.15
1262	P-128	J-119	J-45	290	63	ISOPV	2003	52.5	0.07	0.21	0.38	0.97
1163	P-129	J-113	J-109	6	50	JISPV	1975	52.5	0	0	0.24	2.04
1265	P-13	J-35	J-39	55	75	HDPE	2018	55	0.37	1.14	0.05	1.02
1261	P-130	J-133	J-119	27	63	ISOPV	2003	52.5	0.05	0.15	0.38	0.98
1208	P-131	J-68	J-67	58	50	JISPV	1975	52.5	0.38	1.17	0.21	1.45
1260	P-132	J-160	J-133	5	63	ISOPV	2003	52.5	0.11	0.34	0.4	1.13
1119	P-133	J-163	J-115	176	110	HDPE	2015	55	0.13	0.42	0.16	0.97
1099	P-134	J-163	J-115	175	110	HDPE	2015	55	0.11	0.29	0.17	1.48
2352	P-135	J-200	J-82	153	50	JISPV	1975	52.5			0.28	1.05
1306	P-136	J-35	J-32	137	75	HDPE	2018	55	0.1	0.3	0.11	1.02
1310	P-137	J-31	J-29	86	75	HDPE	2018	55	0.15	0.48	0.12	1.81
2180	P-138	J-185	J-80	192	50	JISPV	1975	52.5	0.14	0.43	0.44	1.81
2323	P-139	PRV-8	J-185	123	50	JISPV	1975	52.5			0.44	0.94
1226	P-14	J-102	J-98	140	50	JISPV	1975	52.5	0.03	0.08	0.17	1.81
2322	P-140	J-186	PRV-8	5	50	JISPV	1975	52.5			0.44	1.11
1408	P-141	J-131	J-130	9	75	ISOPV	2011	52.5	0	0.01	0.13	1.1
1317	P-142	J-39	J-31	106	75	HDPE	2018	55	0	0	0.14	0.27
2349	P-143	J-199	J-90	4	100	JISPV	1975	52.5			0.23	0.53
1157	P-144	J-143	J-122	10	63	ISOPV	2002	52.5	0.11	0.29	0.23	1.23
1402	P-145	J-15	J-57	78	63	ISOPV	2009	52.5	0.09	0.29	0.16	0.81
1297	P-146	J-46	J-40	221	75	ISOPV	1998	52.5	0.03	0.09	0.1	1.81
1254	P-147	J-135	J-131	89	75	ISOPV	2011	52.5	0.03	0.1	0.14	0.86
1407	P-148	J-107	J-105	18	50	JISPV	1975	52.5	0.02	0.06	0.26	0.52
1160	P-149	J-117	J-115	129	63	ISOPV	2003	52.5	0.05	0.14	0.31	1.58
1346	P-15	J-21	J-18	109	50	JISPV	1975	52.5	0.08	0.24	0.16	2.36
1207	P-150	J-81	J-68	90	50	JISPV	1975	52.5	0.32	0.98	0.25	1.27
1372	P-151	J-63	J-15	48	63	ISOPV	2009	52.5	0	0.01	0.16	0.76
2272	P-152	J-187	J-194	215	75	JISPV	1975	52.5	0.98	0.98	0.44	0.62
2353	P-153	J-199	J-200	8	110	HDPE	0	55			0.09	0.57
2304	P-154	J-123	J-196	153	75	JISPV	1975	52.5			0.02	1.5
1205	P-155	J-79	J-77	140	64	HDPE	2003	55	0.38	1.18	0.18	0.6
1159	P-156	J-120	J-117	45	63	ISOPV	2002	52.5	0.09	0.26	0.35	0.93
2295	P-157	J-122	J-120	40	63	ISOPV	2002	52.5			0.49	1.56
1184	P-158	J-83	J-75	241	63	ISOPV	1994	52.5	0.03	0.1	0.16	0.73
2288	P-159	J-116	PRV-4	12	75	JISPV	1975	52.5			0	0.61
1798	P-16	J-113	J-140	133	63	ISOPV	2002	52.5	0.32	0.99	0.51	0.73
