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M.Sc. in Civil Engineering

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MODELING OF WATER AGE IN DISTRIBUTION SYSTEMS: CASE STUDY

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RABER FALAH HASAN

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MODELING OF WATER AGE IN DISTRIBUTION SYSTEMS: CASE STUDY

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ABSTRACT

MODELING OF WATER AGE IN DISTRIBUTION SYSTEMS: CASE STUDY

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Ensuring water quality in water distribution systems (WDS) is paramount for public health. Water authorities aim to deliver an adequate, high-quality water supply to consumers with optimal pressure. This study focuses on a segment of Erbil City's WDS, utilizing EPANET 2.2 software to analyze hydraulic parameters and water quality, particularly water age, based on observed and documented data. The core objective of this research is to determine the age of water as it travels within the distribution system. Specialized computer programs, including EPANET 2.2, are used for a comprehensive case study. Digital loggers monitor pressure, and ultrasonic flow meters measure discharges, while a 72-hour calibration process ensures model reliability. The findings promise to inform new water projects and enhance existing infrastructure, ultimately contributing to responsible water management and public well-being. Access to clean drinking water profoundly influences society, the economy, health, and the environment.

Key Words: Water Distribution System, Water Quality, Water Age, Calibration, EPANET.

ÖZET

DAĞITIM SİSTEMLERİNDE SU YAŞININ MODELLENMESİ: ÖRNEK OLAY ÇALIŞMASI

HASAN, Raber Falah
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Su dağıtım sistemlerinde (WDS) su kalitesinin sağlanması halk sağlığı açısından çok önemlidir. Su otoriteleri, tüketicilere optimum basınçla yeterli, yüksek kalitede su temini sağlamayı amaçlamaktadır. Bu çalışma, gözlemlenen ve belgelenen verilere dayanarak hidrolik parametreleri ve su kalitesini, özellikle de su yaşını analiz etmek için EPANET 2.2 yazılımını kullanan Erbil Şehri WDS'nin bir bölümüne odaklanmaktadır. Bu araştırmanın temel amacı, dağıtım sistemi içinde dolaşırken suyun yaşını belirlemektir. Kapsamlı bir vaka çalışması için EPANET 2.2 dahil olmak üzere özel bilgisayar programları kullanılır. Dijital kaydediciler basıncı izler ve ultrasonik akış ölçerler deşarjları ölçer; 72 saatlik kalibrasyon süreci ise modelin güvenilirliğini sağlar. Bulgular, yeni su projelerine bilgi sağlamayı ve mevcut altyapıyı geliştirmeyi, sonuçta sorumlu su yönetimine ve kamu refahına katkıda bulunmayı vaat ediyor. Temiz içme suyuna erişim toplumu, ekonomiyi, sağlığı ve çevreyi derinden etkiler.

Anahtar Kelimeler: Su Dağıtım Sistemi, Su Kalitesi, Su Yaşı, Kalibrasyon, EPANET.

''I dedicate this thesis to my parents - my beloved dad, mom, wife, and sisters - for their endless love, support, and encouragement throughout my pursuit of education. Their unwavering support has helped me achieve this milestone. I hope that this achievement will fulfill the dream they envisioned for me. Without their constant encouragement and support, I could never have done this."

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Furthermore, I thank my committee members for their insightful comments and suggestions that significantly improved the quality of this work. Their contributions made the thesis defense an enjoyable and enriching experience.

I am deeply indebted to my parents and sisters for their unwavering support and understanding. Their constant prayers and encouragement were a beacon of strength, guiding me through the research and thesis writing process.

To my beloved wife, Dr. Zheen HAZIM, I want to express my love and gratitude for her unwavering support, best wishes, and encouragement.

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Finally, I offer my heartfelt gratitude to God for guiding me through the challenges I encountered. With His divine support, I have completed my degree and will continue to trust God for my future endeavors.

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LIST OF SYMBOLS

h_f	Head loss due to friction in meters
L	The length of the pipe in meters
D	The internal diameter of the pipe in millimeters
C	The Hazen-Williams friction coefficient (dimensionless)
f	Frictional head loss factor
V	The velocity in meters per second
P	The pressure in newton per square meter
γ	The specific weight of water in newtons per cubic meter
z	Elevation in meters
g	The gravitational acceleration constant ($g = 9.81 m/s^2$)
Q	The flow rate in cubic meters per second
OD	Outside diameter
ID	Inside diameter

LIST OF ABBREVIATIONS

EWSD	Erbil Water and Sewerage Directorate
WTP	Water Treatment Plant
MIPS	Maroda Intermediate Pump Station
EPANET	Environmental Protection Agency Network Evaluation Tool
MSL	Mean Sea Level
WDS	Water Distribution System
WDN	Water Distribution Network
AWWA	American Water Work Association
SCADA	Supervisory Control Data Acquisition
DMI	Data Management Interface
EPS	Extended Period Simulation
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization
GIS	Geographic Information System
DI	Ductile Iron
CI	Cast Iron
HDPE	High-Density Polyethylene
PVC	Polyvinyl Chloride
PE	Polyethylene
GRP	Glass-Fiber Reinforced Plastic
GPS	Geographic Positioning System
GZR	Great Zab River
PRV	Pressure-Reducing Valve
SI	(metric) or British systems
DBP	Disinfection by Product
NOM	Natural Organic Matter
Km^2	The square kilometer

CHAPTER 1

INTRODUCTION

1.1 General Overview

Water distribution systems (WDSs) are vital infrastructures that provide clean and potable water to communities worldwide. These systems have evolved from ancient civilizations settling near riverbanks to modern-day public water supply networks. Clean drinking water is essential for life and is recognized as a fundamental human right with significant health and economic benefits. Efficient WDSs are designed to deliver high-quality water to consumers at adequate pressure levels. This involves careful planning and management to maintain a stable hydraulic grade and ensure an uninterrupted water supply, even during emergencies. The different components of distribution systems, such as pipelines, valves, reservoirs, and pumping stations, work together to convey water from treatment plants to consumers' taps, industrial facilities, and public spaces.

There are three main types of WDSs: gravity, pumping, and combined gravity and pumping systems. Gravity systems use water's natural potential energy to flow from higher to lower elevations, while pumping systems require external power to operate. Combined systems utilize gravity and pumps for water conveyance and are the most common distribution system. This research focuses on a specific distribution system that pumps water to a storage tank before distributing it to consumers via gravity. This method ensures continuous access to safe drinking water with satisfactory pressure throughout the network.

Recently, the focus has shifted from WTPs to WDSs to ensure water quality and uninterrupted supply. Predicting and developing water network models plays a crucial role in this endeavor. These models, calibrated through comparisons of measured and calculated results, enable water authorities to predict hydraulic behavior and water quality under various operational conditions.

Calibrated WDN models are essential for master planning, rehabilitation work, water quality management, and system evaluation. They aid in decision-making for water treatment and infrastructure improvements and pave the way for future research and development of more advanced models. Various software tools are available for WDS modeling, offering capabilities such as predicting water age, particle tracing, and chemical concentrations. Calibrating these models is critical to ensure their accuracy by adjusting parameters to minimize discrepancies between simulated and observed data.

Ultimately, water authorities are responsible for ensuring that water is supplied efficiently, with the right amount of pressure and quality that meets acceptable user standards. Access to clean drinking water is crucial for users, and it impacts various aspects of society, the economy, health, and the environment. To determine the quality of drinking water, it is essential to understand its source and the processes involved in treatment and delivery. One way to examine the movement of drinking water through pipes without causing any disruptions for consumers is through computer models. These models can help analyze the age of the water as it reaches different locations, which is a crucial aspect of understanding how water quality changes over time.

1.2 Objectives of the Study

This study aims to determine the water age in the distribution network in a specific area of Erbil City. To achieve this, specialized computer programs like EPANET 2.2 will analyze the water system as a comprehensive case study. The study will investigate the current water supply network, analyze it using EPANET 2.2 software, and then compare the results with the existing network design. The study will also create a model for Erbil City's WDN segment that considers hydraulic characteristics and water quality. This model aims to improve decision-making, management, operation, and future planning related to the distribution network.

The study will undertake three specific objectives to achieve this goal. Firstly, data will be collected from the field and documented to build and develop the hydraulic model. Next, a field study will be conducted to calibrate the hydraulic model based on the field study results. Finally, the hydraulic model will be expanded to include water quality characteristics, such as water age and hydraulic features, under different flow scenarios.

1.3 The Process of Research

As part of a research project, a hydraulic and water quality model was designed for a segment of the WDN in Erbil. The area of Erbil City is approximately 14471 km², with a population of around 1,431,580 people, according to the most recent census. The city's drinking water resources consist of three projects built on the Great Zab River (GZR) and over 1400 artesian wells distributed across Erbil quarters, as shown in Figure 1.1. However, as underground water is a national resource that should be preserved for future generations, a new water treatment plant project named Ifraz 4 has been proposed on the GZR as an alternative source. The GZR is situated in the city's northwest, supplying water to the three current water treatment facilities: Ifraz 1, Ifraz 2, and Ifraz 3.

The process of executing the research involved designing the hydraulic and water quality model, which includes the following steps. Firstly, the problems of the case study area were identified. Then, the software program EPANET 2.2 was chosen as a solver and analyzer for hydraulic and water quality models. The most crucial step in this study was data acquisition, which could be either from documented data or data collected in the field. The data collection process was divided into two levels. The first level involved collecting data to make the hydraulic model, which included discharge measurements from all junction points on the significant and distribution main pipelines using ultrasonic flow meters. Pressure meters were installed at the junctions to record the pressure fluctuation at a specific period, and the elevation of each junction was taken into account using field surveying by one of the surveying instruments (e-Survey2). All these parameters were used to make a hydraulic model after investigating network pipeline diameters, materials, and directions. The Hazen William head loss coefficient C-factor for the case study network was found to complete the hydraulic model and make the calibration process. The calibration process compared the observed field data with computer model data produced by EPANET 2.2 software to identify any discrepancies. Finally, the aim of calibrating the model was to evaluate water quality characteristics such as water age and hydraulic features under various flow scenarios.

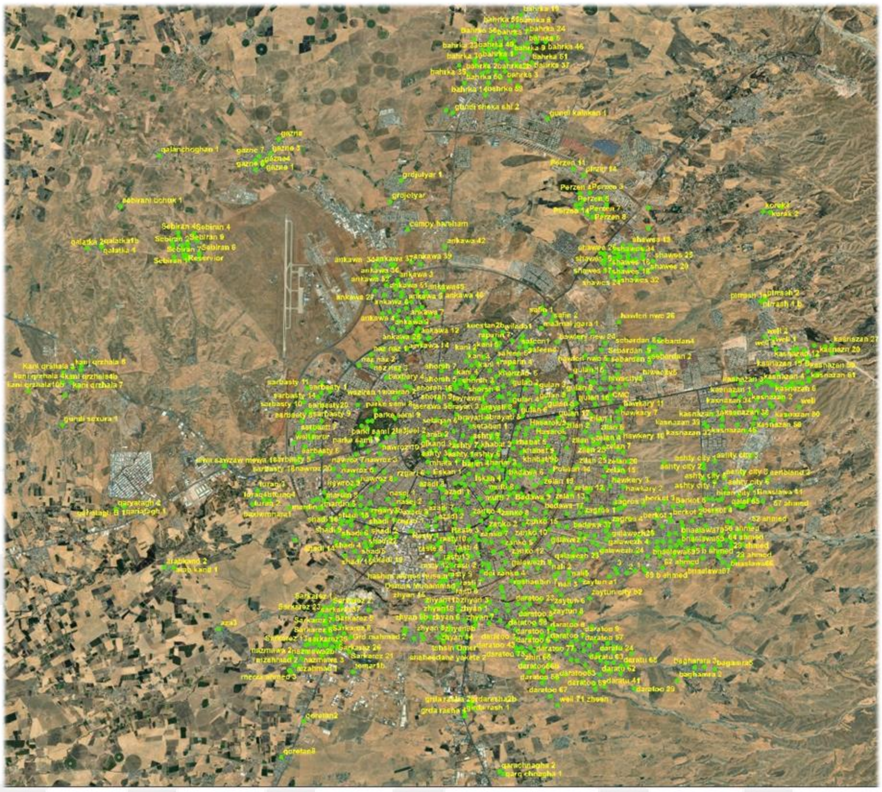


Figure 1. 1 The locations of artesian wells in various quarters of Erbil

Figure 1. 2 The process of conducting research

1.4 Thesis Organization

This thesis consists of six chapters focusing on different aspects of WDSs.

The first chapter is an introduction that highlights the significance of the research topic and provides a brief historical overview. It sets the stage for the subsequent chapters by outlining the importance of water distribution systems and their evolution over time.

The second chapter is a literature review that delves into existing research and literature on WDSs. It discusses the development of models and their impact on understanding these systems. Specifically, it examines advancements in hydraulic modeling, water age modeling, calibration techniques, and available software such as EPANET 2.2.

The third chapter focuses on Erbil City as the study area, providing insights into its WDS, sources, and historical development. It also addresses climatic factors and estimates water demand based on population growth.

Chapter four details the research methodology, mainly focusing on a segment of Erbil city. It elucidates the research methods, including data collection and analysis, and justifies their selection. The chapter outlines the stages of developing and calibrating the model, emphasizing comparing field data with modeled data and assessing water age effects.

Chapter Five presents the results and discusses the research findings, focusing on improving the hydraulic model for a segment of the WDS using field data. This chapter details the calibration process, including comparisons between observed and simulated data, and compares the existing and improved models, highlighting significant hydraulic and water quality advancements.

Finally, the concluding chapter summarizes the essential findings and insights obtained from the research. It reflects on the study's implications and offers suggestions for future research directions, thereby providing a comprehensive closure to the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Drinking Water Distribution

The design and complexity of WDSs vary based on local factors. The primary function of a WDS is to convey and deliver safe, high-quality drinking water in adequate quantities. In transmission systems, large mains or tunnels carry raw water to WTPs, delivering treated water to storage facilities at a steady flow rate. Distribution mains, which tap into these storage facilities or the transmission system, distribute water locally with flow rates and directions varying based on daily consumption patterns. The distribution network can be either branched or looped, with individual buildings connected to the local network through service pipes. Local utilities are typically not responsible for in-house distribution systems.

Pumping stations may be required to provide sufficient pressure in areas where gravity alone is inadequate. Conversely, PRVs are installed where pressures are too high. The system also includes numerous manholes and valves for access and control.

Storage basins, or equalizing basins, serve three main functions (Lindholm et al., 2012). First, they balance pressure and demand fluctuations, particularly during peak consumption periods, by maintaining 30-35% of daily consumption volume. Second, they provide a reserve for firefighting water. Third, they offer a reserve of 0.5 to 2 days of regular consumption in case of major pipe failures or repairs. Proper design includes at least two chambers for maintenance and positioning inflow and outflow to prevent stagnation and maintain water quality.

The choice of pipe material depends on pressure conditions, diameter, corrosion risk, and safety. CI and DI pipes have been used for over a century, offering high strength but requiring corrosion protection. Plastic pipes, such as PVC and PE, resist corrosion, are lightweight and flexible but can introduce chemicals and support microbial growth (Bruaset & Hem, 2014). GRP pipes are another option, while cement-based pipes are less common today.

Looped networks have advantages over branched ones. They provide alternative supply routes to connection points, ensuring continuous service even during pipe failures or maintenance. Looped systems can achieve fire flow capacity with smaller diameters and enhance water circulation, thus improving water quality. However, they pose a risk of water discoloration due to sediment resuspension. While looped systems generally have lower flow velocities, they may not self-clean as effectively as branched systems (Blokker et al., 2007).

A WTP is a technical facility that treats raw water and delivers the treated drinking water to consumers. Its functions typically include coagulation, sedimentation, filtration, disinfection, and sometimes additional treatments like fluoridation or pH adjustment, depending on the specific water quality requirements and regulations. On the other hand, a WDS encompasses the technical facilities responsible for receiving water from the WTP and distributing it to extraction points, such as residential, commercial, and industrial properties. These systems include an extensive network of pipes, valves, pumps, storage tanks, and other infrastructure components designed to convey water efficiently and reliably to end-users (WHO, 2011).

Proper design, operation, and maintenance of WTPs and WDSs are essential to ensure consumers' continuous supply of high-quality drinking water. Effective management practices, regular monitoring, and adherence to regulatory standards are imperative to safeguard public health and meet consumer expectations. This thesis requires a solid theoretical foundation on drinking water production and distribution to conduct water network modeling. In modern public drinking water supply systems, the main goal is to consistently provide adequate quantities of clean, safe, and palatable water to consumers, ensuring sufficient pressure at all times (Smith, 2018). Achieving these objectives demands appropriately designing, operating, and maintaining WTPs and WDSs.

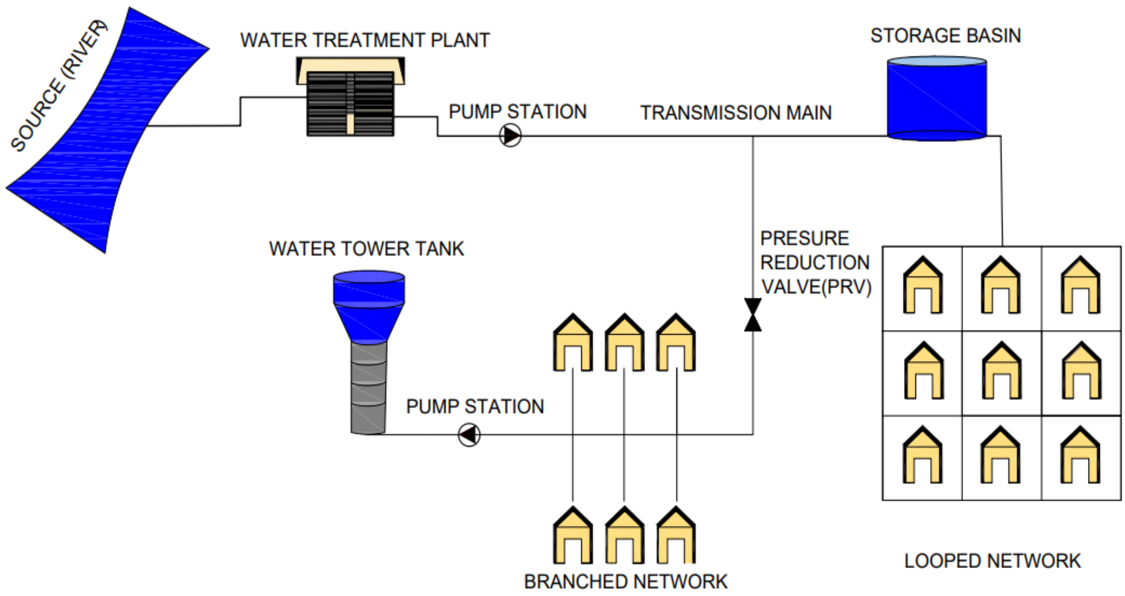


Figure 2. 1 The Diagram of the essential components of a WDS

2.1.1 Water Quality in the Distribution System in Relation to Water Age

Water age is a crucial parameter for assessing water quality in a WDS. EPANET 2.2, a sophisticated hydraulic and water quality modeling software, is widely used to simulate WDS behavior. This tool aids in designing and sizing new networks, retrofitting aging infrastructure, optimizing tank and pump operations, reducing energy consumption, investigating water quality issues, and preparing for emergencies.

Water age measures the time a parcel of water spends in the WDS from the source to the point of consumption or leakage (Burkhart & Janke, 2023). Operators strive to minimize water age to comply with regulations, meet fire suppression needs, maintain system pressure, and ensure customer satisfaction. In most U.S. water systems, the average water age ranges from one to three days (Kourbasis et al., 2020). Although water age does not directly indicate water quality, it influences other parameters like DBPs and microbial contaminants, which increase as water age increases and disinfectant levels decrease (Fischer, 2015).

Water quality degradation occurs during transportation and storage within the WDS. Issues like pipe cracks, joint separations, and interactions with pipe materials and biofilm can introduce contaminants. High water age in tanks and pipes with low or intermittent flow can promote biological contaminant growth. Water age increases with the distance from the WTP and varies with daily and seasonal demand fluctuations. Factors such as pipe size, network configuration, large user locations, recent water consumption, and tank cycles influence water age. External water sources also increase water ages (Burkhart & Janke, 2023).

Extended water age can lead to various water quality issues. Biological, chemical, and physical reactions may occur within the bulk water or between the water and wetted surfaces. Examples include sediment formation from settled particles and corrosion products, chlorine consumption through organic and inorganic materials reactions, and microbial growth due to low chlorine residuals. These conditions can cause microbial corrosion and metal leaching from pipe scales. High water age increases DBP formation due to prolonged chlorine contact with NOM. Monochloramine-disinfected systems may experience nitrification under high water age and warm temperatures. Stagnation in storage tanks and dead-end mains can elevate temperatures, microbial growth, and DBP formation, while changes in water chemistry can enhance biofilm growth, facilitating opportunistic pathogens like Legionella (EPA, 2022).

2.1.2 Water Age Analysis

Water quality within a distribution system is subject to chemical processes influenced by various factors such as water characteristics and the distribution network's infrastructure, including pipe material and age. These processes evolve and impact water quality, making residence time a crucial consideration. The water age, representing the cumulative time water spends in the system, is a reliable indicator of water quality. It aids in assessing the effects of storage tank turnover, disinfectant residual loss, and disinfection by-product formation. Unlike constituent analysis, which requires additional calibration procedures for water quality, water age analysis utilizes information from a calibrated hydraulic model, simplifying the process. Although less precise than constituent analysis, water age analysis provides a straightforward means to assess water quality based on the calibrated model's data.

In a hypothetical project investigating mixing in a tank and its impact on water quality within a troubled network, a calibrated hydraulic model enables immediate water age evaluation. Identification of prolonged residence times in the tank through water age analysis suggests potential water quality degradation. Subsequent detailed analyses, such as assessing tank hydraulic dynamics or conducting constituent analysis, can provide insights into disinfectant residual impacts, facilitating preliminary design or operational changes (Walski et al., 2003).

Using meticulously designed algorithms, water age analysis tracks cumulative residence times for water parcels throughout the network. It employs a zero-order reaction assumption, indicating that constituent concentration growth is proportional to time. The software generates comprehensive water age reports by summing residence times along transport pathways. Considering the intricate dynamics of water quality transport and reaction and the advanced simulation capabilities offered by modern software packages, precise water quality prediction in distribution systems is a possibility and a reality. Water quality modeling aids in optimizing distribution system modifications to reduce residence times and enhances the management of disinfectant residuals and other water quality-related operations. Utilities increasingly leverage these modeling capabilities to comply with stringent quality regulations, ensuring high-quality water delivery to consumers (Walski et al., 2003).

2.2 Digital Modeling

Digital modeling represents real-world systems in a simplified, mathematical form, allowing us to study these systems by defining clear system boundaries (Walski et al., 2001; Reichert, 2009). Effective models include all significant interactions and components relevant to the system under study despite the inherent risk of oversimplification leading to inaccurate results (Gujer, 2008). Nevertheless, digital models are invaluable for understanding complex systems.

Simulation, a process that mimics the behavior of real-world systems through digital models, is particularly useful when real-world experimentation is impractical. Simulations can provide insights into how potential unwanted events in a WDS might impact water quality without risking human health. They can predict system responses under various conditions and scenarios, facilitating safe and cost-effective analysis and planning for future configurations or modifications (Walski et al., 2001).

Calibration ensures the accuracy of digital models by comparing model outputs with real-world observations and adjusting parameters until the results align. This process, which can be automated, is essential for building confidence in a model's performance, identifying sensitive parameters, and uncovering missing or incorrect data (Walski et al., 2001). Lindell and Lingireddy (1997) outline seven steps for model calibration: identifying the model's intended use, estimating initial parameters, collecting calibration data, evaluating results, performing macro-level calibration, conducting sensitivity analysis, and executing micro-level calibration.

