AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

ADDIS ABABA UNIVERSITY

Evaluation of The Hydraulic Performance Of Water Supply Distribution Systems Using WaterGEMS for Optimal Water Management: A case of *Nifas Silk-Lafto* Sub-city, Addis Ababa, Ethiopia

By:

Ismail Abib

Advisor

Tamru Tesseme (PhD)

A Master's thesis submitted to the 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)

Date: June 23, 2024

Addis Ababa, Ethiopia

Africa Center of Excellence for Water Management

Addis Ababa University

School of Graduate Studies

Evaluation Of The Hydraulic Performance Of Water Supply Distribution Systems Using WaterGEMS For Optimal Water Management: A case of *Nifas Silk-Lafto* Sub-city, Addis Ababa, Ethiopia

By:

Ismail Abib

A Master's thesis submitted to the 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:

Tamru Tesseme (PhD)

Date: June 23, 2024
Addis Ababa, Ethiopia

AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT ADDIS ABABA UNIVRSITY

Evaluation of The Hydraulic Performance Of Water Supply Distribution Systems Using Watergems for Optimal Water Management: A case of Nifas Silk-Lafto Sub-city, Addis Ababa, Ethiopia

By:
(Ismail Abib)

A MASTER'S THESIS SUBMITTED TO
AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT
ADDIS ABABA UNIVERSITY

APPROVED 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 proposal for The Degree of Master of Science in Water Management (Water Supply and Sanitation)

S.No	**Title**	**Name**	**Signature**	**Date**
1.	Advisor	Tamru Tesseme Aragaw (Ph.D.)	---------------------	______________
2.	Examiner:		-----------------------	______________
3.	Examiner:		-----------------------	______________
4.	Chairperson		----------------------	______________

Declaration

I, Ismail Abib (GSR/1436/15), hereby declare that this MSc research thesis, titled "**Evaluation of The Hydraulic Performance Of Water Supply Distribution Systems Using Watergems for Optimal Water Management: *A Case of Nifas Silk-Lafto Sub-city*, Addis Ababa, Ethiopia**," is my original work and has not been submitted to any other institution for the award of any academic qualification. All sources and references from other scholars' work have been appropriately cited and referenced. The content of this thesis is entirely original.

Candidate Name	**Signature**	**Date**
Ismail Abib	--------------------------	-----------------------

Acknowledgements

I extend my sincerest gratitude to the Almighty, GOD the Creator, whose boundless grace and guidance have illuminated my path throughout this academic journey.

I am deeply indebted to the Africa Center of Excellence for Water Management (ACEWM), a distinguished institution within Addis Ababa University, in partnership with the World Bank, for the invaluable scholarship opportunity extended to me. This scholarship has not only facilitated my academic pursuits but has also enriched my understanding of water management in profound ways.

My heartfelt appreciation goes out to all the dedicated staff members of ACEWM for their unwavering support and encouragement. I am particularly grateful to the instructors whose wealth of knowledge and expertise have been instrumental in shaping my intellectual growth.

I would also like to express my gratitude to the Addis Ababa Water and Sewerage Authority (AAWSA) for their generous assistance in providing the essential data necessary for the completion of this project. Their cooperation has been indispensable in enabling me to conduct thorough research and analysis.

Special thanks are due to my thesis supervisor, Dr Tamru Tesseme, whose guidance, patience, and mentorship have been invaluable throughout this endeavour. His insightful feedback and constructive criticism have significantly contributed to the refinement of this thesis.

Finally, I extend my appreciation to all those who have supported me directly or indirectly, whether through encouragement, advice, or assistance of any kind. Your belief in me has been a constant source of motivation, and for that, I am truly grateful.

This thesis would not have been possible without the collective efforts and support of all mentioned above, and for that, I am profoundly thankful.

Abstract

Ensuring an adequate and sustainable potable water supply in urban areas of developing countries is often challenging. This study aimed to evaluate the performance of the water supply system in Nifas Silk Lafto, Addis Ababa, Ethiopia using WaterGEMs. The study also examined the water supply distribution system of the sub-city, focusing on the challenges and opportunities for improvement. The Water Geospatial Engineering Modeling System (WaterGEMS) was employed to analyse the hydraulic performance of the distribution network. An intermittent supply and continuous supply scenarios were created based on customer meter data to check the system performance and ability to meet the current demand in the sub-city. Non-Revenue Water NRW and water coverage were also assessed to discover supply adequacy and overall losses. In the intermittent supply scenario, analysis showed that 95% of nodes receive optimal pressure within the range of (15-70 meters). In contrast, Continuous modelling results in only 27% of nodes having pressure within the range. Approximately, 72.3% of nodes experienced excessive pressure exceeding (>70 meters), risking infrastructure issues. The performance analysis demonstrated that nearly 87% of pipes operate below the optimal minimum velocity (0.6 m/s) and 11.78% of pipes operate within the recommended velocity. The results also indicated that the maximum daily water demand exceeds production by 29,990.28 m³/d, resulting in 58% of the water supply for residents. Non-revenue water computation exemplified about 55% of total service water, highlighting a need for better management practices. The study findings highlight that pressure management strategies must address excessive pressure, optimise flow velocities to ensure efficient water distribution, and target interventions to bridge the significant supply and demand gap. The study also suggests implementing a systematic leak detection program using advanced technologies like acoustic sensors and ground-penetrating radar. Regularly inspect and maintain infrastructure, meter connections with high-accuracy meters, and increase surveillance through remote monitoring. Conduct water balance analyses and develop alternative water sources, ensure sustainable management, and involve communities in planning and education.

Key Words: *Nifas Silk Lafto, Addis Ababa, WaterGEMS, Hydraulic Performance Evaluations, Supply Distribution*

Table of Contents

Acronyms and Abbreviation

AAWSA	Addis Ababa Water and Sewerage Authority
ADD	Average Daily Demand
CAD	Computer-aided Design
CSA	Central Statistical Agency
GEMS	Geospatial Engineering Modeling System
GIS	Geographical Information System
GPS	Geographical Position System
GTP	Growth and Transformation Plan
PRVs	Pressure Regulating Valves
USA	United States of America
USEPA	United States Environmental Protection Agency
VSDs	Variable Speed Drives
VSPs	Variable Speed Pumps
WDNs	water distribution networks
WDS	Water Distribution System

List of Tables

List of Figures

CHAPTER ONE

1. Introduction

1.1 Background

Water, essential for sustaining life and promoting socio-economic development, poses a significant global challenge in maintaining a reliable and sustainable supply. The World Health Organization (2022) Reports indicate that around two billion people globally, mostly in developing countries, do not have access to safe drinking water services. This issue is anticipated to worsen due to increasing water demand and decreasing supply. (Heryanto et al., 2021). Water distribution systems, and essential infrastructures delivering quality water at adequate pressure to consumers, require thorough evaluation to facilitate informed decision-making for their effective operation.

In ageing systems, the deterioration of pipelines necessitates targeted upgrades and replacements to uphold functionality (Ainsworth, 2004). While countries like Ethiopia have made strides in addressing historical water access disparities, expanding services often comes at the expense of maintaining existing infrastructure (van Zyl, 2014). Ethiopia's burgeoning population, industrialization, and urbanization have heightened water demand, underscoring the need to overcome challenges and ensure reliable, sustainable drinking water access. The Ethiopian government's ambition to achieve 100% urban clean water coverage aligns with global sustainability goals.

Hydraulic analysis, a longstanding engineering practice, is crucial for assessing flows and pressures in distribution systems. This practice, introduced by Hardy Cross in 2015 (David, 2015), is integral to water supply networks, which comprise pipes, hydraulic equipment, and storage facilities (Shinde, 2018). The hydraulic performance of water distribution systems, influenced by factors such as pump conditions, network layout, pipe materials, and age, is evaluated based on their capacity to meet demand with adequate pressure under various conditions (Hunde & Itefa, 2020). Enhancing hydraulic performance aims to supply specific demand points with suitable flow and pressure while minimizing parameter fluctuations (Jalal et al., 2008). National standards dictate operating pressures between 15–60 meters under normal circumstances and 10–70 meters during exceptional situations, with water velocities ideally ranging from 0.6 to 2 meters per second. However, in looped systems, pipelines with zero velocity can be found (MoWR, 2006).

MoMoreover, According to a preliminary evaluation of the town's water services, there are significant water shortages, days or weeks of frequent supply outages, high rates of water loss in the distribution system, insufficient storage capacity, and poor system maintenance. Addis Ababa, the largest political and commercial hub of Ethiopia, serves as the host city for numerous international organizations and embassies, including the African Union. As of March 2011, data from the Addis Ababa Water Supply and Sewerage Authority (AAWSA) indicate that 23% of the city's area lacks water supply coverage. Consequently, AAWSA faces a significant challenge in ensuring the provision of sufficient and high-quality water to meet the diverse needs of the city's population, thereby maintaining its status and functionality. (Seifemicheal, 2018). The researchers conducted a thorough analysis of the water supply services in response to this assessment to gain a better understanding of the current performance levels and to help them decide how best to improve the system. Despite the widespread application of the WaterGEMS model in various parts of Addis Ababa, there is a scarcity of studies analyzing the city's water system performance in terms of demand and supply. (Alemu, & Dioha, 2020). In this context, the evaluation of water supply systems becomes imperative to ensure adequate provision for growing populations.

Therefore, immediate research shall be conducted to further study the system's performance and assess the current operational problems in the system. This study focuses on assessing the performance of the water supply system in Nifas Silk Lafto, Addis Ababa, Ethiopia. By employing the Water Geospatial Engineering Modeling System (WaterGEMS), a comprehensive analysis is conducted to understand the dynamics of the water distribution network. The research delves into the intricacies of the water supply and distribution system, emphasizing the existing challenges and opportunities for enhancement.

1.2 Problem Statement

According to (Behailu et al, .2016), their study highlights that the critical need for addressing these challenges is to ensure reliable and sustainable water provision. Stating that the primary obstacles faced by water supply systems in urban areas and small towns across Ethiopia predominantly revolve around service disruptions and inadequate supply. In most countries water supply industries, one of the most urgent problems is the water network's recurrent and persistent failures. The Addis Ababa town water supply infrastructure is currently dealing with a lot of strain as the city population has grown rapidly over the past decades. However, Water managers and engineers working toward a dependable network are burdened by the absence of the geospatial locations for various accessories linked to the supply and control processes of water network components in the water distribution network model. Moreover, Nifas Silk's last district in Addis Ababa town is facing inadequate water supply, system water loss, uneven area coverage, uneven pressure distribution within the system, and inconsistent water distribution, which results in uneven water delivery to customers. These issues are linked to sectorial management, economical water scarcity and illegal connections. Along with an increase in population, unplanned city growth has also been noted, driving up the rate of urbanization and the infrastructure needed to provide services. However, no research has been done to assess the hydraulic performance of the water supply distribution system over the study area. This study paper initiated and conducted a detailed study on the current performance of Nifas Silk Lafto district water system network distribution focusing on the hydraulic performance of the system, water supply coverage, water demand & and supply analysis, loss and total distribution system condition assessment.

1.3 Objectives of study

1.3.1 General Objective

The general objective of the study is to evaluate the hydraulic performance of Nifas Silk-Lafto sub-city water supply distribution systems using WaterGEMS for optimal water management

1.3.2 Specific Objectives

- Assess the water supply coverage within the Nifas Silk-Lafto district by analysing the per capita connection from the annual total water consumption.
- To evaluate the hydraulic performance of the existing water distribution system using Watergems that produce assessable pressure and velocity in the distribution model
- To estimate NRW to assess the system water supply losses from overall distribution networks.
- Provide valuable recommendations for urban water distribution management sector through the findings of hydraulic evaluation and modelling.

1.4 Research Questions

- How does the hydraulic performance of the existing water distribution system, assessed using WaterGEMS to generate assessable pressure and velocity in the distribution model, compare to established standards or benchmarks?
- What is the estimated non-revenue water (NRW) within the distribution network, and how does this assessment contribute to understanding the system's water supply losses?

- What is the extent of water supply coverage within the Nifas Silk-Lafto district, and how does it correlate with per capita connection figures derived from annual total water consumption data?
- What are the findings from hydraulic evaluation and modelling be recommended to inform to urban water distribution management in decision making?

1.5 Significance of Study

The findings of this study will serve as a valuable resource and foundational reference for demonstrating the optimal management of the district's current water supply distribution system. It provides critical insights, highlighting that the primary reason for the underperformance of the water distribution system is the loss of a reliable network system. Due to the system's frequent irregular delivery of water to town customers, the Nifas Silk Lafto district water supply distribution network's performance has emerged as one of the most important issues facing the nation's water supply sector and calls for immediate attention. Therefore, assessing and conducting hydraulic analysis via modelling is important to know the problems of the system. The study highlights gives insight for water managers and future researchers to further examine the effect with similar studies. In this sense, the study's findings are important for helping decision-makers plan, upgrade and create a hydraulically functioning water delivery system that can deliver water to customers in a quantity that can accommodate a range of water demands while maintaining the same level of purity and the necessary pressure head. By implementing the recommendations suggested by the associated research projects, the results of this study can close relevant gaps in previous research and provide baseline data for scientific information on the future planning of the development of water supply systems for better management.

CHAPTER TWO

2. Literature Review

2.1 Background

Water supply distribution systems are indispensable and critical infrastructures within urban settings, playing a pivotal role in guaranteeing residents' access to safe and dependable water. Efficient management of these systems is crucial to tackling issues like water scarcity, leakage, and inefficiencies in distribution. Several studies have been conducted to evaluate the performance of water supply networks and propose improvement strategies specifically in Nifas Silk-Lafto, Addis Ababa, Ethiopia.

A study by Tesfaye et al. (2018) delves into the challenges confronting water supply systems in Addis Ababa, shedding light on issues such as non-revenue water and infrastructure maintenance. This research underscores the significance of employing hydraulic modelling tools to pinpoint leakage points and boost system efficiency. Additionally, Abera and Tefera conducted an exhaustive analysis of the water distribution network in Addis Ababa, concentrating on pressure management and leakage reduction strategies. Their study underscores the importance of precise hydraulic modelling in identifying high-pressure zones and implementing measures to curtail water loss.

Tefera et al. utilized WaterGEMS software to simulate and analyze water distribution networks in urban areas of Ethiopia, including Addis Ababa. Their study showcases the efficacy of WaterGEMS in replicating flow patterns, identifying system bottlenecks, and optimizing design parameters for enhanced water management. Additionally, Mekonnen and Hoekstra highlight the worldwide challenge of water scarcity, underlining the importance of sustainable water management practices in urban areas. Their research emphasizes the need for comprehensive approaches that include both supply-side and demand-side management strategies to secure water resources and enhance resilience.

These studies discovered that water supply distribution systems are crucial for providing safe water to urban residents. Effective management of these systems addresses key challenges such as water scarcity, leakage, and distribution inefficiencies. In Addis Ababa, various studies have been conducted to evaluate water supply network performance and propose improvements. Utilizing tools like hydraulic modelling is essential for identifying problems such as leaks and enhancing system performance. Software like WaterGEMS is used to simulate flow patterns, identify issues, and optimize design parameters in water distribution networks. Sustainable water management requires integrated approaches that consider both supply and demand aspects to ensure water security and resilience

2.2 Modelling Softwares review

WaterGEMS V8i is a sophisticated hydraulic modeling software designed for water distribution systems, offering advanced tools for geospatial modeling, optimization, and asset management, as detailed in various journals. It supports a wide range of analyses, including fire flow assessments, constituent concentration evaluations, energy consumption monitoring, and capital cost management. Engineers benefit from its intuitive interface, which facilitates the analysis, design, and optimization of water distribution systems. The software centralizes essential data within a GIS environment, streamlining data handling and enabling comprehensive system evaluations. Sharing similar features, WaterCAD V8i emphasizes streamlined model building, integration with GIS and AutoCAD, and optimized design and operational capabilities. WaterGEMS V8i excels in presenting results attractively through various graphical tools, enhancing communication and understanding of system performance.

Moreover, WATERGEMS V8i serves as a versatile hydraulic and water quality modelling tool for water distribution systems, integrating advanced interoperability features, geospatial model development, optimization tools, and asset management functionalities. Its capabilities extend to various analyses, including fire flow assessments, constituent concentration evaluations, energy usage monitoring, and capital cost management. The user-friendly environment of WATERGEMS V8i empowers engineers to navigate through complex tasks with ease, enhancing their ability to improve water distribution systems effectively.

One of the key strengths of WATERGEMS V8i lies in its ability to centralize water system data, time-series hydraulic results, current and future scenarios, and other essential infrastructure data within a unified GIS environment. This integration streamlines data management and analysis processes, facilitating informed decision-making and comprehensive system evaluations (Mehta et al., 2017).

Furthermore, WaterCAD V8i shares many features and functionalities with WATERGEMS V8i, such as simplified model construction, seamless integration with GIS and AutoCAD tools, optimized model calibration, and efficient design and operational capabilities. Notably, WATERGEMS V8i excels in presenting results in a visually appealing manner, offering a range of graphical tools like ArcMap visualization, thematic mapping, contouring, and colour-coded profiling with symbology. This enhances the communication of findings and facilitates a deeper understanding of system performance.

With a growing user base, WATERGEMS V8i has solidified its position as a leading and user-friendly hydraulic modelling and optimization software package. Its robust design algorithm ensures accuracy in designing water distribution networks and effectively controlling variables like flow, pressure, and velocity, while also optimizing system performance (Sonaje & Joshi, 2015).

WaterCAD V8i (2014) is a comprehensive hydraulic modelling software package that offers a diverse array of functionalities, including graphical enhancements, profiling tools, flexible data archiving, and customizable GUI features. This software excels in providing advanced capabilities for hydraulic and water quality analysis, steady state simulations, extended period simulations, and robust data management. WaterCAD V8i integrates seamlessly with AutoCAD and GIS, enhancing its versatility and usability for engineers working on water distribution systems.

One of the key strengths of WaterCAD V8i lies in its simplified model-building process, supported by geospatial modules and tools like LoadBuilder and TRex. This software also facilitates water quality modelling, fire flow analysis, optimization, and scenario management, offering engineers a user-friendly and adaptable platform for various applications (Sonaje & Joshi, 2015).

On the other hand, Pipe Flow Expert is specifically designed to assist engineers in solving a wide range of hydraulic problems related to determining pressure losses, pumping requirements, and flow rates within a pipe network. This software enables users to create pipeline systems, analyze their performance during flow, calculate pressure conditions, and establish a balanced steady flow within the system. Pipe Flow Expert also allows for the analysis of alternative systems under different operating conditions, providing engineers with a comprehensive tool for hydraulic system evaluation (Kusnayat, A. et al., 2019).