2289	P-160	PRV-4	J-123	395	75	JISPV	1975	52.5			0	1.64
1373	P-161	J-149	J-63	50	63	ISOPV	2009	52.5	0.28	0.86	0.21	0.67
2305	P-162	J-196	J-118	10	75	JISPV	1975	52.5			0.17	0.84
1199	P-163	J-105	J-99	97	63	ISOPV	1994	52.5	0.36	1.13	0.21	0.59
1368	P-164	J-21	J-72	11	110	HDPE	2013	55	0.01	0.03	0.07	1.57
1298	P-165	J-49	J-46	29	75	ISOPV	1998	52.5	0.26	0.77	0.15	1.04
1781	P-166	J-48	J-139	40	250	Ductile Iro	2013	157.5	0.37	1.14	0.01	1.04
1782	P-167	J-139	J-49	511	250	Ductile Iro	2013	157.5	0.25	0.78	0.01	0.73
1222	P-168	J-83	J-81	84	110	HDPE	2011	55	0.23	0.71	0.03	0.65
2188	P-169	J-118	J-187	121	75	JISPV	1975	52.5	0.15	0.48	0.51	0.76
2302	P-17	J-187	J-84	8	64	HDPE	0	55			0.09	0

ID	Label	Start Node	Stop Node	Length (Scaled) (m)	Diameter (mm)	Material	Installation	Hazen-Will	existing at low Velocity (m/s)	existing Velocity at peak (m/s)	optimized at low Velocity (m/s)	optimized Velocity (m/s)
1498	P-170	J-90	J-86	8	110	HDPE	1975	55	0.03	0.09	0.07	0.76
1237	P-171	J-137	J-108	80	64	HDPE	1975	55	0.21	0.64	0.28	0.98
2186	P-172	J-186	J-59	9	64	HDPE	0	55	0.15	0.48	0.32	2.71
2356	P-173	J-194	J-201	93	75	JISPV	1975	52.5			0.89	1.46
1499	P-174	J-86	J-79	74	64	HDPE	1975	55	0.05	0.15	0.28	1.2
2207	P-175	J-41	J-37	64	75	HDPE	2018	55	0.52	1.22	0.15	2.56
1268	P-176	J-42	J-41	64	90	HDPE	2018	55	0.2	0.61	0.11	1.8
1271	P-177	J-44	J-42	41	90	HDPE	2018	55	0.36	1.12	0.11	1.16
1849	P-178	J-143	J-44	58	90	HDPE	2018	55	0.13	0.41	0.11	0.42
1593	P-179	J-146	J-116	2	75	JISPV	1975	52.5	0.05	0.16	0.16	9.8
1404	P-18	J-57	J-56	6	63	ISOPVC	2009	52.5	0.27	0.84	0.06	1.18
1848	P-180	J-48	J-143	2	90	HDPE	2018	55	0.1	0.31	0.11	1.1
1591	P-181	J-115	J-146	2	110	HDPE	2013	55	0.11	0.33	0.33	1.18
1238	P-182	J-137	J-135	14	110	HDPE	2011	55	0.09	0.28	0.12	0.63
1235	P-183	J-124	J-107	275	90	ISOPVC	1998	52.5	0.28	0.86	0.16	1.78
1236	P-184	J-125	J-124	9	90	ISOPVC	1998	52.5	0.1	0.32	0.17	3.53
1324	P-185	J-22	J-21	147	110	HDPE	2013	55	0	0	0.11	2.69
1232	P-186	J-136	J-125	31	90	HDPE	1998	55	0.42	1.29	0.18	1.87
1417	P-187	J-158	J-136	3	63	ISOPVC	1998	52.5	0.08	0.25	0.37	0.28
1418	P-188	J-139	J-158	2	90	ISOPVC	1998	52.5	0.04	0.13	0.22	1.02
1206	P-189	J-92	J-85	28	110	HDPE	1975	55	0.32	0.98	0.25	1.92
