Institute for Water and Energy Sciences (incl. Climate Change)
PAU

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master's degree in
Water Engineering

Presented by

Anthia Sarah Carmel IRAKOZE

DEVELOPMENT OF AN INTEGRATED DRINKING WATER MANAGEMENT MODEL: BUJUMBURA CITY, BURUNDI

Defended on 13th April 2025 Before the Following Committee:

Chair	Mamounata Belem	Prof.	CNRST, Burkina Faso
Supervisor	Abdelhadi Ammari	Dr.	ENSH, Algeria
Co-supervisor	Cherifa Abdelbaki	Prof.	University Of Tlemcen, Algeria
External Examiner	Andrew AKO AKO	Prof.	Ministry of Scientific Research and Innovation, Cameroon
Internal Examiner	Bessedik Madani	Dr.	University Of Tlemcen, Algeria

Development of an integrated drinking water management model in Bujumbura city, Burundi

by

Anthia Sarah Carmel IRAKOZE

Supervisor:

Dr. Abdelhadi Ammari

This thesis is submitted for the partial fulfillment of requirements for the Master of Science degree at the Pan African University Institute for Water and Energy Sciences, Tlemcen, Algeria

APRIL 2025

DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this master's thesis is my original work and has not been wholly or in part presented in this university or any other university for the award of a degree.

Signature:

Date: **30th March 2025**

Name: **Anthia Sarah Carmel IRAKOZE** Reg. No: **PAUWES/2023/MWE07**

RECOMMENDATION

This thesis is the candidate's original work and has been prepared with our guidance and assistance. It is presented for examination with our approval as official University Supervisors.

Signature: ___________ **Date**: 30 **th March 2025**

Supervisor: Abdelhadi AMMARI

AKNOWLEDGEMENT

Above all, my deepest gratitude goes to the Almighty God, whose unwavering faithfulness has sustained me through the challenges of my academic journey. His guidance and strength have been my pillar, enabling me to overcome obstacles and reach this important milestone.

This thesis would not have been possible without the generous financial support of the Pan African University research grant, provided through the African Union Commission, and the invaluable assistance of the PAUWES staff. I extend my deepest appreciation for their contributions to my academic journey.

I am profoundly grateful to my supervisor, **Dr. Abdelhadi Ammari** and my co-supervisor, **Pr Chérifa Abdelbaki**, whose unwavering guidance, expertise, and mentorship have been instrumental in shaping this research. Their encouragement and insightful feedback have not only enriched my work but have also strengthened my skills and determination to achieve the objectives of this thesis, even in the face of challenges.

A special note of appreciation goes to **Mr. Seddik Bouzzari** and **Mr Eric Nzoyihera** my internship mentor, for serving as invaluable scientific references and source of inspiration throughout this process.

I also extend my sincere gratitude to **REGIDESO Company** and its entire staff for providing access to essential data and resources for this study. The opportunity to undertake an internship at their institution has significantly enhanced my understanding of the practical aspects of designing and managing water distribution systems.

Finally, I wish to express my heartfelt thanks to my family, colleagues, and friends for their unwavering encouragement and support. Their belief in me has been a driving force in my pursuit of a **master's degree in water engineering**, and I am truly grateful for their presence throughout this journey.

ABBREVIATIONS AND ACRONYMS

AC	Asbestos Cement
CI	Cast Iron
DEM	Digital Elevation Model
DI	Ductile Iron
GIS	Geographic Information System
GPS	Global Positioning System
HDPE	High density Polyethylene
HMT	Manometric Head
PVC	Polyvinyl chloride
WDN	Water Distribution Network
WTP	Water Treatment Plant

TABLE OF CONTENTS

LISTES OF TABLES

LISTES OF FIGURES

ABSTRACT

Water utilities encounter an enormous obstacle in ensuring the efficient and sustainable distribution of drinking water. That is the case in any growing city like the case of Bujumbura City in Burundi which has an old water system. This study examines the analysis and modeling of a drinking water distribution network, which is an old network to see how to tackle all the issues in order to enhance its performance, reliability, and sustainability. The study employs EPANET 2.2 to assess hydraulic parameters like pressure, flow rate, velocity, and head loss throughout the network of Bujumbura City. The methodology encompasses data acquisition through field surveys, GIS mapping, and network simulations across various demand scenarios. Identified key issues include pressure variations, leakage, and deficiencies in pipe sizing, which affect service delivery. The hydraulic modeling of the existing networks showed very bad hydraulic parameters, too many nodes are of negative pressure, so the network cannot function deserve the entire city in one time. To resolve such obstacles, optimization options like network resizing, the installation of pressure-reducing valves, and alternative network designs were examined, these solutions gave satisfaction with a good hydraulic parameter over the whole network. The findings indicate that effective hydraulic modeling can greatly improve system efficiency, reduce water losses, and ensure equitable water distribution. This study highlights the importance of incorporating modeling methods in water resource management to facilitate accurate choices and sustainable infrastructure planning.

Key words: Water supply, Bujumbura, Hydraulic model, GIS, network resizing.

RESUME

Les services de distribution d'eau rencontrent un énorme obstacle pour assurer une distribution efficace et durable de l'eau potable. Cette étude examine l'analyse et la modélisation d'un réseau de distribution d'eau potable, qui est un réseau ancien, pour voir comment aborder tous les problèmes afin d'améliorer sa performance, sa fiabilité et sa durabilité. L'étude utilise EPANET 2.2 pour évaluer les paramètres hydrauliques tels que la pression, le débit, la vitesse et la perte de charge à travers le réseau de la ville de Bujumbura. La méthodologie comprend l'acquisition de données à travers des enquêtes sur le terrain, la cartographie GIS, et des simulations de réseau à travers différents scénarios de demande. Les problèmes clés identifiés comprennent les variations de pression, les fuites et les déficiences dans le dimensionnement des tuyaux, qui affectent la fourniture du service. La modélisation hydraulique des réseaux existants a montré de très mauvais paramètres hydrauliques, trop de nœuds sont en pression négative, de sorte que le réseau ne peut pas fonctionner pour desservir l'ensemble de la ville en une seule fois. Pour résoudre ces obstacles, des options d'optimisation telles que le redimensionnement du réseau, l'installation de vannes de réduction de pression et d'autres conceptions de réseau ont été examinées ; ces solutions ont permis d'obtenir un bon paramètre hydraulique sur l'ensemble du réseau. Les résultats indiquent qu'une modélisation hydraulique efficace peut grandement améliorer l'efficacité du réseau, réduire les pertes d'eau et assurer une distribution équitable de l'eau. Cette étude souligne l'importance d'incorporer des méthodes de modélisation dans la gestion des ressources en eau afin de faciliter des choix précis et une planification durable des infrastructures.

Mots clés : Approvisionnement en eau, Bujumbura, Modèle hydraulique, SIG, redimensionnement du réseau.

INTRODUCTION

1.1. Background

Access to safe drinking water and adequate sanitation is a critical indicator of a household's socio-economic status and plays a fundamental role in ensuring the health and well-being of its members. Safe drinking water is particularly vital for the survival and development of children, as it helps prevent waterborne diseases that disproportionately affect young populations (Kumar & Das, 2014). In 2020, 74% of the global population had access to clean drinking water services, while 2 billion people were unable to do so, according to the Sustainable Development Goals Report (SDG 2022). On the other hand, 1.2 billion people lacked basic water services (Ingutia, 2024)

Water is provided to our homes through a water distribution network, which is owned and managed by water utility companies. These companies face significant expenses associated with the installation of new pipelines to meet the growing population, with the maintenance and replacement of the aging infrastructure, considering the rapid increase of water requirements due to the increasing population under water resources scarce conditions (Gupta et al., 2019).

However, the situation is worst knowing the deteriorating water infrastructures and distribution systems frequently leads to water leakages, thereby intensifying the problem, especially in urban region (Picazo & Tekinerdogan, 2024).Nowadays, leaks and bursts in water distribution networks contribute to considerable water loss on a global level. Approximately one third of global water utilities indicate a loss of 40% of clean water caused by leakage (Gupta et al., 2019) Water supply network managers should now use and develop local hydraulic models in order to better manage and model various scenarios, comprehend the variety of potential operating points, and guarantee that drinking water is supplied to subscribers under optimal service conditions (Des & Ingénieur, 2019) To secure a sustainable water supply in the 21st century, effective demand management is essential considering the limited supply and spread out urban infrastructure (Dongare et al., 2024)

In addition, Geographic information systems provide detailed knowledge and information on drinking water supply networks, which can update plans as needed. They can also store information about power supply networks in drinking water databases for effective management

(Abdelbaki & Touaibia, 2014). Coupling GIS and hydraulic models provides analytical solutions for water utility modeling, design, and operational intelligence. (Kuma & Abate, 2021), the data can be updated according to supply conditions, and the hydraulic model can be calibrated using field measurements recorded by instruments and remotely sent to the main server.

This study focuses on creating a more efficient management system for water distribution networks in the city, by developing a dynamic model for the management of drinking water supply systems in urban areas, the numerical model can allow us to estimate all hydraulic parameters, an so, suggest technical solutions to improve the functioning of the system through the equilibrium of pressure distribution over the whole network. The results obtained from the use of the combination of Geographic Information Systems (GIS) software with a hydraulic modeling tool will be used to improve integrated urban drinking water management and human health in the study area.

1.2. Problem Statement

The scarcity of water faced by a particular population is not necessarily a result of the prolonged drought experienced in the city, but it can also be a complex and challenging matter of water resource management. This challenge arises from the utilization of outdated investigative tools, such as manual archiving and planning methods, which hinder effective water management practices (Picazo & Tekinerdogan, 2024).

The urban water supply infrastructure in Burundi especially in the economic capital Bujumbura City have become inadequate to meet the growing water demand. Insufficient investment in infrastructure development and maintenance has resulted in outdated and deteriorating systems. According to Picazo & Tekinerdogan (2024), aging pipes, inadequate storage facilities, and limited treatment capacities hinder the provision of reliable and continuous water supply (Picazo & Tekinerdogan, 2024).