Validation, the final step in ensuring model performance and credibility, involves comparing model results with real-world observations. Unlike calibration, the observations used for validation can differ from those used in calibration. The process includes adjusting system demands, initial conditions, and operational rules to match field data conditions, followed by comparing predicted versus observed results to assess the model's validity (Walski et al., 2003).

2.2.1 Understanding the Importance of Modeling and Measuring Water Age

Network models that closely replicate the actual WDS in terms of components like nodes and pipes are known as detailed or all-pipes models. In contrast, skeletonized models are simplified versions that represent only a fraction of the system's nodes and pipes, typically excluding smaller diameter pipes (less than 4 inches). Consequently, these models aggregate demands across fewer nodes (Bahadur et al., 2008). Skeletonized models often predict lower average water age due to the shortened travel path from source to customer compared to detailed models, potentially leading to less accurate and misleading conclusions about water age.

Empirical determination of water age can be achieved through tracer studies, which involve introducing a tracer chemical at the treatment plant or a booster disinfectant station. Ideal tracers are inert, nonreactive, and easily detectable, such as calcium chloride or fluoride. The tracer's travel time through the WDS is measured using sensors like real-time conductivity meters (Boccelli et al., 2004). Although tracer studies provide direct measurements, they can be time-consuming and might need repetition across different operational states or seasons for comprehensive results.

Modeling tools like EPANET 2.2 offer a more efficient and accessible alternative to tracer studies for simulating water age. EPANET's simulation capabilities make it a standard tool for predicting water age in WDS, providing valuable insights without the extensive time and resource commitments required by empirical methods.

2.2.2 EPANET Overview and Usage

EPANET, developed by the EPA in 1993, received a significant update in July 2020 with the release of version 2.2, developed in collaboration with the open water analytics community. This version is available for download from the EPA website and supports steady-state and EPSs. A steady-state hydraulic model simulates a single time period without temporal variations, such as peak or average demand, while an EPS links a series of steady-state conditions to provide a time-varying analysis useful for water quality simulations (EPANET & OWA, 2022).

EPANET 2.2 is designed to model WDS and includes a user-friendly interface for creating realistic models, as shown in Figure 2.2. Key parameters for these models include component properties like pipe length and diameter, time parameters, hydraulic and quality options, and control mechanisms for pumps, tanks, pipes, and valves, as shown in Table 2.1. To run a water age simulation, specific time settings must be configured, including total duration, reporting time step, and statistical processing options. A total duration of 0 hours indicates a single-period analysis, while a non-zero value initiates an EPS, which is required for water age simulations. The reporting time step defines the intervals for result reporting, and statistical processing can be set to "None," "Average," "Minimum," "Maximum," or "Range" to summarize EPS results (EPANET & OWA, 2022).

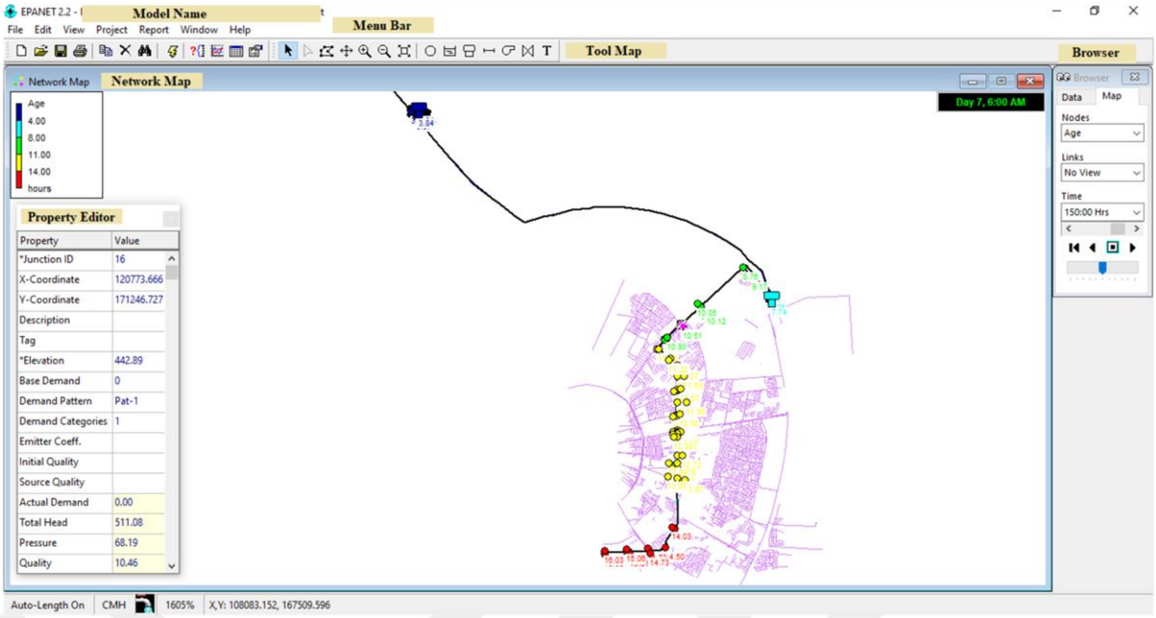


Figure 2. 2 The EPANET user interface displays the workspace and labels.

Table 2. 1 Key Terms and Descriptions in EPANET

Keywords	**Description**
Node	Elements representing points in a network, such as junctions, reservoirs, and tanks.
Junction	A node indicating where water enters or leaves the network.
Reservoir	A node signifying an infinite water source for network entry.
Tank	A node for water storage that does not modify water quantities within the network.
Link	Elements representing lines in a network, including pipes, pumps, and valves.
Base demand	A property of junctions used to specify the standard water demand.
Time pattern	A sequence of multipliers, such as base demand, is applied to a property to vary its value over time.
Controls	Statements that define the operational rules for the network over time.

The behavior of water storage tanks, which significantly impacts water age, can be modeled in EPANET 2.2 using four options: thoroughly mixed (MIXED), two-compartment mixing (2COMP), first-in-first-out (FIFO), and last-in-first-out (LIFO). The MIXED model, the default setting, assumes perfect mixing within the tank. The 2COMP model treats the tank as two compartments, requiring additional parameters for compartment size. FIFO and LIFO models track the order of water parcel entry and exit without mixing, maintaining separate quality calculations for each parcel (EPANET & OWA, 2022).

The EPANET 2.2 update improved water quality simulations by reducing mass imbalance errors through reordering node evaluations, allowing for larger time steps while maintaining accuracy (Davis et al., 2018). Achieving meaningful results in water age simulations requires the simulation to reach a steady state, indicated by a stable or consistently oscillating graph of water age over at least one day. These oscillations relate to system operations, demand cycles, and pumping and tank filling/emptying schedules, which must be considered to determine if a steady state is achieved (Burkhart & Janke, 2023).

EPANET 2.2 provides various tools for analyzing WDS, including graphs, charts, tables, and an animation tool. The data tab allows users to access and edit network model objects, while the map tab controls animation parameters and simulation times. Preconfigured graphs, such as cumulative frequency plots, are available for different analyses, and users can customize legend colors and value bounds. For a typical one-week (168-hour) simulation, peripheral nodes in the network model generally show higher water ages than nodes near the water source. It is helpful to average water ages in specific areas or across the entire model. However, this may obscure significant outliers, such as dead-end nodes and tanks, which often have higher water ages. Identifying nodes with high water age can assist in troubleshooting and optimizing the WDS. Focusing on nodes with nonzero demand (NZD) is particularly useful, as these represent active consumers, providing a more accurate assessment of the water age affecting actual users (Burkhart & Janke, 2023).

2.3 Indicators of High-Water Age

High water age in a distribution system can be identified through various signs, either observed by consumers or detected through system monitoring. While these indicators often point to high water age, they can also result from other factors, such as inadequate source water treatment, pipe materials, and the condition or age of the distribution system (AWWA, 2002).

2.3.1 Aesthetic Indicators

Consumers may notice the following aesthetic indicators during water consumption:

- Poor Taste and Odor: Aged water can foster the growth of microorganisms and substances that cause unpleasant taste and odor.
- Discoloration: Settled deposits can accumulate over time in low-flow areas and dead-ends. These deposits can be stirred up during demand periods, degrading water clarity and color.
- Water Temperature: Stagnant water tends to approach the ambient temperature.

2.3.2 Monitoring Indicators

The following indicators require sample collection and analysis:

- Depressed Disinfectant Residual: Chlorine and chloramines decay over time.
- Elevated DBP Levels: Disinfection byproducts (DBPs) form from the long-term reaction between disinfectants and organic precursors.
- Elevated Bacterial Counts: Heterotrophic plate counts can indicate bacterial growth.
- Elevated Nitrite/Nitrate Levels: Nitrification in chloraminating systems can increase nitrite and nitrate levels.

These indicators provide valuable insights into the quality and condition of water in distribution systems, allowing utilities to identify and address issues related to high water age and its impact on water quality and consumer satisfaction. Regular monitoring and proactive management strategies are essential for mitigating the effects of high-water age and maintaining a safe and reliable drinking water supply.

2.4 Measures for Reducing Water Age

Reducing water age in a WDS can be achieved through several strategies:

- Valve Throttling: Adjusting valve settings at pipe junctions can reduce maximum water age cost-effectively. However, it is crucial to ensure this does not compromise fire-fighting capacity or create excessive water age elsewhere in the system (Machell et al., 2009).
- System Configuration: Renovating WDS areas with water age issues by selecting appropriate pipe diameters and favoring looped-over branched configurations can reduce water age. Construction guidelines from Erbil city recommend looped systems to decrease hydraulic residence time, as they have fewer "dead ends"

where water stagnates. However, looped systems can experience flow reversals and larger volumes, which may impact feasibility.

- Continuous Tapping: Discharging water directly into receiving waters or stormwater systems can mitigate stagnant water problems. Although this approach results in water loss, it may be suitable for consistently problematic pipes.
- Storage Basin Operation: Adjusting the operation of storage basins, such as increasing their utilization through pumping station settings and ensuring good mixing, can effectively reduce water age (AWWA, 2002).

2.5 Strategies for Managing Water Age in Distribution Systems

Effective management of water age in distribution systems requires proactive monitoring, strategic design, and operational practices. Utilities can employ the following strategies to ensure the delivery of high-quality drinking water to consumers (EPA, 2022):

2.5.1 Identifying Areas of High-Water Age

- Data Analysis: Monitoring data should be reviewed for indicators such as low disinfectant residual, elevated DBP levels, bacterial counts, and nitrite/nitrate levels. Customer complaints should also be considered.

- Field Measurements: On-site disinfectant residual and water temperature measurements should be conducted in potential problem areas like dead-end mains and tank outlets.

- Thermal Stratification Assessment: Water temperature should be measured at different depths in storage tanks to detect thermal stratification, which can hinder water circulation.

- Modeling and Tracer Studies: Hydraulic or water quality models can be utilized to assess changes in water demand and tank operations. Tracer studies can also help to understand water movement in the distribution system.

2.5.2 Design Strategies for Water Age Management

- Infrastructure Optimization: Hydraulic models can right-size water mains and storage tanks for efficient water distribution.

- Tank Management Solutions: Tank mixers should be installed, and inlet/outlet placement optimized to enhance water circulation within storage tanks. Dead-end mains should be eliminated to prevent stagnation.

- Valve Optimization: Valve operations should be optimized to promote water circulation and ensure proper flow direction in the distribution network.

- Monitoring Equipment Installation: Sampling taps and automatic monitoring devices should be installed to track residual chlorine levels at critical points in the distribution system. Air valves should also be installed at high points to remove accumulated air, which can hinder water circulation.

2.5.3 Operational Strategies for Water Age Management

- Flushing Procedures: Gentle bulk water turnover flushing should be implemented to remove stagnant water and temporarily restore disinfectant residuals.

- Pumping and Tank Operations: Pumping schedules and tank filling/draining operations should be optimized to maintain adequate water flow and prevent stagnation.

- Regular Monitoring: Routine measurements of disinfectant residual in critical areas, including dead ends and low usage zones, should be conducted.

- Valve Maintenance: Valves should be exercised regularly to ensure proper operation and identify repair needs. Hydraulic models can assess flow direction and valve positions and conduct water age analyses.

- Valve Management: Valves should be reopened promptly after repair work to maintain water flow and circulation.

By implementing these comprehensive strategies, utilities can effectively manage water age within distribution systems, optimize water quality, and enhance system reliability for consumers.

CHAPTER 3

STUDY AREA

3.1 Erbil City

Erbil Governorate is one of the eighteen governorates in Iraq, each having its own administrative and political structures. This governorate is located in the northern part of Iraq. It includes the city of Erbil, also known as Hewlêr in Kurdish, which serves as the Kurdistan Regional Government's (KRG) capital. Erbil is one of Iraq's largest and most populous cities, with a history dating back thousands of years, making it the oldest continuously inhabited area in the world. It is famous for its ancient citadel, vibrant markets, and diverse cultural heritage. The ancient Citadel of Erbil, located at the heart of the city, is over 6000 years BC and has been recognized by UNESCO as one of the world's 100 edifices for its age and importance (UNESCO World Heritage Centre, n.d.). Figure 3.1 displays the location of Erbil and Iraq.

Figure 3. 1 Location of Erbil city on the map

Erbil (Hewler) is the largest in northern Iraq, covering an area of 14471 km² with a population of 1,431,580. Erbil City is in the middle of a large plateau, the Erbil Plane, about 412 meters above mean sea level (MSL). The western border of the plane extends up to the Tigris River. The area involves Qarachogh Mountain, about 5km north of where there is less Zab feedback to Tigris. The northern and northeastern parts of the city are high and comprise the most famous chains of mountains in the Kurdistan Region, with the peak of Hasarost being the highest in the region, in the northeast of Erbil. Many of Kurdistan's most beautiful summer resorts are in Erbil and distributed over the governorate's different parts. Agriculture and animal breeding are the primary economic activities in the governorate, along with various factories, industries, and crafts. Stable security has led to a tremendous increase in tourism activities in recent years.

Erbil's geographical coordinates are 36° 12' 22.6548" N and 44° 0' 31.932" E, with an elevation of 412 meters. The city follows a Mediterranean climate, influenced by cyclones and anticyclones that develop in the Mediterranean Sea basin during winter and summer. The climate is categorized as semi-arid continental, with cold and wet winters and hot and dry summers. Spring and autumn are short but pleasant seasons. The long-term average annual rainfall is over 400 mm, with the rainy season typically starting in mid-October and lasting until late May. The coldest months are December and January, while July and August are the hottest.

3.2 The History of the Water Distribution System in Erbil City

The construction of Erbil City's water distribution network began in 1924, starting at the Citadel (Qelat). Initially, several artesian wells pumped water to storage tanks above the Citadel, from where it was distributed to residents. As new residential areas developed in the lower part of Qelat, the WDS expanded, with significant additions made in 1940.

Figure 3. 2 Erbil Citadel (Qelat)

The government sector manages the water distribution system, founded by the Erbil Water and Sewerage Directorate (EWSD). The EWSD provides high-quality water to customers and handles cleaning processes in treatment plants, delivering water distribution networks, maintenance, and management works. The EWSD offers water to the city and is run by over 2000 employees. They manage treatment plants, artesian well operators, distributing lines and distribution network management, planning, designing, geographic information system (GIS), project construction, laboratory, machinery, administration, billing, and counting. The city water directorate is responsible for ensuring a constant supply of water, maintaining a sufficient water flow, monitoring water quality, identifying and solving problems in the distribution network, modifying and extending the existing distribution system, extending distribution pipelines as needed, data documentation, responding to customer complaints, and improving existing treatment plants and water sources.

Erbil city is serviced by three water treatment facilities, denoted locally as Ifraz 1, Ifraz 2, and Ifraz 3, established in 1968, 1982, and 2006. Ifraz 1 and Ifraz 3 are situated in Ifraz village, approximately 32 km northwest of Erbil city, whereas Ifraz 2 is located on the right side of Erbil-Ankawa Road. The water supply for these facilities is primarily drawn from three intakes positioned along the Greater Zab River (GZR) near

Ifraz Kamal village, equidistant from Erbil city. Ifraz 1 and Ifraz 3 treat water within their respective treatment plants, with the treated water subsequently conveyed to Erbil City. Conversely, Ifraz 2 conveys raw water to its treatment facility downtown Erbil, where the purified water is distributed to city residents. These plants collectively supply the city with potable water at approximately 12834 m3/hour.

Each water treatment plant adheres to a standardized process, typically consisting of five key stages:

1. Raw Water Intake: Water is sourced from the river.

2. Flash Mixing: Additives such as alum, polymer, and chlorine gas are introduced and mixed.

3. Sedimentation: Particles are allowed to settle.

4. Filtration: Remaining impurities are removed.

5. Storage: Water is stored in a high-lift storage unit post-second chlorination, making it suitable for consumption.

The capacities of the existing plants are as follows:

- Ifraz 1 (1968): 36,000 m^3/day

- Ifraz 2 (1982): 68,000 m^3/day

- Ifraz 3 (2006, expanded in 2016): 204,000 m^3/day

Given the existing infrastructure and growing demand, a proposal to construct a fourth water treatment plant, Ifraz 4, to enhance Erbil City's water supply capabilities further is depicted in Figures 3.3 and 3.4.

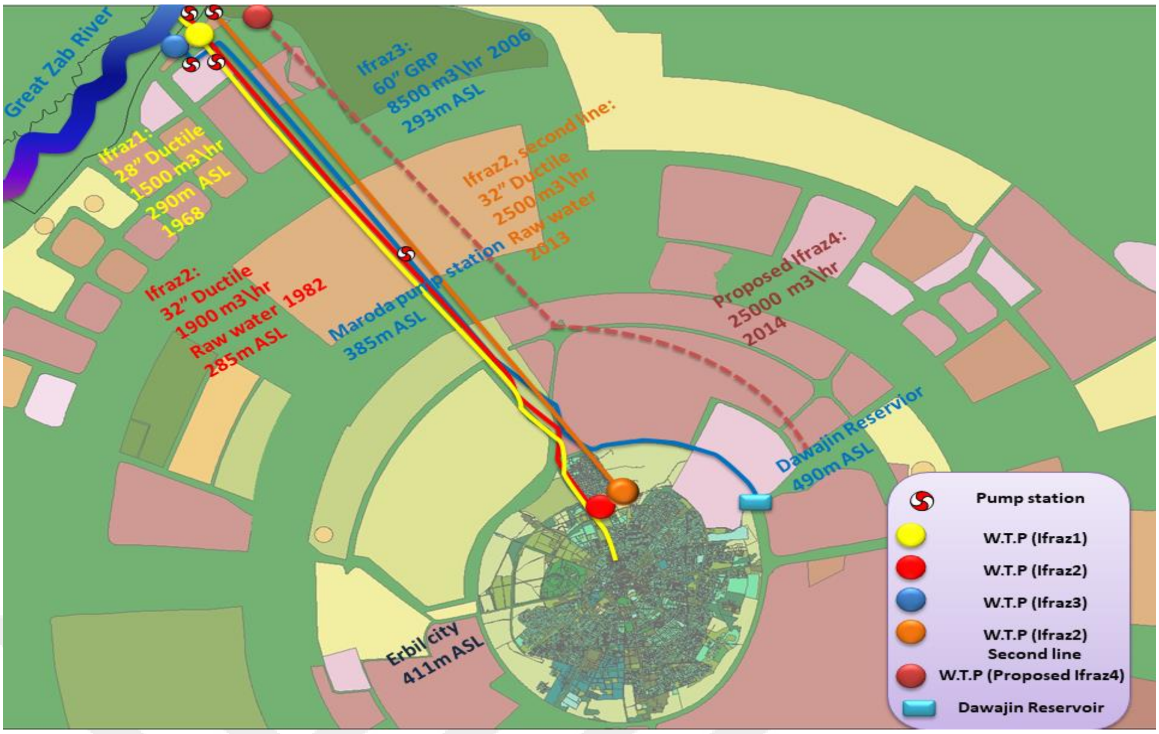


Figure 3. 3 Location of intakes on the GZR and the pipelines that extend from them

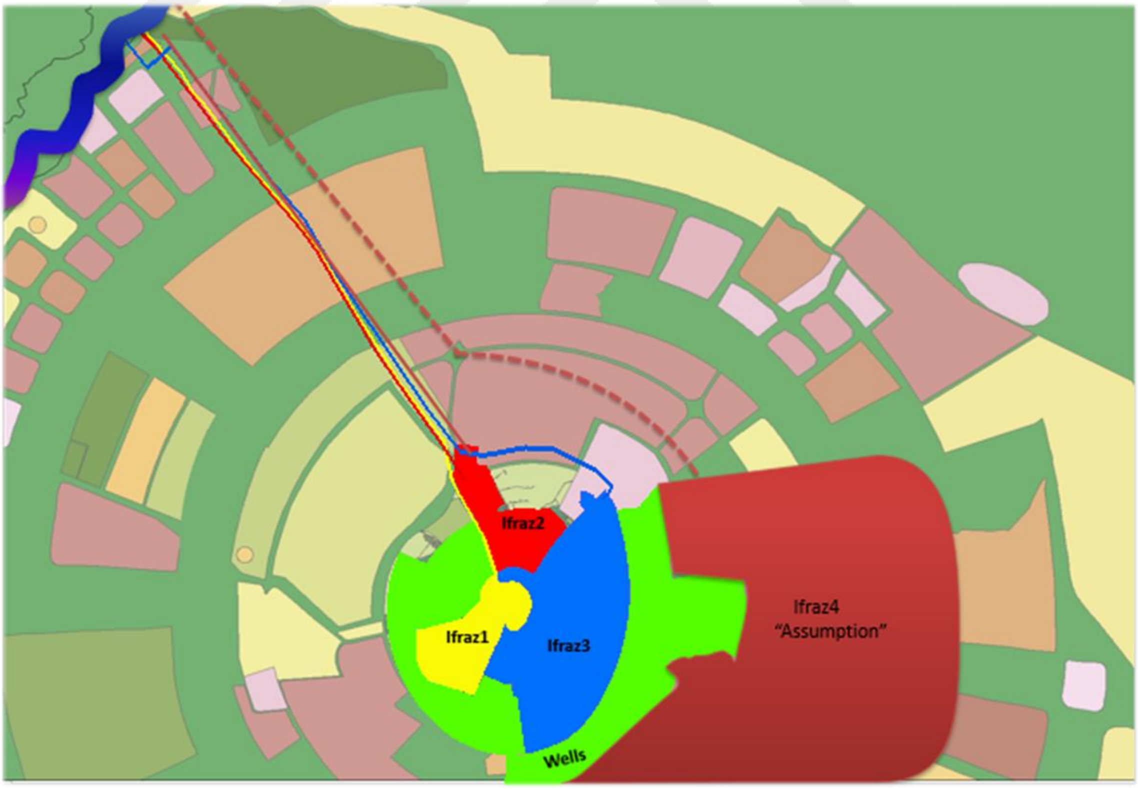


Figure 3. 4 Distribution of regions according to their water resources

More than 1,400 wells are connected to the water distribution system in Erbil City. These wells are distributed according to the water needs of the residents and are used to compensate for any water shortage from Ifraz 1, Ifraz 2, and Ifraz 3. Some wells are more than 500 meters deep and directly connected to the water distribution system or water storage tanks, which supply water to residents.

There are two types of water storage tanks: elevated tanks and ground storage tanks. Elevated tanks provide water to residents through gravity, while ground storage tanks use boosters to pump potable water to consumers. The capacity of both types of tanks ranges from 500 to 50,000 cubic meters, and they are made of either concrete or galvanized materials. Table 3.1 illustrates the increasing annual number of wells in Erbil.