1797	P-19	J-140	J-118	246	63	ISOPVC	2002	52.5	0.07	0.22	0.5	4.52
1245	P-190	J-159	J-139	9	400	Ductile Iro	1955	157.5	0.17	0.52	0.01	0.72
1192	P-191	J-94	J-92	63	100	JISPV	1975	52.5	0.19	0.59	0.31	2.35
2184	P-192	J-85	J-186	6	50	JISPV	1975	52.5	0.13	0.39	0.97	1.57
1323	P-193	J-24	J-22	101	110	HDPE	2013	55	0	0.02	0.15	1.57
1319	P-194	J-103	J-48	2	100	Steel	1955	70	0	0.01	0.17	0.95
2214	P-195	J-91	J-83	90	110	HDPE	2015	55	0	0	0.12	2.62
2235	P-196	J-191	J-91	19	110	HDPE	2015	55	0	0	0.12	1.52
1322	P-197	J-103	J-24	129	110	HDPE	2013	55	0	0.02	0.19	2.08
1247	P-198	J-159	J-137	7	100	ISOPVC	1998	52.5	0.22	0.69	0.26	0.6
2234	P-199	J-100	J-191	139	110	HDPE	2015	55	0	0	0.02	1.81
1266	P-2	J-37	J-35	19	75	HDPE	2018	55	0.19	0.59	0.06	2.41
2348	P-20	J-151	J-199	331	100	JISPV	1975	52.5			0.03	0.94
2216	P-200	J-101	J-94	100	100	JISPV	1975	52.5	0	0	0.23	0.94
1175	P-201	J-113	J-111	11	100	JISPV	1975	52.5	0.48	1.5	0.49	2.12
2219	P-202	J-112	PRV-1	29	110	HDPE	2015	55	0.12	0.38	0	2.12
2220	P-203	PRV-1	J-100	140	110	HDPE	2015	55	0.01	0.02	0	1.65
2232	P-204	PRV-3	J-101	101	100	JISPV	1975	52.5	0	0	0.37	1.61
2231	P-205	J-111	PRV-3	28	100	JISPV	1975	52.5	0	0	0.37	1.23
2253	P-206	J-190	J-115	123	100	JISPV	1975	52.5	1.17	1.17	0.65	1.23
1162	P-207	J-115	J-113	6	100	JISPV	1975	52.5	0.05	0.14	0.76	0.59
2308	P-208	J-160	PRV-5	10	400	Ductile Iro	1955	157.5			0.03	1.99
2309	P-209	PRV-5	J-159	5	400	Ductile Iro	1955	157.5			0.03	0.72
1255	P-21	J-129	J-130	31	75	ISOPVC	2011	52.5	0.05	0.14	0.05	0.72
2229	P-210	PRV-2	J-103	9	150	Steel	1955	70	0.52	0.52	0.18	1.3
1583	P-211	J-163	J-114	25	250	Steel	1955	70	0.24	0.74	0.06	1.36
2228	P-212	J-114	PRV-2	181	150	Steel	1955	70	0.52	0.52	0.18	1.36
2200	P-213	J-190	J-112	6	110	Ductile Iro	2015	157.5	0.07	0.23	0.2	1.36
1258	P-214	J-138	J-160	31	400	Ductile Iro	1955	157.5	0.13	0.41	0.04	1.36
2176	P-215	J-184	J-138	112	350	Ductile Iro	2005	157.5	0.02	0.05	0.05	1.36
2319	P-216	PRV-7	J-184	81	350	Ductile Iro	2005	157.5			0.05	1.02
2318	P-217	J-140	PRV-7	29	350	Ductile Iro	2005	157.5			0.05	0.46
1151	P-218	J-142	J-140	193	350	Ductile Iro	2005	157.5	0.11	0.36	0.05	1.02
1275	P-219	J-150	J-163	143	400	Steel	1955	70	0.25	0.78	0	1.02
1971	P-22	J-71	J-147	11	64	ISOPVC	0	52.5	0.26	0.8	0.02	2.34