Bujumbura has experienced rapid population growth and urbanization. Urban population growth (annual %) in Burundi was reported at 5.2 % in 2022, according to the World Bank collection of development indicators, compiled from officially recognized sources (World Bank, 2024) .The urban growth rate between 2015 and 2020 was 5.68% just about 13.4% of the total population of the country live globally in the urban area, compared to the total land area, which resulted in a rapid increased water demand (United Nations Human Settlements Programme, 2024)

In some areas of Bujumbura, water shortages have become routine. Residents can go for three days or more without water from their taps. During the dry season, which runs from May to August and January to February. A week may pass without water coming out of the taps in the commune of Ntahangwa which is located in the north of the city (Bizimana, 2023). Knowing that the main network of the city is very old, more than 50 years. In some other areas, the taps run dry in the mornings and the water only appears at night, while in others it is common to spend three days without a drop of water (Rukundo, 2024). However, there are still river water consumers in Bujumbura and throughout the country. When there is a water shortage, locals prefer to use the river instead of standing in line at other public water taps or other sources that are far away and this leads to some waterborne diseases due to the consumption of untreated water (Bizimana, 2023).

Figure 1.1: Dry taps leading to people fetching drinking water from the river (BIZIMANA, 2023)

It is necessary that Bujumbura city establish a new master plan for drinking water supply in accordance with the present situation, the city's growing population, and REGIDESO's inability to consistently provide the entire city (Sindayigaya & Toyi, 2023) .

In this city, there is a need for the development of a water supply modelling system that may help in an integrated way with the management of the system. Knowing that a dynamic network model is a powerful tool for observing and operating a city's water supply. It allows knowledgeable choices for upgrading and broadening the system since there is no proper one in the existing system.

1.3. Objectives

1.3.1. Main Objective

The main objective is to diagnosis the existing water supply network of the study area, develop a hydraulic model coupled with GIS tool to estimate all network hydraulic parameters at any nodeover the whole study area, and finally propose technical solutions to improve the network and guarantee a continuous water distribution. The developed hydraulic model will be calibrated to be used as a main tool for network management and monitoring.

1.3.2. Specific Objectives

The specific objectives of this study were:

a) Diagnose the actual situation of water supply over the study area

b) Develop a hydraulic model coupled with GIS,

c) Propose appropriate rehabilitation solutions,

d) Develop a dynamic model for the management and the monitoring of the drinking water supply system in the city.

1.4. Research Questions

1. What are the main issues in the current water supply system of Bujumbura city?
2. What might be the causes of the persistent water shortage in the city?
3. How can GIS and hydraulic modelling be used to develop an integrated urban water distribution system in Bujumbura City? How can it help for an efficient management of the system?
4. What kind of solutions to adopt, to improve the network efficiency and management strategy?

1.5. Justification of the Study

The increase in global population and urbanization have highlighted the necessity for efficient and reliable Water Distribution Networks. As the urbanization trend continues to grow, existing water distribution networks are often unable to meet the increasing water demands, resulting in issues such as water scarcity, pressure down, and elevated operational costs, and high leakage rate. This study is justified by the urgent need to improve both the efficiency and the sustainability of Water Distribution Networks in urban areas, where an insufficient water supply can have significant effects on public health and economic development.

When water shortages occur, many taps remain dry for days, leaving communities without access to clean drinking water. As a result, people are forced to fetch water from unclean sources, increasing the risk of waterborne diseases. Reliable access to clean water is essential for health and well-being, highlighting the urgent need for sustainable water management solutions.

Recent studies have shown that many water distribution networks are characterized by poorly maintained infrastructure and substantial losses due to leaks, which some estimates put as high as 40% in some regions. The integration of innovative computational techniques and software tools, including GIS tools, hydraulic modeling frameworks, provides new opportunities for the detailed analysis and simulation of Water Distribution Networks. Meeting current demands and ensuring sustainability for future demand level, are both required elements of efficient water distribution.

1.6. Scope and Limitation of the Study

The study is of great interest for the Bujumbura population which are suffering from water shortage, this situation is deeply impacting their life especially the public health, and economic and social evolution of the city. The study aims to rehabilitate the actual water system, reduce the leakage rate and enlarge the water distribution system. Also, the study aims to propose a global management strategy, starting from a good hydraulic model and a performant monitoring system in order or have a good understanding of the functioning of the system. But the challenge is to have access to all required data in order to develop and calibrate the hydraulic model.

LITTERATURE REVIEW

2.1. Water Demand and Supply

Water is a vital natural resource essential for our lives, but it is becoming increasingly scarce due to population growth, industrial and agricultural activities, and inadequate rainfall. Water demand is the overall amount of water needed to satisfy the demands of different sectors, such as residential, commercial, agricultural, and environmental usage (Scheele & Malz, 2017). It is an essential principle in urban planning and water resource management since it promotes sustainable water distribution and supply.

When designing water supply systems, one of the essential considerations is population prediction. Therefore, it is important to correctly estimate the population in order to meet the community's ever-growing need for water (Ahmadullah & Dongshik, 2016) .To plan, develop, operate, and manage water supply systems, water authorities and water service providers rely on water demand projections. Different kinds of projection periods and techniques are employed, depending on the particular objectives (Arampatzis et al., 2014).

In other to determine when future shortages of water might occur, demand estimations are an important component of a water supply-demand balance. A water service provider can evaluate how sensitive water demand is to major factors like population growth, behavior, or weather by using multiple demand scenarios (State of Queensland, 2021)

Water demand estimation involves calculating the amount of water required for a specific population or area, typically based on per capita usage rates and demographic data.

In order to predict demographic evolution, several types of forecasting models are being used; the most popular one is as follows:

$$\boldsymbol{Pn = Po \cdot (1 + r)^n} \qquad \textbf{\textit{2.1}}$$

Where:

$Pn\ is\ the\ population\ at\ the\ study\ horizon\ n.$

$Po: population\ during\ the\ reference\ year.$

$r: annual\ growth\ rate$

$n: number\ of\ years.$

2.2. Types of Water Demand

Estimating water demand requires multiple variables, including population size, average water use per person, climate conditions, as well as the needs of many sectors including residential, commercial, agricultural, and industrial.

Table 2.1 : Water Usage and demand

Type of Water Demand	Usage
Residential	Indoor and outdoor household use (drinking, cooking, bathing)
Commercial	Offices, retail stores, hotels, restaurants (cleaning/sanitation)
Industrial	Manufacturing processes (cooling), cleaning/maintenance activities
Agricultural	Irrigation for crops and livestock care
Institutional	Schools, universities, hospitals (hygiene practices)
Public	Municipal services like parks maintenance and street washing
Environmental	Maintaining ecosystems such as rivers or wildlife habitats
Recreational	Swimming pools, water parks, fishing areas

To understand water demand, we can look at two main things: how much water is used on average and when people use it the most. Each type of water use can be examined based on its peak factors. Peak factors are numbers that show how much water is needed at certain times compared to the average amount used over a longer time, like an hour, a day, a week, or a year. The peak factor formula is estimated as follows:

$$\boldsymbol{Peak\ Factor = \frac{Maximum\ demand}{Average\ Demand}} \qquad \boldsymbol{2.2}$$

The word water demand (Qd) is identical to water consumption. In reality, demand is frequently assessed at supply locations, where measurements account for leakage and the volumes utilized to fill any existing balancing tanks within the system. To prevent inaccurate conclusions, a precise difference between measurements at different places in the system must always be made. It is widely accepted that:

$$\boldsymbol{Qd = Qwc - Q_{WL}} \qquad \textbf{\textit{2.3}}$$

Where:

- ✓ $Water\ demand\ Qd\ is\ considered\ as\ the\ need\ of\ the\ population$;
- ✓ $Water\ production\ (Qwp)\ is\ obtained\ from\ water\ treatment\ facilities$;
- ✓ $Water\ consumption\ Qwd\ is\ the\ quantity\ directly\ used\ by\ the\ customers$;
- ✓ $Water\ leakage\ (Qwl)\ is\ the\ physically\ lost\ water\ from\ the\ system$.

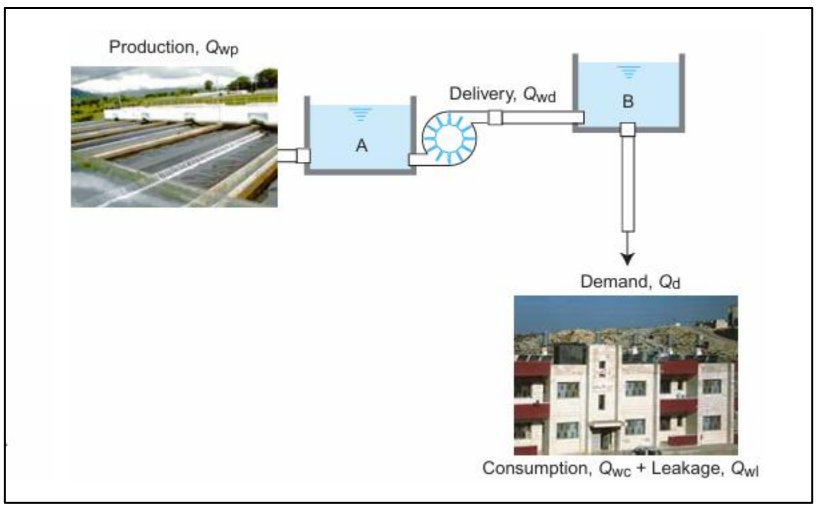


Figure 2.1: Water Supply Processes

Moreover, when supply is estimated without a temporary water storage system, for example when the water is directed immediately to the distribution network: either $Qwd = Qd$ or $Qwd = Qwp$.