Table 3. 1 The annual increase in the number of wells in Erbil City

Years	Number of Wells
2014	935
2015	970
2016	1007
2017	1106
2018	1151
2019	1179
2020	1214
2021	1260
2022	1330
2023	1403
2024	1432

The water distribution pipelines in Erbil are organized into DMIs (District Metered Areas) and sub-DMIs to control flow and pressure within the hydraulic model. Over time, old asbestos and plastic pipes have been replaced with ductile iron and polyethylene pipes, featuring diameters ranging from 110 mm to 1200 mm, depending on design and necessity.

The EWSD prioritizes delivering water to residents, followed by commercial areas and green spaces. From 2006 to 2024, recorded and documented house connections surged from 65,000 to 390,000. However, daily water demand can increase due to illegal or undocumented connections, prompting the installation of roof tanks of various sizes on all residences and buildings. All legal connections are equipped with house water meters.

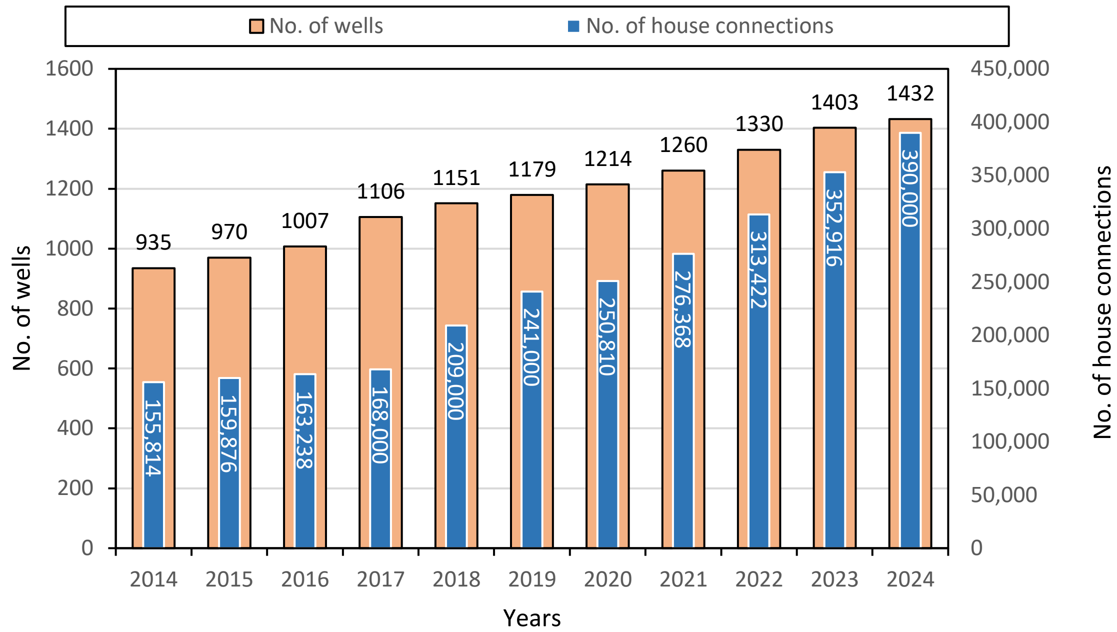


Figure 3. 5 The annual development of house connections and the increasing number of wells over the years

Erbil City heavily relies on groundwater, as over 50% of its water supply comes from artesian wells. However, this dependence poses a significant threat to groundwater levels, especially with the increasing number of wells currently standing at over 1400. Transforming to surface water sources is imperative to preserve groundwater, a valuable national resource.

The consequences of groundwater depletion are numerous and complex. These include:

- Lower Water Levels: As groundwater levels decline, drilling deeper wells or adjusting pumps becomes necessary, which can be costly and technically challenging.

- Reduced Water Availability: Depletion impacts water accessibility for agricultural, industrial, and domestic uses, leading to shortages and conflicts over resource allocation.

- Decreased Water Quality: Diminished groundwater levels can lead to the introduction of poor-quality water, such as seawater intrusion or surface contaminants, compromising water purity and safety.

- Land Subsidence: Groundwater extraction can cause land sinking, damage infrastructure, and alter surface water drainage, posing risks to urban and rural landscapes.

- Ecological Impacts: Ecosystems that rely on groundwater, such as wetlands and streams, suffer from reduced flow rates, endangering aquatic habitats and biodiversity.

- Long-Term Sustainability: Continued depletion threatens aquifer viability, jeopardizing future water security and leading to severe socio-economic and environmental repercussions.

Comprehensive management strategies are necessary to address these challenges. These include sustainable pumping practices, water conservation initiatives, groundwater replenishment projects, and robust regulatory frameworks to safeguard water resources effectively.

3.3 A Brief Description of Water Treatment Plant 3, or Ifraz 3.

The Ifraz 3 WTP supplies clean and safe water to many of Erbil city's population. It is located 32 kilometers away from the city and uses conventional surface water treatment methods to ensure that the water supplied to consumers is potable. The water treatment process starts by collecting raw water from the GZR and then screening and straining it to remove any suspended and dissolved materials. Chemical additives are then introduced to help with the flotation of suspended particles. Coagulation and flocculation processes are also used to improve water quality. A rapid mix unit is used to mix coagulants to encourage the particles to clump together efficiently.

The clarified water then goes through sedimentation and clarification stages to remove any remaining suspended particles. Filtration is a critical step in the treatment process, where water passes through filter units that contain media such as sand and gravel. This effectively removes any remaining impurities. After filtration, disinfection procedures are used to eliminate pathogens and ensure the safety of the water supply. The treated water is then conveyed to storage reservoirs, such as the Dawajin reservoir, through buried Glass-Reinforced Plastic (GRP) pipes with a diameter of 1500 mm. The Dawajin reservoir has a storage capacity of 20,000 cubic meters and serves as a distribution hub for the treated water.

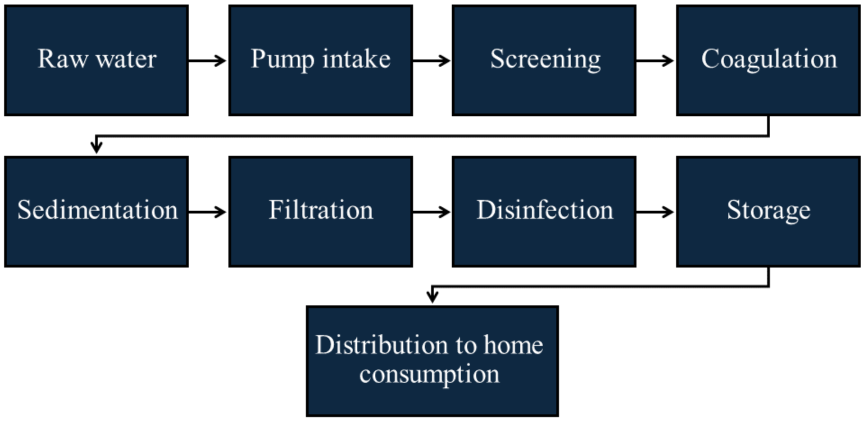


Figure 3. 6 Water treatment process

The Ifraz 3 WTP distributes the treated water to consumers within the study area through a network of buried pipelines that comprise DI and HDPE pipelines ranging in diameter from 110 mm to 1200 mm. Water distribution is gravity-driven, ensuring the designated neighborhoods receive an efficient and reliable water supply. The Ifraz 3 WTP is critical to Erbil City's water infrastructure. It provides a comprehensive approach to water treatment and distribution, safeguarding public health and meeting the water demands of a significant portion of the city's populace. Figure 3.7 presents an image taken by a drone of Ifraz 3 WTP.

Figure 3. 7 The Great Zab River and WTP 3 (Ifraz 3)

3.4 Description of Study Area

The study area is located to the east and northeast of Erbil city. It consists of a network of ductile iron pipelines that carry water from a concrete reservoir to at least eighteen Erbil neighborhoods, including Badawa, Brayati, Langa Bazaar, Safeen 2 & Industry Area, Iskan, Khabat, Khanzad, Kshtwkal, Kwestan, Mamostayan 2, Chnar, Mantkawa, Mufty, Raparin, Runaky, Safeen 1 and Zanayan. This network serves around 20% of the population of Erbil City. The study area includes the significant pipeline of 800mm and 1200mm diameter ductile iron pipes, which carry water from concrete reservoirs to these neighborhoods, and the main pipelines (connections or branches) made from DI and HDPE pipes with diameters ranging from 110mm to 1200mm. Several wells in the study area are directly connected to the water WDN. However, it is not anticipated that the water from these wells will significantly impact the water quality within the pipeline network of the case study zone. The elevated tanks and pipelines dispatch water to residents after pumping groundwater, which is insufficient to reach the leading and significant pipelines. The study area's manholes, constructed on main pipelines, were found through field investigations to measure the pressure and flow of substantial pipelines and observe the status of network components. More than 35,000 documented legal house connections in this study area, including commercial places, are in the EWSD, but more undocumented illegal house connections may exist. The location of the study area in Erbil city is depicted in Figure 3.8.

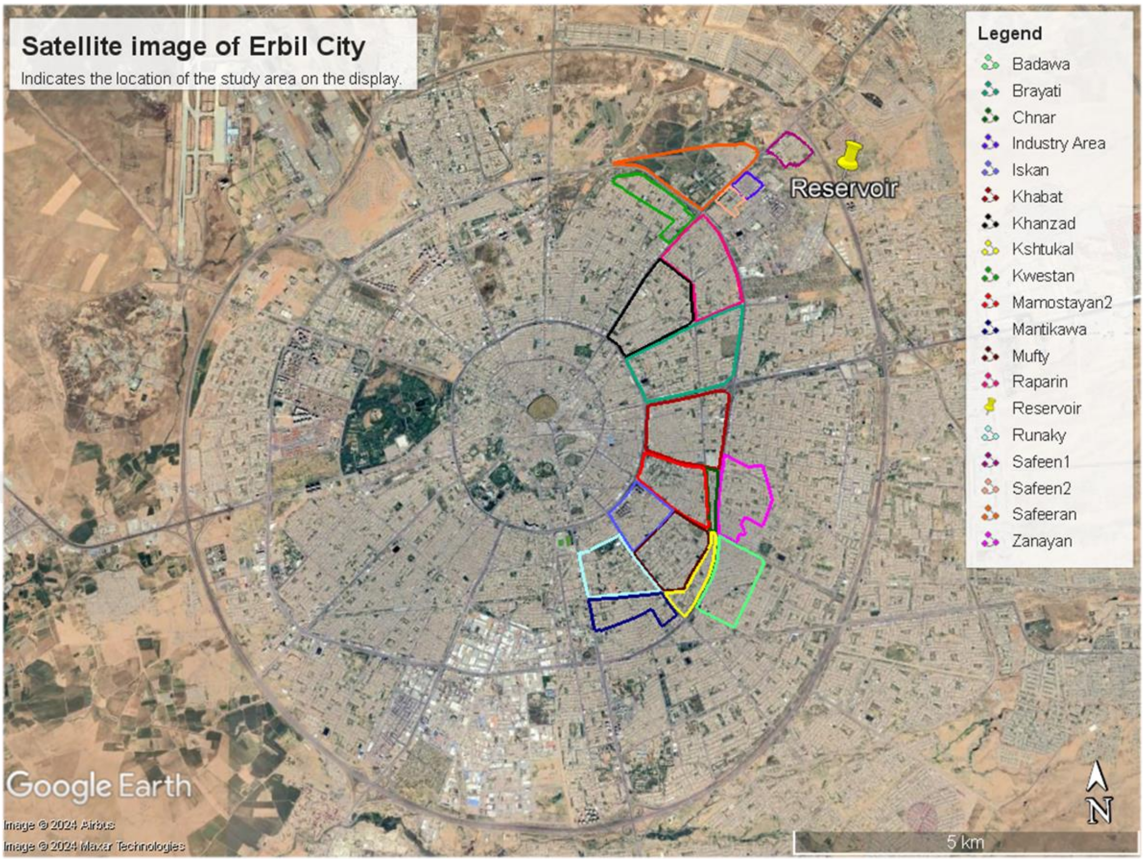


Figure 3. 8 The location of the study area in Erbil city using a satellite image

CHAPTER 4

METHODOLOGY

4.1 Introduction

Water distribution systems have been analyzed using mathematical models since Hardy Cross proposed them in the 1930s. Over time, as illustrated in Figure 4.1, the models have evolved from manual network flow analysis to computer-based hydraulic network models and distribution system water quality models. Nowadays, mapping systems and models are being integrated into user-friendly systems that analyze and display hydraulic and water quality parameters in a distribution system. Water quality models have reached operational status, but research and development continue to further the understanding of the processes and translate that understanding into usable tools.

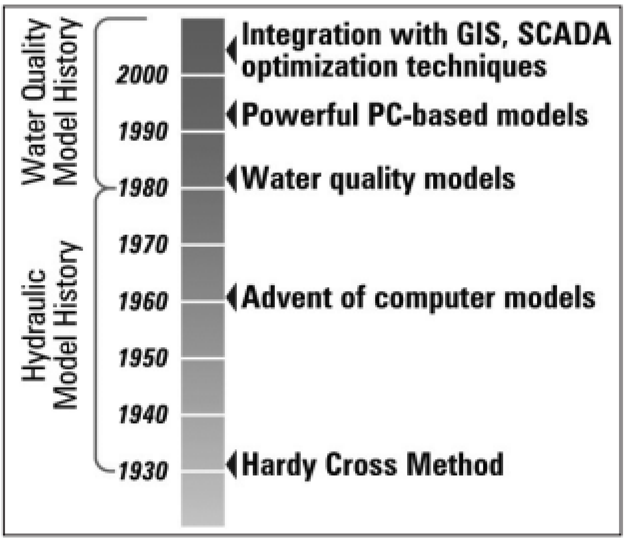


Figure 4. 1 The development of hydraulic and water quality models

The degree of temporal variation and specific issues being studied determine the most applicable models. Steady-state modeling represents external forces as constant in time and determines solutions that would occur if the system were allowed to reach equilibrium (Wood, 1980). Dynamic modeling allows demands and supplies to vary with time and determines the resulting temporal solution (Clark et al., 1988a; Clark et al., 1988b). A link-node network in steady-state and dynamic modeling represents a distribution system where pipes are links, and junctions, wells, tanks, or the start and end of pipes are nodes. Hydraulic models determine flows and velocities in links and pressures at nodes. Water quality models determine variations in the concentrations of a contaminant throughout the distribution system.

WDS models have become widely accepted in the water utility industry for simulating hydraulic and water quality behavior in network systems. Modern modeling software is powerful, sophisticated, and user-friendly, often integrating with GIS and computer-aided design (CAD) technology to facilitate model construction, storage, and result display. Initially, network models simulated only steady-state hydraulic behavior. In the 1970s, capabilities expanded to include EPS models, accommodating time-varying demand and operations. By the early 1980s, water quality modeling was introduced, incorporating steady-state formulations (Clark et al., 1986). Mid-1980s developments included dynamic water quality models for water networks (Grayman et al., 1988). The introduction of the public domain EPANET model and other Windows-based commercial software in the 1990s significantly enhanced these models' functionality (Rossman, 2000).

To achieve optimal results from a model, follow these steps: first, adequately represent the model. Next, conduct field tests to measure hydraulic and water quality factors. Finally, perform laboratory tests for water quality. Once data is collected and organized, input it into modeling software such as EPANET 2.2 to simulate and calibrate hydraulic pressure and water quality. Calibration involves comparing simulated data with observed field data to ensure accuracy. Pressure recordings and water quality data can be collected in the field or from the local water authority to acquire data for the hydraulic model. By using EPANET 2.2, you can efficiently complete the simulation and calibration processes for hydraulic and water quality models by comparing them with collected field data.

4.2 Determination of Water Age

Determining the Age of Water involves a comprehensive analysis of various factors. According to the Water Industry Database (AWWA & AwwaRF, 1992), the retention time of water distribution systems is typically around 1.3 days, with a maximum of 3.0 days. This is based on a survey of over 800 U.S. utilities. However, there are examples of short and long water ages, with the age of water determined by factors such as demand, system operation, and design. As water demand increases, the amount of time water spends in the distribution system decreases. The water demand is influenced by several factors, such as land use patterns, commercial-industrial activities, weather conditions, and water use practices. While conservation practices such as reclaimed water may lead to greater water age, it is essential to consider all other factors involved.

These four examples demonstrate how water age can vary among communities due to various factors. For instance, a utility in North Carolina with 1,100 miles of main and serving 300,000 customers found water ages ranging from 2 to 75 hours throughout the distribution system using a fluoride tracer study (DiGiano et al., 2000). Another Midwest utility serving 800,000 people and 2,750 miles of main recently discovered that the water age in the distribution system was typically less than 80 hours. However, based on a hydraulic model, some sites exhibited a water age of up to 150 hours (Vandermeyden & Hartman, 2001). In California, a utility found water ages exceeding 400 hours in some system regions, particularly dead-end areas, under minimum day and average day demand conditions (Acker & Kraska, 2001). Lastly, a Canadian utility serving 24,000 people estimated the water age using a hydraulic model and found that dead-end nodes had a water age ranging from 300 to 600 hours under average day demand conditions (Prentice, 2001). As a result, the importance of water age as a significant driver for water quality conditions in these distribution systems can vary significantly from system to system and even within each system.

4.2.1 Tracer Studies

Tracer studies are commonly used to determine water age throughout a distribution system. These studies offer a means of calibrating water quality and hydraulic models while examining the relationship between water age and various quality parameters, such as chlorine residual or trihalomethanes. Tracers can take the form of injected chemicals, including fluoride or calcium chloride, or natural constituents found in systems with multiple sources and varying water quality characteristics. In addition, transitional periods in system operation, such as changes in disinfection methods, can also offer opportunities for tracer studies. However, it is essential to consider the stability of the tracer chemical, regulatory compliance, and customer perceptions when planning and implementing such studies. For example, discontinuing fluoride feed may be necessary to avoid interference with uptake on pipe walls in newly fluoridated systems. Conversely, state health departments may not permit the discontinuation of fluoridation. While lithium chloride is used in tracer studies in the United Kingdom, its use is limited in the United States due to customer acceptance issues (Smith et al., 2001).

4.2.2 Mathematical Models

Mathematical models have been utilized to estimate water age in distribution systems by capturing the hydraulic behavior of water movement (Clark & Grayman, 1998). Initially, steady-state travel time models were introduced in the mid-1980s (Males et al., 1985), and later, dynamic models were developed to capture varying water ages throughout the system (Grayman et al., 1988). To predict the concentrations of chlorine, DBPs, and other constituents in a distribution system, water quality models can be used in conjunction with hydraulic models (Vasconcelos et al., 1996). Relationships proposed by Rossman et al. (1994) can be utilized to estimate the interaction of flowing water with pipe walls. Identifying and measuring the rates and mechanisms of reaction (decay and growth) for each non-conservative water quality parameter is necessary for a specific system. Precise calibration of both hydraulic and water quality models is essential to accurately predict water age and water quality conditions under varying demand scenarios. Measuring hydraulic and water quality conditions simultaneously is typically required since changes in water quality are directly related to hydraulic and system operation conditions. SCADA systems may provide hydraulic and facility operational information where feasible. Furthermore, existing chlorine monitor outputs can be utilized by a calibration program. Manual data collection may be necessary when automated data is unavailable at facilities.

Several factors may limit the accuracy of models when predicting water age. One such factor is skeletonization, which may be necessary if the water system has more pipe segments than the model can handle. Skeletonization involves excluding smaller diameter pipes (such as 8-inch ones) while maintaining the physical distance between nodes. This impact on water age predictions can vary depending on the proportion of smaller diameter pipes in the system. Another limitation is insufficient calibration, which typically only looks at a single time step and may not accurately represent flows throughout the system. Water storage tanks are often modeled as completely mixed reactors, which may underestimate water age. Inaccurate total demand or demand allocation can also affect accuracy, as can errors in model development, such as incorrect settings on PRVs or pump curves. Given the complexity of water age calculations and extended period simulations, it is essential to consider these potential limitations when interpreting modeling results.

During the early 1990s, a simplified model for water age in tanks and reservoirs was developed (Grayman & Clark, 1993). Later, this model was further refined as part of a study called "Water Quality Modeling of Distribution System Storage Facilities" by (Grayman et al., 2000). The study also applied more complex computational fluid dynamics (CFD) models, representing the hydrodynamic behavior of tanks and reservoirs. Methods were developed to estimate the mixing characteristics, distribution, and concentration of conservative constituents (or substances that decay according to a first-order decay function) to predict water age in a reservoir.

4.3 Storage Modeling

The impact of storage systems on water quality and contaminant propagation in WDSs is critical. Utilities often use ground or elevated storage to process water during periods when treatment facilities are idle, enabling distribution and storage at multiple locations near users. Distribution storage equalizes demands on supply sources, production facilities, and transmission and distribution mains, allowing for minimized sizes or capacities of these elements and avoiding peak power tariff periods for pumping. It stabilizes system flows and pressures, enhancing service quality across the area and providing reserve supplies for emergencies like firefighting and power outages.

Typically, municipal water systems use less than 25 percent of tank storage volume daily under routine conditions. As water levels drop, tank controls activate high-service pumps to meet demand and refill tanks. The remaining 70 to 75 percent is held in reserve for emergencies, leading to stagnant water that can cause quality issues. Storage tanks and reservoirs, while highly visible, are often misunderstood regarding their water quality impacts. They play a vital role in ensuring hydraulic reliability and service continuity but can also facilitate undesirable chemical and biological changes, degrading water quality. Increased residence time in these storage facilities can lead to disinfectant residual loss and microorganism growth.

Modeling is a valuable tool for understanding water behavior in these facilities and predicting outcomes in existing, modified, or proposed tanks and reservoirs under various operating conditions (Grayman et al., 2004). Three primary model types represent storage tanks and reservoirs: computational fluid dynamics (CFD) models, compartment models, and physical-scale models. CFD models provide detailed representations of hydraulic mixing phenomena, compartment models offer simplified conceptual representations of mixing behavior, and physical-scale models, constructed from wood or plastic, use dyes or chemicals to trace water movement.

4.3.1 CFD Models

CFD models utilize mathematical equations to simulate flow patterns, heat transfer, and chemical reactions, representing the conservation of mass, momentum, and energy. These equations are solved over a two- or three-dimensional grid approximating the tank's geometry. Widely employed in chemical, nuclear, and mechanical engineering, CFD modeling has recently gained traction in the drinking water industry (Grayman & Arnold, 2003). These models can predict temperature variations, unsteady hydraulic conditions, water quality, and the decay of constituents in storage facilities. However, applying CFD models requires considerable expertise and simulations for complex scenarios can take hours to weeks. Numerous CFD software packages are available, differing in capabilities, solution methods, usability, and support. Users must carefully assess their specific needs and capabilities before selecting a package. These packages generally involve substantial costs (around $25,000 annually), and significant training is necessary for effective use (Panguluri et al., 2005).

4.3.2 Compartment Models

Compartment models, also known as black box or input-output models, use conceptual and empirical relationships to represent physical processes such as mixing in tanks or reservoirs. Unlike complex mathematical models, compartment models rely on engineering judgment or historical data to determine the parameters that govern their behavior. In water distribution network models, these models simulate mixing in tanks and reservoirs by making various assumptions, including complete mixing, plug flow, and multi-compartment scenarios. They can simulate both conservative and decaying substances and water age. Compared to CFD models, compartment models are user-friendly and have shorter run times. Many water distribution system models, such as EPANET, incorporate tank compartment models with options for complete mixing, plug flow (FIFO), LIFO, and two-compartment models. Comp-Tank, a stand-alone model, allows users to simulate water age and reactive or conservative substances over extended periods, primarily using tank inflow and outflow data from SCADA records (Grayman et al., 2000).