These studies show that WaterCAD V8i provides advanced graphical tools, profiling capabilities, flexible data handling, and customizable GUI features for hydraulic modelling. It supports hydraulic and water quality analysis, steady state and extended period simulations, and integrates well with AutoCAD and GIS. The software excels in simplified model building, geospatial tools, water quality modelling, fire flow analysis, and scenario management, making it versatile and user-friendly. Pipe Flow Expert, on the other hand, is designed for analyzing hydraulic problems in pipe networks, calculating pressure losses, pumping requirements, and flow rates, and evaluating system performance under various conditions. Both WaterCAD V8i and Pipe Flow Expert offer engineers specialized tools for hydraulic system analysis, each tailored to address specific challenges in water distribution systems and pipe networks. In general, WaterCAD V8i and Pipe Flow Expert serve as valuable resources for engineers involved in hydraulic modelling and analysis, offering specialized features and functionalities tailored to address diverse challenges in water distribution systems and pipe networks.

EPANET (2014) is a versatile public domain software used for designing various types of water distribution networks. It offers numerous benefits, including water quality analysis, extended period simulation, and residual chlorine calculations for disinfection. Additionally, it can be employed to renovate or restore existing water supply systems. Known as EPANET 2.0 and EPANET 2d-2w, this software is publicly available (Sonaje & Joshi, 2015).

Developed by the USA Environmental Protection Agency, EPANET is intended for general public and educational use and is freely accessible online. It serves as a learning tool to enhance understanding of the behaviour and outcomes of drinking-water components within distribution systems. EPANET allows for extended simulations of hydraulic and water-quality behaviour within pressurized pipe networks. The software comes as both an independent program and an open-source toolkit, utilizing the ".inp" input file format (Cristina & Karna, Kalyan, 2022). Its free availability, minimal computer space requirements, and ability to analyze an unlimited number of pipes make it especially advantageous for students, researchers, and professionals in developing economies who may lack the financial resources for more sophisticated tools. EPANET has gained widespread popularity for analyzing both complex and simple water distribution networks globally. Its simulation capabilities are utilized by professionals and researchers in designing, operating, and improving various water network distribution systems. Notable applications of EPANET in solving and optimizing water distribution network problems have been documented by Fabunmi (2010), Guidolin et al. (2010), and Abubakar and Sagir (2013).

A water distribution system (WDS) consists of three main components: pumps, storage tanks, and piping networks. Most water distribution systems require pumps to provide additional heads to overcome friction losses. Several common WDS analysis software, such as WaterCAD and EPANET, are widely used in the planning and maintenance of WDS. These software solutions enable cost and time-efficient planning, maintenance, and evaluation of WDS by simulating and calculating the necessary hydraulic analyses (Kusnayat et al., 2019).

These researches indicate that EPANET offers a range of features including water quality analysis, extended period simulation, residual chlorine calculations, and the capability to renovate existing water supply systems. Developed by the EPA for public and educational use, EPANET is freely available online both as an independent program and as an open-source toolkit. Its free availability, minimal computer space requirements, and ability to analyze an unlimited number of pipes make it particularly advantageous for users with limited financial resources. The software is widely used globally for analyzing both complex and simple water distribution networks, with numerous applications documented by various researchers. A standard water distribution system (WDS) includes essential components like pumps, storage tanks, and piping networks. Pumps are crucial for providing the required head to counteract friction losses within the system. Software tools such as WaterCAD and EPANET are frequently used for planning, maintaining, and assessing WDS, as they offer efficient simulation and hydraulic analysis capabilities.

2.3 Evaluation of water distribution system performance

A water distribution system is a complex arrangement of hydraulic control components that facilitates the movement of water from its sources to end-users, encompassing the condition of all pipes within the network (Hunde and Itefa, 2020). This elaborate infrastructure includes essential hydraulic elements such as pipes, valves, reservoirs, pumps, and pump stations, which are crucial for fulfilling the water needs of communities (Pietrucha and Tchurzewska, 2018). These systems are dynamic, designed to transport water from the source to consumers' taps while ensuring adequate demand, pressure, and flow are maintained in real-time (Abebe, 2020).

The quality of service provided by a water utility is assessed based on how effectively and efficiently its distribution network delivers the required quantity of water at adequate pressure and acceptable velocity under varying operational conditions (Hamza et al., 2021; Milkecha & Itefa, 2020). Factors such as the condition of pumping units, network design, pipe material, and pipe age influence the performance of the water supply system, impacting issues like pipe failure, leakage, and excessive demand (Geleta & Fufa, 2021). Improving the hydraulic performance of a water distribution system is essential, as it ensures the proper flow and pressure to specific demand points while minimizing significant variations in these parameters (Beyene, 2020).

As per national standards, the pressure in a distribution network should typically range from 15 to 60 meters, with allowances of 10 to 70 meters under exceptional conditions. The ideal water velocity is between 0.6 and 2 meters per second, although in some looped system pipelines, zero velocity can occur (Milkecha and Itefa, 2020). The capacity to meet demand and maintain system performance has a significant impact on a region's socio-economic activities. For example, inadequate water supply often forces children and women to fetch water daily from distant, unimproved sources such as hand-dug wells, rivers, and springs (Mekonnen and Yitbarek, 2023). Water modelling software plays a pivotal role in simulating and predicting water behaviour and transportation within distribution systems. These tools help conserve system resources, maintain water quality, and meet demand. Prior to project implementation, numerical hydraulic simulations are conducted to forecast and evaluate outcomes across various scenarios. These simulations are essential for assessing environmental impacts and form the basis for water management decisions. They deliver critical data to water resource agencies, engineers, and designers, facilitating construction project execution and providing technical direction (Awe, 2019)

2.4 Effect of distribution system fluctuation

Regarding challenges to the supply distribution problems, recent studies show Intermittent water supply systems, which operate based on pressure heads at nodes, are particularly vulnerable to unequal water distribution, especially during periods of water scarcity. To mitigate this issue, design considerations such as maintaining pressure head variances within specified ranges or dividing zones into smaller areas can help ensure a more equitable distribution of water. However, water distribution systems (WDS) face a multitude of challenges, including population growth, system expansion, and water pollution, which can compromise both the quality and quantity of water reaching consumers. Additionally, WDS often encounter common problems such as designing new networks, modifying existing ones, managing unexpected service connections, and dealing with ageing infrastructure issues. Given these complexities, it is essential to conduct regular reviews of WDS, incorporating scenario analysis to anticipate and address the impacts of global pressures and changing demands, thereby ensuring optimal system performance and meeting evolving needs. Intermittent water supply systems are designed and operated with considerations for free flow ports and pressure heads at various nodes. The discharge at junctions is directly influenced by the available pressure head at each node, causing variations in the water delivered. However, this factor is frequently neglected in the design of water distribution systems.

During water shortages, unequal distribution becomes more critical, as some nodes receive more water than others, resulting in an unfair allocation. Design guidelines suggest maintaining a specified range of pressure head variance among nodes within a distribution zone or subdividing the region into smaller zones to address this issue (Gottipati & Nanduri, 2014).

Typically, water distribution systems are designed and built for long-term use, taking into account factors such as population growth, system expansion needs, pipe length, diameter, and pump capacity. The growing threat of water pollution adversely affects the quality of life in society. Consumers in certain areas face challenges related to both the quality and quantity of water supplied to them through the outlet. Neelakantan et al. identified common problems faced by water distribution systems (WDS) in designing new networks, modifying existing ones, expanding service areas, and managing operations. Additional challenges include unexpected service connections, network component breakages, service area expansions, and pipe surface roughness due to ageing (Terlumun and Robert, 2019).

Global pressures, such as population growth and environmental changes, can significantly affect the performance of water distribution systems over their lifespan and warrant scenario analysis (Zischg et al., 2017). Regular reviews of water distribution systems are essential due to evolving demands over time, emphasizing the importance of evaluating hydraulic performance within the distribution system (Yirget et al., 2021)

2.5 Pressure Variations

Water pressure in a distribution system can be classified into three categories: static pressure, dynamic pressure, and flow rate. The reduction in water pressure within these systems can be caused by various factors, including;

- **Friction Losses:** Resistance encountered by water as it flows through pipes, valves, and fittings, which reduces pressure.
- **Elevation Changes**: Variations in elevation that cause changes in gravitational potential energy, affecting pressure levels.
- **Pipe Material and Condition**: The roughness and age of pipes can lead to increased friction and leaks, resulting in pressure loss.
- **Flow Rate Variations:** High demand periods can lead to significant pressure drops due to increased flow rates.

- **System Leaks**: Cracks, breaks, or poorly sealed joints within the distribution network can cause water to escape, reducing overall pressure.
- **Pump Efficiency**: The performance and condition of pumps, which provide the necessary head to overcome friction losses, directly impact pressure maintenance within the system.
- **Valve Operations:** The opening and closing of valves can create pressure fluctuations within the network.
- **Hydraulic Transients**: Sudden changes in flow velocity, such as water hammer effects, can cause temporary pressure losses.

Understanding these factors is crucial for maintaining optimal water pressure and ensuring the effective operation of water distribution systems.

The water pressure in a building can be affected by several factors:

Number of Active Plumbing Fixtures: In both municipal and private well water supply systems, the water pressure at individual plumbing fixtures fluctuates based on the number of fixtures being used simultaneously. This effect is more pronounced in private well systems where the overall flow rate may be more restricted.

a) **Variation in Municipal Water Pressure:** The pressure in a municipal water system can vary depending on the community's overall water usage or when maintenance work is being performed on the system.
b) **Water Pipe Characteristics:** The flow rate of water within a building is influenced by the diameter, length, and number of bends or valves in the piping system. Pipes clogged with mineral deposits or debris can decrease the water flow rate even if the static pressure remains high.
c) **Clogged Water Pipes:** Blockages in water pipes primarily reduce the flow rate rather than the water pressure itself.
d) **Building Occupancy Levels**: In buildings with varying water demand, a single pressure-reducing valve may struggle to handle the peak water flow rate, particularly in large apartment or office buildings.
e) **Water Filter Clogging:** Filtration units, such as rapid sand filters, can become clogged if not backwashed regularly, leading to reduced flow in the delivery pipes (Bwire et al., 2015

2.6 Hydraulic Modelling and Headloss

Researchers have recently utilized WaterCAD for planning and evaluating the performance of water distribution systems, as well as for modeling chemical reactions within these systems. Another widely used approach for modeling water distribution systems is the open-source EPANET software, developed by the United States Environmental Protection Agency (USEPA). EPANET employs the Newton-Raphson iteration method to solve simultaneous equations derived from flow and head loss in water distribution networks. Several studies have employed EPANET for modeling water distribution systems, optimizing energy usage, reducing leakage, calibrating systems, and simulating chemical residuals in water networks. EPANET, available as public domain software, is renowned for its capabilities in water quality analysis, extended period simulation, and residual chlorine calculations, which enhance the reliability of its modeling outputs (Eryuruk, 2021). While all three software tools are valuable for water distribution system analysis, WaterGEMS stands out for its accuracy in design and optimization, making it a preferred choice for engineers and researchers seeking precise and reliable results in hydraulic modelling.

2.7 Water distribution network skeletonization and model building

Over the course of the last two thousand years, the practice of water distribution modelling has undergone significant development, tracing its origins back to the ancient Minoans who constructed the earliest known piped water conveyance system. Today, water distribution modelling stands as a crucial element in the design and operation of water distribution systems, ensuring their capacity to serve communities reliably, efficiently, and safely, both presently and in the future. Advancements in computer modelling and simulation technology have substantially enhanced the realization of these objectives (Chowdhury, 2011).

Skeletonized models of Water Distribution Networks (WDNs) are crafted by selectively removing specific pipes while ensuring that the resultant model adequately mirrors the original system. These simplified models are invaluable, if not essential, for operational tasks such as real-time management, water quality surveillance, maintenance coordination, and emergency response. Across the globe, various methodologies for model reduction have been proposed, consistently demonstrating the feasibility of generating reduced models that accurately replicate the hydraulic behaviour of the prototype (Saldarriaga et al., 2009).

The process of skeletonization involves several key stages:

- **Identification** of critical pipes and nodes within the water distribution network that exert significant influence on hydraulic performance.
- **Removal** of non-critical pipes and aggregation of demands at selected nodes to construct a simplified model.
- **Verification** that the skeletonized model retains the capability to faithfully simulate the hydraulic dynamics of the original network.
- **Validation** of the skeletonized model through comparison with field measurements and the detailed original model.

By leveraging skeletonization techniques, both researchers and practitioners can develop streamlined and manageable models of complex water distribution networks. These simplified models facilitate more efficient decision-making, optimization, and real-time management of water distribution systems, thereby contributing to the dependable and sustainable delivery of water services to communities.

2.5.1 Hardy-Cross Method

The increasing complexities of water distribution systems have made it essential to accurately estimate flows and pressures throughout the network. Traditional solutions for single-pipe flow problems are insufficient for modern demands. This necessity has led to the development of "water distribution network analysis" or "pipe network analysis" (Nwajuaku, 2017). For an effective water distribution system, it is crucial to compare various design methods to determine the most suitable approach for network analysis. Many small-scale water supply projects utilize the dead-end method for water distribution. However, alternative methods exist that can provide more comprehensive analyses, particularly regarding energy loss.

One such method is the Hardy-Cross method, which applies to closed-loop pipe networks. This iterative procedure calculates energy loss within the water distribution system. Topacik and San have compared the equivalent pipe and Hardy-Cross methods, while Lopes has developed a program specifically for designing water distribution systems using the Hardy-Cross method. Energy loss in water distribution systems can also be calculated using software tools that model and compare head losses across different systems.

One prominent software tool is WaterCAD, developed by Bentley Systems, Incorporated, located in Exton, PA, United States. WaterCAD employs a gradient algorithm that incorporates specific energy equations and nodal equations for each pipe and node to determine both nodal heads and pipe flows. WaterCAD includes modules such as Darwin Calibrator, Darwin Designer, Skelebrator, and SCADAConnect, which enable users to tailor projects and develop specialized solutions. These tools facilitate detailed and precise water distribution network analysis, enhancing the accuracy and efficiency of water management practices (Eryuruk, 2021).

Hardy–Cross introduced a fundamental algorithm that utilizes systematic approximations and successive corrections. Its simplicity has made it a popular choice for analyzing pipe networks. This method is founded on two main principles:

a) The total inflow at each node is equal to the total outflow, in accordance with the continuity or mass balance equation.

$$\sum_i Q_i = q_j \text{ for } j = 1, 2, 3, \ldots, NJ$$

Where Qi is the discharge in pipe *i* meeting at node *j*, q_j is a nodal outflow and NJ is the total number of junctions.

b) The sum of head loss $h.f_k$ around a closed loop equals zero (the loss or energy balance equation).

$$\sum_{Loop} hf_k = 0$$

The nonlinear relationship between the head loss hfk and discharge Qk in a pipe k connecting nodes i and j may be written as: (Moosavian, N. 2014)

$$hf_k = R_k Q_k^n$$

2.5.2 Headloss

The basic relation that is used in the hydraulic design of a pipeline system is the one that describes the dependence of discharge Q (say in m3/s) on a head loss of hf (m) caused by friction between h_f the flow of fluid and the pipe wall. This section will discuss two of the most commonly used relations of head-loss:

The Darcy-Weisbach and Hazen William $h_f = f\frac{lv2}{2dg}$ *where:* h_f *= headloss friction (m), f = friction coefficient, l = pipe length (m), d = pipe diameter (m), v = velocity (m/s), g = gravitation acceleration (m/s2) and f is Darcy friction factor*

Meanwhile, the Hazen-Williams equation can be seen as shown below: $h_f = 10.67*C^{-1.85}*D^{-4.87}*Q^{1.85}*L$. *hf = headloss friction (m), Q = flow rate (m3/s, C = Hazen-Williams coefficient, l = pipe length (m) and d = pipe diameter (m)*

The roughness of a pipe directly impacts the distance fluid can travel and the energy lost during flow. It is crucial to note that the relationship between the discharge Q and pipe diameter D is highly nonlinear, making it a critical factor in pipeline design. Utilizing a larger diameter pipe can significantly reduce head losses, while a smaller pipe diameter can restrict flow akin to a partially closed valve, emphasizing the importance of selecting appropriate pipe sizes for efficient fluid transport (Kusnayat, A. et al., 2019).

2.8 Non-Revenue Water (NRW) Assessment in Addis Ababa City

Non-Revenue Water (NRW) is a critical concern within water distribution systems worldwide. It refers to water lost before reaching consumers, encompassing physical leaks, unauthorized consumption, and inaccurate metering. The significance of NRW lies in its financial, environmental, and social impacts. Financially, NRW represents lost revenue for utilities, affecting their ability to maintain infrastructure and provide reliable services. Environmentally, NRW contributes to water scarcity and wastage, exacerbating the strain on already limited water resources. Socially, NRW hinders equitable access to clean water, particularly in urban contexts where demand is high and resources are scarce.

Non-revenue water (NRW) stands as a critical concern in water distribution systems globally, encapsulating water lost before reaching consumers due to various factors. Understanding NRW's definition, significance, assessment methods, and strategies for mitigation is pivotal for sustainable urban water management. As previously shown, NRW assessment and mitigation are integral to enhancing water distribution efficiency and sustainability in Addis Ababa. By employing appropriate methodologies and targeted interventions, utilities can minimize losses, optimize resource utilization, and improve service delivery to urban residents.

NRW encompasses water lost through physical leaks, unauthorized consumption, and inaccurate metering, posing financial, environmental, and social challenges. In urban contexts, NRW exacerbates water scarcity issues, impedes equitable access, and strains utility budgets (Munoz, 2020).

Assessing NRW involves diverse methodologies like Component Analysis, Water Balance, and Infrastructure Leakage Index (ILI). These approaches enable utilities to quantify losses, identify leakage points, and prioritize interventions. However, selection and application depend on system characteristics and data availability (Liemberger & Wyatt, 2017).

Studies on NRW in Addis Ababa underscore its prevalence and impacts. For instance, research by Tadesse and Gebreyohannes (2019) revealed high NRW levels, primarily attributed to ageing infrastructure, inadequate maintenance, and illegal connections. These findings highlight the urgency of NRW reduction efforts in the city.

Several factors contribute to NRW in Addis Ababa, including technical, institutional, and commercial aspects. Ageing pipes, irregular maintenance, and inadequate metering exacerbate losses. Effective strategies for NRW reduction involve proactive leak detection, infrastructure rehabilitation, stakeholder engagement, and capacity-building initiatives (Tekleab et al., 2020).