2.3. Water Production

Water is an important renewable natural resource; no one, including humans and animals, can survive without water. Water comes from various sources, such precipitation, surface water, and ground water. Burundi has an abundance of water resources, with over 30,000 natural springs. But the infrastructure needed to effectively collect and distribute this water is still either inadequate or poorly maintained. This is mostly because drinking water providers lack funding, which makes it difficult to maintain and grow the system (Kirchner, 2017) . The city is largely supplied with drinking water from the surface water from Lake Tanganyika and from the emerging springs (underground water) of the MISUMBA, BUHONGA, GATUNGURU and ISALE springs, which rise from the MUMIRWA hills in Bujumbura Rural to the east of the city (Gesellschaft & Zusammenarbeit, 2021) to the following figure:

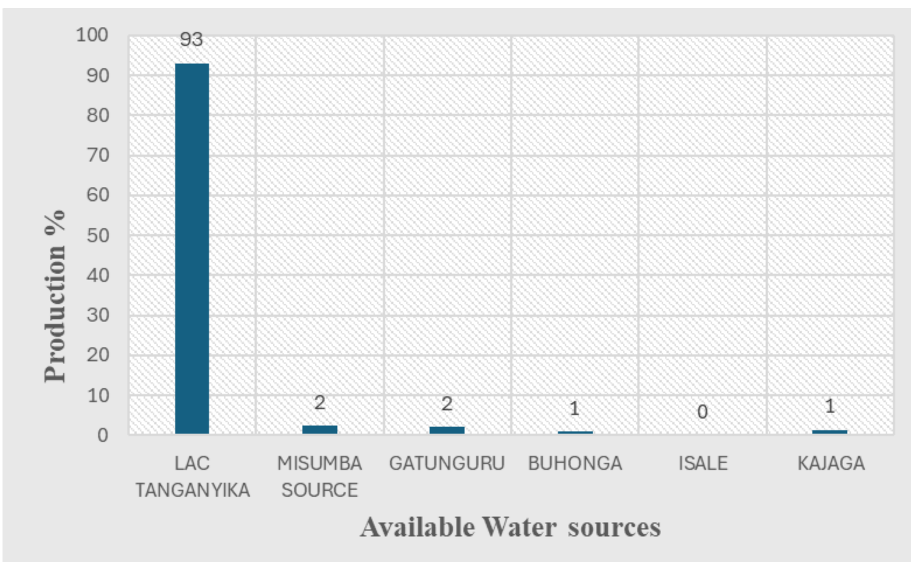


Figure 2.2: Water Production for Bujumbura City's Water Supply
Source: REGIDESO BURUNDI, 2024

Today, water is extracted from Lake Tanganyika at a depth of 25 meters and a length of 3.5 kilometers from the river. Crepes are installed with two 900 mm diameter tubes. The water shortage is not due to the lack of water resources, but to lack of adequate transport and distribution infrastructures.

Under normal operating conditions, the Lake Tanganyika intake can produce around

150,000 m^3/d of water; when the lake water fills up with sediment and waste, the filters can quickly become clogged and fail to produce the desired amount of water. The rates of output, distribution, and leakage define the water consumption quantity at a particular place. At water treatment plants, water production (QWP) takes place; typically, the capacity of the WTP determines the constant along of this process. The water is gathered in a clean water tank after the treatment and supplied into the WDN.

2.4. Water Treatment Process

The Lake Tanganyika water treatment employs gradual open sand filtration, followed by chlorine disinfection. The treatment plant was originally built in 1965/1969 and enlarged in 1986, 2002, and 2006 with new filters. The treatment process begins with 12 filters, including 8 new ones (1825 m2) and 4 old ones.

Figure 2.3: Filters for physical treatment

Each filter has drainpipes at the bottom for collecting filtered water. Above the pipes, there is a 45 cm long layer of gravel with a grain size of 2-12 mm, followed by 1 m of sand with a grain size of 0.2-0. 8 mm. The water occupies roughly 1m. During the rainy season, the turbidity of the raw lake water increases, causing clogging during the filtration process. During the wet season but also related to the age of the sand. The algal masses are removed on a regular basis in a very poor and ineffective manner; only 3/4 of the algae are evacuated, resulting in incomplete removal.

Bujumbura's water distribution network consists of two pipeline systems: primary and secondary. The principal network covers 82 kilometers, with an important part located in the central Zone of the city and extending through the South and North. The secondary network covers 1106 kilometers, extending specifically into KINAMA (North) and KANYOSHA (South). The distribution system includes approximately 332 public water fountains with approximately 45% located in the city's north and 25% in the south.

Storage structures.

2.5. Hydraulics Conditions of pipe Networks

There are physical laws that guide how water distribution systems work. These laws describe how flow works in lines along with hydraulic control elements, as well as customer demand and the layout of the system. Bernoulli's equation, a fundamental principle in fluid dynamics, describes the relationship between a fluid's pressure and velocity. That equation allows one to find the energy balance between any two cross-sections of a pipe and can be expressed as follows:

$$\boldsymbol{Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = z_2 + \frac{P2}{\gamma} + \frac{v_2^2}{2g} \pm h_L} \qquad 2.4$$

Where:

Z (m) = the elevation of the cross-section with regard to a certain reference;

p (m) = the fluid pressure at the cross-section;

v (m/s) = the average flow velocity at the section; and

hL (m)= the friction loss between the two sections.

The most common equations for the calculation of pipe friction losses are the Manning, Hazen-Williams, and Darcy-Weisbach equations. The dimension of the pipe (D in mm), length of the pipe (L in m), flow rate (Q in m3/s), and empirically found friction factors define the friction losses.

$$\boldsymbol{h_f = \frac{\lambda L}{12.1D^5}\, Q^2 \;\; (Darcy - Weisbach)} \qquad \mathbf{2.5}$$

$$h_f = \frac{10.68L}{C^{1.852}D^{4.87}}Q^{1.852}\ (Hazen - Williams) \qquad 2.6$$

$$hf = \frac{10.29n^2L}{D^{16/3}}Q^2\ (Manning) \qquad 2.7$$

The friction factor (f) can be determined using the Moody chart, which is a graphical representation of the well-known Colebrook formula, which considers the Reynolds number and the relative roughness of the pipe.

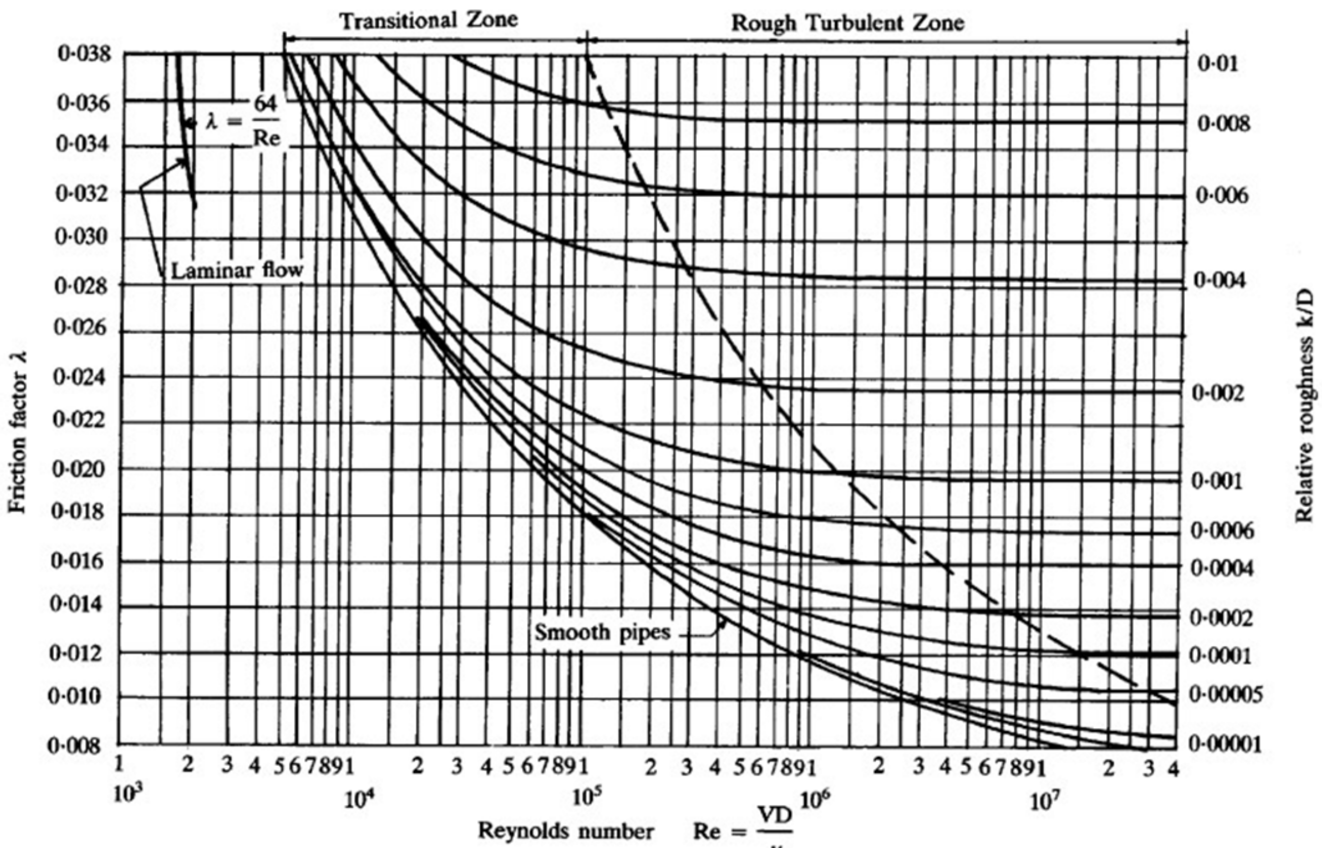


Figure 2.4: Moody Chart

The behavior of fluid flow within a network of pipes follows two fundamental principles: the conservation of mass and the conservation of energy.

According to the principle of conservation of mass, the flow into and out of a stable system must be the same. Both the network as a whole and individual nodes are subject to this interaction. When two or more pipes come together at a junction or at a demand site, a node is added to the network model. The continuity equation is that the demand at every node in a hydraulic network is equal to the total of all flows entering that node minus the sum of all flows leaving. This is expressed mathematically as:

$$\sum Qin - \sum Qout = Qdemand \qquad 2.8$$

Where:

- Qin represents the total flow rate entering a node through various pipes.
- $Q\ out$ represents the total flow rate leaving a node through different pipes.
- $Q\ demand$ is the user demand at that point, which could be positive (water being consumed), negative (water being supplied), or zero (no net consumption).