4.3.3 Physical-Scale Models

Physical-scale models offer a cost-effective approach to studying the mixing characteristics of tanks. In these models, a tracer chemical is introduced to the inflow or within the model, and its movement is tracked throughout the experiment (Grayman et al., 2000). Tracers, such as visible dyes or chemicals like calcium chloride, help develop a qualitative and quantitative understanding of mixing behavior. By using tracers with varying densities or controlled temperatures, the effects of thermal variations on mixing can be examined. Adhering to hydraulic laws of similitude is crucial to account for scaling effects. These models range from small tabletop versions to large-scale models in hydraulics laboratories.

Roberts and Tian (2002) utilized three-dimensional laser-induced fluorescence (3DLIF) to measure tank mixing in detail. Their experiments on jet-induced mixing in various storage tank styles with different inlet geometries revealed that 3DLIF can identify complex flow patterns without buoyancy effects. In cylindrical tanks, the dimensionless mixing time increases with the depth-to-diameter ratio. The most efficient mixing occurs with vertical nozzles at the bottom, especially near a sidewall, and mixing speeds up with more nozzles. Rectangular tanks exhibit similar mixing times to cylindrical ones. However, a tube intended to enhance mixing hindered it in standpipe tanks. Tian and Roberts (2008a, 2008b) also found that small density differences can inhibit mixing. The primary factors affecting mixing include total inflow momentum flux, density differences, water depth, and nozzle placement and orientation. Effective mixing can be achieved with simple nozzle configurations, making complex mixing devices unnecessary.

4.4 Model Representation and Field Testing

This section outlines the process of model representation and field testing essential for constructing a hydraulic model for a water distribution network. The initial step in developing a hydraulic model involves collecting observed data from various components and locations within the network. This data, including junction locations, demand, pressure, and elevation, is assembled and introduced into the EPANET 2.2 program to build the hydraulic model. Data collection for links (pipes) encompasses gathering information on pipe location, diameter, and material. Pressure loggers and ultrasonic flow meters are typically employed on distribution main pipelines to measure pressure and calculate discharge, as illustrated in Figure 4.2.

Figure 4. 2 Digital pressure loggers and ultrasonic flow meters

Data collection methods involve obtaining existing drawings and documented data from the EWSD or conducting site investigations to gather field data directly. It is imperative that all collected data be sourced from reliable sources and that the instruments used for data collection provide precise measurements to ensure the model's accuracy. Data preparation for physical components of the hydraulic system includes identifying parameters such as diameter, length, and roughness (Hazen Williams C-factor) of the entire system. Additionally, specifications for junctions, valve locations, water demand calculations, pump locations, and initial water tank qualities are essential.

In addition to physical parameters, two main non-physical parameters are crucial for the EPANET 2.2 program: the daily time pattern for water consumption, which identifies 24-hour demand estimates and peak hours for each node, and pump performance curves, as shown in Figures 4.3 and 4.4.

Figure 4. 3 The daily time patterns of individual nodes

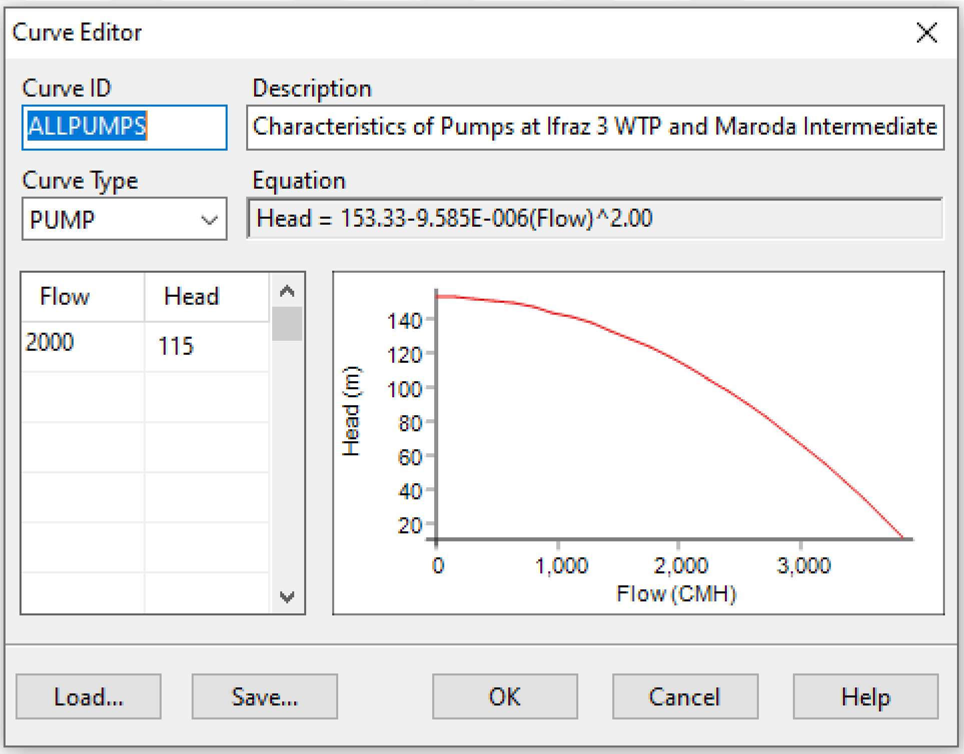


Figure 4. 4 The performance curve of the pumps

Pump performance curves depict the relationship between the pump head and flow (discharge), with pump efficiency curves identifying pump efficiency apart from factory efficiency.

In order to construct a hydraulic model for steady-state simulation, it is necessary to measure flow rates at the outlet of sources that are affected by gravity or pump efficiency. The steady-state model can be extended for an EPS model to determine hydraulic and water quality parameters throughout a spatially and temporally dynamic distribution system. It may be necessary to develop an EPS model if the steady-state model's calibration process results in unacceptable system presentation errors, which can lead to improper model outputs during the analysis process. The EPS feature allows users to modulate the status of control elements (on/off) and pipes (open/closed) based on pressure or water levels at perception nodes. The EPS analysis period can be set for 24 hours or more, and it is simple to set up and launch; users can specify EPS data, such as simulation duration and computational period.

4.5 Model Calibration

In modeling drinking water distribution systems, calibration is a crucial component. Model calibration involves adjusting the input data (or sometimes even the model structure) so that the model's hydraulic and water quality outputs accurately reflect observed field data. A helpful way to think of calibration is to imagine a TV screen displaying both observed and predicted values, with adjustable knobs available to tweak the expected values. Calibration is the process of tweaking those knobs until the predicted values come as close as possible to the actual observed values. Unfortunately, calibration can be a challenging, expensive, and time-consuming task. However, developing an accurate representation of the network and its components can help minimize the extent and difficulty of calibration. Collecting precise system performance and operations data to validate the network simulations is essential. A traditional calibration method is to use fire-flow pressure measurements. By measuring pressures and flow in isolated pipe sections in the field, the pipe friction factors can be adjusted to reflect the data better. Another method is to use water quality tracers. These are naturally occurring or added chemical tracers that can be measured in the field and calibrated hydraulic and water quality models. Remember that calibration should be an ongoing process in which the simulations' accuracy is continuously improved (Cesario, 1995). A popular method for calibrating water quality models involves using fluoride as a tracer. Typically, for systems that regularly fluoridate their water and have a negligible background level of fluoride, fluoride injection is stopped during distribution system sampling. Further sampling can occur during the transient period when fluoride injection begins again.

4.6 Hydraulic Model Calibration

Hydraulic model calibration is a crucial process that involves measuring pressure at various points in the water distribution network. To achieve this, manometers are used to obtain pressure readings at several junctions of the hydraulic model. The sensitivity of data collection is paramount, and the type of digital pressure gauge used is the SEWAD 30 W/S. The manometers are directly connected to the distribution main pipelines, with a reading frequency of one measurement over 30 minutes. To ensure the accuracy of the field data collection process, the locations of pressure recording points are selected by considering accessibility and the capacity for installing, safety, and reading loggers. The data collected from the manometers can be converted to a format suitable for direct introduction into EPANET 2.2 for the calibration process. The success of this calibration is determined by the agreement between the modeled and measured data. A close match indicates a successful calibration for the conditions being modeled. However, significant deflections between the measured and modeled data necessitate further hydraulic model calibration.

Hydraulic models and EPANET 2.2 software offer various head loss formulas, such as the Darcy-Weisbach, Hazen-Williams, and Manning equations. The Darcy-Weisbach formula is based on fundamental principles derived from Newton's Second Law, making it a sound option for calculating head loss in pipe flow. When paired with corresponding fluid properties, it works well for different flow regimes and fluid types. This formula relates head loss to flow rate, pipe diameter, pipe length, and fluid properties. On the other hand, the Hazen-Williams formula is based on empirical data and is a simpler option than the Darcy-Weisbach equation. It is commonly used in engineering to estimate head loss in pressurized pipe systems and is usually preferred for turbulent water flow conditions, especially in the United States. Conversely, the Darcy-Weisbach formula is more commonly used in Europe. It should be noted that the Hazen-Williams formula is generally used for water distribution modeling. The Manning formula is another empirical equation primarily used for calculating flow velocity in open channels like rivers, streams, and sanitary sewers. It is widely used but less versatile than the Darcy-Weisbach formula. This summary provides an accurate overview of the key points regarding the selection and application of head loss formulas in hydraulic modeling and water distribution analysis.

As previously indicated, the Hazen-Williams equation is prevalent in engineering practices for approximating head loss in pressurized pipe systems. This equation is widely preferred due to its simplicity compared to the Darcy-Weisbach equation.

The Hazen-Williams equation is expressed as follows:

$$h_f = \frac{10.67 * L}{C^{1.852} * D^{4.87}} * Q^{1.852} \tag{4.1}$$

Where:

h_f = Head loss in meters

L = Length of the pipe in meters

D = Inside diameter of the pipe in meters

Q = Flow rate through the pipe in cubic meters per second

C = Hazen-Williams coefficient (unitless), representing the roughness of the pipe and properties of the fluid

Here is a step-by-step procedure for calibrating a hydraulic model in the field and comparing it to EPANET 2.2 results:

1. Selection of Nodes: Choose two nodes in a distribution main pipeline to measure flow and pressure. These nodes should be strategically located to capture representative conditions along the pipeline.

2. Measurement Instruments: Use ultrasonic flow meters and pressure loggers to accurately measure flow and pressure. Ensure that these instruments are properly calibrated and installed to obtain reliable data.

3. Isolation of Nodes: Check that there are no additional links between the selected nodes and that no valves are opened before these nodes to prevent interference with the measurements.

4. Measurement Process: Measure the flow and pressure at the specified nodes under normal operating conditions. Record the data for subsequent analysis.

5. Valve Adjustment: Open the valves indicated to alter the flow and pressure conditions in the pipeline segment. Repeat the measurement process to capture the new flow and pressure readings.

6. Calculation of C-Factor: Use the pressure drop and flow rate data obtained from the field measurements in the Hazen-Williams equation to determine the field C-factor for each pipeline segment. Repeat this process for multiple segments to obtain a representative sample.

7. Average C-Factor Calculation: Calculate the average C-factor by taking the mean of all the C-factors obtained from the field measurements. This average C-factor represents the actual roughness of the pipeline as determined in the field.

8. Comparison with EPANET Results: Once the field C-factors are determined, compare them with those used in the EPANET model for the corresponding pipeline segments. Discrepancies between the field and model C-factors may indicate the need for calibration adjustments.

9. Calibration Process: Use the comparison results to guide the calibration process of the EPANET model. Adjust parameters such as pipe roughness, pump characteristics, or valve settings to bring the model predictions closer to the field measurements.

This process provides a systematic approach to calibrate the hydraulic model using field measurements and validate its accuracy against EPANET 2.2 results. However, it is crucial to ensure proper data collection techniques, instrument calibration, and attention to detail throughout the process to achieve reliable calibration outcomes.

4.7 EPANET

EPANET is a powerful modeling software for water supply and network distribution systems. It can simulate the structure of a water pipeline in both steady-state and EPS modes. The steady-state mode determines the system status, while the EPS mode evaluates system performance for many sequential time intervals. This enables network engineers and designers to model hydraulic achievements, such as pressures, flows, and head losses, for a set format and demands at nodes. Hourly nodal pressures, water levels in tanks, pipe flows, and pump rates are determined through EPS. This is vital to understanding water usage and the water level variety of the tank and pump operation. EPANET also models both network hydraulics and water quality using a coordinated process. It employs basic hydraulic equations to achieve this.

The following are some of the fundamental hydraulic equations that are utilized in EPANET:

1. The hydraulic equations of flow in the model are based on mass and energy conservation principles. According to the law of mass conservation, the inflow and outflow of a system must be balanced with its storage rate.

In each node, mass conservation can be expressed as follows:

$$\sum Q_{in} - \sum Q_{ou} = \sum Q_{ext} \tag{4.2}$$

Here, Q_{in} denotes the inflows of the node, Q_{out} denotes the outflows, and Q_{ext} is the external demand.

2. The law of conservation of energy states that the difference in energy between two points is equivalent to the losses due to friction and minor losses, as well as the energy added to the flow component between these points. The total loss for each of the network's fundamental loops is expressed as follows:

$$\sum_{i,j \in I_p} h_{i,j} - \sum_{Mx \in J_p} PE = 0 \tag{4.3}$$

Here, $h_{i,j}$ refers to the head loss of the pipe linking nodes i and j, I_p is the set of pipes in loop P, M_x is for pumps, J_p is the set of pumps in loop P, and PE is the energy of the pump M_x.

This can be expressed simply as:

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + h_{1-2} \tag{4.4}$$

Where P is pressure (N/m^2), h_{1-2} is head loss, V represents the velocity (m/s), Z refers to the elevation (m), g is the gravitational acceleration constant ($g = 9.81 m/s^2$), and γ is the specific weight of water (N/m^3).

3. The head loss is the difference between the nodal heads at both ends of the pipe. The head losses are computed using the Hazen-Williams equation technique (4.1) mentioned earlier.

EPANET is a network connection that includes pipes, nodes, valves, pumps, and storage tanks. It helps to simulate the flow of water in pipes, the water level in tanks, and the pressure at junctions. It also helps to track the chemical species and water age in the network. EPANET can check, edit, and change the system's input information and run hydraulic simulations. It can also simulate water quality and show the results in various formats like data tables, color-coded network maps, time series graphs, and contour plots.

For efficient water quality modeling, EPANET has a powerful hydraulic analysis engine that can:

- Analyze networks of any size.

- Calculate friction head loss using different formulas.

- Model pumps with constant or variable speed.

- Calculate energy and cost of pumping.

- Model different types of valves.

- Allow any shape for storage tanks.

- Consider various demand categories at junctions.

- Model pressure-dependent flow issuing from emitters.

- The base system operates on simple tank level or timer controls and complex rule-based controls.

EPANET 2.2 can help analyze water supply and network distribution systems. The following are required as input data:

• Node Report (Junctions)

• Link Report (Pipes)

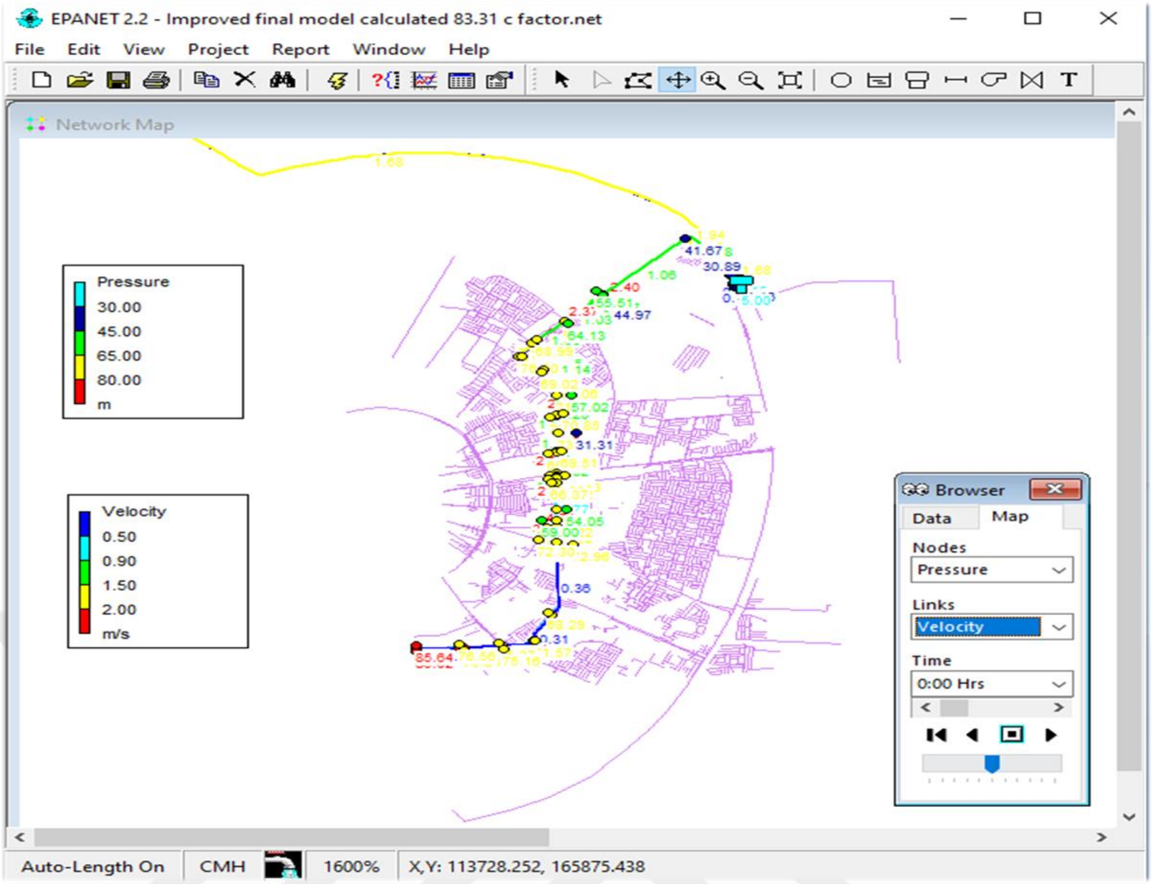


Figure 4. 5 A screenshot of the workspace in EPANET

4.7.1. The Node Report (Junctions)

Junctions or nodes are points in the network where water flows in or out of the system. To properly analyze these nodes, the following input information is necessary:

• The elevation of the node about a reference point, usually MSL.

• The average amount of water required at each node.

• The initial water quality.

Throughout the simulation, the following outcomes will be calculated for each node:

• Pressure.

• Hydraulic head, which is the internal energy per unit fluid weight.

In addition, water quality junctions can also:

• Vary their demand with time.

• Be allocated different categories of demands.

• Have negative demands, which means water is flowing into the system.

• Serve as sources for water quality constituents to enter the system.

• Contain emitters, such as sprinklers, which cause the outflow rate to depend on pressure.

4.7.2 The Link Report (Pipes)

Pipelines serve as conduits that connect different points in a water distribution system. According to EPANET, pipelines are always assumed to be filled with water. The flow of water is from the end with a higher hydraulic head (internal energy per unit weight of water) to the end with a lower hydraulic head.

The following are the critical hydraulic parameters that are essential for pipelines:

• Start and end nodes.

• Diameter.

• Length.

• Status (closed, open, or with a check valve).

• Roughness coefficient (for determining head loss).

The calculated outputs include the following:

• Flow rate.

• Head loss.

• Velocity.

• Darcy-Weisbach friction factor.

• Average reaction rate (over the length of the pipe).

• Average water quality (over the length of the pipe).

4.8 Modeling of Water Age

Water age modeling in distribution systems has significantly developed over the past two decades. Early work by Males et al. (1985) laid the foundation, and recent projects, such as those sponsored by the Water Research Foundation, have expanded its application. These projects demonstrated that controlling retention time effectively manages water quality within distribution networks, creating an interactive electronic guidance manual that integrates hydraulic and water quality models for distribution systems and storage facilities (Brandt et al., 2006). The Stage 2 Disinfectants and DBP Rule requires most water utilities to perform an initial distribution system evaluation (IDSE) to identify future DBP sampling locations. One method for this evaluation is using hydraulic models to calculate water age and select sampling sites that reflect a range of water ages (EPA, 2006).

Water age significantly impacts water quality, particularly concerning the reaction of chlorine with NOM. As water ages, DBP concentrations increase, and chlorine residuals decrease, making water age a reliable indicator of water quality (Clark, 2012). Simulations of water age start with an initial age of zero at all nodes and tanks and depend on the operational state of WTPs and their supply. Water age can be measured through tracer studies in the field, but hydraulic and water quality modeling software like EPANET 2.2 offers a more efficient method. EPANET 2.2 is a free and user-friendly tool allowing extended-period simulation calculations to analyze water age in distribution systems. Its updated algorithms enable longer Quality Time Steps, eliminate mass balance errors, and reduce run times. However, accurate water age modeling requires considering several factors, including junction distance from the WTP, tank design and operation, source influence, and network layout. The design and operation of water storage tanks are particularly influential, necessitating the selection of an appropriate tank model for accurate results. A well-calibrated network model of the WDS is essential to achieving precise water age modeling. Water operators and managers should utilize EPANET 2.2 to enhance water quality across their service areas.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

Water authorities are responsible for providing users with a consistently high-quality water supply and optimal pressure. Access to clean drinking water is crucial, profoundly impacting society, health, the economy, and the environment. The quality of drinking water is influenced by several factors, including its source and the treatment and delivery processes. Using computer models, it is possible to study the movement of drinking water through pipes without interrupting consumers. This modeling can help determine the water age at different locations and how water quality changes over time. This study aims to develop, analyze, and calibrate a model that accurately represents the hydraulic and water quality characteristics of a specific segment of the distribution network in Erbil City. The model aims to enhance the credibility of the system's operation and assist decision-makers in future planning. The study focuses on determining the water age in a specific area within Erbil City.

A comprehensive case study will analyze the water system using specialized computer programs like EPANET 2.2. The data used to create and refine the model were meticulously gathered from various reliable sources, including documented files, site investigations, and field tests. The primary data source was the documented files from different departments of EWSD, which provided comprehensive information about the pipes, valve locations, pump numbers, and pump capacity curves. Site investigations and field tests were employed to enhance the data's accuracy and rectify any potential inaccuracies in the documented information. The newly acquired data were then utilized to build a physically accurate model using EPANET 2.2. Following this, the model was hydraulically calibrated using pressure values measured at various locations to ensure its reliability and accuracy.

5.2 Model Representation and Field Testing

Data was meticulously gathered from various sources to create an accurate hydraulic model of the water network in the study area. The EWSD used ArcGIS and GPS devices to develop precise digital versions of their distribution network. To ensure the EPANET model's accuracy, data collection focused on both nodes (junctions, tanks, reservoirs) and links (pipes, pumps, valves). Each node and link were assigned a unique ID, and several parameters were meticulously recorded:

- Pipe Characteristics: Diameter, length, and roughness coefficient.
- Valve Specifications: Diameter, minor losses coefficient, and location.
- Node Elevation: Elevations for nodes, tanks, and reservoirs.
- Water Demand: Demand at nodes and temporal variations.
- Tank Capacity: Diameter, lower and upper levels, initial quality coefficient.
- Pump Specifications: Operating capacity curves.
- Control Rules: Timed control rules for pumps and valves.
- Initial Water Quality: Quality at source nodes and temporal changes at all nodes.
- Calibration Data: Pressure data collected over time from field observations.