2.9 Addis Ababa City Distribution system: case studies

2.9.1 Water supply Sources of Addis Ababa City

The city of Addis Ababa currently relies on a combination of surface water and groundwater sources for its water supply. Major surface water sources include the Gafarsa, Lagadadi, and Dire dams, situated respectively 14 km west, 17 km east, and about 7 km from the Legadadi treatment plant. Groundwater is also extracted from the Akaki well field, located around 22 km southeast of the city, as well as the Legadadi well field, and various wells and springs within and around the city. The Ethiopian Water Works Construction Enterprise (EWWCE) has been undertaking projects aimed at maximizing the city's water supply capacity to 1,000,000m3/d by the end of the second Growth and Transformation Plan (GTP). Notably, the construction of the Siblu and Gerbi dams is among the key projects. The completion of these projects within the 2018/19 – 2021 budget period aims to benefit the community both in the short and long term. These projects include the Koye-Fechea groundwater development, Legadadi Deep Well Phase II, South Ayat North Fanta borehole water development, Study & construction of the Gerbi dam & treatment plant, and Sebeta-Holeta borehole water development. Evaluation of Addis Ababa's water supply involved an assessment of existing provisions and the use of SWAT to project potential water supply from reservoirs. In 2019, the city received approximately 599,000 cubic meters of water per day, sourced from reservoirs (225,000 m3/day) and groundwater (374,000 m3/day), with primary surface water sources being Legedadi, Gefersa, and Dire reservoirs, and the Akaki wellfields being the main groundwater sources. However, despite these efforts, the current water supply coverage in Addis Ababa stands at only 54%, indicating a significant shortfall. Without improvements to the water supply system or the implementation of new infrastructure projects to accommodate population growth, the city faces the risk of severe water shortages in the future. Such inadequate water coverage could have profound impacts on sanitation, food security, public health, and overall community well-being (AAWSA, 2018).

2.9.2 Water Supply Challenges in Addis Ababa

The city of Addis Ababa has witnessed a consistent increase in its water supply infrastructure since the 1970s. However, despite these efforts, the gap between water supply and demand has widened, presenting significant challenges for the city. The burgeoning population growth and improvements in lifestyle have led to a surge in water demand that surpasses the available supply capacity.

One of the key contributing factors to the water supply challenges in Addis Ababa is poor land use management, which has resulted in increased soil erosion in the reservoir catchments. This has led to sedimentation and a reduction in the storage capacity of the reservoirs, further straining the city's water resources. Additionally, the interplay of land use practices and climate change has exacerbated the imbalance between water supply and demand, posing additional challenges for sustainable water management.

The exploitation of groundwater resources by mining companies, government entities, and private industries in the Akaki well fields has added complexity to the water supply issues in Addis Ababa. This overexploitation and contamination of the Akaki well fields have further stressed the already strained water supply system. Notably, a significant portion of the current pumping rates exceeds the sustainable pumping capacity, indicating an unsustainable water extraction trend.

The study by Muleta and Abate (2020) highlights the pressing need for comprehensive water resource management strategies in Addis Ababa to address the escalating water supply challenges. Sustainable land use practices, effective reservoir management, and stringent regulations on groundwater extraction are crucial aspects that need to be prioritized to ensure the long-term sustainability of the city's water supply.

the water supply challenges faced by Addis Ababa underscore the importance of integrated water resource management approaches that consider the complex interactions between land use, climate change, and groundwater exploitation. Addressing these challenges requires a multi-faceted strategy that involves collaboration between stakeholders, implementation of sustainable practices, and robust regulatory frameworks to safeguard the city's water resources for future generations.

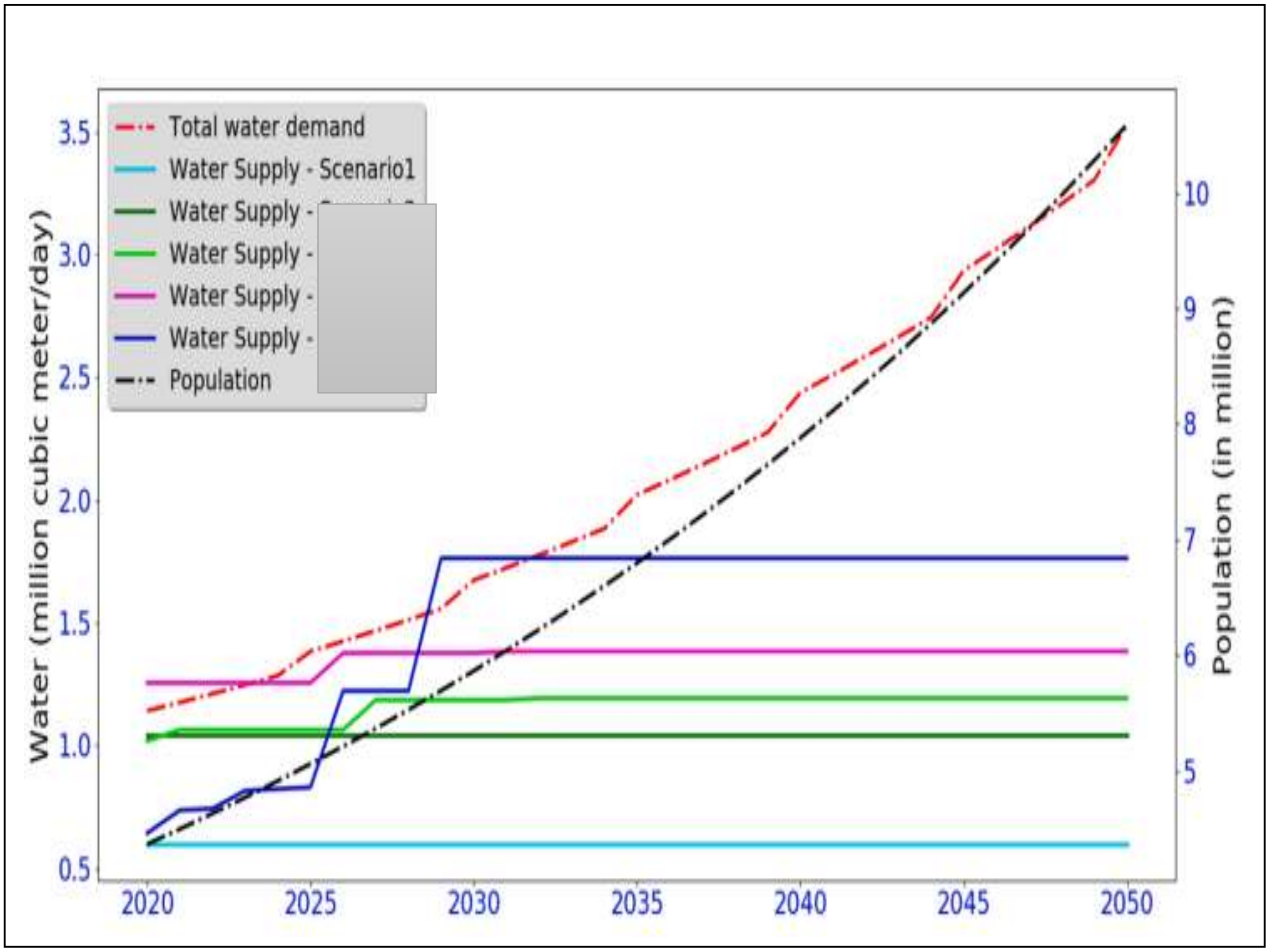


Figure 2.1: Projected Water Demand and Supply from 2020 – 2050 (Tefera et al., 2023)

2.9.3 Water Supply Coverage Analysis in Addis Ababa

Access to clean and reliable water is essential for sustainable urban development, and assessing water supply coverage is crucial for ensuring equitable access to this vital resource. In the context of Addis Ababa, the capital city of Ethiopia, understanding water supply coverage is imperative due to rapid urbanization and increasing water demand. Previous studies concluded that understanding water supply coverage in Addis Ababa is essential for promoting equitable access to clean water and ensuring sustainable urban development. By employing a combination of assessment methodologies, considering relevant factors, and drawing insights from case studies, stakeholders can develop targeted strategies to improve water supply coverage and enhance water access for all residents of the city.

Assessing water supply coverage involves various methodologies, with per capita connection analysis being one of the key approaches. This method calculates the ratio of water connections to the population served, providing insights into the level of access to piped water within the city. Other methodologies may include GIS mapping, household surveys, and utility data analysis, each offering unique perspectives on water supply coverage (UNICEF, 2019).

Several studies have examined water supply coverage in Addis Ababa and its implications for water access and equity. Research by Abate et al. (2018) investigated disparities in water access between different socio-economic groups within the city, highlighting the need for targeted interventions to address inequalities. Similarly, a study by Gebrehiwot and van der Zaag (2017) analyzed the impact of rapid urbanization on water supply infrastructure and service delivery in Addis Ababa, emphasizing the importance of sustainable planning and management practices.

2.9.4 Factors Influencing Addis Ababa Water Supply Coverage:

Several factors influence water supply coverage in Addis Ababa, including population growth, infrastructure development, and socio-economic factors. Rapid urbanization has led to increased water demand, placing pressure on existing water supply systems. Infrastructure challenges, such as ageing pipes and inadequate distribution networks, further impact coverage levels. Additionally, socio-economic factors, such as income inequality and informal settlement patterns, can affect access to water services within the city (Berhanu et al., 2020).

Case studies from similar urban settings provide valuable insights into water supply coverage assessments and potential strategies for improvement. For example, research conducted in other African cities, such as Nairobi and Dar es Salaam, has explored innovative approaches to expanding water access and improving service delivery in rapidly growing urban areas. These case studies offer valuable lessons and best practices that can inform water supply coverage assessments and interventions in Addis Ababa (Katko et al., 2019).

Therefore, Conducting a thorough examination of water supply coverage and water loss is essential for effective and sustainable water management in Addis Ababa.

Analysis of Water Supply Coverage: This entails evaluating the level of access to safe and dependable water supply services among the population in Addis Ababa. It includes assessing the proportion of households, communities, and institutions with access to piped water, as well as the frequency and duration of interruptions in water supply. By identifying areas with insufficient coverage, stakeholders can prioritize investments in infrastructure and expansion projects to extend water supply services to underserved regions.

Analysis of Water Loss: The objective of water loss analysis is to quantify and address losses within the water distribution network. This process involves identifying and evaluating various forms of water loss, such as physical losses from leaks and bursts, and non-revenue water resulting from unauthorized consumption and metering errors. Through the implementation of programs for leak detection and repair, strategies for managing pressure, and enhancements in metering accuracy, utilities can minimize water losses, preserve valuable water resources, and enhance the financial sustainability of the water supply system.

2.9.5 The Significance of Water Coverage Assessment

Equity Assessment: Equity assessment is a crucial tool for pinpointing disparities in water access across various demographic groups within a district. Through a per capita connection analysis that compares the number of water connections to the population served, areas with insufficient access to water services, especially in marginalized or underserved communities, can be identified and addressed effectively.

Resource Allocation: Resource allocation decisions are significantly informed by identifying regions with low per capita connection rates. This analysis aids in prioritizing investments in water infrastructure development and service expansion initiatives to bridge gaps in coverage and enhance equity in water access.

Policy Development: The utilization of equity assessment supports the formulation of policies and programs aimed at fostering fair access to water resources. By comprehending the distribution of water connections concerning population distribution, policymakers can tailor interventions to cater to specific areas or demographic groups requiring enhanced access.

Monitoring and Evaluation: Equity assessment serves as a valuable monitoring and evaluation tool for gauging progress towards achieving water access objectives. Through regular updates and analysis of per capita connection data, authorities can monitor changes in water coverage levels over time and assess the efficacy of intervention measures in enhancing distribution equity.

Community Empowerment: Empowering communities with data on water access levels within their district is a key outcome of equity assessment. This information enables communities to advocate for improved water services and infrastructure investments, fostering increased community engagement and participation in decision-making processes related to water resource management.

2.9.6 Water loss in the distribution

Yadeta (2019) discusses how water scarcity and topographical obstacles at several AAWSA branch offices have necessitated dividing water distribution networks in the service area into multiple pressure zones, requiring alternating water pumping. This operational strategy, not originally accounted for in design assumptions, results in intermittent pumping within each zone and across the entire network. The aging pipe network in Addis Ababa, approaching a century in age, struggles to accommodate the city's rapid population growth and urban expansion, leading to various operational difficulties. The use of modeling techniques to analyze pipe systems has emerged as a contemporary approach to evaluating the efficiency of water distribution networks. The unconventional and inefficient management practices in municipal water supply networks are expected to affect network performance by influencing pressure and velocities, and increasing the occurrence of pipe breakages due to fluctuating pressures caused by delivering large water volumes to numerous households within short timeframes.

Furthermore, inadequate coverage and significant water losses, primarily attributed to physical losses, account for over 40% of urban water supplies. These losses stem from pipe leaks, joint and valve failures, overflowing service reservoirs, and unauthorized connections, including non-metered household connections (Shimeles, 2011).

2.9.7 Supply distribution quality and safety

Ensuring the quality and safety of drinking water presents significant challenges arising from a combination of man-made and natural sources of contaminants. Microorganisms found in drinking water are a leading cause of diseases within communities, with these contaminants originating not only from faecal matter but also thriving within piped water distribution systems. Therefore, prioritizing the quality and safety of water is essential for preventing and managing pathogenic microorganisms like bacteria, viruses, protozoa, and helminths. Chlorination is a widely adopted disinfection method known for effectively eradicating a wide range of microorganisms, serving as a key indicator of a safe water supply free from harmful organisms. The assurance of safe and high-quality water provision is a critical aspect of safeguarding human health and overall well-being.

In regions such as Addis Ababa, characterized by heavy rainfall during the wet season, the risk of bacterial and parasitic contamination in drinking water escalates. Despite this heightened risk, there is a notable lack of comprehensive assessments regarding the quality and safety status of water sources in Addis Ababa during the wet season (Wolde et al., 2020). Addressing this research gap is crucial for enhancing our understanding of water quality issues in the region and improving strategies for monitoring and ensuring safe drinking water for the local population

2.9.8 Hydraulic Performance Analysis advantages

- ✓ *Enhancing Efficiency and Reliability of Water Supply Distribution System*

  Support tools play a crucial role in developing management scenarios aimed at enhancing the effectiveness and reliability of existing and prospective water distribution networks (WDNs). Hydraulic models utilize well-established equations to calculate key variables like flow rate, velocity, and water pressure at various network locations. These results are typically presented in tables and graphs for evaluation by users. The reliability of predictions generated by hydraulic models hinges on precise identification and estimation of input parameters, as well as thorough calibration and verification studies (Kara et al., 2016)

- ✓ *Importance of Supply Pressure Management in Urban WDNs*

In managing urban water distribution networks, maintaining optimal supply pressure is crucial to meet water demand while minimizing leakages and energy consumption (Kara et al., 2016). Supervisory Control and Data Acquisition (SCADA) systems are integral to achieving this balance by enabling real-time monitoring and control. When integrated with accurate hydraulic models, SCADA systems provide essential data for model calibration and validation, facilitating effective network performance enhancement (Hunde & Itefa, 2020). By leveraging advanced tools and technologies, water utilities can optimize the operation of WDNs, ensuring reliable water supply, minimizing energy usage, and effectively managing system performance. The synergy between hydraulic modelling, SCADA systems, and management strategies is essential for achieving sustainable and efficient water distribution practices in urban environments.

2.10 Urban Water Resource Supply and Infrastructure Improvement

City water resources management and infrastructure enhancement are critical aspects of ensuring sustainable water supply and distribution in rapidly growing cities like Addis Ababa. The integration of hydraulic evaluation and modelling plays a significant role in informing decision-making processes and optimizing water management practices in urban areas.

2.10.1 The Role of Hydraulic Evaluation and Modeling

- *Enhancing Water Management through Hydraulic Evaluation and Modelling in Addis Ababa*

The utilization of hydraulic evaluation and modelling offers valuable concepts into the performance of water supply systems, helping policymakers and planing bodies in making best proactive decisions for the infrastructure development and budget allocation . In Addis Ababa, a city facing rapid urbanization and population growth, hydraulic modelling serves as a vital tool for identifying areas of water stress, optimizing distribution networks, and forecasting future demand (Dessie et al., 2018).

- ✓ *Integration of Hydraulic Modelling in Water Infrastructure Planning*

Studies underscore the significance of integrating hydraulic modelling into water infrastructure planning and management in Addis Ababa. Girma et al. (2019) highlighted the pivotal role of modelling in evaluating the resilience of water supply systems to climate change impacts and guiding adaptation strategies. Similarly, Tekle et al. (2020) showcased how hydraulic modelling supports the optimization of water distribution networks and enhances service delivery in urban settings.

- ✓ *Impact of Hydraulic Modelling on Infrastructure Development*

Past research in Addis Ababa has demonstrated the profound impact of hydraulic modelling findings on infrastructure development initiatives. For instance, Abraha and Zegeye (2017) illustrated how modelling identified critical infrastructure upgrades necessary to address water supply deficiencies in specific neighbourhoods. Additionally, Kebede et al. (2018) exemplified how modelling informed the design of new water treatment plants and distribution pipelines to meet the escalating demand in the city.

- ✓ *Practical Applications and Case Studies*

Case studies from Addis Ababa exemplify the practical application of hydraulic modelling in optimizing water management practices in urban areas. Lemma et al. (2021) documented how modelling guided the expansion of the city's water distribution network to underserved areas, enhancing access to clean water for numerous residents. Similarly, Alemayehu et al. (2019) emphasized the use of modelling to identify and prioritize infrastructure investments aimed at reducing water losses and enhancing system efficiency.

- ✓ *Role of Hydraulic Modelling in Urban Water Resource Management*

In summary, hydraulic evaluation and modelling play a pivotal role in informing decision-making for urban water supply management and distribution development projects in Addis Ababa. By integrating modelling into planning processes and leveraging its predictive capabilities, policymakers can effectively address water challenges and devise sustainable strategies to sustain a regular water supply for the city residents. The integration of hydraulic modelling stands as a key component in the proactive management of water resources in rapidly evolving urban environments like Addis Ababa

2.11 integration of Findings for Urban Water Resource Management and Infrastructure Development

- Integration of Findings for Informed Decision-making by conducting a comprehensive review and analysis of the findings obtained from hydraulic evaluation, NRW estimation, and water supply coverage analysis.
- Facilitate interdisciplinary discussions among researchers and experts to explore connections between hydraulic performance, water losses, and distribution coverage.
- Use qualitative and quantitative methods to assess the interplay between different variables and their impact on urban water resource management and infrastructure development decisions.
- Develop a structured framework for synthesizing and interpreting the research findings to derive actionable insights.
- Apply statistical analysis techniques, such as regression analysis or correlation analysis, to identify significant relationships between variables.
- Engage in scenario analysis to evaluate the potential implications of different management strategies and investment options on water resource sustainability and infrastructure performance.
- Establish a multi-stakeholder engagement process involving water utility officials, policymakers, community representatives, and relevant stakeholders.
- Foster collaboration and knowledge exchange among stakeholders to co-create solutions and prioritize action areas based on identified needs and priorities.
- Ensure transparency and inclusivity in decision-making processes, allowing for meaningful participation and representation of all stakeholders involved.