2.6. Water distribution networks

One of the most crucial components of a nation's critical infrastructure is its water distribution network. The distribution system is certainly an extremely complicated and vulnerable element of all critical infrastructure networks. It usually consists of an underground pipeline that varies in age, composition, installation quality, etc. (Vališ et al., 2020). The water supply network is an important and essential element of the entire distribution system. It is designed to provide water of the appropriate quality, quantity, pressure, and time to users. To function correctly, the network must be properly designed, constructed and used effectively.(Coelho & Andrade-Campos, 2014)

Water distribution networks transport water from sources and treatment plants to customers.
The water distribution network consists of pipes, nodes, pumps, valves, and storage tanks or reservoirs. Failure of any of these components could result in a significant impact on the water supply to consumers.
There are various water distribution methods, including gravity, pumping, and a combination of both. The selection of the most suitable method primarily depends on the topography of the area, as well as economic considerations and operational requirements.

2.7. Water distribution Methods

The distribution of water is an essential component of any water supply system, ensuring that water is delivered to end consumers effectively and dependably. The selection of a distribution system depends on things like topography, energy availability, cost, and demand patterns.
The three primary categories of water distribution systems are:

- **Gravity System**: Employs natural variations in elevation.
- **Pumping System**: Utilizes pumps to transport water under pressure.
- **Combined System**: Combines gravitational and pumping systems to improve supply efficiency.
- **Counter reservoir system**: pumping system coupled with storage tank, to equilibrate the pressure and water flows according to the diurnal distribution diagram.

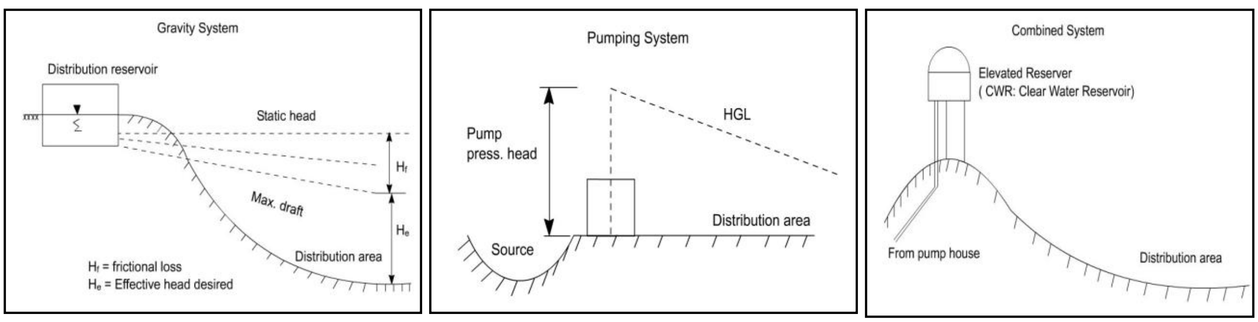


Figure 2.5: Water Distribution Methods

Water supply networks are integrated into master plans for cities, counties, and municipalities. City planners and civil engineers are responsible for planning and designing these systems, considering issues such as location, demand, growth, leakage, pipe size, pressure loss, and firefighting flows (Anisha et al., 2016). Supplying drinking water in networks is a challenging task both quantitatively and qualitatively. A considerable quantity of potable water is lost during transit through the distribution system, resulting in both apparent and real losses (Kuma & Abate, 2021).

To conduct a more realistic analysis of water supply network behavior, physical, hydraulic, and experimental models need to be used together.

2.8. Pressure

Pressure in pipes is a critical aspect of fluid dynamics that affects the flow and efficiency of hydraulic systems. Understanding the types of pressure and their implications is essential for effective design and operation (Savić & Walters, 1995).Water Distribution Networks are often obsolete and affected by several points of water losses. Leakages are mainly affected by pressure; in fact, water utilities usually apply the technique of pressure management to reduce physical losses. It is clear how pressure plays a important role in the management of Water Distribution Networks and in water safety.

2.8.1. Static Pressure

Static pressure is defined as the pressure exerted by a fluid when it is at rest. In hydraulic systems, static pressure is crucial for determining the potential energy available for fluid movement. It is measured when the system is not in operation, providing valuable insights into the system's design and efficiency. Static pressure arises from the random motion and collisions of fluid molecules, and it is influenced by factors such as fluid density and the height of the fluid column in cases where gravity is involved. The formula for static pressure is:

$$\boldsymbol{P = \rho g h} \qquad \textbf{\textit{2.9}}$$

Where:

P: $is\ the\ static\ pressure,$

ρ: $is\ the\ density\ of\ the\ fluid,$

g: $is\ the\ acceleration\ due\ to\ gravity, and$

h: $is\ the\ height\ of\ the\ fluid\ column\ above\ a\ reference\ point$

2.8.2. Dynamic Pressure

Dynamic pressure, on the other hand, is associated with the motion of the fluid. It is calculated based on the fluid's velocity and represents the additional pressure exerted by the fluid due to its movement. Dynamic pressure is essential for understanding how the fluid behaves when in motion, particularly in applications involving high-speed fluid flow. As the velocity of the fluid increases, the dynamic pressure also increases, which can significantly affect the overall performance of hydraulic systems. In summary, both static and dynamic pressures are critical parameters in hydraulic systems. Static pressure provides insights into the potential energy of the fluid at rest, while dynamic pressure is vital for analyzing fluid behavior during motion.

The dynamic pressure formula can be derived from Bernoulli's equation:

$$\boldsymbol{Dynamic\ Pressure\ = Total\ Pressure - Static\ Pressure} \qquad \textbf{\textit{2.10}}$$

Alternatively, it can be expressed as:

$$\boldsymbol{Dynamic\ Pressure = \frac{1}{2}\rho v^{2}} \qquad \textbf{\textit{2.11}}$$

Where:

$v\ is\ the\ velocity\ of\ flow.$

2.8.3. Piezometric line

The piezometric line illustrates the variation in hydraulic head within the system and represents the potential energy available to facilitate flow. Under stable circumstances, the piezometric line generally demonstrates a slope that drops in the direction of flow, indicating the change of mechanical energy into thermal energy due to friction as water transits the system.

The piezometric head (H) can be expressed as:

$$\boldsymbol{H = z + \frac{p}{\rho_g}} \qquad \textbf{\textit{2.12}}$$

where:

- z is the elevation head,
- p is the pressure at the measurement point,
- ρ is the fluid density,
- g is the acceleration due to gravity.

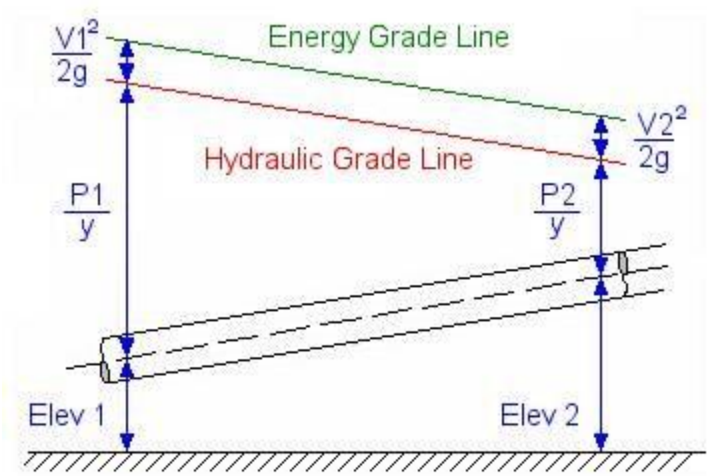


Figure 2.6: Sloped pipe System

A slop illustrates the Energy Grade Line (EGL) and Hydraulic Grade Line (HGL). The entire energy, which combines pressure head, velocity head, and elevation head, is represented by the Energy Grade Line (EGL). The velocity head (V^2 /2g) ensures that it will always be above the Hydraulic Grade Line (HGL). The pressure and elevation head, excluding velocity head, is represented by the HGL. The HGL drops down as a result of energy losses along the conduit. Friction and minor losses result in a progressive reduction in both the EGL and HGL as water flows.

2.8.4. Water losses in a Water Distribution Network

Water losses in a drinking water delivery network (WDN) refer to the water that fails to arrive at where it was supposed to go. These losses can be evaluated annually, monthly, or daily, depending on the characteristics of the water resources. There are two categories of losses:

- Technical losses: losses resulting from treatment and distribution, such as network leakage.
- Commercial losses: losses resulting from illicit connections, unauthorized withdrawals, or metering errors.

2.9. GIS and hydraulic modelling

2.9.1. Application of GIS in water distribution networks

GIS is comprehensive and multifunctional computer-based software being used in water transmission and distribution systems in modern and systematic water supply.

For today's water utilities around the world, it is the greatest application for managing, modifying, and maintaining geographic data as well as for creating and maintaining asset management (Ahmadullah & Dongshik, 2016).Geo-spatial information systems (GIS) offer a significant advantage in managing both spatial and descriptive data. GIS is a valuable tool for modeling data in Water Distribution Networks to help with decision-making (Tabesh & Saber, 2012).To manage and regulate Water Distribution Network, we need to create a geodatabase and knowledge-base for keeping water background data layers and features in ArcGIS.(Ahmadullah & Dongshik, 2016)