The network model focused on the distribution main and sub-main pipes, ranging from 110mm to 1200mm in diameter, covering almost all supplies from Ifraz 3's WTP. Due to limited data, smaller-diameter pipes were excluded. Site investigations included examining over six manholes within the study area. These manholes were cleaned and visually inspected, and their node elevations were verified using GPS devices, as shown in Figures 5.1 and 5.2. Where necessary, flow meters and pressure loggers were installed, and pipe diameters were confirmed.

Data from these investigations were integrated into the model, with special attention to pipes removed or modified during past repairs or upgrades. The internal diameters of these pipes were measured for accuracy. Any discrepancies between documented data and on-site measurements were addressed to ensure the model's precision. The length, diameter, and material of pipes were carefully examined, with details of the distribution main pipe characteristics provided in Table 5.1.

Figure 5. 1 Verifying and determining junction elevations through field surveying

Figure 5. 2 Site investigations, including cleaning and visually inspecting manholes

Table 5. 1 Characteristics of the distribution main pipes in the study area

Main Pipes Type	Construction Year	OD (mm)	Length (m)	Volume (m^3)	Percent Volume (%)
DI	1984	800	7406.42	3722.87	45.8%
DI	2006	1200	3896.39	4406.71	54.2%
Total			11302.81	8129.58	100%

The study measured the flow rate at the main outlet pipe of Ifraz3 WTP through the transmission main pipeline, which is made of GRP with a diameter of 1500mm and a length of 20137 m. This pipeline supplies water to the reservoir located at the Maroda pumping station with a flow rate of 7590 m^3/hr. The water is then conveyed to the Dawajin reservoir through pipelines with the same characteristics as the previous ones, with a flow rate of 7992 m^3/hr and a length of 11142 m. From the Dawajin reservoir, water with a flow rate of 4560m^3/hr is conveyed via gravity to the study area distribution network through distribution main pipes. These pipes are made of DI and have 800 mm and 1200 mm diameters, totaling 11302.81 meters. These distribution main pipes are responsible for transporting the entire water volume. The remaining sub-main pipes are made of plastic, CI, HDPE, PVC, and DI.

The Hazen-Williams equation calculates hydraulic parameters such as head losses due to pipe friction. The initial friction C-factor was based on literature values, considering the pipeline's age, condition, and material (Walski et al., 2003). Site inspections verified that the valves were fully open and under maintenance, ensuring they did not impact the network system or the hydraulic simulation for head loss and pressure drop. Figure 5.3 displays the WDN model after being drawn in the CIVIL3D program. The figure indicates the location of the GZR, Ifraz 3 WTP, MIPS, Dawajin reservoir, transmission main, and distribution main pipes.

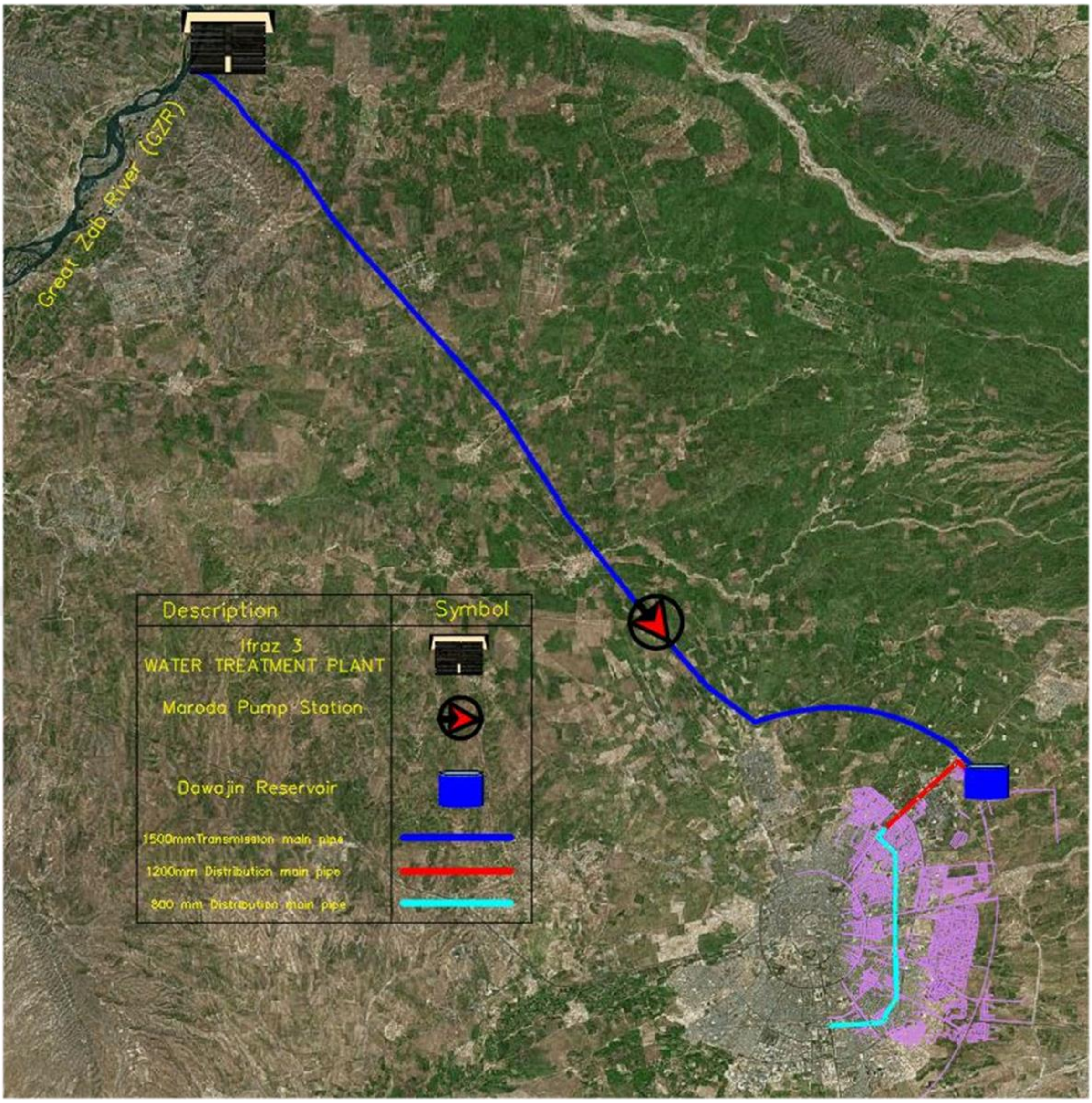


Figure 5. 3 The WDN model in the CIVIL 3D program

5.3 Characteristics of Pumps at Ifraz 3 WTP and MIPS

Seven high-service pumps with identical characteristics are located at each of the Ifraz 3 WTP and MIPS. Currently, three of them are on standby, with a discharge capacity of 2000 m^3/h and a head of 115m, as shown in Figure 5.4. These pumps convey treated water to the MIPS reservoir through a GRP transmission main pipeline. The pipeline has a length of 20137 m and a diameter of 1500mm. From there, the water is conveyed to the Dawajin reservoir through four intermediate pumps with a flow rate of 2000 m^3/h and a head of 115m. These pumps are connected to pipelines with the same characteristics as the previous ones, with a length of 11142 m. Finally, the water is conveyed from the Dawajin reservoir to the distribution network of the study area through gravity-fed distribution main pipes.

It is important to note that the pumps' performance degrades over time. To address this issue, actual performance measurements of the pumps were taken and inputted into the EPANET 2.2 curve editor. The software then calculates the flow and head using equation 5.1. Figure 5.5 displays the capacity curves of the pumps, with the head governed by the following equation:

$$\mathrm{Head} = 153.33 - 9.585\mathrm{E} - 006(\mathrm{FLOW})\text{\textasciicircum}2.00 \quad (5.1)$$

Here,

Flow represents the pump flow (m^3/hr), and Head represents the pump head (m).

Figure 5. 4 High-service pumps are located at Ifraz 3 WTP and MIPS

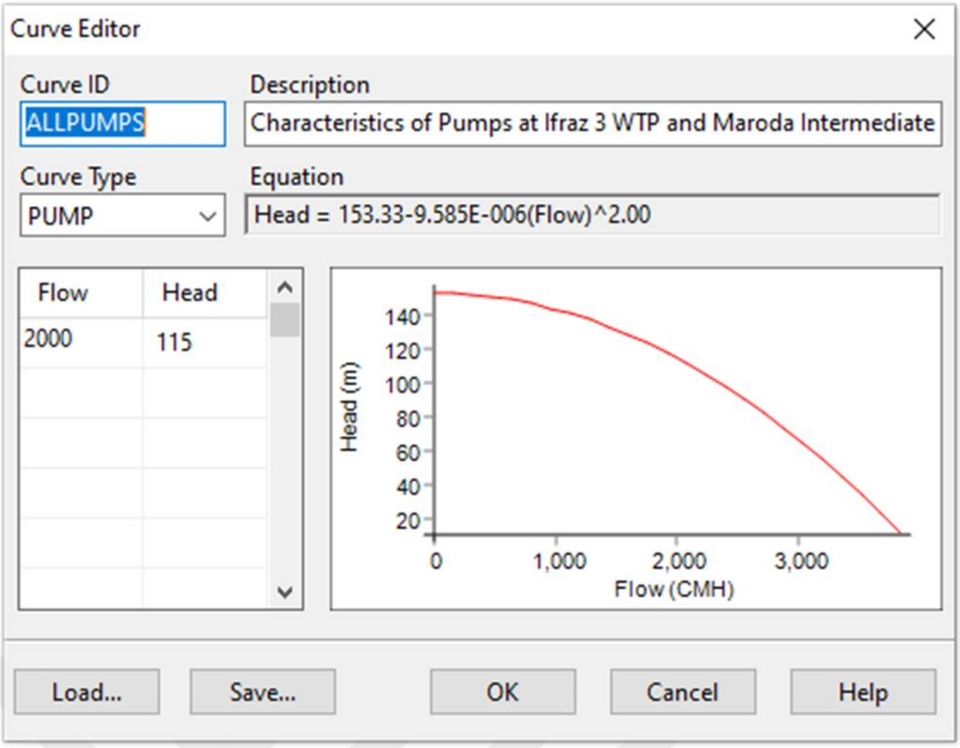


Figure 5. 5 The capacity curve for pumps at Ifraz 3 WTP and MIPS

5.4 Network Water Demand Analysis

The assessment of network water demand for the Ifraz 3 WTP was undertaken meticulously to accurately gauge the volume of water required to meet the needs of consumers within the study area. In this regard, a comprehensive methodology was employed to determine water demand and its distribution across various nodes within the distribution network. This section outlines the detailed methods used for this purpose. To begin with, the water demand assessment commenced with calculating the total volume of water conveyed from the Dawajin reservoir to the distribution network. This volume served as the baseline for determining the overall demand within the study area. The distribution of water demand across different nodes within the network was achieved by dividing the total volume of conveyed water by the number of registered connections within each neighborhood of the study area, as illustrated in Table 5.2. This approach ensured a fair and equitable water demand distribution based on each neighborhood's population density and consumption patterns.

Notably, the study area predominantly consists of residential, commercial, government offices, schools, hospitals, and an industrial area (which is only for repairing cars). The demand profile primarily reflects the needs of ordinary consumers with typical water usage patterns. A consistent approach was adopted across the entire system to simulate the demand fluctuations accurately. The same flow fluctuation pattern was applied to develop the demand pattern for all nodes within the EPANET 2.2 model. This ensured uniformity and reliability in the representation of changing demand dynamics throughout the distribution network. The meticulous analysis of network water demand using the outlined methodology provides a comprehensive understanding of consumption patterns and requirements within the study area. By accurately assessing demand dynamics and distribution, stakeholders can make informed decisions regarding infrastructure planning, resource allocation, and operational management of the Ifraz 3 WTP. Figure 5.6 illustrates the simulated demand pattern showing diurnal changes in consumption across the distribution network using the EPANET 2.2 model. The visualization provides insights into the spatial and temporal distribution of water demand, highlighting areas of high and low consumption within the study area.

Figure 5. 6 EPANET's daily demand pattern fluctuates throughout the day

Table 5. 2 Presents the number of consumers with and without water meters in each neighborhood and the percentages for easier comparison and analysis

No.	Neighborhood	Consumers with a water meter	Consumers without a water meter	Total No. of Consumers	% with Water Meter	% without Water Meter
1	Badawa	3548	202	3750	94.61%	5.39%
2	Brayati	3293	142	3435	95.86%	4.14%
3	Langa Bazzar	1077	285	1362	79.04%	20.96%
4	Safeen 2 & Industrial Area	817	251	1068	76.52%	23.48%
5	Iskan	1254	43	1297	96.70%	3.30%
6	Khabat	3313	147	3460	95.76%	4.24%
7	Khanzad	3153	181	3334	94.58%	5.42%
8	Kshtukal	768	14	782	98.21%	1.79%
9	Kwestan	1199	3	1202	99.75%	0.25%
10	Mamostayan 2 & Chnar	2757	154	2911	94.71%	5.29%
11	Mantikawa	1048	7	1055	99.34%	0.66%
12	Mufty	1581	48	1629	97.06%	2.94%
13	Raparin	2969	74	3043	97.57%	2.43%
14	Runaky	931	89	1020	91.18%	8.82%
15	Safeen1	701	85	786	89.17%	10.83%
16	Zanayan	2525	21	2546	99.18%	0.82%
	Total	30934	1746	32680	93.70%	6.30%

5.5 Enhancing Model Accuracy

After meticulously calibrating the steady-state model of the Ifraz 3 WTP with parameters such as pressure, elevation, demand, and C-factor, the calibration process transitions to the EPS phase. EPS calibration is crucial in enhancing the hydraulic model's accuracy and reliability. The following outlines the significance and methodology of EPS calibration. EPS calibration is essential in refining the hydraulic model's performance by adjusting temporal demand variations and assessing its predictive capabilities over an extended period. Unlike steady-state calibration, which focuses on achieving equilibrium under static conditions, EPS calibration enables the model to capture dynamic changes and fluctuations in demand and system behavior over time. The initiation of EPS calibration involves fine-tuning the model to accurately reflect temporal variations in water demand. This entails aligning model-predicted demand patterns with observed fluctuations in consumption over different time intervals, such as daily, weekly, or seasonal variations.

The calibration objectives may vary based on the intended function of the hydraulic model. For instance, the calibration process in hydraulic studies may prioritize accurately predicting tank water levels and flows at system meters to validate field conditions. Conversely, EPS calibration may focus on energy analysis and the model's capacity to anticipate pump station cycling and energy consumption. EPS calibration involves assessing the model's ability to predict energy usage and efficiency, particularly in pump stations and other energy-intensive water distribution system components. By aligning model predictions with actual energy consumption data, stakeholders can optimize operational strategies to minimize energy costs and enhance system sustainability. EPS calibration is critical in refining the hydraulic model to accurately simulate real-world conditions and operational dynamics. By aligning model predictions with observed data and functional objectives, EPS calibration enhances the model's predictive accuracy, reliability, and utility for hydraulic analysis, energy optimization, and operational decision-making.

5.6 Enhancing Hydraulic Analysis through Model Characterization

Developing a hydraulic model for a case study WDN involves collecting and inputting all field data and documented information, including junction positions, pipe characteristics (such as diameter and length), demand, elevation, and initial Hazen-Williams head loss coefficient (C-factor) assumptions, as shown in Table 5.3. The C-factor is typically estimated at the start of the model creation process. According to the Ductile Iron Pipe Research Association (2016), the average C-factor for new pipes is 144, while older systems generally range from 135 to 140. Thus, a C-factor of 135 is considered realistic for long-term operations in Ductile Iron Pipes. Once the appropriate C-factor is determined through field investigations, it is calculated using the Hazen-Williams head loss formula. Under normal conditions, the model operates smoothly, as shown in Figure 5.7. However, introducing the realistic C-factor into EPANET 2.2 can cause operational issues, such as the model failing to run and the emergence of negative pressure zones, which require exploring alternative solutions.

Figure 5. 7 The model operates smoothly with an assumed C-factor, displaying node elevations in EPANET

Table 5. 3 Provides a comprehensive data compilation that accurately characterizes an existing model

	Length	Diameter	Flow	Velocity	Unit Headloss
Link ID	m	mm	CMH	m/s	m/km
Pipe 2	20136.67	1510	9670.87	1.5	1.01
Pipe 3	11141.99	1510	9670.16	1.5	1.01
Pipe 9	204.78	90	59.5	2.6	75.28
Pipe 10	17.16	1196	4567.22	1.13	1.92
Pipe 11	112.86	110	59.5	1.74	28.32
Pipe 12	672.04	1196	4507.72	1.11	1.88
Pipe 13	62.54	125	113.05	2.56	49.89
Pipe 14	567.05	1196	4394.67	1.09	1.79
Pipe 15	16.95	798	3317.72	1.84	7.63
Pipe 16	77.82	125	101.15	2.29	40.6
Pipe 17	7.86	798	3216.57	1.79	7.2
Pipe 18	6.13	250	238	1.35	6.77
Pipe 19	13.64	798	2978.57	1.65	6.25
Pipe 23	382.61	798	2978.57	1.65	6.25
Pipe 24	239.3	798	2829.82	1.57	5.69
Pipe 25	81.65	160	89.25	1.23	9.67
Pipe 26	49.39	110	148.75	4.35	154.58
Pipe 27	289.91	798	2740.57	1.52	5.36
Pipe 28	185.2	110	109.48	3.2	87.62
Pipe 29	346.19	798	2631.09	1.46	4.97

Pipe 30	86.96	160	185.64	2.56	37.56
Pipe 31	13.88	798	2445.45	1.36	4.34
Pipe 32	99.1	160	98.77	1.36	11.67
Pipe 33	310.29	798	2346.68	1.3	4.02
Pipe 34	241.7	110	171.36	5.01	200.89
Pipe 35	327.32	798	2175.32	1.21	3.49
Pipe 36	73.23	110	76.16	2.23	44.74
Pipe 37	26.28	798	2099.16	1.17	3.27
Pipe 38	101	110	105.91	3.1	82.4
Pipe 39	375.83	798	1993.25	1.11	2.97
Pipe 40	33.35	798	1993.25	1.11	2.97
Pipe 41	94.02	160	89.25	1.23	9.67
Pipe 42	19.9	798	1904	1.06	2.73
Pipe 43	103.08	160	-178.5	2.47	34.93
Pipe 44	29.65	798	1725.5	0.96	2.28
Pipe 45	112.49	160	114.24	1.58	15.28
Pipe 46	95.05	798	1611.26	0.89	2
Pipe 47	71.09	110	102.34	2.99	77.33
Pipe 48	466.76	798	1508.92	0.84	1.77
Pipe 49	131.58	125	224.91	5.09	178.35
Pipe 50	188.81	798	1284.01	0.71	1.32
Pipe 51	205.74	110	111.86	3.27	91.18
Pipe 52	117.36	798	1172.15	0.65	1.11
Pipe 53	140.59	110	53.55	1.57	23.3
Pipe 54	70.07	798	1118.6	0.62	1.02
Pipe 55	32.03	125	96.39	2.18	37.13
Pipe 56	205.44	798	1022.21	0.57	0.86
Pipe 57	247.63	250	196.35	1.11	4.74
Pipe 58	211.95	250	121.38	0.69	1.94
Pipe 59	1336.29	798	704.48	0.39	0.43
Pipe 60	63.95	125	98.77	2.24	38.85
Pipe 61	563.1	798	605.71	0.34	0.33
Pipe 62	17.51	125	97.58	2.21	37.99
Pipe 63	477.98	798	508.13	0.28	0.24
Pipe 64	72.84	798	232.05	0.13	0.06
Pipe 65	565.68	798	115.43	0.06	0.02
Pipe 66	55.73	125	61.88	1.4	16.34
Pipe 67	60.51	110	102.34	2.99	77.33
Pipe 68	60.15	110	116.62	3.41	98.5
Pipe 69	47.24	125	53.55	1.21	12.5
Pipe 70	505.79	798	334.39	0.19	0.11
Pipe 71	71.57	160	73.78	1.02	6.8
Pipe 72	60.94	160	-99.96	1.38	11.93

Pipe 73	320.53	1196	1076.95	0.27	0.13
Pipe 74	308.29	798	2978.57	1.65	6.25
Pipe 76	316.99	698	1931.11	1.4	2.2
Pipe 77	256.99	698	1934.62	1.4	2.21
Pipe 78	230.31	698	1936.18	1.41	2.21
Pipe 79	236.65	698	1935.81	1.41	2.21
Pipe 80	281.98	698	1933.15	1.4	2.2
Pipe 81	102.97	1510	9670.87	1.5	1.01
Pipe 82	135.83	1510	9670.87	1.5	1.01
Pipe 83	93.24	1510	9670.16	1.5	1.01
Pipe 84	67.19	1510	9670.87	1.5	1.01
Pipe 85	14.22	1510	-9670.16	1.5	1.01
Pipe 91	65.2	698	1934.38	1.4	2.21
Pipe 92	55.88	698	1934.93	1.4	2.21
Pipe 93	62.9	698	1934.52	1.4	2.21
Pipe 94	77	698	1933.68	1.4	2.2
Pipe 95	94.3	698	1932.66	1.4	2.2
Pipe 98	119.71	1510	9670.16	1.5	1.01
Pipe 4	1161.53	1196	4719.54	1.17	2.04
Pipe 5	1478.61	1196	4626.72	1.14	1.97
Pipe 6	360.17	110	92.82	2.71	64.54

Once the WTP has treated the water, it is conveyed to the reservoir. The concrete reservoir is situated in the Dawajin neighborhood atop a hill with an elevation of 490 meters above MSL. It comprises two compartments with a total capacity of approximately 20,000 cubic meters, with effective dimensions measuring 50X50X8 meters. These precise values have been meticulously entered into the hydraulic model to ensure accurate representation. Consumers access water from the reservoir through WDNs. It is crucial to determine the amount of water reaching users, which is determined by the discharge parameter. This parameter is vital in hydraulic and water quality models and is critical in designing parameters such as pipe diameter and pump size. Providing comprehensive data for each parameter is crucial to evaluate any model properly.

The source discharge parameter has been identified within the current hydraulic model framework as carrying the highest significance level. Consequently, this parameter is measured using digital ultrasonic flow meters at various times throughout a single day, specifically at the outlet pipe of the reservoir, as illustrated in Figure 5.8. These measurements serve as the basis for creating demand patterns and calculating the daily water demand for the entire system. The hydraulic model's performance can be assessed through the existing system's flow rate.