- Generate a detailed report summarizing the research findings, key insights, and actionable recommendations for improving water management practices and optimizing infrastructure investments.
- Develop policy briefs and decision support tools tailored to the needs of different stakeholder groups, providing clear guidance on policy options and implementation strategies.
- Advocate for the adoption of evidence-based approaches and best practices in urban water resource management and infrastructure development.
- Monitor and evaluate the implementation of recommendations over time, adjusting strategies as needed to address emerging challenges and opportunities in the Nifas Silk-Lafto district.

CHAPTER THREE

3. Materials and Methods

3.1 Description of the Study Area

The study area, Nifas Silk Lafto sub-city, is a prominent subdivision among the ten sub-cities in Addis Ababa, encompassing a total area of 68.3 square kilometres at the coordinates of 8°57′41.76″N 38°43′39″E. As reported by the population unit of the Finance and Economy Development Bureau, the estimated total population in this sub-city stands at approximately 335,740 individuals, with 158,126 being male and 177,614 female residents. The population density per square kilometre is calculated at 4,915.7, reflecting the urban density within this area. Nifas Silk Lafto sub-city is further divided into 12 Weredas, each contributing to the administrative structure and governance of this vibrant urban locale (Nifas Silk Lafto Sub-City Administration) (Teklu, 2020). The study's focus on evaluating water supply distribution in this dynamic sub-city aims to offer valuable insights into hydraulic efficiency, accessibility of water supply, and the sustainability of pressure and velocity in water resources for the residents of Nifas Silk Lafto. These findings will contribute to informed decision-making and strategic planning, enhancing water management practices in urban settings.

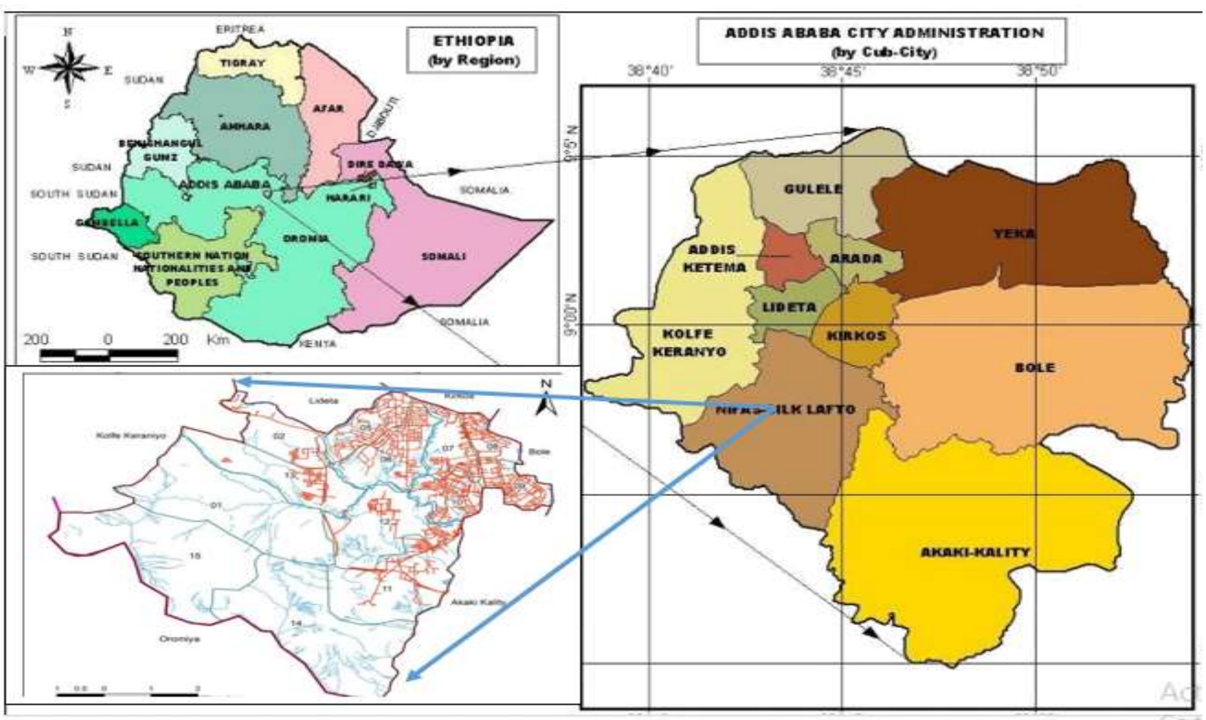


Fig.3.1 The map of the study area in the country map

3.2 Selection of this study area

As a case study reflecting the current operational situations, this study has been carried out on the Addis Ababa Water Supply Mains, primarily in the Nifas Silk Lafto sub-city. This research focuses on the Dertu PIII-A subsystem within the Nifas Silk Lafto sub-city, an essential urban area in Addis Ababa. This specific subsystem is chosen for its representation of typical urban water management challenges within the larger sub-city context. Dertu PIII-A project water network covers a significant portion of the Nifas Silk Lafto sub-city's water distribution needs. Analyzing this subsystem allows for insights into water access and distribution patterns affecting a substantial population within the sub-city. The alignment of the AAWSA pipeline network does not correspond with the Addis Ababa city administrative boundaries. Consequently, neighbouring subsystem networks to Dertu transborder Nifas Silk Lafto sub-city, leading to shared water of other sub-cities sources. Moreover, the Dertu PIII-A project represents an isolated water distribution subsystem within this sub-city, consisting of both new and old pipelines. This renewable of the existing pipelines provides studying the impact of system updates and infrastructure improvements on water supply reliability and quality. Given the uniqueness of the Dertu PIII-A subsystem and its specific challenges, there are no previous similar studies conducted in this area. This presents an opportunity for original research and contributes to filling existing knowledge gaps in urban water management. The Nifas Silk Lafto sub-city experiences water shortage and insufficient supply, adversely affecting residents' access to clean water. Investigating the effect of system updates on addressing this issue is crucial for identifying sustainable solutions and improving water management practices in the area.

3.3 Scope of the study

The study has concentrated on the Nifas Silk-Lafto area within the city of Addis Ababa, Ethiopia. The research encompasses the water supply distribution system serving the Nifas Silk-Lafto especially the Dertu PIII-A project covering the study area, including pipes, pumps, storage reservoirs, valves, and any associated infrastructure. The primary objective is to assess the hydraulic performance of the water distribution system using WaterGems software. This evaluation was limited to the analysis of parameters such as flow rates, pressures, velocities, and hydraulic grade lines to understand system behaviour comprehensively. Comprehensive data collection on the water distribution system has been conducted, including network layout, pipe characteristics, demand patterns, and operational data. This data was utilised to develop an accurate hydraulic model of the system using WaterGems software. The study is conducted with a specific focus on the

- Assessing the pressure and velocity conditions in the distribution network
- Identifying areas with insufficient water supply coverage
- Estimating non-revenue water and water losses
- Identifying challenges and opportunities for improving the water supply system.

Subsequently, the research will provide actionable recommendations and implementation strategies for optimising water management practices in the Nifas Silk-Lafto sub-city, Addis Ababa, Ethiopia. Limitations or constraints, such as data availability, modelling assumptions, and resource limitations, may affect the scope and reliability of the research outcomes.

3.4 Data Collection

To gather the necessary information, a combination of primary and secondary data collection methods was employed. Primary data, encompassing details such as the locations of water sources, service reservoirs, and nodal pressures, was acquired through on-site observations and measurements. Secondary data, sourced from the Addis Ababa Water and Sewerage Authority (AAWSA), included metrics like water production, consumption figures, and assessments of water supply coverage and losses in the city. Population data was obtained from the Ethiopian Statistical Agency (ESA). Subsequently, utilizing Water GEMS v8i software, a model was constructed based on survey data, design specifications, and the existing layout of the town's water distribution network. The model's accuracy was validated by conducting pressure measurements at ten selected nodes using a pressure gauge.

3.5 Modeling of Water Supply Distribution System using Bentley Water GEMS

WaterGEMS, a hydraulic modelling software developed by Bentley Systems, was selected for modelling hydraulic parameters such as headloss, pressure, and velocity in the water distribution system. The choice of WaterGEMS was based on its user-friendly graphical interface, integration with external software like AutoCAD and ArcGIS, and the relatively shorter time and effort required to build a model compared to other software options.

The network modelling procedures employed in this study were conducted using WaterGEMS software, following a structured approach:

- **Importing Shapefiles and Model Creation:**

Shapefiles of the pipe network were imported, and a model was created using the ModelBuilder tool in WaterGEMS.

- **Assigning Elevations to Nodes:**

Elevations were assigned to all nodes in the network based on collected elevation data.

Loading Nodes with Demands:

Demands were loaded onto nodes to represent the water usage in different parts of the network.

- **Adjusting Pipe Diameters and Selecting Materials:**

Pipe diameters were adjusted, and appropriate materials were selected to reflect the actual network characteristics.

- **Assigning Hazen-Williams C-Factors:**

Hazen-Williams C-factors were assigned to pipes based on their age to account for frictional losses.

- **Adjusting Settings for Throttle Control Valves (TCVs):**

Settings for throttle control valves were adjusted to manage flow and pressure within the network.

- **Inputting Demand Multipliers for Extended Period Simulation (EPS):**

Demand multipliers were inputted for extended period simulation to analyze variations in demand over time.

- **Running a Demand-Driven Analysis (DDA):**

A demand-driven analysis was conducted to evaluate the initial performance of the water distribution system.

- **Switching to Pressure-Driven Analysis**:

If the DDA results indicated low residual pressures, the analysis was switched to a pressure-driven approach to better simulate real-world conditions.

Calibrating the Hydraulic Model:

The hydraulic model was calibrated using field measurements, ensuring accuracy by adhering to industry criteria.

- **Performance Assessment:**

Interpretations and decisions were made based on acceptance criteria for performance measure parameters, finalizing the performance assessment of the network

3.5.1 Assigning Roughness Coefficients to Pipelines

In this study, roughness coefficients were assigned to existing pipes based on their age and material. The remaining pipe sections' C-values were also considered to ensure comprehensive modelling. Hazen-Williams roughness factors were used to account for frictional losses in the pipelines. These coefficients were inputted into the WaterGEMS software to accurately simulate hydraulic conditions.

3.5.2 Assigning Demand Patterns

Demand patterns were assigned to model the NSL's water distribution system effectively. Both intermittent and continuous simulations were conducted to evaluate the system's performance under current operational conditions. A thorough understanding of the town's demand patterns and their fluctuations was necessary. The demand patterns included residential, commercial, public, and industrial categories. These patterns were incorporated into the WaterGEMS model to simulate realistic water usage scenarios.

3.5.3 Model Calibration

The model was calibrated and validated using data from sample junctions selected in the field. Minor adjustments to the input data were made to ensure accurate reproduction of the system's pressure rates. Pressure gauge instruments were employed throughout the water distribution system to collect data, which was then used to fine-tune the model in WaterGEMS.

3.5.4 Pressure Measurement

Pressure measurements were taken at various points within the water distribution system to monitor service quality and gather data for model calibration. Using Metrolog device, the pressure was measured at various junctions by injecting the it. The device prouces a report of the pressure at that junction. During the investigation, water pressure was measured closer to the supply nodes rather than at the points where it disconnected from the mains. This approach provided more accurate data for calibrating the WaterGEMS model.

3.5.5 Network Simulation

The WaterGEMS software was used to simulate the current performance of the water distribution system and to provide insights for future behaviour. The simulation encompassed a variety of scenarios, including tank filling and emptying, valve operations (opening and closing), pressure variations, and flow rate changes. This type of analysis enabled the evaluation of the system's response to different operational conditions and helped in planning for potential future scenarios

3.6 Sample Size in Water Distribution Model Calibration

In the context of water distribution model calibration, the ideal scenario involves adjusting each link and node individually. However, practical constraints such as limited financial resources and labour availability often necessitate the use of a representative sample for calibration purposes. International guidelines, as proposed by the American Water Works Association (AWWA, 2008), recommend specific limits for sample sizes in medium to highly detailed network models.

Guidelines for Sample Size:

a) **Pressure Readings:** It is recommended that 3% of the nodes in the network should be tested for pressure readings.

b) **Flow Readings:** Similarly, it is recommended that 5% of the pipes in the network undergo flow readings for calibration purposes. In the specific study area being examined, the network comprises a total of 2217 junctions. According to guidelines, the minimum acceptable sample size is 3% of the total junctions. Thus, the calculation for determining the sample size is as follows:

Sample Size=0.03×2217=66.5

Rounded to the nearest whole number, approximately 66 junctions were selected as the representative sample for this study area from the entire water distribution system. This approach ensures a practical and efficient calibration process while adhering to established guidelines for determining sample sizes in water distribution modeling

3.7 Model calibration and validation

During calibration, model parameters like pipe roughness coefficients, demand patterns, and pump curves are adjusted to minimize differences between simulated and observed system behavior. After calibration, the model is validated with independent data to assess its accuracy and reliability for future use.

In calibrating and validating the WaterGEMS model, various methodologies ensure accurate simulations. Collaboration with experts from the Addis Ababa Water and Sewerage Authority (AAWSA) was crucial for understanding the operational status of intermittent supply valves. This helped develop accurate simulations of their behaviour. Demand multipliers from AAWSA records were adjusted iteratively to align model outputs with real-world data, ensuring the model accurately represents water demand dynamics over time.

3.8 Water Supply Coverage and Water Loss

3.8.1 Water Supply Coverage Analysis

The calculation of domestic water usage involved converting annual consumption data into an average daily per capita consumption rate, considering the projected total population for 2023. This approach was applied to determine per capita consumption.

$$\textit{Per capita consumption} = \frac{Annual\ consumption(1000m3*\frac{1}{m3})}{Population*365} \quad (2)$$

Based on annual water production and annual water demand, the sub- city's water supply coverage has been assessed according to the following formula:

$$\textit{Water supply coverage} = \frac{Annual\ Production*100\%}{Annual\ Demand} \quad (3)$$

3.8.2 Water Loss Analysis

In order to carry out a water loss assessment in Nifas Silk Lafto, Addis Ababa, data were gathered regarding the total water generated and consumed. The percentage of non-revenue water was determined by subtracting the amount of water used by metered customers from the total water generated, dividing this difference by the total water generated, and then multiplying the outcome by 100.

$$\text{Total water loss \%} = \frac{(Total\ water\ produced - Total\ water\ billed - Authorised\ Cons.)*100\%}{Total\ water\ produced} \quad (4)$$

3.8.3 Non-Revenue Water and Water Loss Estimation

The water balance method is a widely accepted approach for estimating NRW and water loss in urban water supply systems. The methodology involves assessing the difference between the system input volume (SIV) and the authorized consumption (AC), encompassing both billed and unbilled authorized consumption (IWA, 2000). The remainder represents non-revenue water (NRW), which can be segmented into apparent losses, real losses, and unbilled authorized consumption.

For this research, data from 2023 for the Nifas Silk Lafto sub-city was utilized to determine the water balance components. SIV was calculated based on the total water supplied to the distribution system, while AC was estimated considering both billed and unbilled authorized consumption. Apparent losses were computed using projections of unauthorized consumption and metering inaccuracies, while real losses were derived by subtracting apparent losses from total water losses.

The overall non-revenue water, which does not generate revenue for the Addis Ababa Water and Sewerage Authority, can be estimated using the formula:

Non-revenue water NRW% = $\frac{(Total\ water\ produced - Total\ water\ billed) * 100\%}{Total\ water\ produced}$

3.9 Data analysis

Both qualitative and quantitative methodologies were utilized for analyzing primary and secondary data in this study. Qualitative data were analyzed using tables, charts, and descriptive language, while quantitative data analysis employed Bentley Water GEMS v8i software. Spatial mapping of the research area was conducted using ArcMap 10.1 and GPS. Microsoft Excel facilitated the analysis of qualitative data. The estimation of domestic water usage was based on annual consumption figures, converted into average daily per capita consumption rates, projected for the year 2023 G.C. These tools, instruments, and software enabled comprehensive data collection, processing, and analysis, ensuring the study's findings were reliable and accurate.

3.10 Data Quality Control

The AWWSA IT department assembled the monthly consumption data in Excel format after eight branches gathered it. Additionally gathered are the average consumption numbers as established by various consultants during the water supply demand assesment done for AAWSA, which is displayed based on various levels for every month. Given the size of the data, it is essential to confirm its quality before using it. A comparison with data from other months and a comparison with corresponding months from prior years will be the two criteria used for data quality checking. Assessment predicated on seasonal expectations for consumption level. While reviewing the consumption data, notable variations between months will be noted, which may result from irregular meter readings. To ensure data quality and accuracy throughout the study, a range of tools and software were employed in addition to WaterGEMS. ArcGIS played a critical role in delineating and precisely locating the study area, facilitating the accurate depiction of geographic features. Excel Spreadsheet was utilized for comprehensive data management, including preparation, analysis, and interpretation of results, ensuring systematic handling of information. Pressure gauges were strategically used to measure pressure at nodes, faucets, and pump outlets, enabling the collection of precise pressure data essential for hydraulic analysis. Water meters were deployed to measure pipe flows accurately, providing essential flow rate data crucial for hydraulic modelling. Global Positioning System (GPS) instruments were employed to collect elevation data, ensuring the accuracy of spatial information used in the modelling process. Furthermore, Global Mapper was utilized for network point checking, elevation examination, and the seamless import/export of various elevation, vector, and raster datasets, enhancing the overall data quality control measures employed in the study

3.11 Limitations of Study

The study on the hydraulic performance of the sub-city water supply system in Addis Ababa encountered several limitations.

1. **Data Availability and Accuracy**: The accuracy of the hydraulic model heavily depends on the availability and accuracy of input data, such as pipe characteristics, demand patterns, and pressure measurements. Although the data used in this research was some extent relable but incomplete or outdated data can lead to less reliable results.
2. **Model Calibration and Validation:** Proper calibration and validation of the WaterGEMS model are crucial for accurate simulations. As the study relies on only 3% of the total junctions, limited availability of field data for calibration and validation may affect the model's performance.
3. **Simplified Assumptions:** The model may require certain assumptions or simplifications, such as steady-state conditions or average demand patterns, which might not fully capture the dynamic nature of the water distribution system.
4. **Infrastructure Condition**: The model may not account for the varying conditions of the existing infrastructure, such as pipe aging, leaks, and unrecorded connections, which can impact the hydraulic performance of the water supply system.
5. **Operational Changes:** Changes in operational strategies or interventions during the study period, such as valve operations or network reconfigurations, might not be fully represented in the model, affecting the results.
6. **External Factors:** The study may not consider external factors such as climatic changes, population growth, and urban development, which can significantly impact water demand and distribution patterns over time.

7. **Limited Geographic Scope:** Focusing solely on Nifas Silk-Lafto Sub-city may limit the generalizability of the findings to other areas with different demographic, geographic, and infrastructural characteristics.
8. **Software Limitations**: While WaterGEMS is a powerful tool, it has its own limitations and may not perfectly simulate all aspects of the water distribution system, such as transient states or complex hydraulic phenomena.
9. **Resource Constraints:** Constraints in terms of time, budget, and technical expertise might limit the comprehensiveness of the study, including detailed field investigations and extensive model testing.
10. **Policy and Institutional Challenges:** The implementation of recommendations from the study might face policy, regulatory, and institutional challenges, which could hinder the practical application of the research findings.