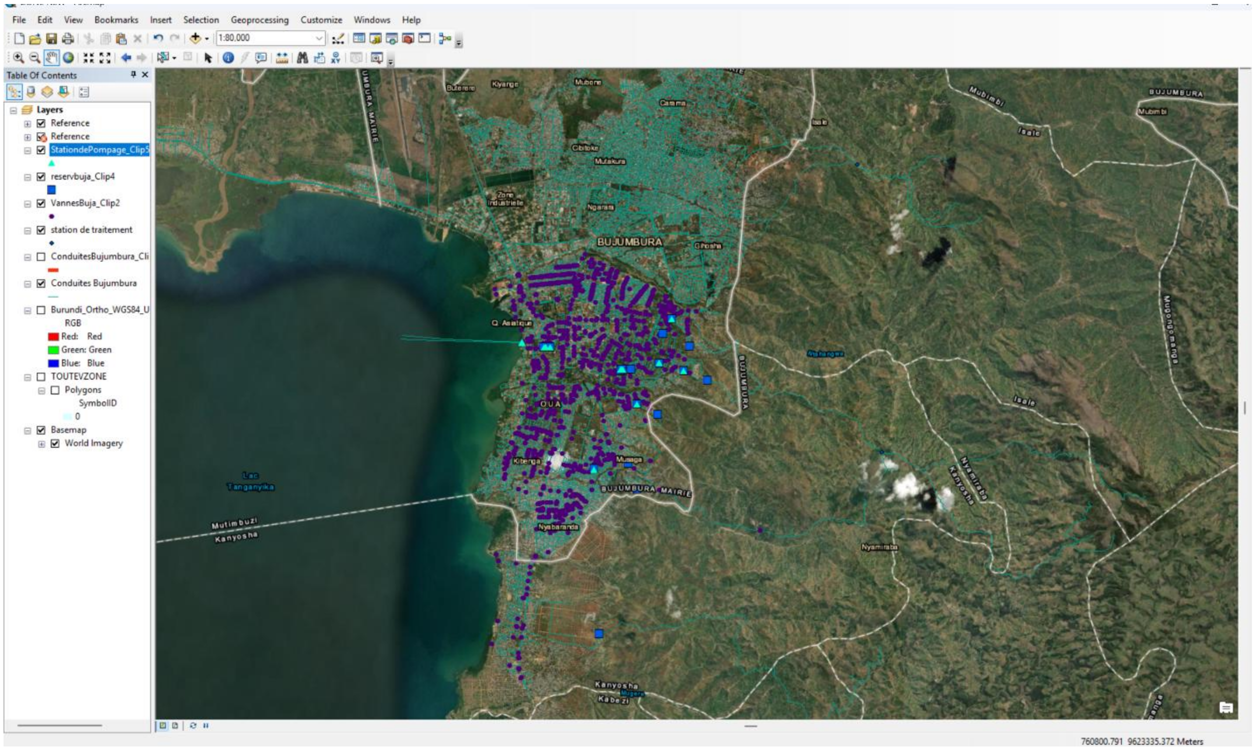


Figure 2.7: Illustrating WDN in ArcGIS

ArcGIS is a complete set of technical geographic information system (GIS) applications that are used to communicate, visualize, and interpret an idea, a plan, a conflict, an issue, or the state of a situation; to solve problems; to fulfill a task; to improve efficiency; and to make better decisions (Awad et al., 2012).The use of ArcGIS in geographic data preparation and visualization provides for a simpler user input and output, as well as the presentation of data in a desired format. ArcGIS is used to organize the digital elevation model (DEM), soil data, land use/coverage, and spatial hydraulic data for the area of interest.(Tsegaye et al., 2024)

2.9.2. Hydraulic Modeling

Information technology and software provide numerous solutions to water distribution issues that traditional approaches lack the capacity for. In this context, a hydraulic model is an adaptable tool that can be used both throughout the operation of an existing network and during the design phase of a new network. Furthermore, the computer simulation of network operation allows a water supply company to effectively make important decisions regarding its continuous operations, A Water Distribution Network hydraulic modeling helps to identify network operational conditions (Kepa, 2021).

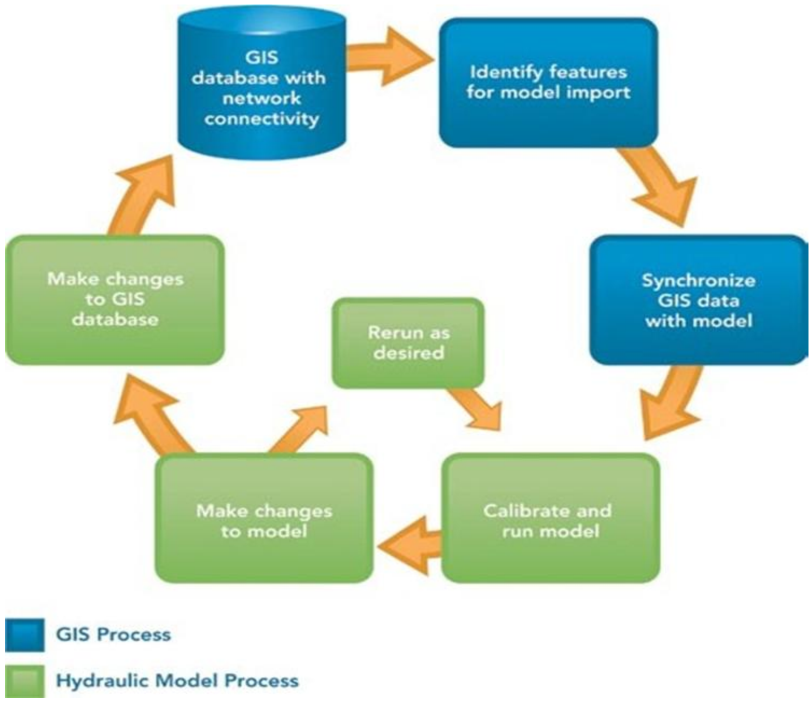


Figure 2.8: Lifecycle of a sustainable Hydraulic Model (Edwards et al., 2012)

Hydraulic modeling is used for water supply and distribution network planning, which involves connecting consumers, evaluating network capacity, reconstructing pipes, evaluating pressure zones, and comparing simulated and measured data.

2.9.3. Hydraulic Modeling using EPANET Software

EPANET is a software program that operates extended period simulations of hydraulic and water quality dynamics in pressurized pipe networks. A network includes pipelines, nodes (junctions), pumps, valves, and storage tanks or reservoirs (Rossman, 2000) .EPANET monitors the water flow in each pipe, the pressure at each node, the water level in each tank, and the concentration of a chemical species throughout the network during a simulation period consisting of various steps (Kumar & Thakur, 2015). EPANET is designed to be a research tool for improving our understanding of the movement and fate of drinking water constituents within distribution systems.(Anisha et al., 2016)

EPANET tracks the following parameters:

• Water flow in each pipe,

• Pressure at each node,
• Water height in each tank,
• Chemical concentration throughout the network during the simulation period.
• Age of water,
• Origin, and
• Tracing methods.

EPANET features an advanced hydraulic analysis engine with the following capabilities:

- does not restrict the size of the network that can be examined
- uses Hazen-Williams, DarcyWeisbach, or Chezy-Manning formulas to calculate friction head loss
- incorporates small head losses for bends, fittings, etc.
- models pumps with constant or variable speed
- calculates pumping energy and cost
- Models various types of valves, including shutoff, check, pressure regulating, and flow control valves.
- Allows storage tanks to have any shape, with diameter varying with height.
- Considers multiple demand categories at nodes, each with its own pattern of time variation.
- Models pressure-dependent flow issuing from emitters, such as sprinkler heads.
- Can base system operation on both simple tank level or timer controls and complex rule-based controls.

The data linked to each pipe consists of the identification number, length, diameter, and roughness. Each junction node is associated with data that includes the junction identification number, elevation, and demand.

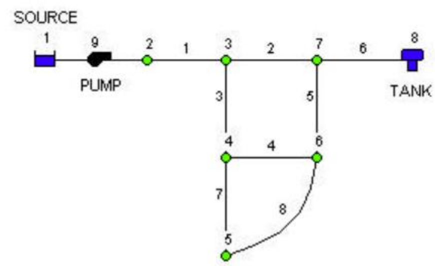


Figure 2.9: Example of network in Epanet

2.9.4. Calibration of Water Distribution Networks

When developing a water distribution network model, it's important to compare projected results to field data. If the model input is correct, the anticipated pressures and flows will match the observed values (Walski, 1983).Calibration of water distribution models is the process of adjusting network parameters such as pipe roughness and nodal demand to reduce the disparities between simulation results and actual observations. To be reliable, a hydraulic model must undergo a calibration process that adjusts the most sensitive parameters.(Zanfei et al., 2020)
The critical phase in the creation of a water distribution network model is comparing the model's anticipated outcomes with field observations. If the model's input is accurate, the projected pressures and flows will correspond with the actual values. During preliminary design study, system simulation is validated when estimated pressures match observed field gage readings for certain field source send-out and storage conditions. The calibration validation step is crucial to guarantee that the model outcomes are similar to real hydraulic parameters (Pressure and discharge). The Calibration consists to calibrate pressure and discharge based on measured values through the pipes characteristics, roughness is the widely used physical parameter to calibrate a networks. We must keep some observed data to compare with the models' outputs, the errors should be as minimum as possible. The errors depend on several parameters: number of observed data points, state of the network…. The calibration is a continuous procedure, even after the rehabilitation of the network, by a well-designed monitoring system.

MATERIAL AND METHODS

3.1. Description of the Study Area

Bujumbura city, also known as 'Bujumbura Mairie', is located in Burundi, East Africa at latitudes 3° 18' 11"
S and 3° 29' 8" S, and longitudes 29° 17' 16" E and 29° 25' 32" E, WGS84. The region grows in both Northern and Southern directions, with the Eastern and Western limits confined by high mountains and Lake Tanganyika. (Niyongabire & Rhinane, 2019)
Located in the western region of Burundi, it encompasses an area of 10,462 hectares, a significant increase from the estimated 30 hectares in 1907. Administratively, it is divided into three communes (Muha, Mukaza, and Ntahangwa) that include thirteen urban zones or administrative units. (Kabanyegeye et al., 2023)