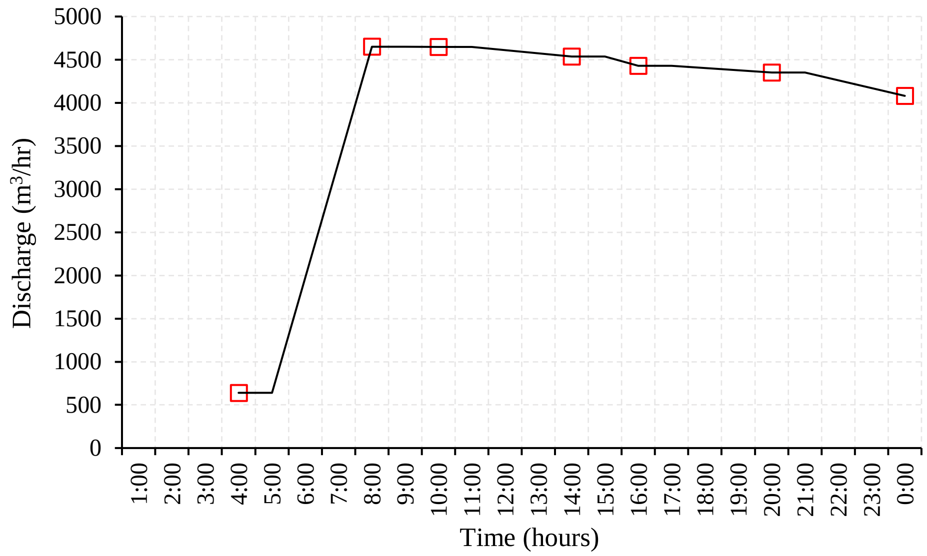


Figure 5. 8 The variation in the flow rate of a reservoir over 24 hours

5.7 Field Measurement of Hazen-Williams (C-factor)

To determine the Hazen-Williams head loss coefficient (C-factor) directly in the field, flow tests and pressure measurements must be conducted on the pipe system to determine the head loss for known flow rates. The following procedure can be used to find the C-factor directly in the field:

1. Setup Flow Test Equipment: Set up flow meters, pressure gauges, and other necessary instruments along the pipe section where the C-factor is to be determined. Ensure that the flow test setup allows for accurate measurement of flow rates and pressure drops along the pipe.

2. Select Test Locations: Choose multiple test locations along the pipe network where flow conditions represent the system. Ensure that the selected test locations provide sufficient straight pipe lengths upstream and downstream to achieve fully developed flow conditions.

3. Measure Flow Rates: Use flow meters to measure the flow rates through the pipe system at each test location. Record the flow rates corresponding to each test condition.

4. Measure Pressure Drops: Use pressure gauges to measure the pressure drops across the pipe section at each test location. Record the pressure drops corresponding to each flow rate.

5. Calculate Head Loss: Use the Hazen-Williams equation to calculate the head loss for each test condition using the measured flow rates and pressure drops:

$$h_f = \frac{10.67 * L}{C^{1.852} * D^{4.87}} * Q^{1.852} \tag{5.2}$$

Where:

h_f = Head loss in meters

L = Length of the pipe in meters

D = Inside diameter of the pipe in meters

Q = Flow rate through the pipe in cubic meters per second

C = Hazen-Williams coefficient (unitless), representing the roughness of the pipe and properties of the fluid

6. Iterative Process: Adjust the C-factor iteratively for each test location until the calculated head loss closely matches the measured head loss. Compare the calculated head loss using different C-factor values with the measured head loss obtained from field tests. Adjust the C-factor until a satisfactory agreement between calculated and measured head losses is achieved.

7. Validation: Validate the determined C-factor by comparing it with published values for similar pipe materials and conditions. Ensure that the determined C-factor falls within a reasonable range of expected values.

8. Documentation: Document the determined C-factor and relevant details such as pipe material, diameter, and testing conditions for future reference.

9. Quality Assurance: Ensure the measurement and calculation processes comply with relevant standards and guidelines to maintain accuracy and reliability.

Following the procedure outlined, the Hazen-Williams head loss coefficient (C-factor) between junctions J20 and J26, which are 308.3 meters apart and are connected by an 800 mm diameter ductile iron pipe on the distribution main, can be determined, as illustrated in Figure 5.9. Accurate calculation of the C-factor was made possible by installing flow meters and pressure loggers at both junctions J20 and J26, which recorded the discharge and pressure. Executing this process in numerous locations throughout the water distribution system is advisable to guarantee precision. This water distribution system's average calculated Hazen-Williams head loss coefficient C-factor is 83.3.

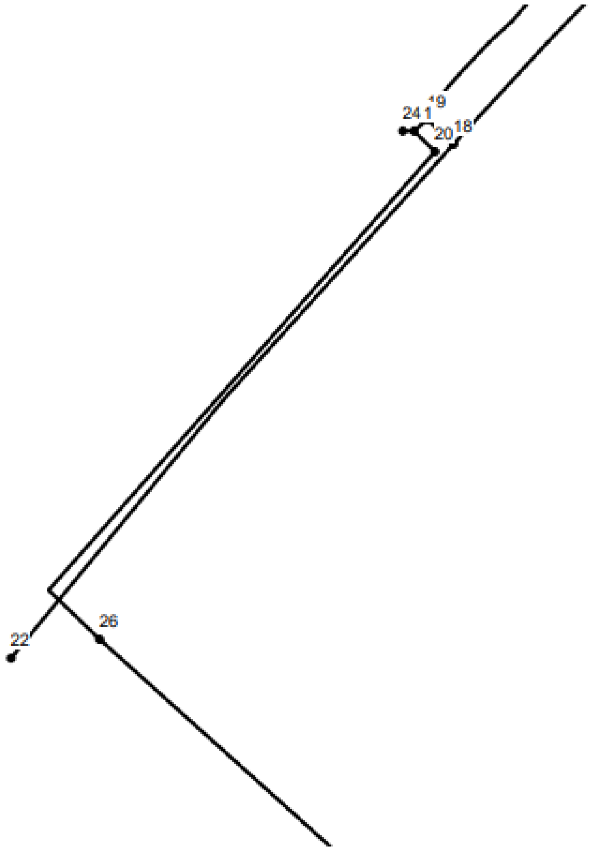


Figure 5. 9 The location of junctions J20 and J26 can be used to find the C-factor

Field pressure observations were conducted every 30 minutes over two weeks at six specific locations along the distribution main pipeline. These locations, identified as junctions J12, J20, J26, J41, J50, and J63, represent the system's overall working pressure. The data collected from these observations were used for model calibration and validation. Data collection is crucial for managing water distribution systems as it provides valuable insights into the system's actual performance. The primary objective of planning field data collection is to determine the optimal locations for observing system behavior and to ensure that the data collected for calibration purposes yields the most accurate results. Field pressure measurements reflect the actual C-factor, offering the advantage of calibrating the hydraulic model by comparing observed field data with computed data.

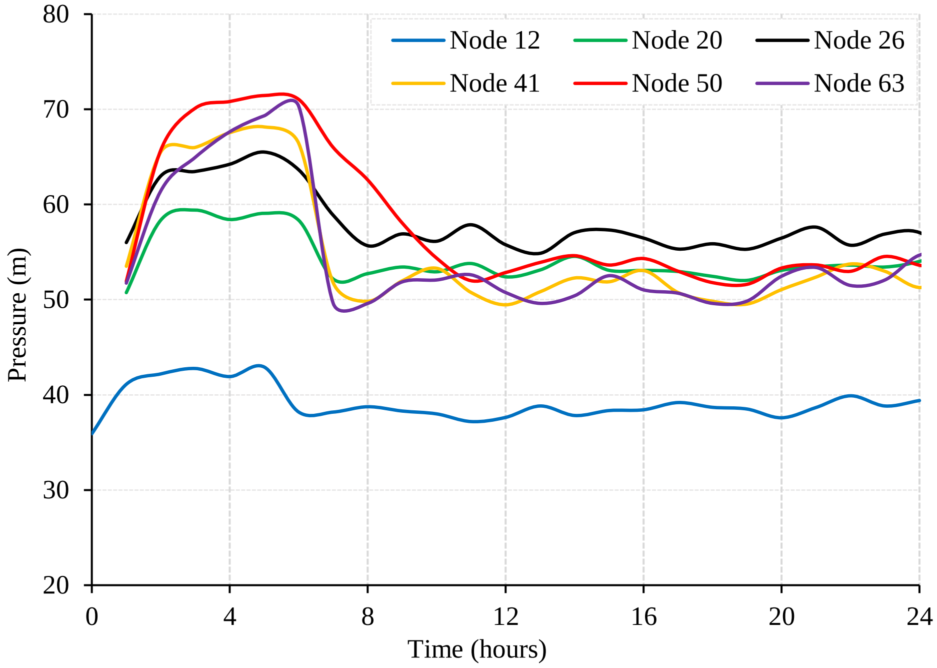


Figure 5. 10 Observed field pressure for selected nodes (12, 20, 26, 41, 50, and 63)

In Figure 5.10, the daily pressure fluctuations at all tested nodes during normal operation are depicted. The pressure heads consistently remain above 30 meters throughout the 24 hours at all nodes. These findings suggest the system operates as a unified pressure zone, with similar pressure variations observed across all nodes.

5.8 Addressing Negative Pressure Zones in Hydraulic Model

Once the hydraulic model has been characterized and the actual Hazen Williams C-factor has been determined, the analysis can begin. It has been observed that negative pressure zones have appeared in specific Distribution Management Interfaces (DMIs) within the distribution system, indicating that the hydraulic model's performance does not meet acceptable standards. Therefore, it is crucial to make improvements to address the shortfall in water supply caused by the impact of the actual C-factor on the model. The identification of negative pressure zones in EPANET 2.2 suggests that water is not reaching users within these areas. This issue requires immediate attention and remedial measures to ensure equitable water distribution throughout the network and mitigate any adverse effects of inadequate water supply. Figure 5.11 illustrates the water distribution network, highlighting negative pressure zones resulting from the actual C-factor inputs processed in EPANET. Red areas indicate zones with negative pressure, while other colored areas represent zones with positive pressure.

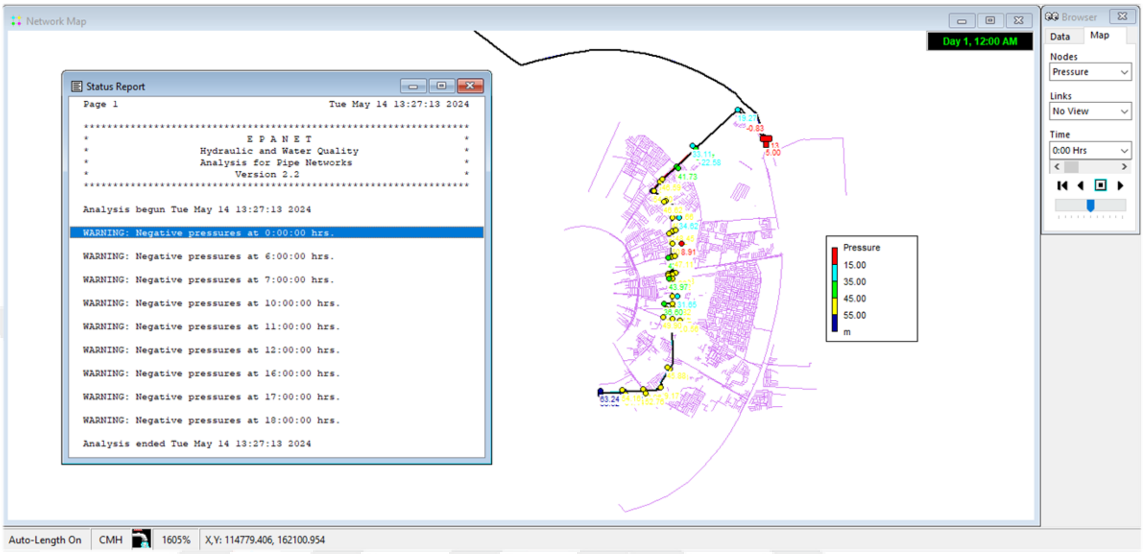


Figure 5. 11 Negative pressure zones in a WDN with actual C-factor input

In the context of system reinforcement, it is essential to consider introducing additional pumps or booster stations where necessary to maintain adequate pressure. Furthermore, upgrading pipes or adding parallel pipelines enhances flow capacity and reduces resistance. The proposed interventions aim to address water shortages in negative-pressure DMIs within the water distribution network. Specifically, the focus is on high-demand junctions such as J8 and J36.

5.9 Hydraulic Model Calibration

The recommended strategies to reinforce the system include adding extra pumps and upgrading pipes to improve flow capacity and decrease resistance. The addition of more pumps will involve installing a pump station downstream of the reservoir outlet. This station will include booster pumps to increase the energy needed to deliver water to consumers, changing the system from a gravity-based one to a pumping system. This change will ensure that water pressure is maintained even at higher elevations and during periods of peak demand. To address the low pressure in the current hydraulic model, three pumps were installed downstream of the reservoir outlet to increase the flow rate to 1600 m³/hr and maintain a constant head of 20 meters. The capacity curve of these pumps is shown in Figure 5.12.

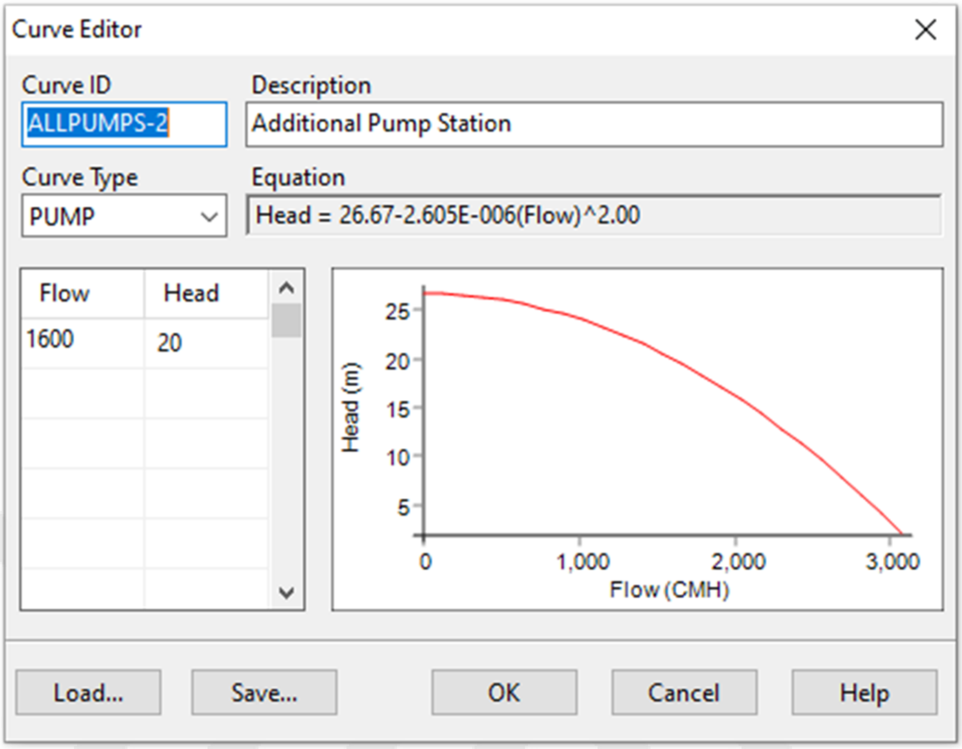


Figure 5. 12 Capacity curve for supplementary pumps

The installation of pumps led to a significant pressure increase throughout the system. Consequently, there were noticeably higher pressures at all junctions than in the existing hydraulic model and the pressures observed in the field. Figure 5.13 illustrates the pressure changes at the nodes, emphasizing the improved pressure distribution achieved through the added pumping capacity.

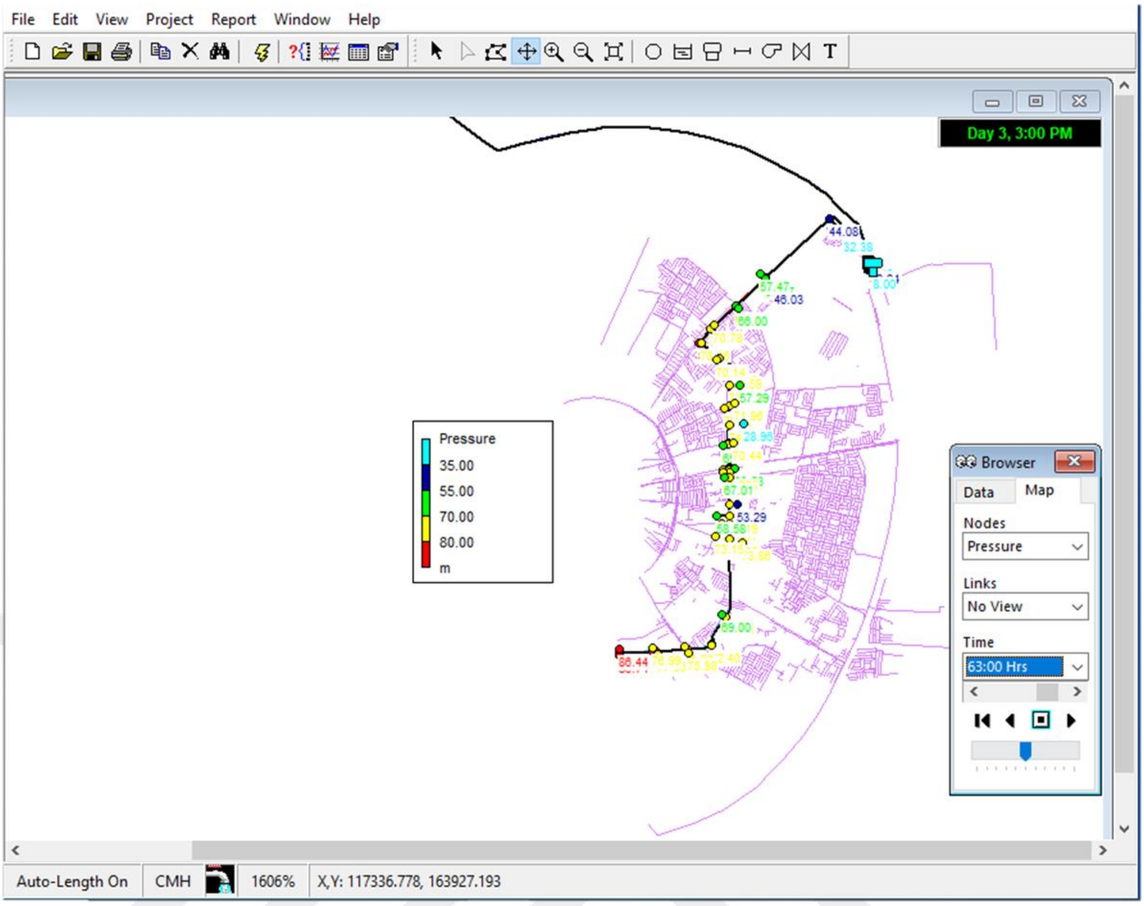


Figure 5. 13 Modified water distribution network

A calibration process adjusted the model's pressure profile to align with the observed field data. This process involved fine-tuning the model parameters to ensure that the pressure readings at various nodes matched the real-world measurements. Figures 5.14 and 5.15 show the comparison between the simulated and observed pressure data at different nodes.

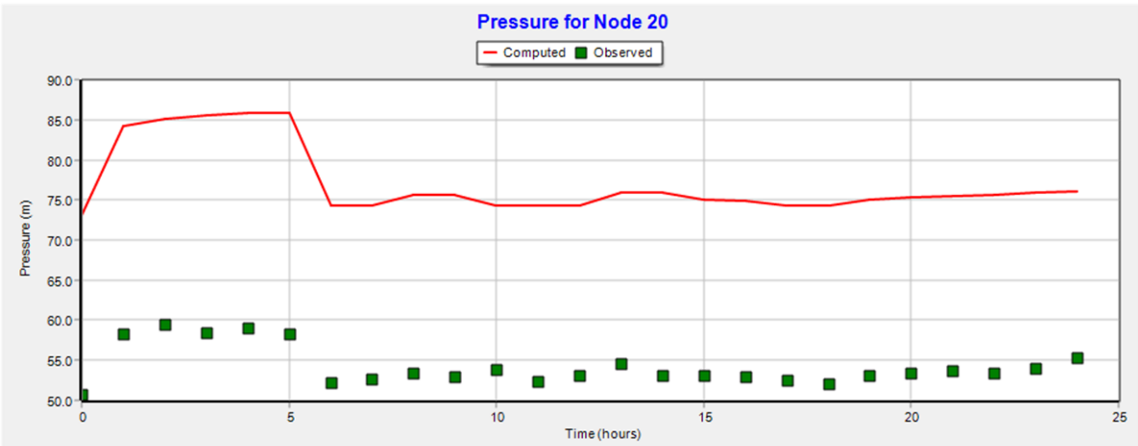


Figure 5. 14 Calibrated pressure for J20

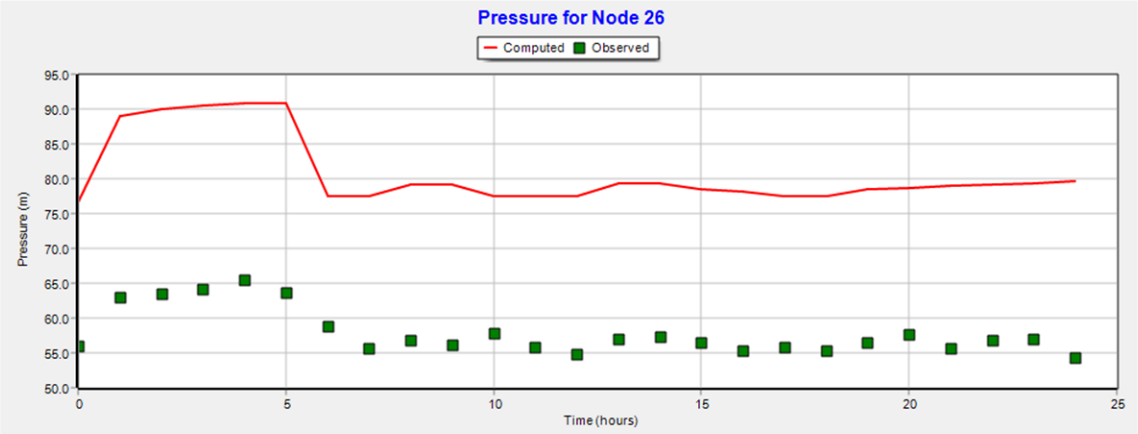
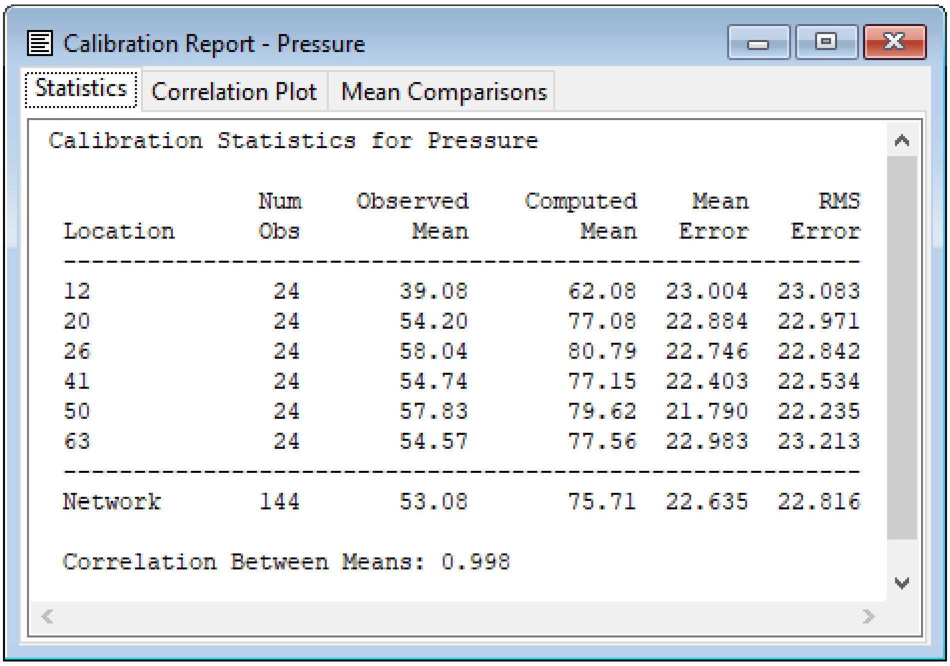


Figure 5. 15 Calibrated pressure for J26

As previously noted, a significant increase in pressure throughout the system was observed after the installation of the pumps. This resulted in noticeably higher pressures at all junctions than the existing hydraulic model and the pressures observed in the field. Although the computed pressures are higher than the observed pressures, a strong correlation between them is indicated, suggesting that the model accurately reflects the system's behavior, as illustrated in Figure 5.16. The system pressure is now composed of two main components: topographical pressure (or static pressure), which is the pressure produced by the elevation differences within the system, and pump pressure, which is the additional pressure introduced by the newly installed pumps.