CHAPTER FOUR

4. Results And Discussions

4.1 Water supply distribution performance modelling using WaterGEMS

4.1.1 Resulted intermittent modelling in peak hours

Model validation

The comparison of measured and simulated pressures under peak demand conditions further substantiates the robustness of the calibrated model. The high coefficient of correlation (**R^2 = 0.9227)** indicates a strong linear relationship between the observed and predicted pressures, demonstrating the model's proficiency in capturing the system dynamics accurately.

The remarkable agreement between the measured and simulated pressures underscores the model's efficacy in replicating real-world scenarios and forecasting system behaviour under varying demand conditions. This level of validation not only validates the model's predictive capabilities but also enhances its applicability in practical decision-making processes within the realm of [insert relevant field]. The findings from this validation process contribute significantly to advancing modelling techniques and their practical implementation in real-world scenarios.

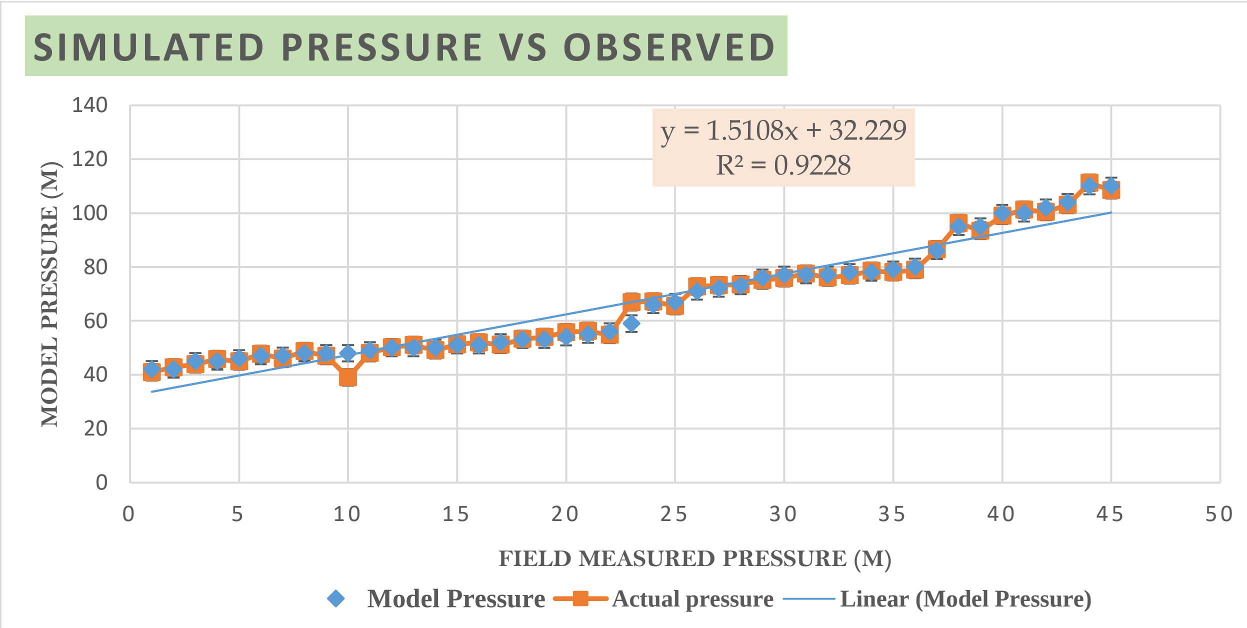


Figure 4.1 Correlation of field observed pressure vs. model pressure for validation

4.1.2 Model limitation

- Verification of data posed significant challenges due to the scarcity of reliable information.
- During the study period, most bulk flow meters were non-operational.

- Previous local research studies in comparable network zones were notably absent.
- Meandering bends in the system were approximated as straight lines during skeletonization, which conservatively influenced modeled pressure values.
- Water supply to the city is intermittent, leading to irregular shifts and inconsistent rationing times at pumping stations, thereby hindering consistent results at fixed locations and times.
- The interconnected nature of the water supply network across sub-systems complicates the establishment of practical boundaries for sub-system flows.

4.1.3 Results for intermittent modelling of the current distribution system

The following drawbacks are taken into account while simulation the model of the water supply distribution system of the sub-city. The assumptions and limitations delineated herein are somewhat reductive and grounded in empirical realities. Nonetheless, these assumptions, when coupled with rigorous temporal and spatial representative testing during the calibration and simulation processes, are unlikely to deviate from the overarching objective of developing a model that closely approximates real-world scenarios. This alignment will be ascertained through the meticulous comparison of actual data with simulated values. The obvious assumptions include that pipe friction factors were determined solely based on age and material, without considering other influential factors like bedding slope, water treatment standards, leakage points, and dead ends. As metal pipes age, their roughness increases due to encrustation and corrosion, lowering the Hazen-Williams C-factor and affecting flow in pipelines of varying ages, diameters, and materials.

4.1.4 Model results in the intermittent supply

The study investigates the operating pressures of Ethiopia's water supply distribution system, revealing a significant variation in pressure levels of distribution. According to the Ministry of Water Resources (MOWR, 2006), the pressure in the distribution network ranges from a minimum of 15 meters to a maximum of 70 meters.

Table 4.1 provides an analysis of the pressure distribution across the nodes in the water distribution network under off-peak demand conditions. The results indicate that nearly 5% of the nodes are subjected to excessive pressure, exceeding the recommended limit of 70 meters, while 1.2% of the nodes experience pressure below the minimum allowable threshold of 15 meters. Notably, there are no nodes with negative pressure, and only one node fails to meet the minimum pressure acceptance criteria. Furthermore, the table reveals that around 94% of the nodes are supplied with optimum pressure, falling within the standard pressure zone of 15 to 70 meters. This suggests that the majority of nodes in the network function efficiently under off-peak demand conditions

Table 4.1 Pressure behaviour in the intermittent supply system

REGION	PRESSURE (m)	NO OF NODES	PER CENT
Below	15m	27	1.22%
In Range	15-70m	1782	93.9%
Above	70m	108	4.9%
Outrange Total	<15 or >70m	135	6.09%
Total		**2217**	**100.0%**

When compared to the peak-hour demand conditions, the off-peak demand scenario shows a decrease in the number of nodes supplied with optimal pressure. However, the presence of nodes with minimum pressure is reduced in the off-peak demand conditions. The small percentage of nodes experiencing excessive pressure (5%) indicates the need for pressure management strategies, such as the installation of pressure-reducing valves or the optimization of pump operations, to maintain pressure within the recommended limits. Excessive pressure can lead to increased water losses through leakage, reduced pipe lifespan, and potential damage to household appliances. The small percentage of nodes (1.2%) with pressure below the minimum allowable threshold may require further investigation to identify the underlying causes, such as inadequate pipe sizing, high elevation differences, or insufficient water supply. Ensuring that all nodes meet the minimum pressure criteria is crucial for providing adequate water service to consumers. The presence of only one node failing to meet the minimum pressure acceptance criteria suggests that the overall network design and operation are effective in maintaining acceptable pressure levels. However, it is essential to monitor and address any potential issues at this specific node to ensure consistent water supply and pressure throughout the network. The high percentage of nodes (94.9%) supplied with optimum pressure indicates that the network is well-designed and operated to maintain pressure within the standard pressure zone. This optimal pressure range ensures efficient water distribution, minimizes water losses, and provides consumers with a reliable and consistent water supply.

High pressure during low-demand conditions is typically attributed to serving customers at elevations below the pressure zone or due to oversized piping mains. The existence of excessive pressure in the system can result in pipe bursts, leading to increased leakage losses (Workneh et al., 2023

4.1.5 Continuous modelling in 24hrs

The continuous modelling of the Nifas Silk Lafto water distribution system for the year 2023, conducted using WaterGEMS, aimed to analyze the system's ability to satisfy the current demand of the study area under a continuous supply scenario. The pressure head results obtained from WaterGEMS, as summarized in Table 4.1, provide valuable insights into the system's performance.

Table 4.2 Pressure performance during continuous modelling scenario

REGION	PRESSURE (m)	NO OF NODES	PER CENT
Below	15	19	0.86%
In Range	15-70m	596	26.9%
Above	70	1602	72.3%
Outrange Total	<15 or >70m	1621	73.12%
Total		**2217**	**100.0%**

The analysis of the pressure distribution reveals that only about 27% of the nodes are provided with pressure within the desirable range of 15 to 70 meters, which is the allowable minimum and maximum pressure for the system. This finding suggests that a significant portion of the study area receives water with insufficient pressure, potentially leading to inadequate supply to taps.

Furthermore, the majority of the nodes (72.3%) have a pressure exceeding 70 meters, and 73.12% of the nodes are outranged. This excessive pressure can result in pipe bursts, undesirable infrastructure deformation, and increased leakage in the pipe network. Such high pressures are necessary to avoid in the current system to maintain its integrity and minimize water losses.

Additionally, a small percentage (0.86%) of nodes in the system have a pressure of less than 15 meters, indicating that water cannot be supplied sufficiently to those regions. This observation is particularly concerning, as it suggests that certain areas within the study area may experience water scarcity or inadequate supply.

The design of the water distribution system relies on gravity for the distribution of water from the reservoir to the junctions. However, areas with similar heights to the reservoir are likely to receive water with less pressure, as evidenced by the low-pressure nodes identified in the analysis.
The findings from the continuous modelling exercise highlight the need for targeted interventions to optimize the pressure distribution within the water distribution system. Strategies such as pressure management, network rehabilitation, and the installation of pressure-reducing valves may help mitigate the issues of excessive and insufficient pressure. Additionally, considering the topography of the study area and incorporating appropriate design modifications can contribute to a more equitable distribution of water pressure throughout the system.

4.1.6 Flow velocity analysis

Flow velocity is a crucial parameter in the design and operation of water distribution systems. According to the Ministry of Water Resources (MoWR, 2006), the desired flow velocity in pipes should range between 0.6 and 2 meters per second (m/s). This range is recommended to ensure efficient water delivery while minimizing the risks associated with both low and high flow velocities, such as sediment deposition and pipe erosion, respectively.

Table 4.3 The flow velocity in the pipes during peak consumption

REGION	VELOCITY (M/S)	NO OF PIPES	PER CENT
BELOW	0.6m/s	2662	86.85%
IN RANGE	0.6-2m/s	361	11.78%
ABOVE	2m/s	42	1.37%
OUTRANGE	<0.6 or >2m/s	2704	88.22%
TOTAL		**3065**	**100.00%**

Table 4.3 presents the distribution of flow velocities in the water supply system during peak hour demand. It was observed that 87% of the total pipe length exhibited flow velocities below the optimal minimum velocity of 0.6 m/s. Conversely, only 11.78% of the pipes operated within the recommended velocity range of 0.6–2 m/s. A small fraction, accounting for 1.37% of the pipes,

experienced flow velocities exceeding the maximum threshold of 2.0 m/s. This disparity in flow velocities highlights a significant operational challenge within the system.

The analysis reveals that a substantial portion (88.22%) of the pipe network operates outside the recommended velocity range, indicating a significant deviation from the optimal flow conditions. Such discrepancies in flow velocities can have detrimental effects on the overall performance of the water supply distribution system. The prevalence of velocities below the minimum threshold suggests potential issues with water distribution efficiency and system functionality. Conversely, the presence of velocities surpassing the maximum limit raises concerns regarding potential pipe wear, increased energy consumption, and hydraulic inefficiencies.

Addressing the disparities in flow velocities is crucial for optimizing the system's performance and ensuring efficient water distribution. Strategies such as hydraulic modelling, network redesign, and flow control measures may be necessary to mitigate the adverse effects of suboptimal flow velocities and enhance the overall operational efficiency of the water supply distribution system

4.2 Supply and demand gap analysis

The analysis of the maximum daily water demand and current daily water production for the sub-city under investigation reveals a significant gap between supply and demand. The maximum daily water demand was calculated to be 40,726.86 m^3/d (471.38 l/s), while the current daily water production stands at 10,736.58 m^3/d (124.27 l/s). This discrepancy between production and demand consumption amounts to 29,990.28 m^3/d (347.11 l/s). The substantial supply and demand gap highlights the pressing need for the water supply service to address the inadequacies in water production and distribution within the sub-city. The current water production capacity is unable to meet the maximum daily water demand, leading to water scarcity and unmet needs among the population.

Several factors may contribute to this gap, including ageing infrastructure, water losses due to leakages, and insufficient investment in water supply projects. Additionally, the rapid population growth and urbanization in the sub-city have outpaced the expansion of water supply infrastructure, exacerbating the imbalance between supply and demand.

To mitigate this issue, the water supply service should prioritize the following interventions:

- ✓ Undertaking a thorough evaluation of the water supply infrastructure to pinpoint and rectify areas of water loss and inefficiency.

- ✓ Allocating funds for the renovation and expansion of water supply networks to enhance production capacity and distribution efficiency.
- ✓ Introducing water conservation initiatives and public awareness campaigns to promote efficient water use among residents.
- ✓ Investigating alternative water sources and technologies, such as conjunctive use of groundwater extraction and surface water in addition to wastewater treatment and reuse, to supplement the current water supply.
- ✓ Enhancing coordination and collaboration with relevant stakeholders, including local authorities, community organizations, and development partners, to mobilize resources and ensure the effective implementation of water supply interventions.

4.2.1 Supply and planned production discrepancies

The discrepancy between planned water production and actual supply in the Nifas Silk Lafto sub-city, Addis Ababa, was investigated in this study. The daily water supply data in cubic meters and the planned daily production of 32,000 m³/day were analyzed to assess the gap between expected and actual water supply**.** The following graph summarizes the unmeeting trend of average daily production and supply of the sub-city.

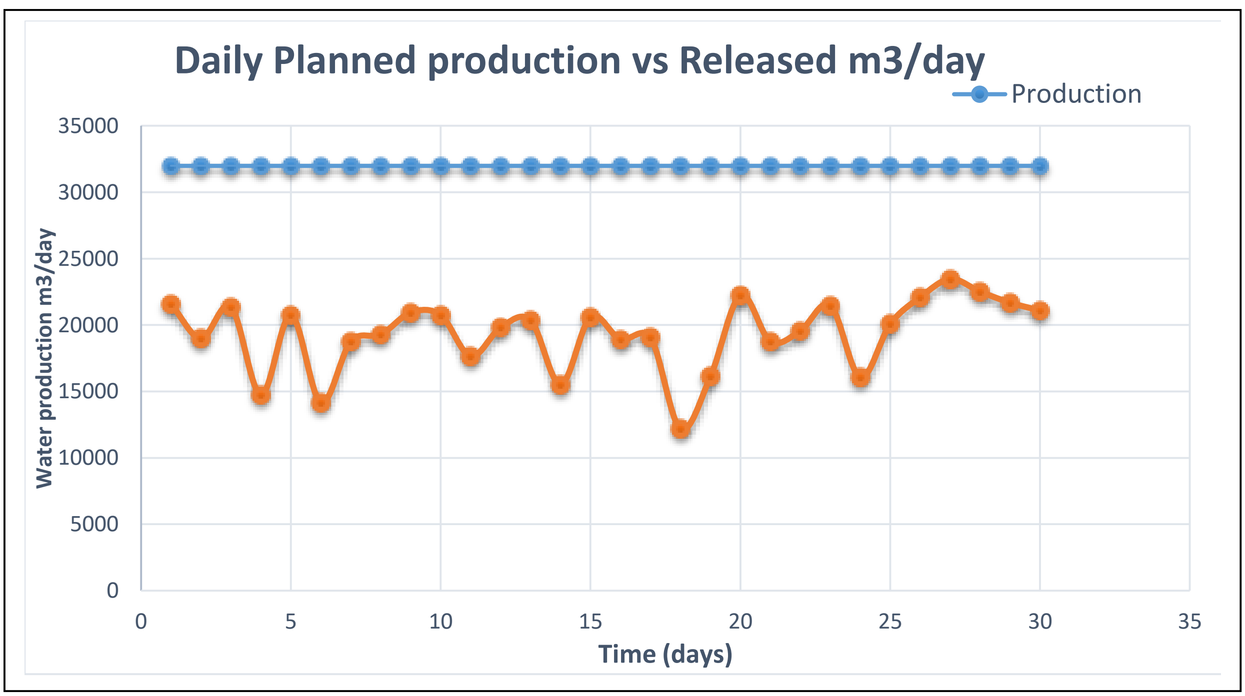


Figure 4.2 The average daily water production vs daily water supply for the Nifas Silk sub-city

The gap between planned water production and actual supply in the Nifas Silk Lafto sub-city raises concerns about the efficiency and reliability of the water supply system, indicating a significant shortfall in meeting community water demand. During my stay in field observations, it has been identified the contributing factors which include operational challenges, infrastructure limitations, and distribution inefficiencies. Issues such as inadequate maintenance, leaks, inaccurate demand forecasting, power supply interruptions, pump failures, supply schedule problems, and pipe clogging which in turn exacerbate this gap.

To address these issues, A comprehensive approach is needed to address these water supply issues, involving infrastructure improvements, operational enhancements, and effective management strategies. Regular maintenance, leak detection, and repair programs can reduce losses and improve efficiency. Advanced technologies for real-time monitoring and data analysis can optimize water production and distribution. Collaboration among water utilities, local government, and community stakeholders is crucial to bridge the supply-demand gap. By identifying root causes and implementing targeted interventions, the water supply system in Nifas Silk Lafto can effectively meet growing demand. This study highlights the importance of proactive management and continuous improvement for sustainable urban water services.

4.2.2 Water Supply Coverage Analysis

Water supply coverage is the percentage of people with access to water services in a town. Rapid urban growth in developing cities like Addis Ababa increases water demand, requiring more sources and infrastructure. Financial constraints and poor management hinder adequate coverage, creating disparities among different areas. Evaluating the city's distribution system is crucial to identify problem areas. The analysis considers factors like domestic connections per family and average daily per capita consumption, comparing Addis Ababa's coverage with other developing cities. Insights are gained by examining the distribution of consumption and connections per family (Shimeles, 2011)

The evaluation of water supply coverage in the Nifas Silk Lafto sub-city, Addis Ababa, was performed using per capita consumption and family connection levels. The coverage was determined by calculating the ratio of annual water production to annual water demand. The data provided indicates that the annual water production in Nifas Silk Lafto is 8,712,449 cubic meters, while the annual water demand is significantly higher at 14,865,304.5 cubic meters. Consequently, the water supply coverage was calculated to be 57.806%. This coverage percentage signifies a lower level of water supply adequacy in the town. The fact that annual water production does not meet a substantial portion of the town's water demand reflects a negative and inefficient water supply system. The disparity between production and demand, with a coverage of only 57.806%, indicates that nearly half of the sub-city water needs are unmet, underscoring significant challenges in the current water supply infrastructure. The 57.806% water supply coverage in the Nifas Silk Lafto sub-city indicates a significant shortfall in meeting residents' water needs, reflecting inefficiencies in the water supply system such as limited production capacity and high distribution losses. The 42.194% gap between water production and demand underscores the urgent need for strategic improvements. Failing to address this issue will continue to compromise residents' quality of life, socioeconomic development, and public health.