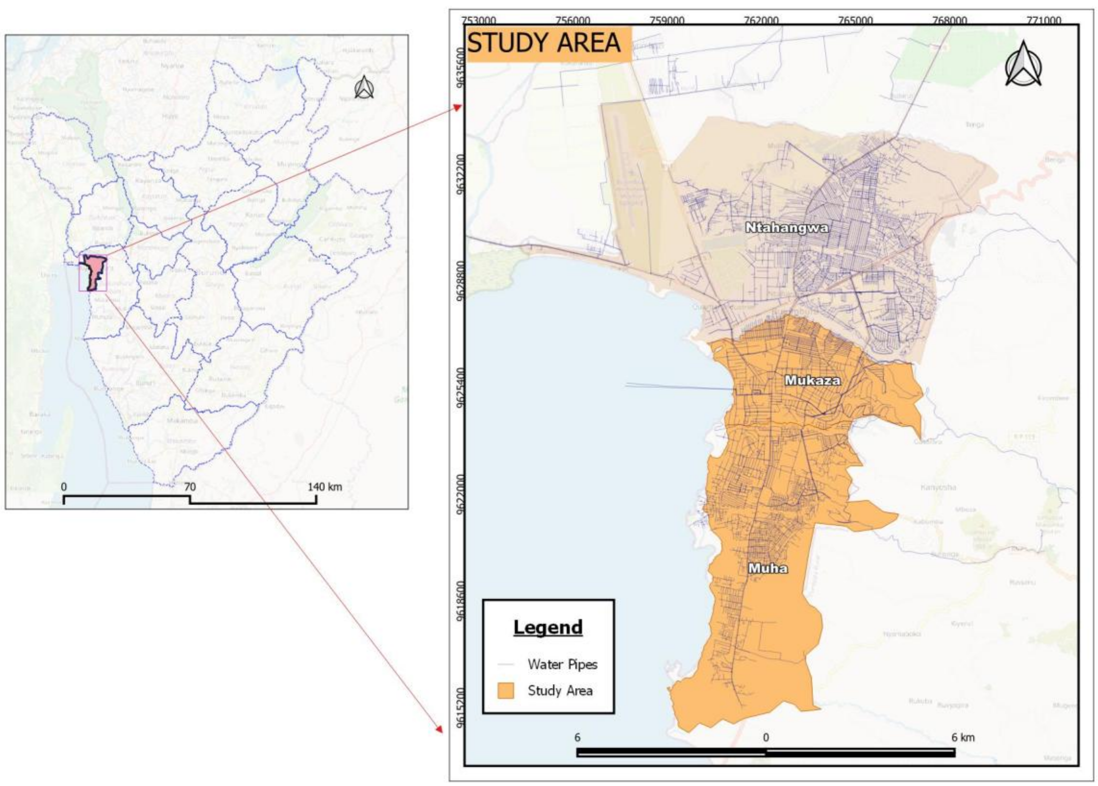


Figure 3.1: Study Area

With 792 504 residents as of 2022, Bujumbura is the most populous region in Burundi.

3.2. Climate

Bujumbura Mairie has a wet and dry tropical climate. There are four seasons in this city: the long dry season (June– August), Short-wet season (September to December), Short dry season (mid-January-mid February), and long-wet season (February to May). Bujumbura is located near the equator, but for this reason, it is not as hot as one might expect, due to its altitude (Rhugwasanye et al., 2022).

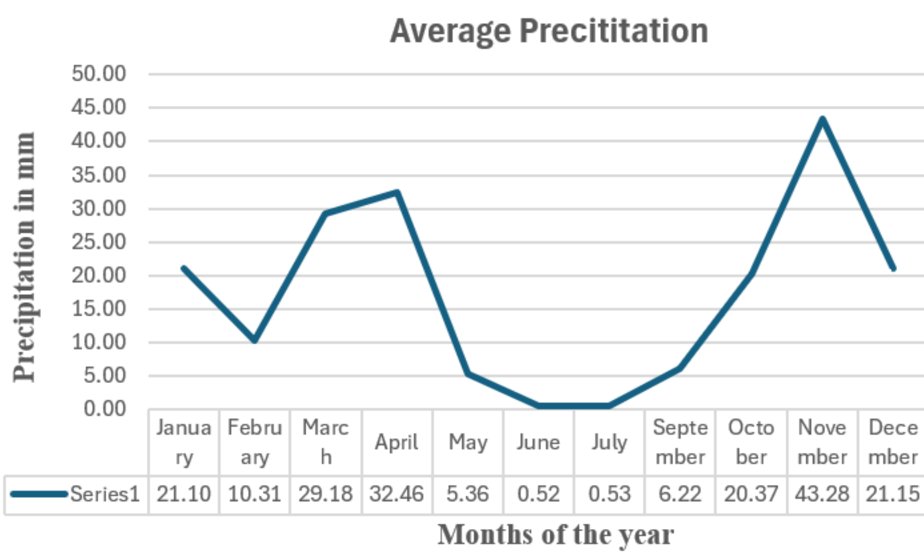
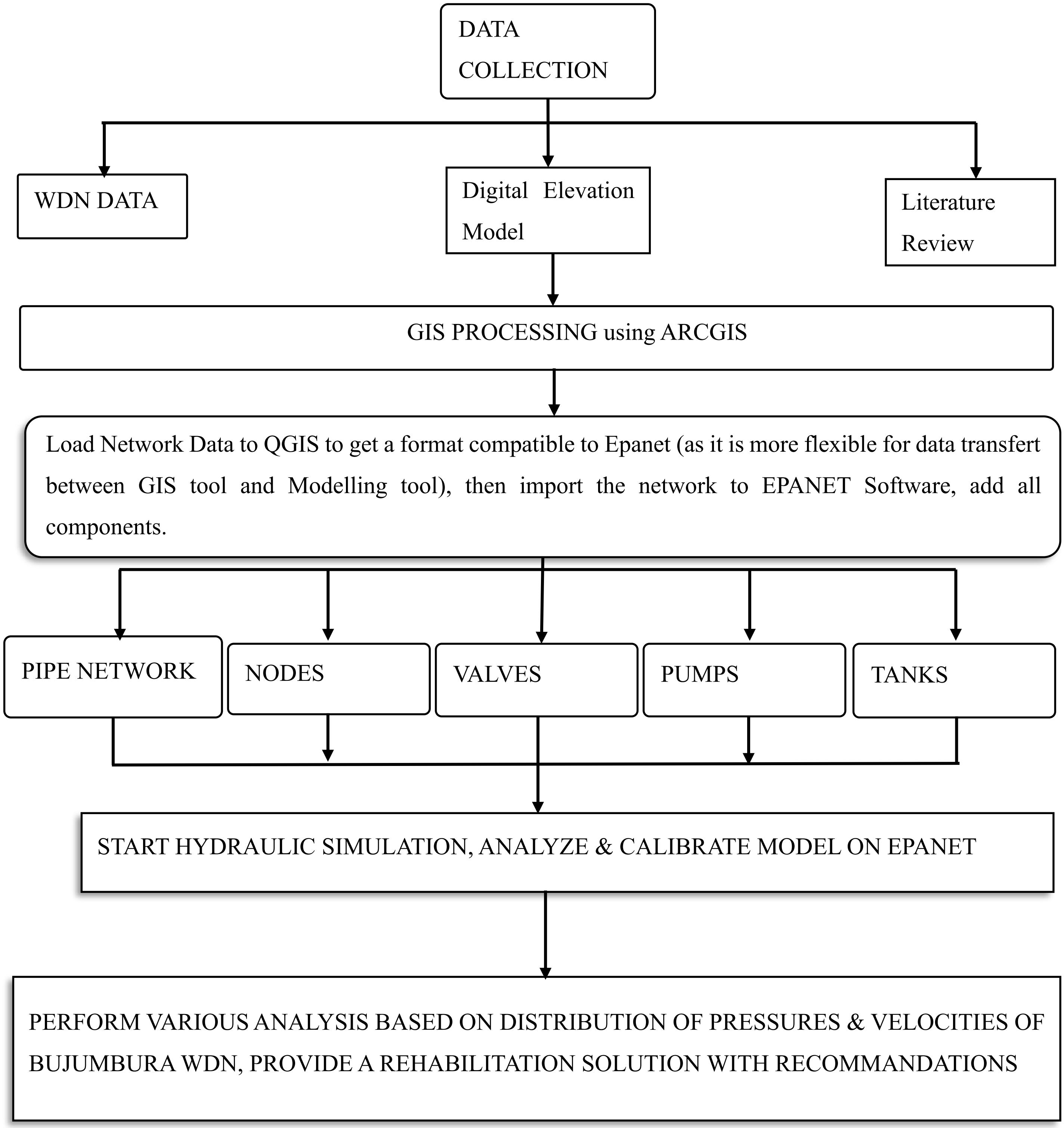


Figure 3.2: Monthly average precipitation (2014-2024)

Precipitation variation analysis reveals that rainfall fluctuates significantly throughout the year with distinct wet and dry seasons, with the highest precipitation levels occurring in November (43.28 mm) and April (32.46 mm),indicating the presence of two rainy seasons, while the driest months are June (0.52 mm) and July (0.53 mm), followed by May (5.36 mm) and September (6.22 mm),revealing a prolonged dry season from May to September. This rainfall distribution is typical of tropical climates and has significant implications for water resource management, agriculture, and infrastructure planning

3.3. Study Design



3.4. Data Collection

Data collection is a key step in modeling, which involves meeting with companies visiting structures, and researching information in the database. The accuracy of this data can help determine the model's accuracy and precision. In our case, data including Bujumbura's potable water distribution network were requested from the water distribution company, which includes storage tanks, pipes, and the coordinates of pump stations.

This data contains information about:

Table 3.1 : Data Characteristics

Data	Characteristics
Distribution Network	Material, diameter, length
Storage structures	Capacity and their location in the network
Valve	Location in the network
Pump	Flow rate, Total Manometric Head

A Digital Elevation Model (DEM) was used to analyze the water distribution network, while also providing vital elevation data. This data is helpful in analyzing pressure differentials and determining the direction of flow.

3.5. Materials and Software used

The study utilized various materials and tools for data collection and analysis. A base map was used to assess the general state of the town's water delivery system. A GPS device was employed to measure the (x, y, and z) coordinates for specific location in order to geo-reference the network and ensuring accurate spatial data on the specific points where field data were measured. A flow meter and a manometer were used to measure the flow rate and pressure, respectively. The flow meter helped determine the amount of water moving through the system, while the manometer measured the pressure within the pipes to ensure proper operation and efficiency.

Table 3.2 : List of Software used in this study

No	Software list	Purpose of the use
1	ArcMap (GIS 10.8)	To create a master plan and maps preparation of shape files
2	AUTOCAD	Refine network layout, junction placement and elevation data
3	QGIS	To create the current layout in the EPANET-required format
4	EPANET	To analyze models and perform automatic calibration and validation

3.6. Methods

3.6.1. Creation of a Database in ArcGIS

This process creates an initial database to serve as a foundation for further analysis and simulation. This database includes not only geographical features, but also material attributes like the type of pipe and the service capacity of the junction. This level of granularity is important for carrying out evaluations that are vital for decision-making regarding the rehabilitation, expansion or optimization of the water distribution network.