Calibration Report - Pressure

Statistics | Correlation Plot | Mean Comparisons

Calibration Statistics for Pressure

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
12	24	39.08	62.08	23.004	23.083
20	24	54.20	77.08	22.884	22.971
26	24	58.04	80.79	22.746	22.842
41	24	54.74	77.15	22.403	22.534
50	24	57.83	79.62	21.790	22.235
63	24	54.57	77.56	22.983	23.213
Network	144	53.08	75.71	22.635	22.816

Correlation Between Means: 0.998

Figure 5. 16 The calibration report for pressure

Figure 5.16 presents the statistical assessments of the calibration report. These assessments reveal an average absolute deviation (mean error) of 22.635 between the observed and computed pressure data, primarily due to the pump head effect. The report also highlights an excellent correlation between field measurements and computed data, with a correlation coefficient (R) of 0.998. This high R-value indicates that the calibration was conducted successfully, with field observations closely aligning with the EPANET 2.2 simulation results. Furthermore, the increase in the mean of the computed data directly corresponds to the pressure introduced by the pumps.

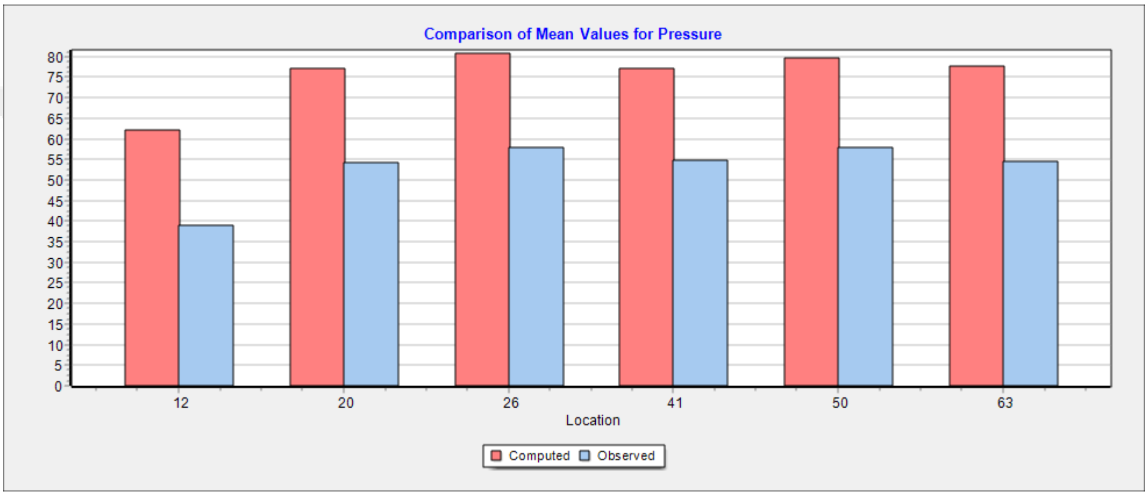


Figure 5. 17 Calibration report comparing the mean pressure values for all junctions

The proposed system reinforcement strategy has undergone thorough analysis and design stages to ensure its feasibility and effectiveness. This includes running the hydraulic model for a continuous 72-hour period to simulate various operational scenarios and identify potential issues. Additionally, a meticulous examination of potential sources of errors in the model was conducted to ensure the accuracy and reliability of the simulation. The feasibility of implementing the proposed model in real-world conditions was also assessed, considering cost efficiency and practicality. The proposed solution was evaluated to represent a low-cost, long-term solution, and all financial implications were carefully considered to minimize expenses while maximizing effectiveness.

5.10 Determining Water Age by Simulating it in EPANET

The simulation of water age in water distribution systems is a critical aspect of water quality management. This parameter, which represents the time duration a water parcel spends within the network, is a key concern for ensuring the delivery of high-quality drinking water to consumers. EPANET, a widely used hydraulic and water quality modeling tool, simulates water age within water distribution systems.

Water age cannot be directly measured using physical tools but is simulated through mathematical modeling, with EPANET being a prominent tool for this purpose. As water travels through the network, its age increases incrementally. EPANET employs zero-order kinetics to track the movement of water parcels and calculate water age at different points within the system. Understanding water age distribution within the network is crucial for identifying areas where water quality may be compromised due to prolonged water age, optimizing operational strategies, and guiding infrastructure planning.

By simulating the water age using EPANET, water authorities can identify areas within the distribution system where the water age is prolonged, leading to potential quality degradation. This information is invaluable for implementing operational and infrastructure interventions to minimize water age and ensure compliance with health standards. Therefore, water age simulation using EPANET is essential for managing water quality in distribution systems with multiple water sources, ultimately providing the public with safe, high-quality drinking water.

The model simulated the water age at five nodes over a period of 72 hours until a steady state was achieved for both the existing and improved models. For the existing model, the average water age across all nodes was approximately 13 hours and 40 minutes. The maximum water age was observed at node 63, with a value of 15 hours and 55 minutes, while the minimum water age was recorded at node 20, with a value of 12 hours and 17 minutes, as illustrated in Figures 5.18 and 5.19.

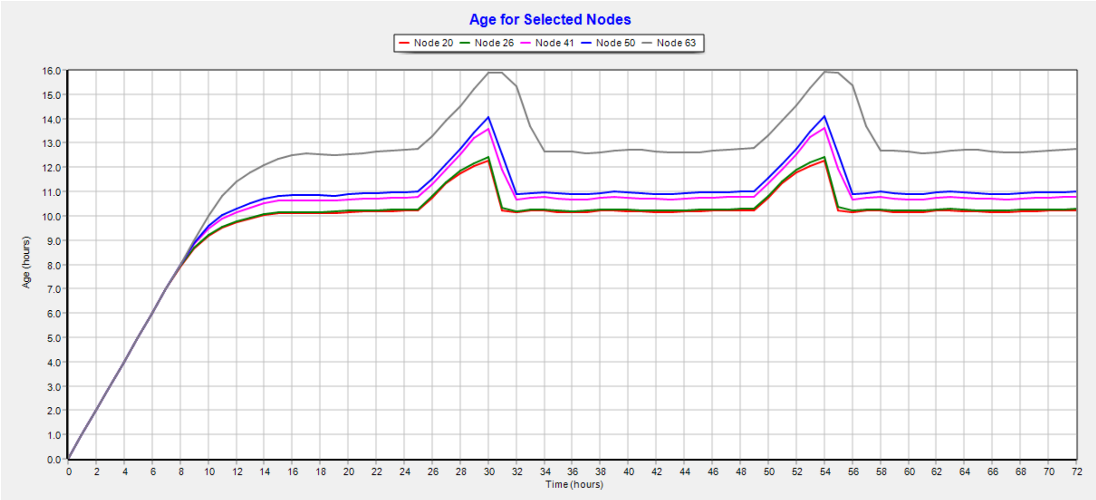


Figure 5. 18 Water age for the existing model at nodes (20, 26, 41, 50, 63)

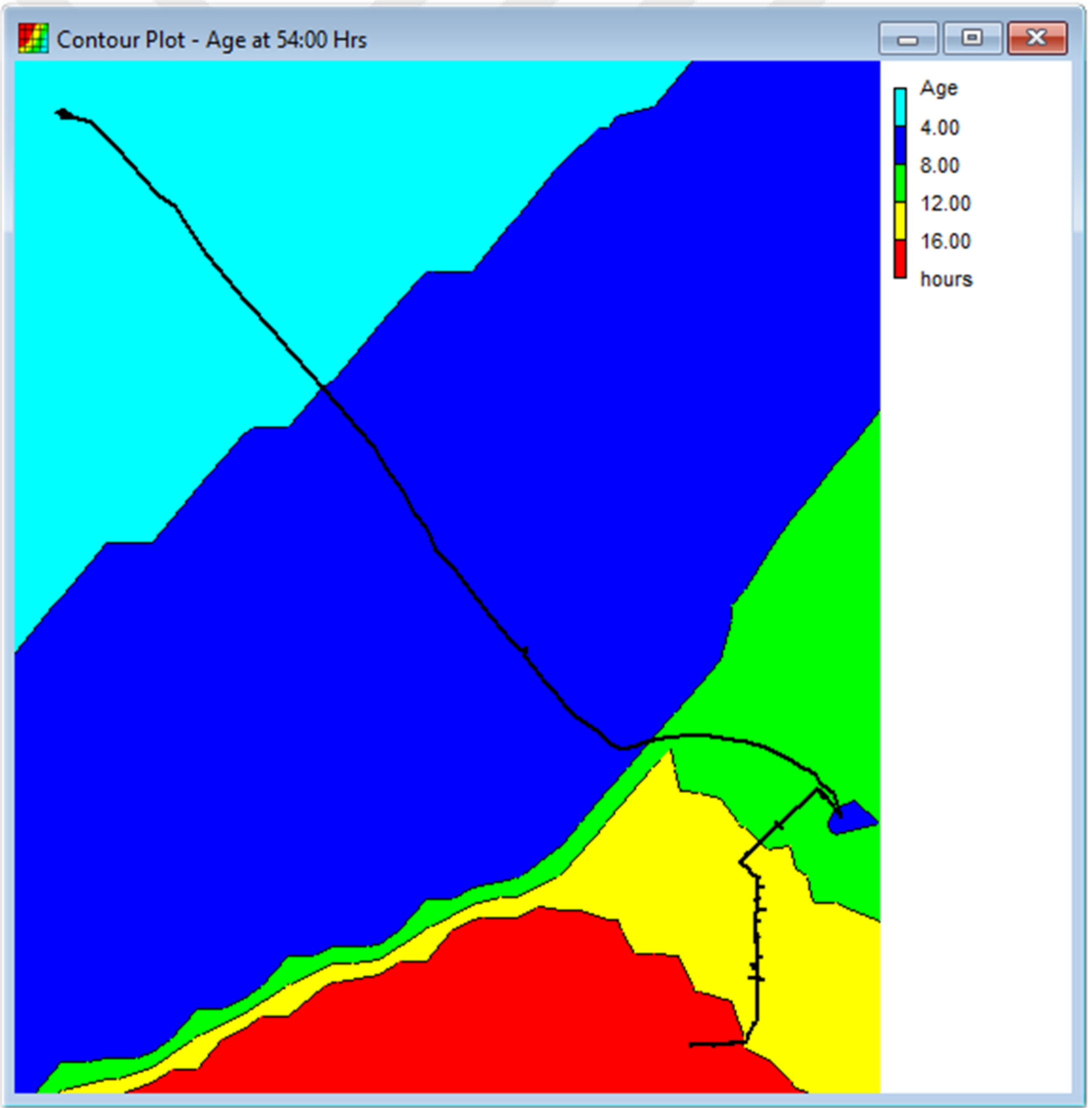


Figure 5. 19 Contour plot of water age for the existing model at 54:00 hours

After making some improvements to the existing model, including adding extra pumps downstream of the reservoir outlet and upgrading pipes to improve flow capacity and reduce resistance, the average water age across all nodes decreased to 12 hours and 45 minutes. The highest water age was observed at node 63, with a value of 14 hours and 59 minutes, while the lowest water age was observed at node 20, with a value of 11 hours and 22 minutes. These improvements are shown in Figures 5.20, 5.21, and Table 5.4, illustrating the enhanced water age simulation results.

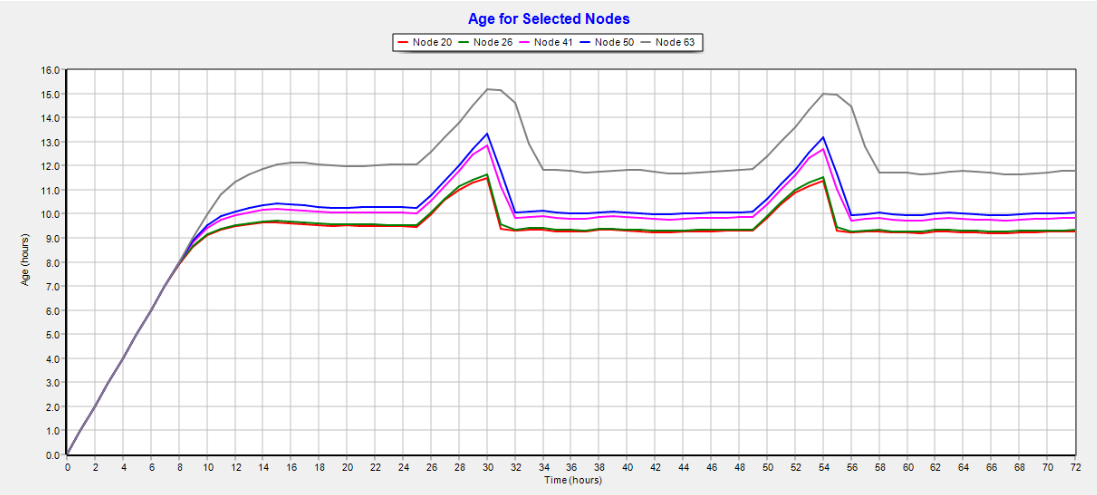


Figure 5. 20 Water age for the improved model at nodes (20, 26, 41, 50, 63)

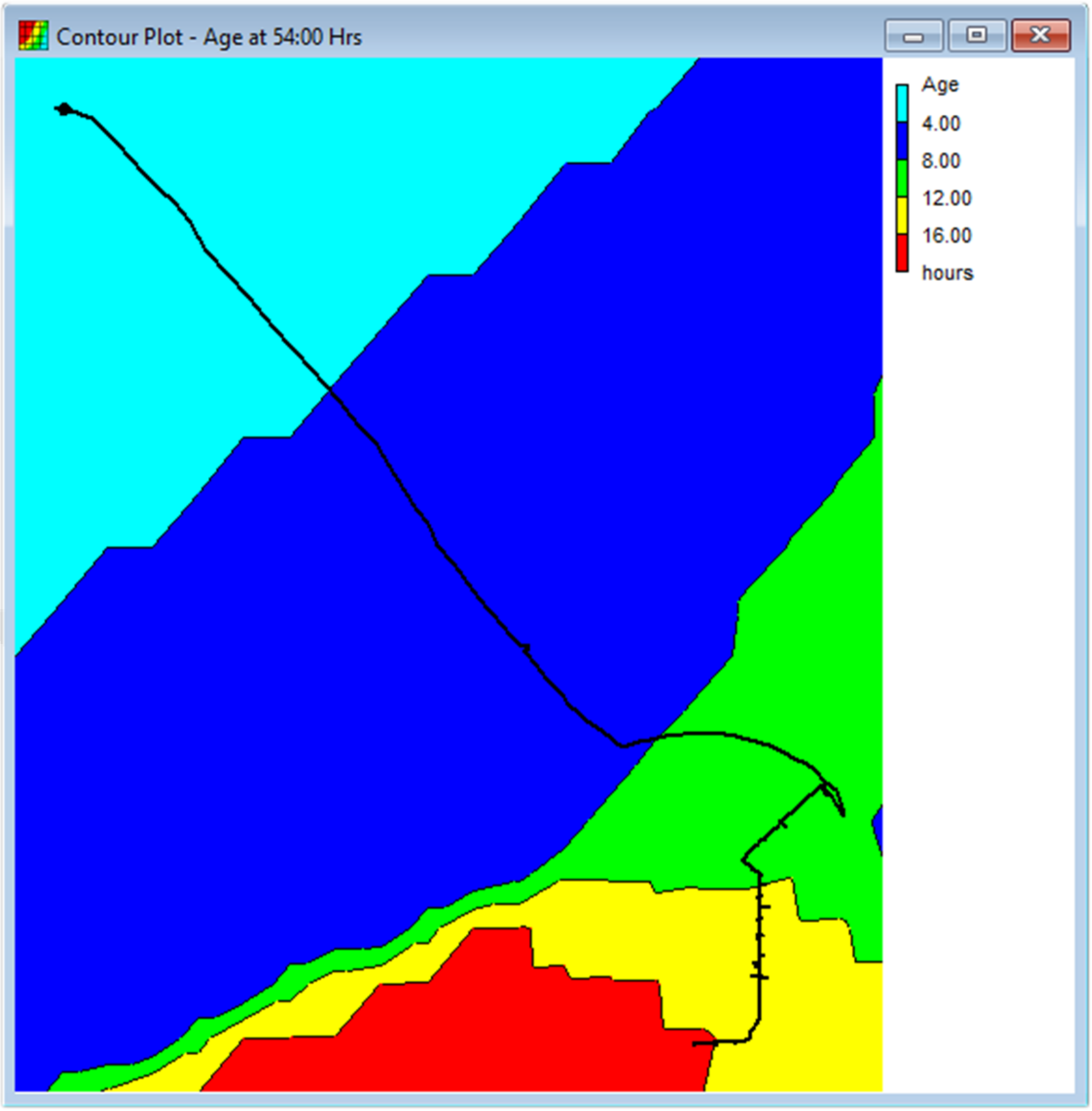


Figure 5. 21 Contour plot of water age for the improved model at 54:00 hours

Table 5. 4 Comparison of water age between existing and improved models at selected nodes

Node	Existing Model Water Age (hour)	Improved Model Water Age (hour)
n20	12:17	11:22
n26	12:25	11:31
n41	13:36	12:42
n50	14:05	13:10
n63	15:55	14:59
Average	13:40	12:45

The analysis presented in Table 5.4 offers a comprehensive comparison of water age at specific nodes within a water distribution network for both the existing and improved models. For this comparative study, the selected nodes are 20, 26, 41, 50, and 63, with each node's water age presented in hours and minutes (hh).

Observations reveal noteworthy differences between the existing and improved models at each node, with reductions in water age consistently observed in the improved model. For instance, at Node n20, the water age decreases by 55 minutes in the improved model, indicating a significant improvement in water freshness. Similar trends are observed across the other selected nodes, culminating in an average water age reduction of 55 minutes across the entire network in the improved model compared to the existing model.

The data suggests that the implemented improvements have resulted in a more efficient circulation and turnover of water within the network, leading to fresher water at each node. This decrease in water age carries several important implications, including potential improvements in water quality, system efficiency, and operational benefits. Lower water age typically signifies enhanced water quality, reduced potential for contamination, improved system efficiency, and operational advantages such as increased customer satisfaction and reduced maintenance costs.

5.11 Discussing of Results

The development and analysis of existing and improved hydraulic and water quality performance models of a water distribution network were conducted to address issues related to negative pressure zones, especially during periods of low pressure or peak demand. The primary goal was to use EPANET 2.2, a powerful tool for simulating water distribution networks, to mitigate negative pressure zones that can compromise the integrity of the water distribution system, lead to contamination, and disrupt supply during high-demand periods.

The methodology involved a comprehensive evaluation using EPANET 2.2 to conduct a detailed comparative analysis of critical parameters between the existing and improved models. The hydraulic analysis included measuring pressure at various nodes throughout the network, evaluating water flow velocity in pipes, and calculating hydraulic head loss to identify areas experiencing negative pressure and understand inefficiencies within the system. Additionally, water age was determined at different points in the network to gauge the quality of water delivered to consumers.

The comparison between the existing and improved models revealed significant enhancements in the network's performance. The evaluation was based on the following parameters:

- Pressure: The improved model demonstrated higher pressures than the existing model, a change attributed to adding a pump head to the existing elevation head. This addition ensures a more stable and reliable pressure throughout the network, as depicted in Table 5.5 and Figure 5.22.

Table 5. 5 Pressure Comparison between the existing and improved models

Node ID	Existing Model Pressure (m)	Improved Model Pressure (m)
Junc 12	38.19	59.84
Junc 13	38.15	59.81
Junc 14	22.77	58.25
Junc 15	34.96	58.93
Junc 16	46.53	68.19
Junc 17	43.41	67.79
Junc 18	52.87	74.52
Junc 19	52.74	74.39
Junc 20	52.6	74.25
Junc 21	52.68	74.34
Junc 22	58.03	79.68
Junc 24	52.64	74.28
Junc 25	48.12	72.53
Junc 26	55.87	77.52
Junc 27	52.51	74.16
Junc 28	51.72	73.83
Junc 29	49.6	71.26
Junc 30	33.38	70.31
Junc 31	51.93	73.59
Junc 32	51.99	73.65
Junc 33	50.78	73.11
Junc 34	48.73	73.19
Junc 35	51.43	73.08
Junc 36	2.87	72.13
Junc 37	50.33	71.99
Junc 38	50.25	71.9

Junc 39	41.93	71.42
Junc 40	47.06	71.22
Junc 41	49.8	71.46
Junc 42	49.7	71.36
Junc 43	48.79	70.98
Junc 44	49.65	71.31
Junc 45	46.05	70.8
Junc 46	49.58	71.24
Junc 47	47.86	70.52
Junc 48	48.89	70.55
Junc 49	43.39	70.18
Junc 50	51.99	73.65
Junc 51	28.53	72.79
Junc 52	53.44	75.1
Junc 53	52.25	74.95
Junc 54	53.22	74.88
Junc 55	49.95	73.98
Junc 56	52.84	74.5
Junc 57	34.08	74.07
Junc 58	50.88	72.54
Junc 59	50.47	72.03
Junc 60	49.71	71.08
Junc 61	47.93	69.58
Junc 62	45.44	69.27
Junc 63	49.61	71.27
Junc 64	48.95	71.19
Junc 65	53.24	73.77
Junc 66	52.75	73.06
Junc 67	52.51	73.51
Junc 68	58.33	78.32
Junc 69	59.13	79.07
Junc 70	53.65	78
Junc 71	53.21	78.67
Junc 72	63.45	83.31
Junc 73	63.28	83.47
Junc 74	62.96	83.33
Junc 75	54.57	76.22
Junc 76	46.93	75.78
Junc 8	-1.3	42.25
Junc 9	21.95	43.6

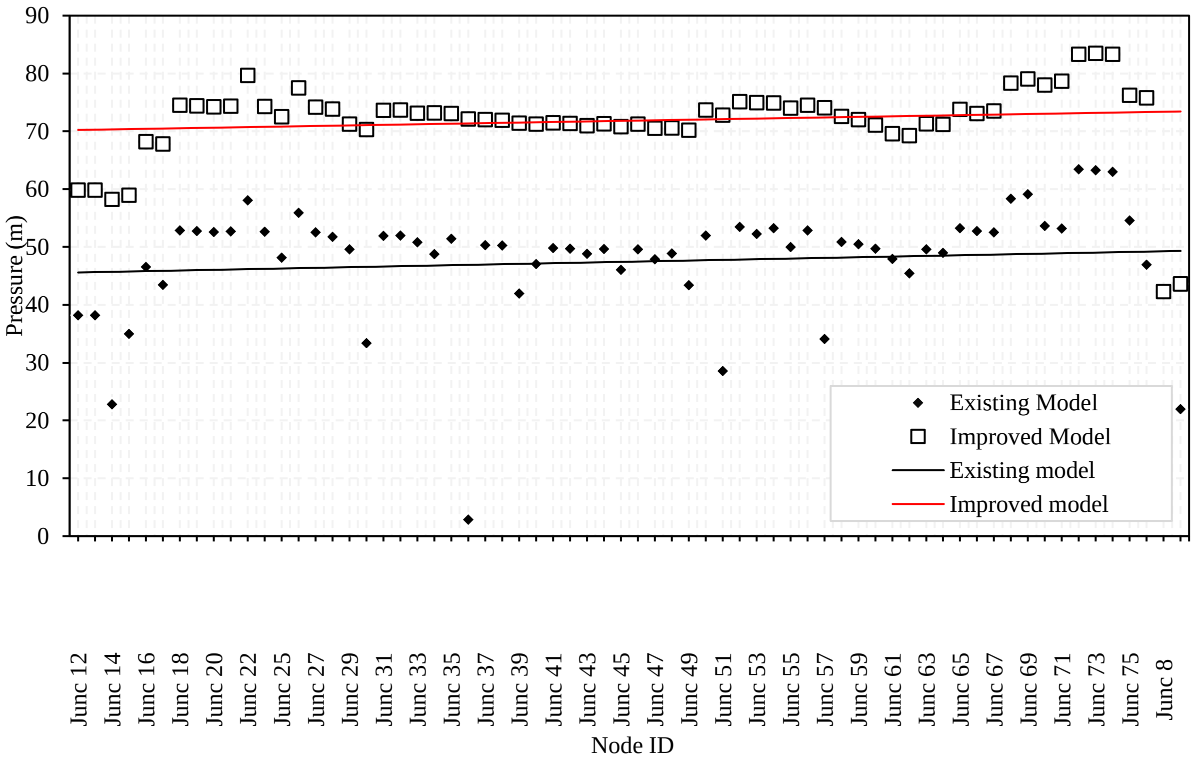


Figure 5. 22 Pressure Comparison between the existing and improved models

- Velocity: The analysis of the existing model indicated velocities exceeding the economic threshold, reaching up to 5 m/s in certain junctions during specific hours. To address this issue, pipe upgrades were implemented. The post-upgrade analysis demonstrated that the improved model reduced velocities to within the economically acceptable range, as depicted in Table 5.6 and Figure 5.23.