In a related study conducted by Shimeles (2011), it was determined that the water supply coverage in the city provided water services 7 days a week for 12-24 hours per day, reaching 50% of the total area of Addis Ababa. This service catered to nearly the entire population of 2,072,028 residents out of the total population of the city. The case requires a great deal of attention before the case gets worse than it is now.

The findings of this study reveal that the average per capita water consumption in the study area of Nifas Silk sub-city of Addis Ababa city is significantly lower than the national minimum target set by the Ministry of Water, Irrigation, and Energy (MoWIE) in 2019. The average per capita water consumption was found to be 74.3 litres per capita per day (l/c/d), which is substantially below the recommended minimum of 100 l/c/d for urban areas, particularly category 1 towns/cities with populations exceeding 1 million (MoWIE, 2019). Given that Addis Ababa, with a population of over 5 million residents, falls within this category, it is evident that there is a significant gap between the current water consumption levels and the national standards. The results highlight the urgent need for Addis Ababa's water supply service to improve per capita water consumption. This involves upgrading infrastructure, promoting water conservation, and ensuring equitable distribution to meet the city's growing demands. Collaboration among government, water authorities, and stakeholders is essential to develop and implement effective strategies. Additionally, regular monitoring and evaluation of water supply and consumption are crucial for informed decision-making and resource allocation, addressing water scarcity, and ensuring sustainable water provision for the city's rapidly growing population.

The study by Ayala (2018) examined the water supply situation in Holeta town, located just 35.5 km from the study area, finding that only 52.57% of the population had access to water. Despite the overall scarcity, water distribution was generally fair among neighbourhoods, though some exceptions existed where certain kebeles consumed disproportionately high amounts of water relative to their population size. Conversely, some kebeles with larger populations used less water. The study also noted that many villagers relied on alternative water sources due to concerns about tap water quality, habitual use, and the availability of cheaper or free sources. Furthermore, water consumption dropped significantly when the quality or convenience of water sources decreased.

The issue of inadequate water supply coverage is widespread across Ethiopian towns, not just in Addis Ababa. A study by Belachew and Tadele (2021) in Shinshincho Town found that the town's water source could produce a maximum of 1,296 m^3/day, meeting only 49% of the town's water demands. The average per capita domestic water consumption was 32.6 litres per day. Additionally, the town's water supply distribution system had a service coverage of only 42.249% in 2020. These findings are consistent with Ayala's (2018) study in Holeta town, where only 52.57% of the population had access to water. Despite overall water scarcity, the distribution was generally fair among neighbourhoods, with some exceptions where water consumption was disproportionately high in certain kebeles relative to their population size, while others with larger populations used less water.

These findings underscore the need for comprehensive water management strategies in Ethiopian towns to ensure equitable distribution and efficient use of limited water resources. Addressing issues such as inadequate infrastructure, poor water quality, and uneven distribution is crucial for improving access to safe and reliable water for all residents. This requires an inclusive plan from national and regional levels to improve water supply services.

4.2.3 Non-Revenue Water and Water Loss Estimation for Nifas Silk Lafto Sub-City in 2023 Using the Water Balance Method

The results of the non-revenue water (NRW) and water loss estimation for the Nifas Silk Lafto sub-city in 2023 using the water balance method based on IWA standards are presented in Table 1.

Table 4.4 Water balance components for Nifas Silk Lafto sub-city in 2023

S.No	*Water Balance Component*	*Volume (m^3/year)*	*Percentage of SIV*
1	System Input Volume (SIV)	8,712,449	100%
2	Authorized Consumption (AC)	3,918,932	45%
3	Water Losses	4,793,517	55%
4	Apparent Losses	1,529,664	17.6%
5	Real Losses	3,263,852	37.5%
6	Billed Authorized Consumption	3,918,932	45%
7	Unbilled Authorized Consumption	16,973	0.2%
8	Revenue Water	3,918,932	45%
9	Non-Revenue Water	4,793,517	55%

The system input volume (SIV) for the Nifas Silk Lafto sub-city in 2023 was estimated to be 8,712,449 m^3/year. The authorized consumption (AC) accounted for 45% of the SIV, amounting to 3,918,932 m^3/year. The remaining 55% of the SIV, equivalent to 4,793,517 m^3/year, was classified as water losses.

The water losses were further divided into apparent losses and real losses. Accordding to AAWSA estimations, apparent losses, which include unauthorized consumption and metering inaccuracies, accounted for 17.6% of the SIV, amounting to 1,529,664 m^3/year. Real losses, which represent physical losses from the distribution system, accounted for 37.5% of the SIV, amounting to 3,263,852 m^3/year.

The billed authorized consumption, which represents the volume of water that is billed to customers, was estimated to be 3,918,932 m^3/year, accounting for 45% of the SIV. The unbilled authorized consumption, which includes water used for firefighting, street cleaning, and other authorized but unbilled purposes, was estimated to be 16,973 m^3/year, accounting for 0.2% of the SIV. The revenue water, which represents the volume of water that generates revenue for the utility, was estimated to be 3,918,932 m^3/year, accounting for 45% of the SIV. The non-revenue water (NRW), which represents the difference between the SIV and the revenue water, was estimated to be 4,793,517 m³/year, accounting for 55% of the SIV. The main contributing factors to such excessive losses includes illegal connections and lower authority surveillance and monitoring.

The study highlights significant non-revenue water and losses in Nifas Silk Lafto's water supply system. High water losses, especially real losses, indicate potential for improved management and maintenance. Unauthorized consumption, a key contributor to apparent losses, can be mitigated with better monitoring and enforcement. Upgrading and regularly testing water meters can reduce inaccuracies. Real losses, the largest portion, can be addressed through targeted leak detection and repair programs using advanced technologies like acoustic leak detection and pressure management. Installing bulk meters and implementing regular calibration programs can improve water consumption data accuracy. A comprehensive water loss reduction strategy involving technical and managerial interventions, and stakeholder participation, is essential for sustainable reductions in non-revenue water and losses.

Table 4.5 Water Balance (m3/year) for Nifas Silk Laft in the year 2023

System Input Volume 8,712,449 100.0%	Authorized Consumption 3,918,932 m3/year 45%	Billed Authorized Consumption 3,918,932 m3/year 45%	Billed Metered Consumption 3,918,932 m3/year 45%	Revenue Water 3,918,932 m3/year 45%
			Billed Unmetered Consumption 0m3/year 0%	
		Unbilled Authorized Consumption 0 m3/year 0%	Unbilled Metered Consumption 0m3/year 0%	Non-Revenue Water 4793517 m3/year 55%
			Unbilled Unmetered Consumption 0m3/year 0%	
	Water Losses 4793517 M3/year 55%	Commercial Losses 1529664 m3/year 17.56%	Unauthorized Consumption 16,973 m3/year 0.195%	
			Customer Meter Inaccuracies and Data Handling Errors 1,512,692 m3/year 17.36%	
		Physical Losses 3,263,852 m3/year 37.46%		

The significant water supply losses in the Nifas Silk Lafto sub-city, which impact its coverage, are consistent with findings from studies conducted across Addis Ababa and its other sub-cities. Welday (2005) revealed that despite the already low water supply coverage in Addis Ababa, the city experienced a total water loss of 41%. Further analysis showed that the Colfe Core sub-city, located at a lower elevation, suffered even higher water losses due to pressure imbalances in the distribution system, leading to leaks.

Alemu and Dioha (2020) found that this issue contributed to a 48% increase in unmet water demand in Addis Ababa over 15 years, emphasizing the urgent need for government intervention to prevent a future water crisis. Additionally, Yadeta (2019) conducted a study on the Jan Meda water supply subsystem in Addis Ababa, which revealed an excessive rate of unaccounted-for water at 38.24%. Domestic water supply coverage was also assessed, showing only 48.51% of families had direct connections, while others relied on alternative means.

These findings underscore the necessity for comprehensive water management strategies in Addis Ababa to address the high rates of water loss and unmet demand. Key steps include improving the distribution system, reducing leakage, and increasing water supply coverage to ensure all residents have equitable access to safe and reliable water sources.

4.3 Strategies to improve the water distribution systems

1) Pressure ans Velocity Management Strategies:

Install pressure-reducing valves or optimize pump operations to address nodes experiencing excessive pressure, which can lead to increased water losses and infrastructure damage.vInvestigate nodes with pressure below the minimum threshold to identify causes like inadequate pipe sizing or insufficient water supply, ensuring all nodes meet minimum pressure criteria for consistent water service. On the other hand, velocity should maintained in the optimum level by considering pipe zises and metarials in the affected areas through pipe annovation and optimization strategy.

2) Optimization of Water Suply Network System:

Targeted interventions such as pressure management, network rehabilitation, and installation of pressure-reducing valves are essential to optimize pressure distribution within the water distribution system. Incorporate appropriate design modifications considering the topography to ensure equitable water pressure distribution throughout the system.

3) Flow Velocity Analysis:

Address disparities in flow velocities to optimize system performance and ensure efficient water distribution.Consider hydraulic modelling, network redesign, and flow control measures to mitigate the adverse effects of suboptimal flow velocities and enhance operational efficiency.

4) Supply and Demand Gap Mitigation:

Evaluate water supply infrastructure to rectify inefficiencies and losses, allocate funds for network renovation and expansion, promote water conservation, and explore alternative water sources to bridge the supply-demand gap. Enhance coorperation with stakeholders for effective implementation of water supply interventions and ensure sustainable water provision for the growing urban population.

5) **Sources Development (Conjunctive Use of Groundwater and Surface Water):**

Implement conjunctive use of groundwater and surface water to reduce unmet water demands in the Nifas Silk Lafto sub-city, leveraging the advantages of each resource to optimize water supply and meet population needs. Ensure consistent year-round water supply and reduce the risk of shortages by promoting long-term sustainability through efficient management of water resources.

6) **Water Supply Coverage Enhancement:**

Improve infrastructure, promote water conservation, and ensure equitable distribution to meet growing demands and enhance per capita water consumption in line with national standards. Collaborate with stakeholders for effective strategies, monitoring, and evaluation to address water scarcity and ensure sustainable water provision for the rapidly growing urban population.

7) **Non-Revenue Water and Water Loss Management:**

implement leak detection and repair programs to reduce real losses, upgrade water meters, address unauthorized consumption through improved monitoring and enforcement, and develop a comprehensive water loss reduction strategy involving technical and managerial interventions.

Install bulk meters, calibrate regularly, and involve all stakeholders for sustainable reductions in non-revenue water and water losses, ensuring accurate water consumption data and efficient water management.

8) **Integrated Water Resources Management:**

Implement an integrated approach to water resources management involving collaboration among stakeholders, capacity building for water professionals, public awareness campaigns, and regular monitoring and evaluation to adapt management strategies based on changing conditions and emerging challenges

CHAPTER FIVE

5. Conclusions And Recommendations

5.1 Conclusion

The research conducted on the performance of the water supply distribution system of the Nifas Silk sub-city, Addis Ababa has shed light on various critical aspects impacting the efficiency and effectiveness of the water distribution network. Through detailed analysis of pressure distribution, flow velocities, supply-demand gaps, water supply coverage, non-revenue water estimation, and water loss assessment, several key findings have emerged.

The assessment of pressure distribution across nodes revealed that while a majority of nodes receive optimum pressure, areas are experiencing excessive or insufficient pressure, highlighting the need for pressure management strategies. Similarly, the analysis of flow velocities indicated significant deviations from the recommended range. Nearly 88% of network pipes' velocities outperform emphasising the importance of addressing flow velocity disparities to optimise system performance.

The study identified a substantial gap between water production and demand, underscoring the pressing need for infrastructure improvements and enhanced production capacity to meet the growing water needs of the sub-city. Moreover, the assessment of water supply coverage revealed a significant shortfall in meeting residents' water needs. Only 58% of the sub-city residents are covered by this system, emphasising inefficiencies in the current water supply system that require urgent attention.

Furthermore, the estimation of non-revenue water and water losses highlighted the need for improved management practices, leak detection programs, and infrastructure upgrades to reduce losses and enhance system efficiency. The Non-revenue Water approximately accounts for 55% of the total service water. Addressing unauthorized consumption, metering inaccuracies, and real losses through targeted interventions can significantly contribute to minimizing water losses and improving revenue generation for the utility. However, The study faced limitations such as the scarcity of similar research in the area, network interconnections and complexity, the likelihood of data centralization issues, metering inaccuracies, and data handling errors. This generally, implies poor management in the existing supply distribution, the inadequacy of service and substantial challenges in the authority to deal with these issues. The research calls for additional studies covering the future scenarios for models to predict to behavior of the distribution for the long-term operation.

Finally, the research findings provide valuable insights for decision-making processes related to urban water resource management and infrastructure development. By addressing the identified challenges, implementing targeted interventions, and fostering collaboration among the government, AAWSA, donors, researchers and the community, the water supply system in the sub-city can be optimized to ensure reliable, sustainable, and equitable water services for the growing urban population in Nifas Silk Lafto Sub-city, Addis Ababa, Ethiopia.

5.2 Recommendation

Based on the results of this study these optimal Water management strategies are required:-

5.2.1 Benefits for Nifas Silk Lafto Sub-City Water Distribution

The study identified strategies to manage excessive water pressure and reduce water losses, such as implementing pressure reducing valves (PRVs) and utilizing advanced leak detection technologies. This can help mitigate infrastructure damage and improve the efficiency of the water distribution system. Ensuring all connections are periodically metered using high-accuracy meters can improve measurement accuracy and reduce discrepancies in water usage data. Increased surveillance with remote monitoring technologies can also help detect unauthorized connections. Proposing the conjunctive use of groundwater and surface water resources can help address unmet water demands in the sub-city. This approach can ensure a consistent year-round water supply, reduce the risk of shortages, and promote long-term sustainability of the water resources.

5.2.2 Future Research Engagement

The research on water supply planning and management in Nifas Silk Lafto sub-city provides a solid foundation for future studies. Potential areas for further engagement include:

- Evaluating the implementation and impact of the recommended water management strategies, such as the use of PRVs and advanced leak detection technologies.
- Assessing the feasibility and effectiveness of the proposed conjunctive use of groundwater and surface water resources to meet the growing water demands.
- Investigating the socio-economic and environmental implications of the water supply interventions, particularly on the local community and the surrounding ecosystem.
- Exploring innovative financing mechanisms and policy frameworks to support the sustainable management of water resources in the sub-city.

5.2.3 Advice for Stakeholders

Based on the findings of this research, the following recommendations are provided for key stakeholders**:**

a. For the Addis Ababa Water and Sewerage Authority (AAWSA):

- Prioritize the implementation of the recommended water management strategies, such as pressure control and advanced leak detection, to improve the efficiency and reliability of the water distribution system in Nifas Silk Lafto sub-city.

- Invest in the necessary infrastructure and technologies to enable the conjunctive use of groundwater and surface water resources, ensuring a sustainable water supply for the growing population.
- Enhance customer metering and monitoring systems to improve data accuracy and detect unauthorized connections, thereby increasing revenue and reducing non-revenue water.

b. For the Nifas Silk Lafto Sub-City Administration:

- Collaborate closely with AAWSA to ensure the timely and effective implementation of the water supply interventions in the sub-city.
- Raise awareness among the local community about the importance of water conservation and the responsible use of water resources.
- Promote the integration of water supply planning with broader urban development strategies to ensure the equitable and sustainable provision of water services

References

1. AAWSA Communication Affairs support Process, Vol. (6), No.2, June, 2015.
2. AAWSA Magazine, (2011). ―Weha ena Fesash‖. A monthly Magazine Published by AAWSA Communication Affairs support Process, June 2011.
3. AAWSA Magazine, (2015). ―Weha ena Fesash‖. A biannual Magazine Published by
4. AAWSA Magazine, (2017). ―Weha ena Fesash‖. Publication of AAWSA Communication Affairs support Process, Vol. (10), No.4, pg. 5.
5. AAWSA Magazine, (2017). ―Weha ena Fesash‖. Publication of AAWSA Communication Affairs support Process, Vol. (10), No.1, pg. 5.
6. AAWSA Magazine, (2017). ―Weha ena Fesash‖. Publication of AAWSA Communication Affairs support Process, Vol. (10), No.2, pg. 4 (Implementation of a hydraulic model to reduce the quantity of Non-Revenue Water Loss).
7. AAWSA Magazine, (2017). ―Weha ena Fesash‖. Publication of AAWSA Communication Affairs support Process, Vol. (10), No.3, December 2017 pp. 1-3.
8. AAWSA Magazine, (2018). ―Weha ena Fesash‖. Publication of AAWSA Communication Affairs support Process, Vol. (11), No.3, pp. 1-3.
9. Abate, S., et al. (2018). Socio-economic determinants of inequality in access to improved drinking water supply in Addis Ababa, Ethiopia. Geographical Journal of Social Issues, 28(3), 325-341.
10. Abebe H (2020) Hydraulic performance of water supply distribution system in case of Aiytyef subsystem, Dessie, Ethiopia (Doctoral dissertation)
11. Abera, M. F., & Tefera, M. M. (2019). Analysis of Water Distribution Network Performance: The Case of Addis Ababa, Ethiopia. Journal of Water Resource and Protection, 11(3), 263–276.
12. Abraha, M. S., & Zegeye, A. D. (2017). Hydraulic modelling of water distribution system: The case of Addis Ababa, Ethiopia. International Journal of Scientific and Research Publications, 7(5), 124-131.
13. Abubakar, A. S. and Sagar, N. L. (2013): Design of NDA Water Distribution Network Using EPANET, International Journal of Emerging Science and Engineering (IJESE) ISSN: 2319–6378, Volume-1, Issue-9, July 2013.

14. Agunwamba, J.C., Ekwule, O.R. and Nnaji, C.C. (2018) 'Performance evaluation of a municipal water distribution system using WaterCAD and EPANET', *Journal of Water, Sanitation and Hygiene for Development*, 8(3), pp. 459–467. doi:10.2166/washdev.2018.262.

15. Ainsworth, R. 2004 Safe piped water: managing microbial water quality in piped distribution systems. World Health Organization, Geneva. Available from: https://apps.who.int/iris/handle/10665/42785.

16. Alemayehu, T., et al. (2019). Application of hydraulic modelling for water distribution system optimization: The case of Addis Ababa, Ethiopia. Journal of Water Supply: Research and Technology-AQUA, 68(3), 178-190.