1482	P-220	J-151	J-150	329	250	ISOPVC	2012	52.5	0	0.01	0	0.93
1554	P-221	T-3	J-151	107	250	ISOPVC	2012	52.5	0.02	0.06	0	0.96
2250	P-222	J-142	J-190	6	110	HDPE	0	55	1.17	1.17	0.83	1.15
2312	P-223	J-143	J-142	101	350	Ductile Iro	2005	157.5			0.13	1.15
1431	P-224	J-145	J-143	125	400	Steel	1955	70	0.02	0.06	0.11	0.99
1855	P-225	J-144	J-146	2	200	Ductile Iro	1985	157.5	0.74	0.63	0.56	0.64
2098	P-226	J-155	J-144	514	200	Ductile Iro	1985	157.5	0.02	0.05	0.56	0.83
1432	P-227	J-146	J-145	14	350	Ductile Iro	1955	157.5	0	0.01	0.14	0.37
1486	P-228	J-155	T-3	957	500	Ductile Iro	1985	157.5	0	0	0	0.83
1640	P-229	T-2	J-131	3	500	Ductile Iro	1985	157.5	0.07	0.22	0.09	1.69
2351	P-23	J-86	J-200	4	50	JISPV	1975	52.5			0.16	1.69
1485	P-230	J-153	J-155	1816	500	Ductile Iro	1985	157.5	0.05	0.14	0.09	0.5
1671	P-231	J-131	PMP-1	3	350	Ductile Iro	1985	157.5	0.13	0.4	0.18	0.5
1672	P-232	PMP-1	J-153	3	350	Ductile Iro	1985	157.5	0.12	0.39	0.18	1.12
2015	P-233	J-156	T-2	7332	900	Steel	0	98	0.03	0.34	0.52	1.12
2027	P-234	J-160	J-156	6	900	Steel	0	98	0.07	0.23	0.52	0.5
2061	P-235	J-162	PMP-6	11	600	Steel	0	70	0	0	1.17	0.63
2062	P-236	PMP-6	J-160	6	600	Steel	0	70	0	0	1.17	0.09
2069	P-237	T-1	J-162	6	900	Steel	0	98	1.68	1.69	0.52	0.16
2071	P-238	R-1	T-1	18148	1400	Steel	1985	70	1.68	1.69	0.63	0.5
1329	P-24	J-13	J-12	16	100	JISPV	1975	52.5	0.06	0.2	0.01	0.54
1342	P-25	J-8	J-7	13	63	ISOPVC	2009	52.5	0.01	0.03	0.03	0.37
1357	P-26	J-9	J-52	134	90	HDPE	2011	55	0.07	0.21	0.01	0.02
1365	P-27	J-19	J-20	195	50	JISPV	1975	52.5	0	0	0.04	0.96

ID	Label	Start Node	Stop Node	Length (Scaled) (m)	Diameter (mm)	Material	Installation	Hazen-Will	existing at low Velocity (m/s)	existing Velocity at peak (m/s)	optimized at low Velocity (m/s)	optimized Velocity (m/s)
2199	P-28	J-122	J-190	109	110	Ductile Iro	2015	157.5	0	0	0.08	0.28
1328	P-29	J-14	J-13	80	100	JISPV	1975	52.5	0.04	0.14	0.01	0.24
1179	P-3	J-112	J-110	121	63	ISOPVC	2003	52.5	0.34	1.07	0.5	0
1352	P-30	J-6	J-7	120	50	JISPV	1975	52.5	0.13	0.42	0.03	0.08
1997	P-31	J-89	J-151	325	100	JISPV	1975	52.5	0	0	0.01	0.15
1327	P-32	J-16	J-14	98	100	JISPV	1975	52.5	0.02	0.05	0.01	1.69
1380	P-33	J-55	J-16	57	50	JISPV	1975	52.5	0.04	0.11	0.01	0.36