Table 5. 6 Velocity Comparison between the existing and improved models

	Existing Model	Improved Model
Link ID	Velocity (m/s)	Velocity (m/s)
Pipe 9	2.6	0.94
Pipe 10	1.13	1.13
Pipe 11	1.74	0.94
Pipe 12	1.11	1.11
Pipe 13	2.56	1
Pipe 14	1.09	1.09
Pipe 15	1.84	1.84
Pipe 16	2.29	0.89
Pipe 17	1.79	1.79
Pipe 18	1.35	1.35
Pipe 19	1.65	1.65
Pipe 23	1.65	1.65

Pipe 24	1.57	1.57
Pipe 25	1.23	0.79
Pipe 26	4.35	1.32
Pipe 27	1.52	1.52
Pipe 28	3.2	0.97
Pipe 29	1.46	1.46
Pipe 30	2.56	1.05
Pipe 31	1.36	1.36
Pipe 32	1.36	0.87
Pipe 33	1.3	1.3
Pipe 34	5.01	0.97
Pipe 35	1.21	1.21
Pipe 36	2.23	1.2
Pipe 37	1.17	1.17
Pipe 38	3.1	0.94
Pipe 39	1.11	1.11
Pipe 40	1.11	1.11
Pipe 41	1.23	0.79
Pipe 42	1.06	1.06
Pipe 43	2.47	1.01
Pipe 44	0.96	0.96
Pipe 45	1.58	1.01
Pipe 46	0.89	0.89
Pipe 47	2.99	0.9
Pipe 48	0.84	0.84
Pipe 49	5.09	1.27
Pipe 50	0.71	0.71
Pipe 51	3.27	0.63
Pipe 52	0.65	0.65
Pipe 53	1.57	0.84
Pipe 54	0.62	0.62
Pipe 55	2.18	0.85
Pipe 56	0.57	0.57
Pipe 57	1.11	1.11
Pipe 58	0.69	0.69
Pipe 59	0.39	0.39
Pipe 60	2.24	0.87
Pipe 61	0.34	0.34
Pipe 62	2.21	0.86
Pipe 63	0.28	0.75
Pipe 64	0.13	0.34
Pipe 65	0.06	0.17
Pipe 66	1.4	0.97

Pipe 67	2.99	0.9
Pipe 68	3.41	1.03
Pipe 69	1.21	0.84
Pipe 70	0.19	0.5
Pipe 71	1.02	1.16
Pipe 72	1.38	0.88
Pipe 73	0.27	0.27
Pipe 74	1.65	1.65
Pipe 76	1.4	1.4
Pipe 77	1.4	1.4
Pipe 78	1.41	1.4
Pipe 79	1.41	1.4
Pipe 80	1.4	1.4
Pipe 91	1.4	1.4
Pipe 92	1.4	1.41
Pipe 93	1.4	1.4
Pipe 94	1.4	1.4
Pipe 95	1.4	1.4
Pipe 4	1.17	1.17
Pipe 5	1.14	1.14
Pipe 6	2.71	0.82

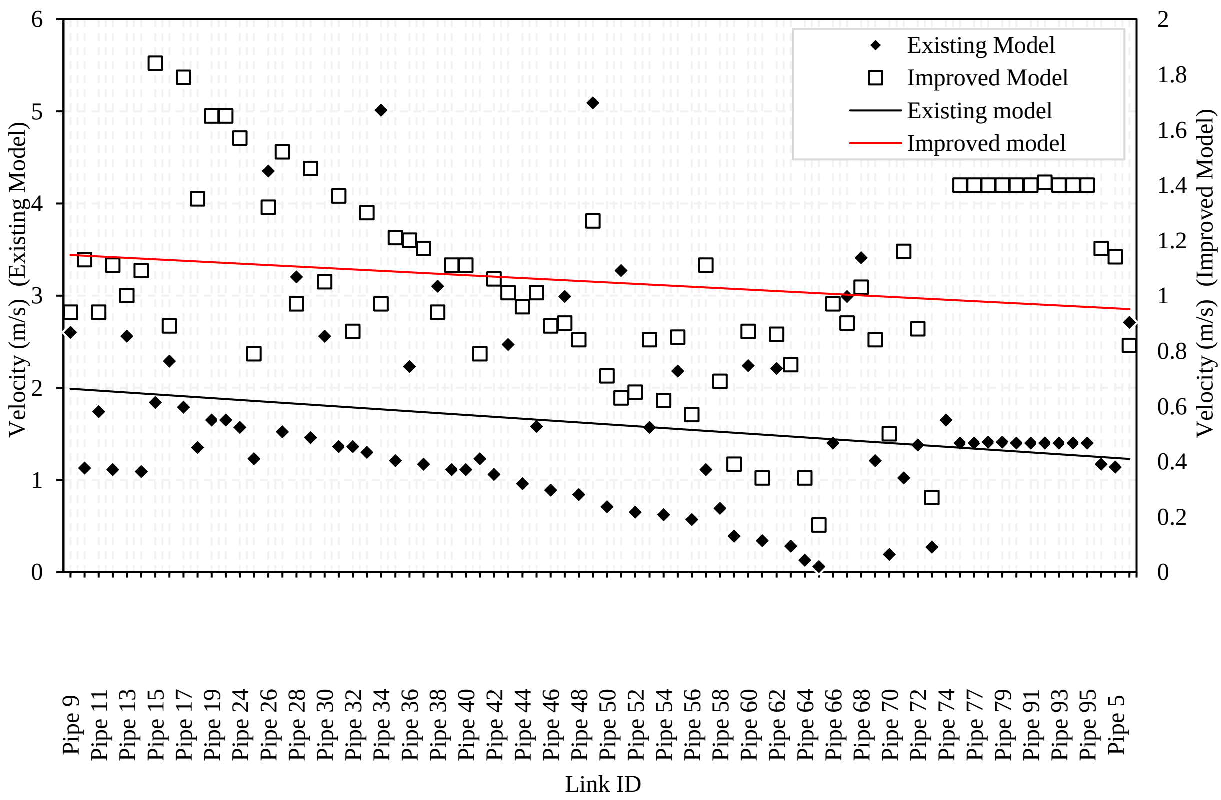


Figure 5. 23 Velocity Comparison between the existing and improved models

- Unit Headloss: The analysis revealed that the existing model exhibits a higher unit head loss than the improved model. After implementing pipe upgrades, the unit head loss decreased, leading to more appropriate pressure levels and desirable discharge rates within the system. This reduction in unit head loss enhances the overall efficiency of the water distribution network, ensuring timely and adequate water delivery to consumers, as depicted in Table 5.7 and Figure 5.24.

Table 5. 7 Unit headloss Comparison between the existing and improved models

	Existing Model	Improved Model
Link ID	Unit Headloss (m/km)	Unit Headloss (m/km)
Pipe 9	75.28	7.78
Pipe 10	1.92	1.92
Pipe 11	28.32	7.78
Pipe 12	1.88	1.88
Pipe 13	49.89	6.29
Pipe 14	1.79	1.79
Pipe 15	7.63	7.63
Pipe 16	40.6	5.12
Pipe 17	7.2	7.2
Pipe 18	6.77	8.42
Pipe 19	6.25	6.25
Pipe 23	6.25	6.25
Pipe 24	5.69	5.68
Pipe 25	9.67	4.06
Pipe 26	154.58	9.01
Pipe 27	5.36	5.36
Pipe 28	87.62	5.11
Pipe 29	4.97	4.97
Pipe 30	37.56	5.31
Pipe 31	4.34	4.34
Pipe 32	11.67	4.9
Pipe 33	4.02	4.02
Pipe 34	200.89	3.95
Pipe 35	3.49	3.49
Pipe 36	44.74	10.59
Pipe 37	3.27	3.27
Pipe 38	82.4	4.8
Pipe 39	2.97	2.97
Pipe 40	2.97	2.97
Pipe 41	9.67	4.06
Pipe 42	2.73	2.73

Pipe 43	34.93	4.94
Pipe 44	2.28	2.27
Pipe 45	15.28	6.41
Pipe 46	2	2
Pipe 47	77.33	5.23
Pipe 48	1.77	1.77
Pipe 49	178.35	6.54
Pipe 50	1.32	1.32
Pipe 51	91.18	2.08
Pipe 52	1.11	1.11
Pipe 53	23.3	6.4
Pipe 54	1.02	1.02
Pipe 55	37.13	4.68
Pipe 56	0.86	0.86
Pipe 57	4.74	5.89
Pipe 58	1.94	2.42
Pipe 59	0.43	0.43
Pipe 60	38.85	4.9
Pipe 61	0.33	0.33
Pipe 62	37.99	4.79
Pipe 63	0.24	2.59
Pipe 64	0.06	0.61
Pipe 65	0.02	0.17
Pipe 66	16.34	7.21
Pipe 67	77.33	5.23
Pipe 68	98.5	6.66
Pipe 69	12.5	5.52
Pipe 70	0.11	1.19
Pipe 71	6.8	9.99
Pipe 72	11.93	4.32
Pipe 73	0.13	0.13
Pipe 74	6.25	6.25
Pipe 76	2.2	2.2
Pipe 77	2.21	2.21
Pipe 78	2.21	2.21
Pipe 79	2.21	2.21
Pipe 80	2.2	2.2
Pipe 91	2.21	2.21
Pipe 92	2.21	2.21
Pipe 93	2.21	2.21
Pipe 94	2.2	2.21
Pipe 95	2.2	2.2
Pipe 4	2.04	0.84

Pipe 5	1.97	1.97
Pipe 6	64.54	3.76

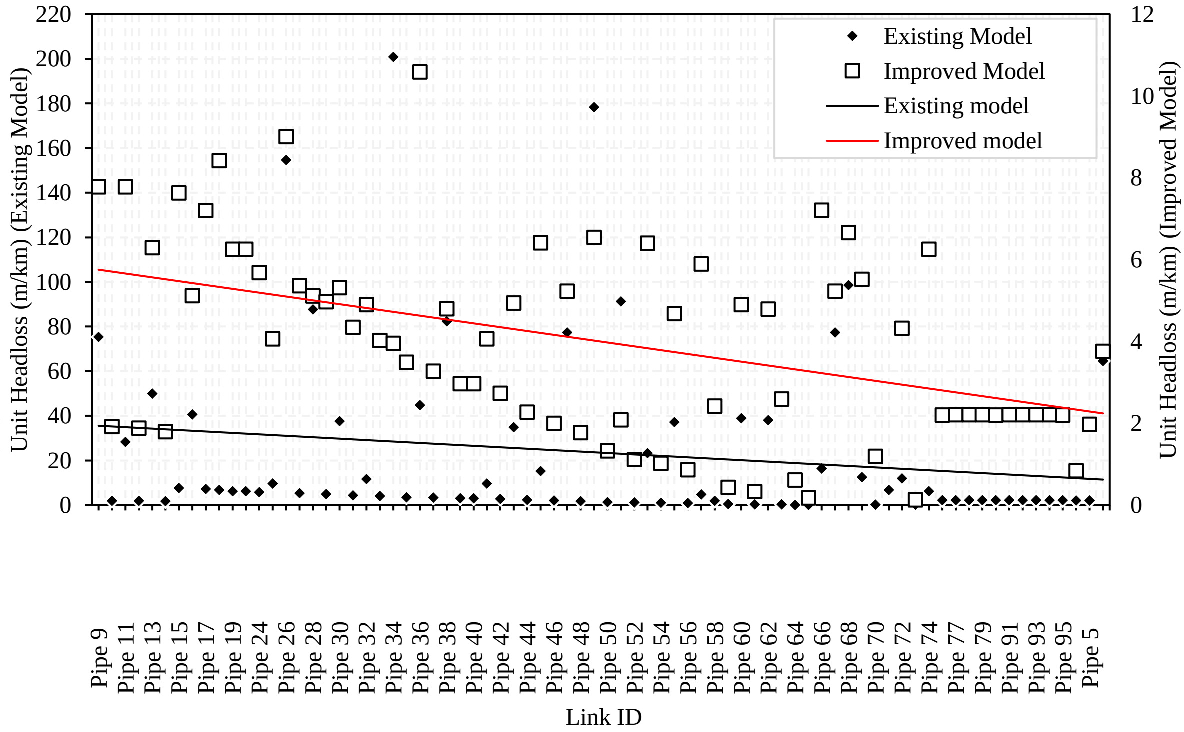


Figure 5. 24 Unit headloss Comparison between the existing and improved models

- Water Quality Parameter (Water Age): The water quality analysis revealed that the improved model had a reduced water age compared to the existing model. This reduction implies better water turnover, leading to higher water quality and fresher water delivery to consumers, as depicted in Table 5.8 and Figure 5.25.

Table 5. 8. Water age Comparison between the existing and improved models

	Existing Model	Improved Model
Node ID	Age (hours)	Age (hours)
Junc 12	11.33	10.44
Junc 13	11.35	10.45
Junc 14	11.4	10.61
Junc 15	11.4	10.55
Junc 16	11.84	10.95
Junc 17	11.86	11
Junc 18	12.26	11.35
Junc 19	12.27	11.36
Junc 20	12.28	11.37
Junc 21	12.27	11.36

Junc 22	13.14	12.24
Junc 24	12.27	11.37
Junc 25	12.29	11.43
Junc 26	12.42	11.51
Junc 27	12.69	11.79
Junc 28	12.74	11.87
Junc 29	12.84	11.93
Junc 30	12.88	12.08
Junc 31	13.02	12.12
Junc 32	13.01	12.11
Junc 33	13.07	12.19
Junc 34	13.04	12.17
Junc 35	13.18	12.28
Junc 36	13.22	12.44
Junc 37	13.37	12.46
Junc 38	13.38	12.47
Junc 39	13.4	12.55
Junc 40	13.39	12.5
Junc 41	13.6	12.7
Junc 42	13.62	12.72
Junc 43	13.68	12.8
Junc 44	13.64	12.73
Junc 45	13.66	12.8
Junc 46	13.66	12.75
Junc 47	13.71	12.83
Junc 48	13.73	12.83
Junc 49	13.75	12.88
Junc 50	14.09	13.17
Junc 51	14.1	13.22
Junc 52	14.3	13.36
Junc 53	14.3	13.37
Junc 54	14.26	13.33
Junc 55	14.29	13.38
Junc 56	14.21	13.28
Junc 57	14.23	13.37
Junc 58	14.41	13.47
Junc 59	14.5	13.57
Junc 60	14.48	13.54
Junc 61	15.44	14.51
Junc 62	15.45	14.53
Junc 63	15.92	14.99
Junc 64	15.93	15
Junc 65	16.44	15.2

Junc 66	16.45	15.22
Junc 67	16.45	15.22
Junc 68	17.24	15.49
Junc 69	17.39	15.55
Junc 70	17.25	15.51
Junc 71	17.4	15.57
Junc 72	19.94	16.52
Junc 73	19.95	16.53
Junc 74	19.95	16.53
Junc 75	12.58	11.68
Junc 76	12.59	11.71
Junc 8	10.26	9.66
Junc 9	10.14	9.25

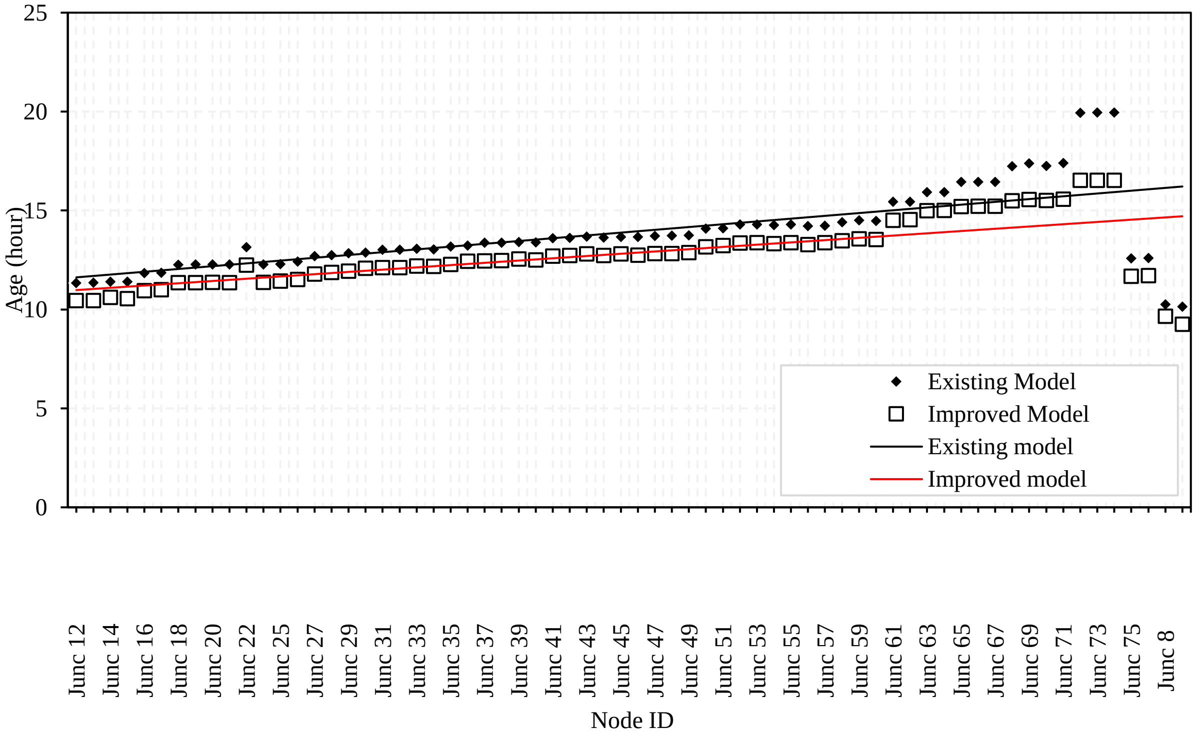


Figure 5. 25 Water age Comparison between the existing and improved models

CHAPTER 6

CONCLUSION

6.1 Conclusion

This study focused on developing, analyzing, and calibrating a model to accurately represent the hydraulic and water quality characteristics of a segment of Erbil City's WDN. The main goal was to enhance system credibility and provide a valuable tool for future planning, particularly in determining the water age within the targeted area.

Key findings include:

- Hydraulic Model Calibration: The calibration revealed a significant reduction in the C-factor for the 800mm distribution main pipelines from standard 140 to 83.3, indicating critical issues related to pipe age and non-economic velocities contributing to elevated unit head loss.
- System Improvements: The addition of booster pumps and pipeline upgrades in the EPANET 2.2 hydraulic model effectively addressed negative pressure zones, ensuring consistent water delivery to high-demand areas and enhancing system performance and reliability.
- Enhanced Performance: The improvements in both hydraulic and water quality models resulted in better pressure management, economic velocities, increased discharge rates, reduced unit head loss, and decreased water age, thereby addressing deficiencies in the existing model.
- Impact of Modifications: The modifications significantly reduced water age across the network, validating the effectiveness of the proposed changes and providing a basis for further optimization of the WDN.
- Model Reliability: The improved models are reliable and suitable for long-term application under various conditions, ensuring stable performance and adaptability to different scenarios. The model's robustness ensures water delivery to all network points within its designed capacity, free from operational disruptions.

- Future Challenges: While the current model meets present demands, it may struggle to address future demands due to aging infrastructure amid rapid population growth. Continuous monitoring and periodic reassessment are necessary to maintain the model's effectiveness and address emerging challenges.

This study substantiates the effectiveness of the improvements made to Erbil City's WDN, providing a reliable and efficient framework for urban water supply and serving as a valuable reference for future optimization and sustainability efforts.

6.2 Recommendations

It is essential to consider utilizing additional software tools such as WaterGEMS, InfoWater, or Mike Urban for redesigning the study area analysis. These tools provide advanced features and diverse modeling capabilities that can be instrumental in conducting a comprehensive evaluation and validation of the results obtained with EPANET 2.2.

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APPENDIX

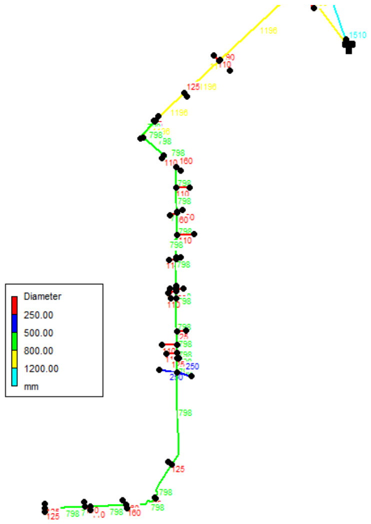

Figure A. 1 The diameter of pipelines in the existing model of the case study

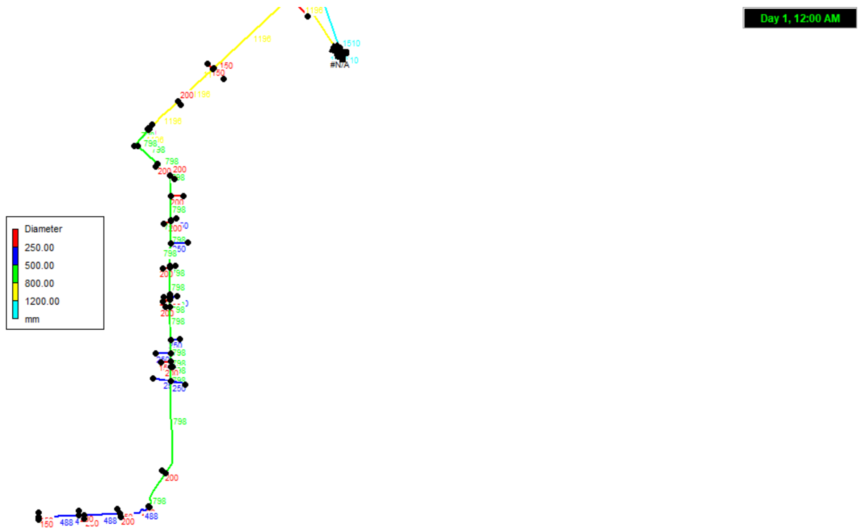

Figure A. 2 The diameter of pipelines in the Improved model of the case study

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