17. Alemu, Z. A., & Dioha, M. O. (2020). Modelling scenarios for sustainable water supply and demand in Addis Ababa city, Ethiopia. Environmental Systems Research, 9(1). https://doi.org/10.1186/s40068-020-00168-3

18. Awe, Michael & Okolie, Sociis & Fayomi, Ojo Sunday Isaac. (2019). Review of Water Distribution Systems Modelling and Performance Analysis Software. Journal of Physics: Conference Series. 1378. 022067. 10.1088/1742-6596/1378/2/022067.

19. AWWA & ANSI 2016 Granular Filter Material. Available from: https://www.abpsoil.com/images/refrences/Standard_awwa-b1002016.pdf.

20. Ayele, R. F. & Abate, B. 2018 Urban Water Supply System Performance Assessment: The Case of Holeta Town, Ethiopia.

21. Azagew, S., & Worku, H. (2020). Accessibility of urban green infrastructure in Addis-Ababa city, Ethiopia: current status and future challenge. Environmental Systems Research, 9(1), 26. https://doi.org/10.1186/s40068-020-00187-0

22. Behailu, Beshah & Hukka, Jarmo & Katko, Tapio. (2016). Service Failures of Rural Water Supply Systems in Ethiopia and Their Policy Implications. Public Works Management & Policy. 22. 10.1177/1087724X16656190.

23. Belachewa, Tadele, T. D. D. and D. H. (2021). Evaluating Hydraulic Performance of Water Supply Distribution Network: a Case of Asella Town, Ethiopia. International Research Journal of Modernization in Engineering Technology and Science Www.Irjmets.Com @International Research Journal of Modernization in Engineering, 3(10), 2582–5208. https://doi.org/10.35629/5252-031014181433

24. Berhanu, B. A., et al. (2020). Urban water supply in Ethiopia: Trends, challenges, and future directions. Water Policy, 22(1), 1-22.

25. Beyene TB (2020) Hydraulic modelling of water supply and water losses in the water supply distribution system of Adwa Town, Ethiopia

26. Bwire, C., Onchiri, R., & Mburu, N. (2015). SIMULATION OF PRESSURE VARIATIONS WITHIN KIMILILI WATER SUPPLY SYSTEM USING EPANET. In International Journal of Civil Engineering and Technology (Vol. 6). www.jifactor.com

27. Chowdhury, (2011), Modeling for water distribution system management in the 21st Century, Civil Engineering Congress, Dhaka, Bangladesh

28. Christopher Bwire, Richard Onchiri And Njenga Mburu, 2015. Simulation Of Pressure Variations Within Kimilili Water Supply System Using Epanet.International Journal Of Civil Engineering And Technology (Ijciet) - Volume:6, Issue:4, Pages:28-38.

29. CHRISTOPHER BWIRE, RICHARD ONCHIRI and NJENGA MBURU, 2015. SIMULATION OF PRESSURE VARIATIONS WITHIN KIMILILI WATER SUPPLY SYSTEM USING EPANET.International Journal of Civil Engineering and Technology (IJCIET) - Volume:6, Issue:4, Pages:28-38.

30. David, (2015), UN-Water, United Nations, MDG, water, sanitation, financing, gender, IWRM, human rights, transboundary, cities, quality, food security (2015) United Nations. Available at: https://www.un.org/waterforlifedecade/ (Accessed: 18 February 2024).

31. Demir, Selami & Manav, Neslihan. (2008). Development of a modified Hardy-Cross algorithm for time-dependent simulations of water distribution networks. Fresenius Environmental Bulletin. 17.

32. Department, Ministry of Water, Irrigation and Energy, Addis Ababa, Ethiopia. pp. 1–60

33. Dessie, A. B., et al. (2018). Hydraulic modelling for water distribution network management in Addis Ababa, Ethiopia. Journal of Water Resources Planning and Management, 144(10), 04018073.

34. Eryürük, K. (2021). Hydraulic Models for Calculating Head Loss in Water Distribution System: A Case Study in Konya. European Journal of Science and Technology, (28), 275-279

35. Fabunmi A. O. (2010): Design of Improved Water Distribution Network for UNAAB Campus, Unpublished B.Sc. Dissertation, Federal University of Agriculture, Abeokuta, Nigeria. ww.unaab.edu.ng/ugproject/2010bcfabunmiao.pdf accessed 19-11-12

36. Fulle, 2017, "ASSESSMENT OF URBAN STORM WATER DRAINAGE NETWORK SYSTEM AND ROAD FLOODING RISK MANAGEMENT IN ADDIS ABABA, NEFAS SILK LAFTO SUB-CITY" http://repository.smuc.edu.et/handle/123456789/3249

37. Gebrehiwot, S. G., & van der Zaag, P. (2017). Urbanization, water supply, and development in Ethiopia: The case of Addis Ababa. Journal of Urban Planning and Development, 143(4), 05017004.

38. Geleta Ebsa D, Fufa F (2021) Hydraulic performance Analysis of water supply distribution network using water GEM v8i. Drink Water Eng Sci Discuss 1–18

39. Girma, M. G., et al. (2019). Assessment of climate change impacts on urban water supply systems using hydraulic modelling: The case of Addis Ababa, Ethiopia. Sustainability, 11(10), 2901.

40. Gottipati, P. V. K. S. V., & Nanduri, U. V. (2014). Equity in water supply in intermittent water distribution networks. Water and Environment Journal, 28(4), 509–515. https://doi.org/10.1111/wej.12065

41. Gowda, Ramesh & L G, & Jagadeesha, C.J.. (2012). Simulation of Hydraulic Parameters in Water Distribution Network Using EPANET and GIS.

42. Guidolin, M., Burovskiy, P., Kaplan, Z., and Savid, D. (2010), CWSNET: An Object-Oriented Toolkit For Water Distribution Analysis: Proceedings of American Society of Civil Engineers Water Distribution System Simulation, 2010.

43. Haestad Methods 2003, WaterCAD Version 6 User's Manual. Haestad Methods Inc., Waterbury, CT, USA.

44. Hamza MA, Saqib M (2021) Evaluating the hydraulic performance of water supply distribution network: A Case of Asella Town, Ethiopia

45. Heryanto, T., Sharma, S. K., Daniel, D. & Kennedy, M. 2021 Estimating the economic level of water losses (ELWL) in the water distribution system of the city of Malang, Indonesia. Sustainability 13(6604), 1–15. doi.org/10.3390/su13126604.

46. Hunde, Chalchisa & Itefa, Habtamu. (2020). Hydraulic Performance Analysis and Modeling of Water Supply Distribution System of Addis Ababa Science and Technology University, Ethiopia. 10.20944/preprints202002.0149.v1.

47. IWA (International Water Association). (2000). Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures. IWA Task Force on Water Losses

48. IZINYON AND B. U., 2010; Ms. P. S. Salunke, An Overview: Water Distribution Network by Using Water GEMS Software, 2018)

49. Izinyon, O.C. and Anyata, B.U. (2011) Water Distribution Network Modelling of a Small Community Using Watercad Simulator. Global Journal of Engineering Research, 10, 35-47.

50. Jalal, M. M., Science, A. & Engineering, C. 2008 «Performance Measurement of Water Distribution Systems (WDS). A critical and constructive appraisal of the state-of-the-art» Performance Measurement of Water Distribution Systems (WDS).

51. Jilo TF (2020) Analysis of the hydraulic performance of Aleta Wondo Town water supply distribution system (Doctoral dissertation)

52. Kadhim, N.R., Abdulrazzaq, K.A. and Mohammed, A.H. (2021) 'Hydraulic analysis and modelling of water distribution network using WATERCAD and GIS: Al-Karada Area', E3S Web of Conferences, 318, p. 04004. doi:10.1051/e3sconf/202131804004.

53. Kara, S., Ethem Karadirek, I., Muhammetoglu, A., & Muhammetoglu, H. (2016). Hydraulic Modeling of a Water Distribution Network in a Tourism Area with Highly Varying Characteristics. Procedia Engineering, 162, 521–529. https://doi.org/10.1016/j.proeng.2016.11.096.

54. Katko, T. S., et al. (2019). Water supply challenges in rapidly growing African cities: Case studies from Nairobi and Dar es Salaam. Journal of Water and Health, 17(1), 1-15.

55. Kebede, M. T., et al. (2018). Hydraulic modelling for water infrastructure design: The case of Addis Ababa, Ethiopia. Journal of Water Supply: Research and Technology-AQUA, 67(6), 478-491.

56. Kilinç Y, Özdemir Ö, Orhan C, Firat M (2018) Evaluation of the technical performance of pipes in water distribution systems by analytic hierarchy process. Sustain Cities Soc 42:13–21

57. Kusnayat, A. et al. (2019) 'Hydraulic analysis software comparison of the water distribution system at Telkom University Area III', International Journal of Simulation: systems, science & amp; technology [Preprint]. doi:10.5013/ijssst.a.20.02.15.

58. Lemma, A. T., et al. (2021). Optimization of water distribution network using hydraulic modelling: A case study of Addis Ababa, Ethiopia. Water Science and Technology: Water Supply, 21(3), 1007-1018.

59. Liemberger, R., & Wyatt, A. (2017). Water loss reduction: Analyzing the nature of non-revenue water. Water International, 42(4), 343-358.

60. Maina, K. M. Assessment of water supply and sanitation challenges in uncontrolled residential developments. Nairobi country, 2015.

61. Mehta, Darshan & Yadav, Vipin & Prajapati, Keyur & Waikhom, Sahita. (2017). DESIGN OF OPTIMAL WATER DISTRIBUTION SYSTEMS USING WATERGEMS: A CASE STUDY OF SURAT CITY.

62. Mekonnen Y. A. 2018 Population forecasting for design of water supply system in Injibara Town, Amhara Region, Ethiopia. Civil and Environmental Research 10(10), 54–65.

63. Mekonnen, M. M., & Hoekstra, A. Y. (2016). Four Billion People Facing Severe Water Scarcity. Science Advances, 2(2), e1500323.

64. Mekonnen, Yitbarek. (2023). Evaluation of current and future water demand scenario and hydraulic performance of water distribution systems, a case study for Addis Kidam Town, Ethiopia. Applied Water Science. 13. 40. 10.1007/s13201-022-01843-9.

65. Milkecha C, Itefa H (2020) Hydraulic performance analysis and modelling of water supply distribution system of Addis Ababa Science and Technology University. Preprints, Ethiopia

66. Moosavian, N. (2014) 'Hydraulic analysis of water supply networks using a modified Hardy Cross method', International Journal of Engineering, 27(9 (C)). doi:10.5829/idosi.ije.2014.27.09c.02.

67. MoWIE 2019 Second Growth and Transformation National Plan for the Water Supply and Sanitation Sub-Sector (2015/16–2019/20) Ministry of Water, Irrigation and Energy, Addis Ababa, Ethiopia.

68. MoWR 2006 Urban water supply design criteria. Water Resources Administration Urban Water Supply and Sanitation Department, 1–60.

69. MoWR 2006 Urban Water Supply Design Criteria. Water Resources Administration Urban Water Supply and Sanitation

70. Muleta, D., Abate, B., 2020. Groundwater hydrodynamics and sustainability of Addis Ababa city aquifer. Groundwater. Sustain. Dev.

71. Munoz, J. A. (2020). Non-revenue water management: Challenges and opportunities. Journal of Infrastructure Systems, 26(4), 04020029.

72. Nwajuaku (2017) 'Saudi Journal of Engineering and Technology', Analysis of Head-loss Equations under EPANET and Hardy Cross Method [Preprint]. doi:10.21276/sjeat.

73. OWWDSE 2008 Oromia Water Works Design and Supervision Enterprise, Design Guideline for Water Supply Projects.

74. Pathan, Azazkhan Ibrahimkhan & Agnihotri, Prasit & Patidar, Nilesh & Mohseni, Usman & Patel, Dhruvesh & Prieto, Cristina & Karna, Kalyan. (2022). Design and Analysis of Water Distribution Network Using Epanet 2.0 and Loop 4.0 – A Case Study of Narangi Village. 10.1007/978-3-030-93247-3_65.

75. Pietrucha-Urbanik K, Tchórzewska-Cieślak B (2018) Approaches to failure risk analysis of the water distribution network about the safety of consumers. Water 10(11):1679

76. Pravinkumar Shinde 1, P. P. (2018). Design and Analysis of Water Distribution Network Using Water GEMS. International Journal of Advanced Research in Science and Engineering, 7(03), 545.

77. Rameshwari D. Bhoyar1, M. S. Modelling and optimisation of water distribution system. International Journal of Advance Engineering and Research Development, 4(7), 210-220, 2017

78. Rossman, L. A. 2000 Epanet User's Manual. Risk Reduction Engineering Laboratory, Office of Research & Development, US Environmental Protection Agency, Cincinnati, Ohio, USA

79. Saldarriaga, Juan & Ochoa-Rodriguez, Susana & Nieto, L. & Rodríguez, D.. (2010). Methodology for the skeletonization of water distribution network models with demand aggregation. 423-429.

80. Saldarriaga, Juan & Ochoa-Rodriguez, Susana & Rodriguez, D. & Arbelaez, Juliana. (2009). Water Distribution Network Skeletonization Using the Resilience Concept. 1-13. 10.1061/41024(340)74.

81. Shimeles K. (2011). Water Supply Coverage and Water Loss in Distribution System with Modeling (Case Study of Addis Ababa).

82. Sinha, S. K., & Tiwari, K. K. (2010). Calibration and validation of water distribution network model using EPANET. Water Science and Technology: Water Supply, 10(4), 596-603.

83. Sonaje, Nitin & Joshi, Mandar. (2015). A REVIEW OF MODELING AND APPLICATION OF WATER DISTRIBUTION NETWORKS (WDN) SOFTWARE. International Journal of Technical Research and Applications e-ISSN: 2320-8163,. 3. 174 - 178.

84. Tadesse, B., & Gebreyohannes, T. (2019). Assessment of non-revenue water in Addis Ababa: A case study of Kality and Bole Sub-cities. Journal of Water, Sanitation, and Hygiene for Development, 9(1), 130-140.

85. Tefera, T. A., Shimeles, F. B., & Wondwosen, T. (2020). Hydraulic Modeling of Water Distribution Networks Using WaterGEMS: A Case Study of Lideta Sub-City, Addis Ababa, Ethiopia. Journal of Water Resource and Protection, 12(6), 502–517.

86. Tekle, A. G., et al. (2020). Integration of hydraulic modelling into water infrastructure planning: The case of Addis Ababa, Ethiopia. Journal of Urban Planning and Development, 146(3), 04020003

87. Tekleab, S., et al. (2020). Non-revenue water reduction strategies in Addis Ababa: Challenges and opportunities. Water Policy, 22(5), 871-886

88. Teklue, 2020, "HYDRAULIC PERFORMANCE OF STORM WATER DRAINAGE NETWORK IN NIFAS SILK LAFTO SUB-CITY"

89. Terlumun, Utsev & Ekwule, Oloche. (2019). Evaluation of Municipal Water Distribution Network Using Watercard and Watergems. 5. 147-156.

90. Tesfaye, A., Muluken, W., & Dereje, H. (2018). Challenges and Opportunities of Water Supply in Addis Ababa, Ethiopia: A Review. Journal of Water Resource and Protection, 10(10), 901–914.

91. UNICEF. (2019). Rapid assessment of water supply coverage: Guidance note. Retrieved from https://www.unicef.org/media/63591/file/Rapid-assessment-of-water-supply-coverage.pdf

92. Van Zyl, J. E. 2014 Introduction to operational and maintenance of water distribution systems. Water Research Commission TT 600/14.

93. Walski, M., Chase, D. V., Savic, D. A., Grayman, W., Beckwith, S. & Edmundo, K. 2003 Advanced Water Distribution Modeling and Management. Civil and Environmental Engineering and Engineering Mechanics Faculty Publications. Paper 18.

94. Weday, D. (2005). Water supply Coverage and water loss in the distribution system in the case of Addis Abib. Indian Journal of Medical Research, 63(9), 1317–1322.

95. WHO 2022 Guidelines for Drinking-Water Quality, 4th ed. World Health Organisation, Geneva. Available from: https://www.who.int/publications/i/item/9789240045064 (accessed 8 September 2023).

96. Wolde, Amsalu & Jemal, Kemal & Woldearegay, Gebru & Desta, Kassu. (2020). Quality and safety of municipal drinking water in Addis Ababa City, Ethiopia. Environmental Health and Preventive Medicine. 25. 10.1186/s12199-020-00847-8.

97. Workneh, T., Smith, J., & Johnson, R. (2023). High pressure during low demand conditions: Causes and consequences. Journal of Water Supply and Management, 45(3), 215-230

98. WSDOH 2009 Water System Design Manual, Washington State Department of Health 123, 32. Available from: http://www.sswm.info/sites/default/files/reference_attachments/DOH2009WaterSystemDesignManual.pdf

99. Yadeta, (2019) "Modeling Water Supply Coverage and Water Loss in Distribution System of Addis Ababa City Water Supply: The Case Study of Jan Meda Zone" Addis Ababa SCIENCE & TECHNOLOGY UNIVERSITY.

100. Yuan Zhang, Shaoyuan Li Yi Zheng, Yuanyuan Zou 2020, Multi-model based pressure optimization for large-scale water distribution networks, control engineering practice 95 (2020)104232

101. Zischg, J., Mair, M., Rauch, W., Sitzenfrei, R., 2017. We are enabling efficient and sustainable transitions of water distribution systems under network structure uncertainty. Water 9 (9).