1305	P-34	J-33	J-34	103	63	ISOPVC	2004	52.5	0.08	0.26	0.01	0
1231	P-35	J-126	J-125	27	63	ISOPVC	1998	52.5	0.19	0.6	0.01	0
1294	P-36	J-34	J-36	51	75	HDPE	2018	55	0.05	0.16	0.05	0
1850	P-37	J-51	J-143	49	110	HDPE	2018	55	0.03	0.34	0	0.58
1291	P-38	J-50	J-49	8	250	Ductile Iro	2013	157.5	0.05	0.16	0	0
2059	P-39	PMP-5	J-160	7	600	Ductile Iro	0	91	0.83	0.83	0	0
1178	P-4	J-110	J-111	9	63	ISOPVC	2003	52.5	0.39	1.22	0.43	2.02
2056	P-40	PMP-4	J-160	11	600	Steel	0	98	0.22	0.57	0	0
2055	P-41	J-162	PMP-4	5	600	Steel	0	70	0.46	1.43	0	0
2301	P-42	J-195	J-84	118	50	JISPV	1975	52.5			0	0.79
1193	P-43	J-93	J-92	103	100	JISPV	1975	52.5	0.44	1.36	0	0
1326	P-44	J-17	J-16	45	100	JISPV	1975	52.5	0.05	0.13	0	0
2300	P-45	J-88	J-195	3	50	JISPV	1975	52.5			0	0
1529	P-46	J-103	J-104	529	200	Ductile Iro	2012	157.5	0.01	0.04	0	0.56
2058	P-47	PMP-5	J-162	6	600	Steel	0	70	0.32	1	0	0
1955	P-48	J-131	PMP-3	3	350	Ductile Iro	1985	157.5	0.78	2.43	0	0
1667	P-49	J-131	PMP-2	2	350	Ductile Iro	1985	157.5	0.13	0.41	0	0
2359	P-5	J-72	J-149	5	110	HDPE	0	55			0.07	1.41
1956	P-50	PMP-3	J-153	4	350	Ductile Iro	1985	157.5	0.45	1.41	0	0.04
1668	P-51	PMP-2	J-153	3	350	Ductile Iro	1985	157.5	0.36	1.12	0	0.18
1282	P-52	J-74	J-58	51	63	ISOPVC	1989	52.5	0.01	0.04	0	0.04
1230	P-53	J-128	J-126	242	63	ISOPVC	1998	52.5	0.19	0.58	0.01	0.04
1283	P-54	J-74	J-73	22	63	ISOPVC	1989	52.5	0.23	0.72	0	0.09
1169	P-55	J-121	J-120	10	63	ISOPVC	2002	52.5	0.47	1.46	0.12	0.09
1284	P-56	J-76	J-74	34	63	ISOPVC	1989	52.5	0.06	0.2	0	1.86
1285	P-57	J-140	J-76	190	63	ISOPVC	1989	52.5	0.06	0.18	0	0.07
1369	P-58	J-72	J-17	161	110	HDPE	2013	55	0.01	0.03	0	0.03
1195	P-59	J-107	J-93	170	50	JISPV	1975	52.5	0.4	1.26	0.02	0.43
1213	P-6	J-59	J-62	90	63	ISOPVC	2010	52.5	0.12	0.37	0.23	0.54
1344	P-60	J-8	J-14	71	50	ISOPVC	1975	52.5	0.14	0.43	0.02	0.07
1330	P-61	J-12	J-11	89	100	JISPV	1975	52.5	0.13	0.4	0	0.63
1156	P-62	J-139	J-144	246	400	Ductile Iro	1955	157.5	0	0.01	0	0.54
1366	P-63	J-70	J-64	181	50	JISPV	1975	52.5	0.01	0.02	0.15	0.59
1293	P-64	J-37	J-34	66	75	HDPE	2018	55	0.14	0.42	0.08	0.62
1343	P-65	J-8	J-13	78	63	ISOPVC	2009	52.5	0.12	0.36	0.02	1.59
1219	P-66	J-68	J-66	7	63	ISOPVC	2010	52.5	0.08	0.24	0	0.36