3.6.2. Calculation of Nodal Flow

When the database is ready, the next task is to identify the network's nodes. These typically include reservoirs and measuring points. The flow rates of each node are calculated with the use of hydraulics. This part is important in tracing the flow of water in the network, as well as understanding the problems that should be solved in the modeling stage.

3.6.3. Creation of an EPANET Model

After the nodal flow is calculated, the next phase involves exporting data from ArcGIS and importing it to EPANET. In EPANET the model is assembled by defining the nodes, pipes, and reservoirs that form the water distribution system. The geographical data is changed to a dynamic model which can simulate the behavior of the network.

3.6.4. Initial Simulation and Model Error Corrections

Once the model is created, an initial simulation is run to observe how the water distribution system performs under specified conditions. This phase often reveals errors or inconsistencies in the model, which must be identified and corrected. Addressing these issues is essential for ensuring that the model accurately represents the real-world system.

3.6.5. Calibration of the Model with Field Observations

Calibration involves the comparison of results obtained from the EPANET simulation with actual field data relating to flow and pressure measurements. By adjusting model parameters to better align with observed data, the accuracy of the model is improved. Measurements of pressure and/or flow rate, obtained from a set of field measurements, are incorporated into the model at each time-step interval (Preis et al., 2011) . This procedure refers directly to the calibration process. This iterative process may require several rounds of adjustments to achieve a satisfactory level of precision. Unfortunately, we were unable to obtain field measurements, this procedure is very difficult to conduct to several reasons which will be discussed later.

3.6.6. Validation of the Model with Field Observations

Validation is the final step to ensure the model's reliability. This involves a comprehensive comparison between the simulation results and the actual field data. Successful validation indicates that the model can be trusted for predicting system behavior under various scenarios, making it a valuable tool for decision-making.

RESULTS AND DISCUSSIONS

This chapter addresses the study's findings on the Water Supply System in Bujumbura Centre and South Zone, particularly emphasizing the current difficulties and prospective solutions to increase accessibility and sustainability. The results are based on data gathered from the water company, field surveys, hydraulic modeling with EPANET 2.2, and stakeholder discussions.

4.1. Current state of the Water distribution networks

4.1.1. Water Distribution Network

The pipelines in the distribution network of the study area are composed of steel, ductile iron, PVC, and PEHD. Steel is followed by an important part of the network, which is composed of PVC pipelines. Nevertheless, the observed network issues, including leaks, pressure losses, and reduced efficiency, may be significantly influenced by the fact that a significant number of these pipelines have been in service for more than 50 years. The risk of leaks and deterioration in water quality is elevated by the aging infrastructure, potential corrosion in steel pipelines, and material degradation in PVC.

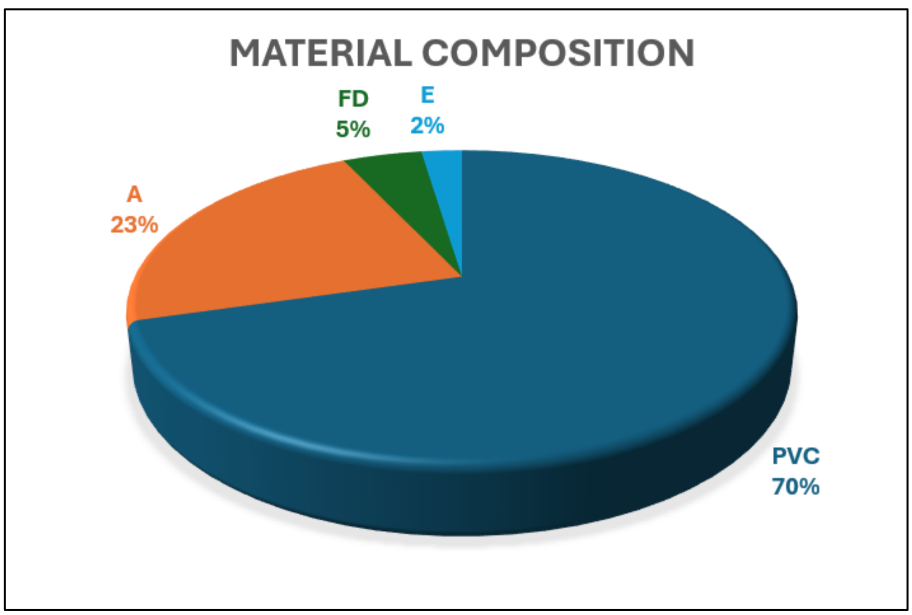


Figure 4.1 : Distribution of Pipe Materials

The consequences of such water supply network materials are confirmed by the high rate of leakage recorded by the REGIDESO and high number of interventions recorded every year too.

This demonstrates the pressing necessity for strategies that prioritize rehabilitation and replacement to guarantee a more sustainable and dependable water supply.

4.1.2. Water demand

According to the methodology forementioned, the current population of the study area is: 533857 inhabitants

Estimated projected population of the study area will be: 1295811 inhabitants

Table 4.1: Population of the Study area

Population	2025	2055
Muha	183411	445187
Mukaza	350446	850625
Total	533857	1295812

The projected population in the horizon was calculated using the following formula

$$P2055 = P2025 * (1 + 0.03)^{30}$$

$$P2055 = 533857 * (1 + 0.03)^{30} = 1295811 \; inhabitants$$

$$Water\ demand\ per\ capita\ that\ was\ used\ in\ 2055 = 120l/day/capita$$

$Q_{average.d}$ = 1295811*0.12= 155497.32 m^3/day , for 2055

$Q_{average.d}$=533857*0.12= 64062.84 m^3/day for 2025

4.1.3. Reservoirs and tanks

A major part of the reservoirs of our case study are made in Reinforced concrete, followed by some in metal and a few in rubble masonry. Because of its strength, longevity, and capacity to resist great water pressures, reinforced concrete is the most often used material to construct for reservoirs. Because of their lighter weight and simplicity of installation, raised tanks are built from metal reservoirs often steel.

Table 4.2 : Lists of reservoirs and their construction materials

Name	**Volume**	**Materials**
R3	700	Reinforced Concrete
R1d	1600	Reinforced Concrete
R1e	500	Reinforced Concrete
R6	100	Reinforced Concrete
R4	700	Reinforced Concrete
R.Sorezo Haut	150	Reinforced Concrete
R5	700	Reinforced Concrete
R.Gasekebuye Bas	350	Reinforced Concrete
R9	700	Reinforced Concrete
RSP2bc	3500	Reinforced Concrete
R2 c	3000	Reinforced Concrete
R10	1600	Reinforced Concrete
R2 d	4000	Reinforced Concrete
R2 a	700	Reinforced Concrete
R. Mutanga A	700	Reinforced Concrete
R2 b	700	Reinforced Concrete
R8	3800	Reinforced Concrete
R8 Bis	700	Reinforced Concrete
R Gihosha Rural	2400	Reinforced Concrete
R1b	500	Reinforced Concrete
R1a	500	Reinforced Concrete
R1c	500	Reinforced Concrete
RSP2d	2000	Reinforced Concrete
RSP2a	700	Reinforced Concrete
R.Gasekebuye Haut	500	Reinforced Concrete
R.Sororezo Bas	150	Reinforced Concrete
Bâche d'asp Kajaga	200	Reinforced Concrete
R SAGAMBA	350	Reinforced Concrete

Name	Volume	Materials
R. palais présidentiel	350	Rubble Masonry
R.Karama	500	Rubble Masonry
Château Mutanga Surelevé	100	Metal
R.Kamesa	150	Metal
R.Kajaga	150	Metal
R Rusizi	150	Metal
R. GAHAHE	200	Metal
Rés. Camp Mil. Gatumba	150	Metal
Palais Surlevé	50	Metal
Total	33800	

Most of these reservoirs are rectangular and few of them circular. Older reservoirs can potentially have hydraulic performance impacted. Over the years, sedimentation can lower the effective storage capacity and promote growth of bacteria, therefore influencing water quality.

Estimation of the minimum storage capacity needed:

Using the balance method between the diurnal consumption (according to the diurnal diagram) and the production (24h pumping system) we can estimate the minimum storage needed for both two horizons 2025 and 2055

Table 4.3: Production/Consumption balance

Time	Consumtion_h (%)	Production (%)	Difference %	Cumul %
0 to 1	3.35	4.17	-0.82	-0.82
1 to 2	3.25	4.17	-0.92	-1.73
2 to 3	3.3	4.17	-0.87	-2.60
3 to 4	3.2	4.17	-0.97	-3.57
4 to 5	3.25	4.17	-0.92	-4.48
5 to 6	3.4	4.17	-0.77	-5.25
6 to 7	3.85	4.17	-0.32	-5.57
7 to 8	4.45	4.17	0.28	-5.28
8 to 9	5.2	4.17	1.03	-4.25
9 to 10	5.05	4.17	0.88	-3.37
10 to 11	4.85	4.17	0.68	-2.68
11 to 12	4.6	4.17	0.43	-2.25

Heures	Consumtion_h (%)	Production (%)	Difference %	Cumul %
12 to 13	4.6	4.17	0.43	-1.82
13 to 14	4.55	4.17	0.38	-1.43
14 to 15	4.75	4.17	0.58	-0.85
15 to 16	4.7	4.17	0.53	-0.32
16 to 17	4.65	4.17	0.48	0.17
17 to 18	4.35	4.17	0.18	0.35
18 to 19	4.4	4.17	0.23	0.58
19 to 20	4.3	4.17	0.13	0.72
20 to 21	4.3	4.17	0.13	0.85
21 to 22	4.2	4.17	0.03	0.88
22 to 23	3.75	4.17	-0.42	0.47
23 to 24	3.7	4.17	-0.47	0.00

$$\boldsymbol{V_{storage} = R_{max} * Q_{max.d}} \qquad \textbf{4.1}$$

$$\boldsymbol{R_{max} = |V\%|^{-} + |V\%|^{+}} \qquad \textbf{4.2}$$

R_{max} : max storage residual volume

$|V\%|^{-}$: max negative cumulus between production and consumption

$|V\%|^{+}$: max positive cumulus between production and consumption

For the calculation, the maximum residual volume is:

Table 4.4 : Maximum residual volume

V+	0.88333333
V-	-5.5666667
Rmax	6.45

4.1.4. Results of the simulation

EPANET is designed to help us understand water flow and consumption in Water distribution networks. In the analysis of distribution systems, it can be used for several kinds of purposes. For this study simulations were made to analyze the functionality of our distribution network.