APPENDIX

Appendix – A Pressures Measured

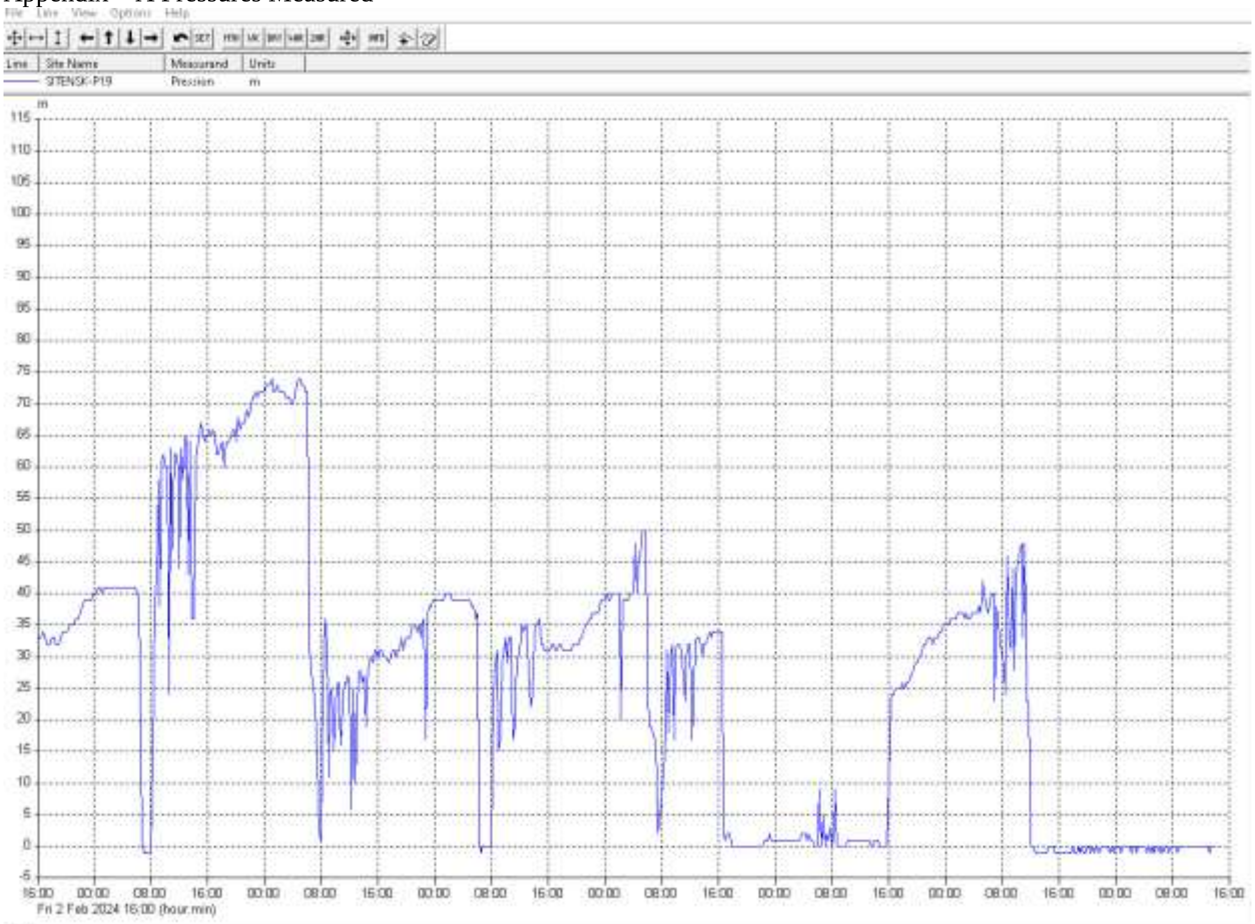


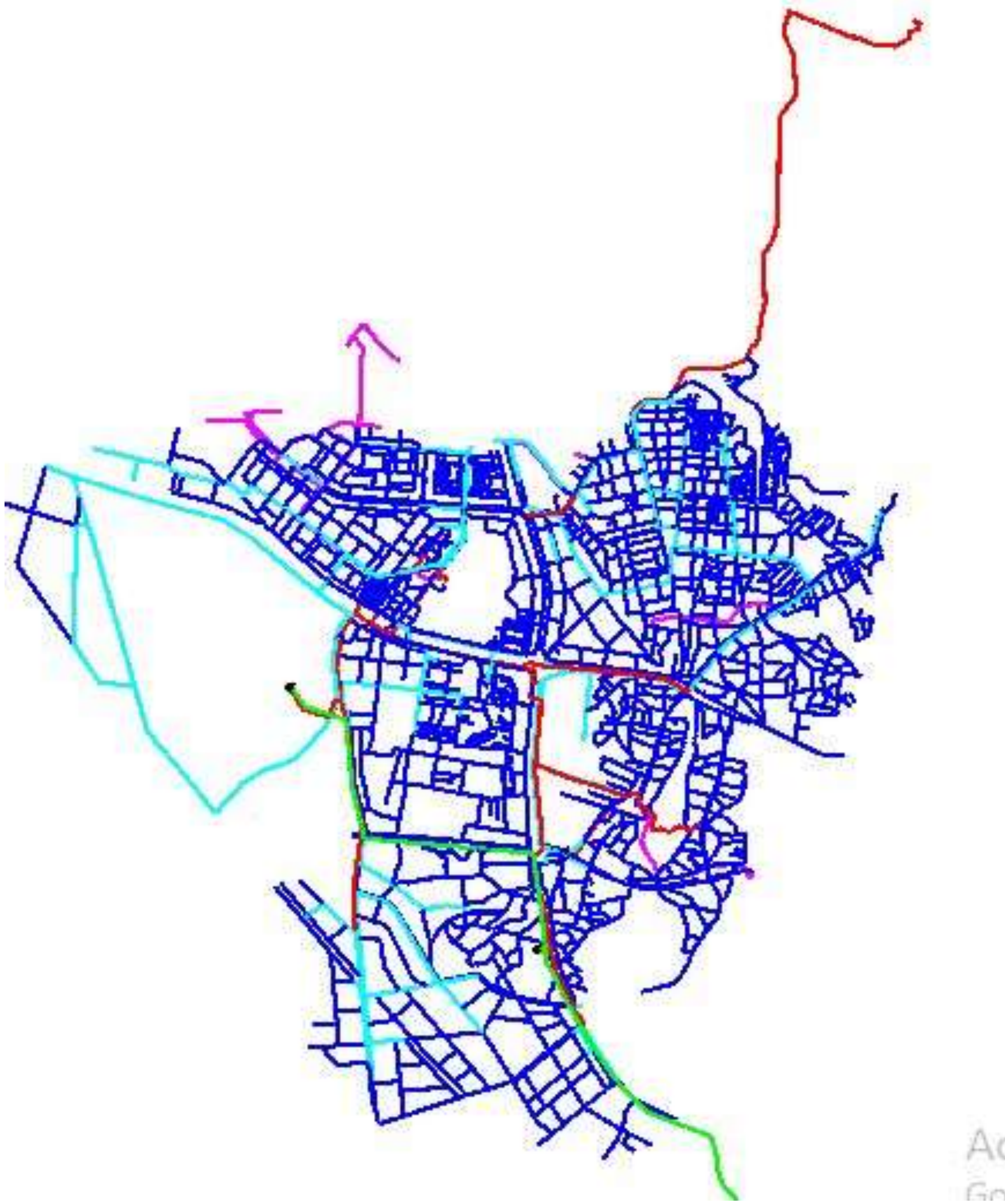
Figure. Pressure measured in the field

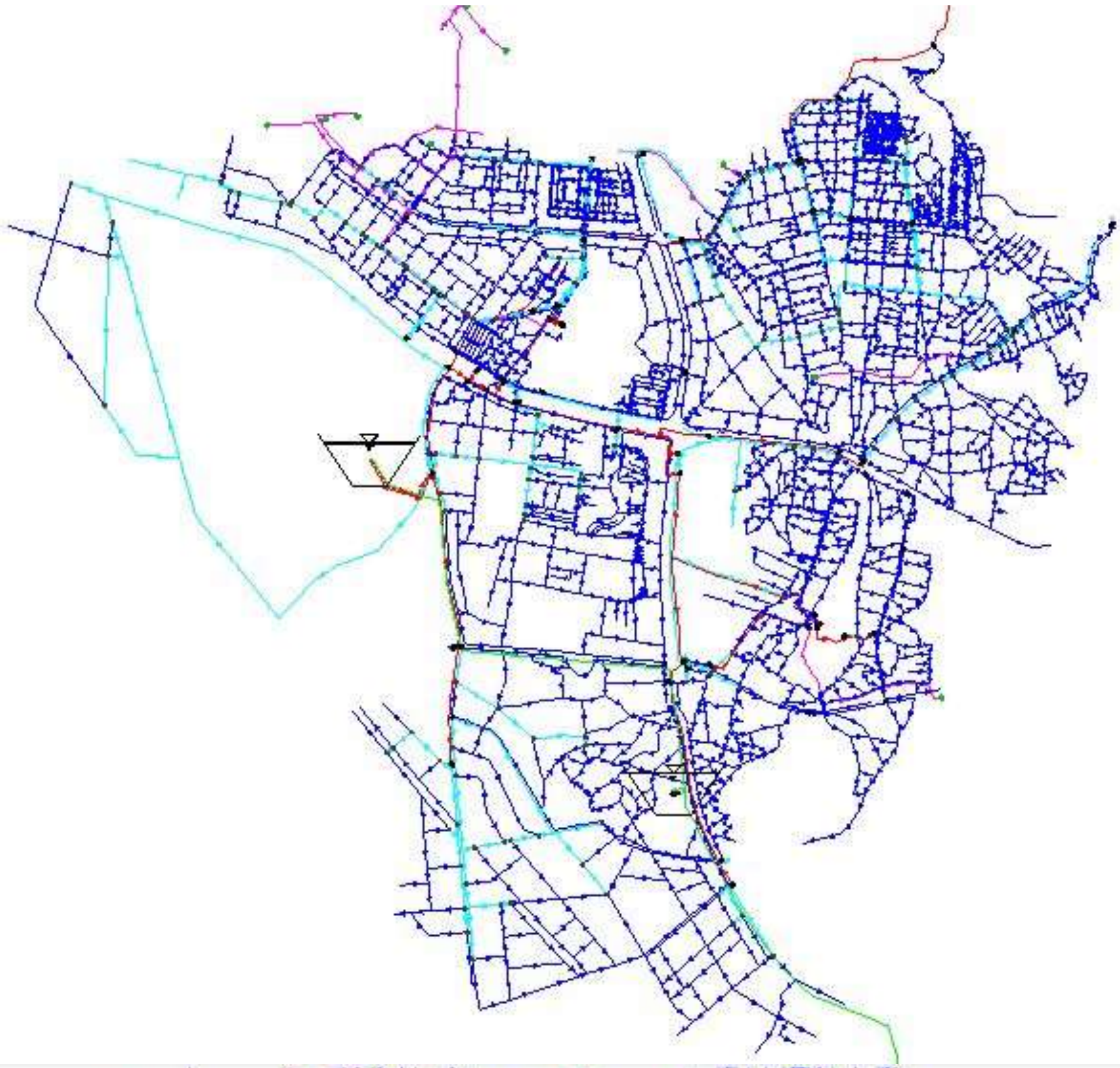
Field-measured pressure compared to the model pressure m

Node label	X (m)	Y (m)	Model Press. M	Field Press. M
J-57	471,504.50	989,727.73	42	40.95
J-59	471,642.62	989,730.90	42	42.751
J-56	471,877.30	989,737.52	45	43.95
J-1329	471,613.95	989,651.42	45	45.751
J-20594	472,024.64	989,591.12	46	44.95
J-55	472,029.72	989,643.19	47	47.751
J-20595	472,035.43	989,725.58	47	45.95
J-14	472,134.48	989,670.95	48	48.751
J-20596	471,969.09	989,624.95	48	46.95
J-20597	471,967.88	989,607.95	48	39
J-20598	471,965.24	989,574.42	49	48.11
J-20599	471,965.75	989,588.00	50	50.24

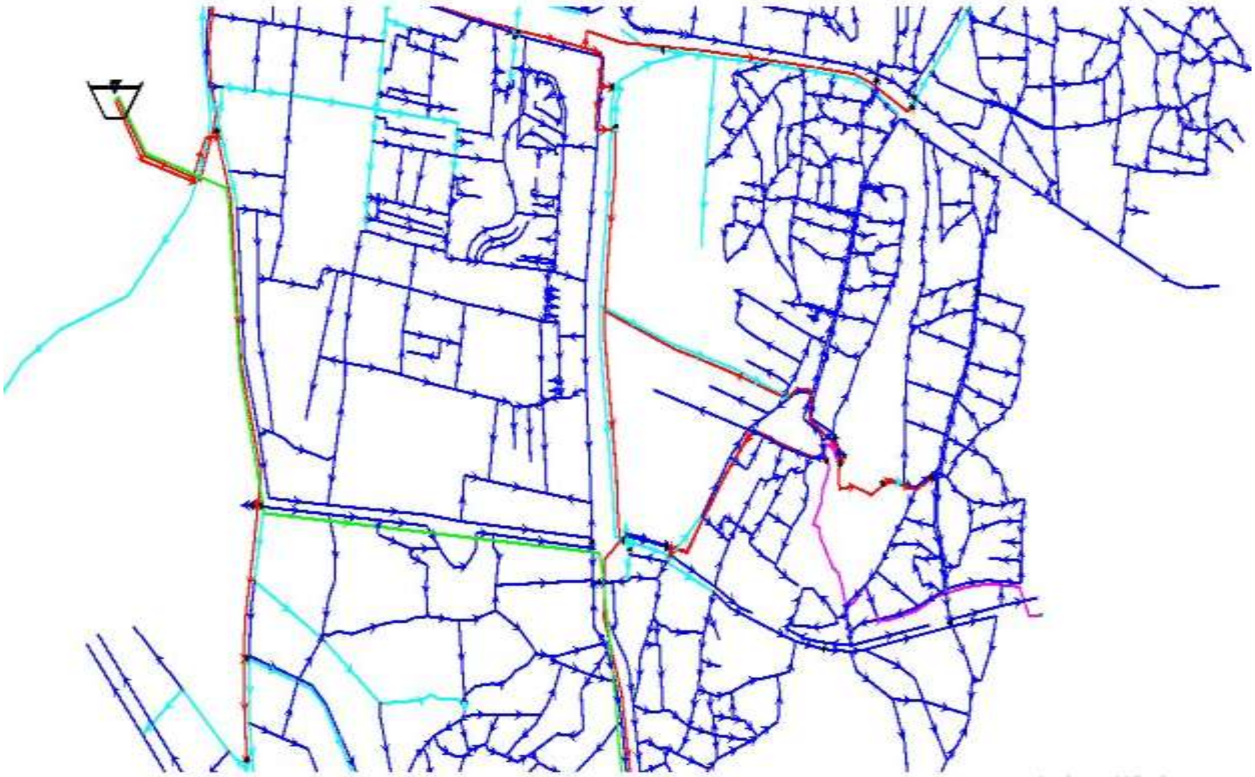
J-20600	471,980.53	989,555.37	50	51
J-20601	471,978.26	989,534.09	50	49.11
J-20605	471,977.79	989,530.82	51	51.24
J-20606	471,952.73	989,535.59	51	52
J-20602	471,931.03	989,505.43	52	51.11
J-13	471,930.28	989,492.16	53	53.24
J-20604	471,959.59	989,502.69	53	54
J-1328	471,961.34	989,520.69	54	55.8
J-15	472,260.96	989,969.73	55	56.2
J-1325	472,275.46	989,985.54	56	54.8
J-12	472,144.38	990,019.35	59	67
J-1324	472,210.07	990,000.36	66	67.2
J-1325	470,160.59	988,960.49	67	65.48
J-1321	470,157.93	989,200.00	71	72.8
J-20623	470,153.97	989,121.39	72	73.2
J-1322	470,153.66	989,115.27	73	73.53
J-1323	470,151.52	989,072.66	76	75.08
J-20629	471,077.14	987,120.85	77	75.89
J-1326	469,193.05	989,149.70	77	77.53
J-1328	469,774.73	987,170.35	77	76.08
J-20627	469,262.51	989,246.94	78	76.89
J-20628	471,835.16	987,511.12	78	78.53
J-1327	469,455.65	989,218.49	79	78.08
J-20626	468,900.03	989,270.09	80	78.89
J-1327	471,902.33	989,440.82	86	86.53
J-1322	468,937.73	989,307.79	95	96.22
J-1326	472,268.83	988,598.13	95	93.48
J-20609	469,379.85	989,400.62	100	98.99
J-20610	472,248.18	988,752.73	100	101.22
J-20607	469,535.95	989,386.06	102	100.48
J-20608	472,168.17	989,418.08	104	102.99
J-1321	469,525.37	989,253.77	110	111.22
J-1323	472,169.46	989,583.15	110	108.48

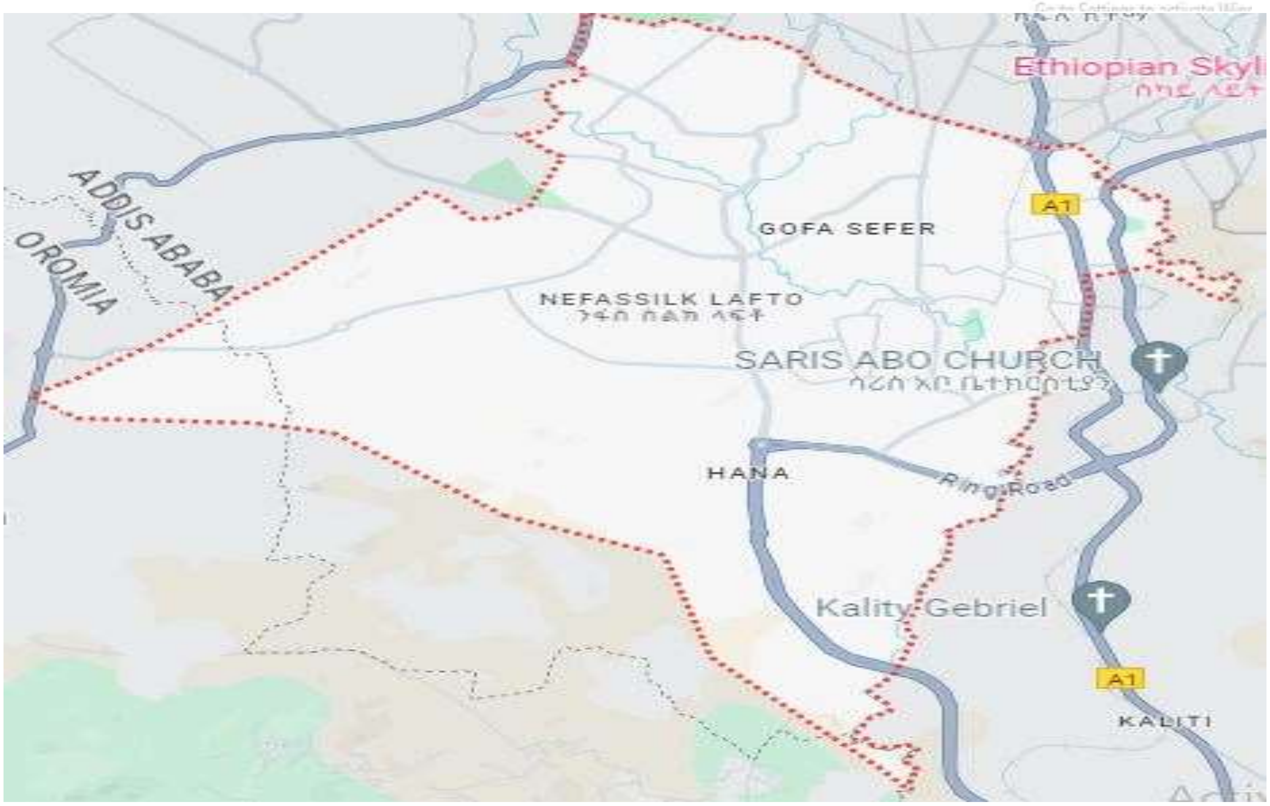
Appendix-B Project layouts






Activate Windows





(Source: BINGMAPS)