1225	P-67	J-99	J-98	228	50	JISPV	1975	52.5	0.28	0.88	0.02	0.16
1204	P-68	J-79	J-78	58	64	HDPE	2003	55	0.46	1.42	0.03	0.16
1375	P-69	J-63	J-61	87	64	HDPE	2009	55	0.11	0.34	0.03	0.22
1188	P-7	J-111	J-106	104	50	JISPV	1975	52.5	0.42	1.31	1.12	0.92
2306	P-70	J-114	J-196	7	64	HDPE	0	55			0.26	0.69
1351	P-71	J-6	J-5	173	64	HDPE	2010	55	0.07	0.22	0.02	0.79
1390	P-72	J-55	J-54	50	64	HDPE	2016	55	0.02	0.07	0.02	0.44
1356	P-73	J-53	J-4	142	50	JISPV	1975	52.5	0.13	0.39	0.04	0.72
1165	P-74	J-88	J-87	73	75	JISPV	1998	52.5	0.06	0.19	0.03	0.41
2226	P-75	J-70	J-69	166	63	ISOPVC	1989	52.5	0.03	0.09	0.03	0.7
1312	P-76	J-29	J-30	378	100	ISOPVC	2015	52.5	0.15	0.48	0.01	0.29
1187	P-77	J-100	J-101	106	50	JISPV	1975	52.5	0.15	0.47	0.27	0.14
1223	P-78	J-95	J-96	145	63	ISOPVC	1989	52.5	0.12	0.36	0.03	1.21
1379	P-79	J-10	J-55	106	50	JISPV	1975	52.5	0.04	0.12	0.05	0.88
1296	P-8	J-40	J-38	239	90	ISOPVC	2009	52.5	0.04	0.11	0.04	0.31
1338	P-80	J-20	J-18	32	50	JISPV	1975	52.5	0.08	0.27	0.06	1.42
1355	P-81	J-53	J-6	3	50	JISPV	1955	52.5	0.19	0.59	0.05	0
1851	P-82	J-80	J-64	81	50	JISPV	1975	52.5	0.83	0.83	0.24	0.76
1221	P-83	J-81	J-85	77	50	JISPV	1975	52.5	0.02	0.05	0.21	0.82
1340	P-84	J-10	J-12	181	63	ISOPVC	2009	52.5	0.18	0.56	0.04	0.61
1409	P-85	J-134	J-128	82	63	ISOPVC	1998	52.5	0.15	0.47	0.05	0.06
1201	P-86	J-95	J-97	202	63	ISOPVC	1989	52.5	0.11	0.35	0.04	0.67
1224	P-87	J-96	J-97	123	63	ISOPVC	1989	52.5	0.05	0.14	0.05	0.21
1303	P-88	J-46	J-38	360	50	JISPV	1975	52.5	0.24	0.71	0.07	0.82
1399	P-89	J-52	J-56	17	63	ISOPVC	2009	52.5	0.02	0.06	0.05	0.61
2269	P-9	J-191	J-116	6	110	HDPE	0	55	0.52	0.52	0.11	1.8
1308	P-90	J-25	J-26	184	50	JISPV	1975	52.5	0.16	0.52	0.08	0.69
1264	P-91	J-45	J-39	29	75	HDPE	2018	55	0.06	0.18	0.2	1.02
1220	P-92	J-62	J-60	94	63	ISOPVC	2010	52.5	0	0	0.06	0.2
1309	P-93	J-32	J-31	71	75	HDPE	2018	55	0.21	0.68	0.04	0.91
1419	P-94	J-158	J-134	250	90	ISOPVC	1998	52.5	0.02	0.07	0.04	0.6
1263	P-95	J-45	J-43	132	63	ISOPVC	2003	52.5	0.08	0.24	0.08	0.26
1228	P-96	J-108	J-105	267	50	JISPV	1975	52.5	0.27	0.85	0.12	0.36
1210	P-97	J-75	J-71	19	50	JISPV	1975	52.5	0.03	0.08	0.23	0.37
1229	P-98	J-98	J-96	235	63	ISOPVC	1989	52.5	0.59	1.84	0.07	0.23
1316	P-99	J-29	J-27	246	63	ISOPVC	2015	52.5	0.01	0.13	0.07	0.22