Table 4.5 : Results of the simulation of the actual network (Flow and velocities)

	Length	Diameter	Roughness	Flow	Velocity
Link ID	m	mm	mm	LPS	m/s
Pipe p917	289.3	700	0.01	-461.53	1.2
Pipe p793	28.31	376	0.01	-457.08	4.12
Pipe p7	39.29	280	0.01	-65.24	1.06
Pipe C15	100	200	0.01	-39.05	1.24
Pipe C25	100	200	0.01	-34.71	1.1
Pipe C1	100	200	0.01	-31.44	1
Pipe p536	241.2	71.9	0.01	-29.83	7.35
Pipe p1563	5.905	71.9	0.01	-28.64	7.05
Pipe p947	595.6	71.9	0.01	-24.55	6.05
Pipe p606	17.08	92	0.01	-24.5	3.68
Pipe p2584	179.5	35	0.01	-20.4	21.2
Pipe C14	100	200	0.01	-19.6	0.62
Pipe C22	100	200	0.01	-19.44	0.62
Pipe C20	100	200	0.01	-18.25	0.58
Pipe p3502	187.1	55	0.01	-16.84	7.09
Pipe p959	3.285	73.6	0.01	-15.57	3.66
Pipe p1214	903.6	73.6	0.01	-15.19	3.57
Pipe C21	100	200	0.01	-14.5	0.46
Pipe p2082	18.99	55	0.01	-14.43	6.07
Pipe C27	100	200	0.01	-12.44	0.4
Pipe p1391	43.41	92	0.01	-10.77	1.62
Pipe p2810	92.68	70	0.01	-10.2	2.65
Pipe p1191	81.44	39.6	0.01	-9.87	8.02
Pipe p2539	4.346	39.6	0.01	-8.41	6.83
Pipe p896	59.79	73.6	0.01	-8.1	1.9
Pipe p1456	321	92	0.01	-7.74	1.16
Pipe p1633	68.4	35	0.01	-7.44	7.73

	Length	Diameter	Roughness	Flow	Velocity
Pipe p265	18.44	55	0.01	-7.37	3.1
Pipe p2525	180.1	39.6	0.01	-6.96	5.65
Pipe C8	100	200	0.01	-6.66	0.21
Pipe p1145	57.62	39.6	0.01	-6.43	5.22
Pipe C9	100	200	0.01	-5.87	0.19
Pipe p72	1114	39.6	0.01	-5.79	4.7
Pipe p1899	2203	488	0.01	-5.25	0.03
Pipe p2912	68.9	92	0.01	-4.8	0.72
Pipe p1625	347.6	55	0.01	-4.76	2
Pipe p1966	1716	39.6	0.01	-4.75	3.85
Pipe p2671	61.39	115.4	0.01	-4.75	0.45
Pipe p1414	3.082	39.6	0.01	-4.19	3.41
Pipe p1664	134.2	39.6	0.01	-3.17	2.58
Pipe p788	51.91	140	0.01	-3.09	0.2
Pipe p1077	4.498	39.6	0.01	-3.08	2.5
Pipe p1364	642.6	39.6	0.01	-2.72	2.21
Pipe p1639	575.4	57	0.01	-2.44	0.96
Pipe p1938	39.02	94	0.01	-2.21	0.32
Pipe p3260	387.7	73.6	0.01	-1.64	0.39
Pipe p830	343	70	0.01	-1.45	0.38
Pipe p1650	251.6	74	0.01	-1.07	0.25
Pipe p336	244.9	140	0.01	-1.04	0.07
Pipe p2171	242.7	39.6	0.01	-1.03	0.84
Pipe p2946	241	73.6	0.01	-1.02	0.24
Pipe p3612	187.4	39.6	0.01	-0.79	0.64
Pipe p1739	93.45	71.9	0.01	-0.4	0.1
Pipe p2189	69.56	55	0.01	-0.29	0.12
Pipe p2140	17.25	39.6	0.01	-0.07	0.06
Pipe p1050	7.992	71.9	0.01	-0.03	0.01

	Length	Diameter	Roughness	Flow	Velocity
Pipe p1078	5.871	55	0.01	0.02	0.01
Pipe p3834	4.446	39.6	0.01	0.02	0.02
Pipe p2551	7.151	39.6	0.01	0.03	0.02
Pipe p1215	9.692	73.6	0.01	0.04	0.01
Pipe p2111	9.473	55	0.01	0.04	0.02
Pipe p2222	222.4	39.6	0.01	0.07	0.06
Pipe p3570	20.81	73.6	0.01	0.09	0.02
Pipe p3772	23.48	94	0.01	0.1	0.01
Pipe p2241	681.6	39.6	0.01	0.19	0.16
Pipe p74	48.21	143	0.01	0.2	0.01
Pipe p2774	51.39	42.7	0.01	0.22	0.15
Pipe p17	60.76	55	0.01	0.26	0.11
Pipe p2127	19.3	39.6	0.01	0.26	0.21
Pipe p2284	61.92	94	0.01	0.26	0.04
Pipe p3757	60.61	184.6	0.01	0.26	0.01
Pipe p3553	65.69	73.6	0.01	0.28	0.07
Pipe p2454	71.48	55	0.01	0.3	0.13
Pipe p3795	71.62	39.6	0.01	0.3	0.25
Pipe p709	80.18	309.8	0.01	0.34	0
Pipe p3933	80.56	39.6	0.01	0.34	0.28
Pipe C5	100	200	0.01	0.44	0.01
Pipe p2199	107.5	39.6	0.01	0.46	0.37
Pipe p1492	112.9	73.6	0.01	0.48	0.11
Pipe p3869	112.1	39.6	0.01	0.48	0.39
Pipe p225	123.3	290	0.01	0.52	0.01
Pipe p2468	122.9	39.6	0.01	0.52	0.42
Pipe p3437	122.8	39.6	0.01	0.52	0.42
Pipe p1085	128.8	39.6	0.01	0.55	0.44
Pipe p1204	137.7	39.6	0.01	0.58	0.47

	Length	Diameter	Roughness	Flow	Velocity
Pipe p385	139.3	73.6	0.01	0.59	0.14
Pipe p668	138.5	39.6	0.01	0.59	0.48
Pipe p2977	138.1	94	0.01	0.59	0.08
Pipe p3833	139.1	184.6	0.01	0.59	0.02
Pipe p2982	140.4	39.6	0.01	0.6	0.48
Pipe p138	81.37	55	0.01	0.7	0.29
Pipe p1244	166.5	785	0.01	0.71	0
Pipe p462	19.79	71.9	0.01	0.82	0.2
Pipe p173	198	73.6	0.01	0.84	0.2
Pipe p1632	617.7	55	0.01	0.9	0.38
Pipe p727	219.7	73.6	0.01	0.93	0.22
Pipe p2956	236.9	39.6	0.01	1	0.82
Pipe p3777	4.889	140	0.01	1.03	0.07
Pipe p2473	255.3	73.6	0.01	1.12	0.26
Pipe p1688	267.9	94	0.01	1.14	0.16
Pipe p285	12.1	184.6	0.01	1.52	0.06
Pipe p1291	60.29	71.9	0.01	1.73	0.43
Pipe p2961	92.85	39.6	0.01	1.76	1.43
Pipe p1838	43	39.6	0.01	1.96	1.59
Pipe p1977	51.39	55	0.01	2.3	0.97
Pipe 17	100	200	0.01	2.46	0.08
Pipe p2668	185.7	73.6	0.01	2.5	0.59
Pipe p983	17.29	192	0.01	2.53	0.09
Pipe p2325	40.22	39.6	0.01	2.67	2.17
Pipe p2679	36.62	39.6	0.01	2.81	2.28
Pipe p579	493.2	71.9	0.01	3.16	0.78
Pipe p3793	124.7	140	0.01	3.49	0.23
Pipe p67	115.4	55	0.01	3.69	1.55
Pipe p35	61.42	39.6	0.01	3.82	3.11

	Length	Diameter	Roughness	Flow	Velocity
Pipe C6	100	200	0.01	3.94	0.13
Pipe p3395	966.6	73.6	0.01	4.1	0.96
Pipe p1935	989.8	39.6	0.01	4.19	3.41
Pipe 2	10	200	0.01	4.21	0.13
Pipe p2811	395.8	71.9	0.01	4.47	1.1
Pipe p2564	9.389	39.6	0.01	4.67	3.79
Pipe p108	902	39.6	0.01	5.28	4.29
Pipe C29	100	200	0.01	5.3	0.17
Pipe p3499	1661	290	0.01	7.04	0.11
Pipe C7	100	200	0.01	8.62	0.27
Pipe p3506	103.3	92	0.01	9.23	1.39
Pipe p2983	7.624	100	0.01	10.79	1.37
Pipe C10	100	200	0.01	10.93	0.35
Pipe p3947	51.33	200	0.01	12.08	0.38
Pipe p1420	1035	73.6	0.01	13.5	3.17
Pipe C28	100	200	0.01	16.23	0.52
Pipe p2197	6.215	785	0.01	17.22	0.04
Pipe p3836	169.6	55	0.01	17.96	7.56
Pipe p3475	43.07	94	0.01	18.07	2.6
Pipe p2557	232.4	39.6	0.01	18.92	15.36
Pipe p118	633.8	71.9	0.01	19.34	4.76
Pipe p3845	1046	39.6	0.01	20.1	16.32
Pipe p1870	37.1	39.6	0.01	20.18	16.39
Pipe p1936	89.95	73.6	0.01	23.74	5.58
Pipe p2302	124.2	39.6	0.01	27.5	22.32
Pipe p1839	18.12	55	0.01	30.94	13.02
Pipe p2751	461.9	193.8	0.01	35.18	1.19
Pipe C30	100	200	0.01	37.56	1.2
Pipe p2117	31.3	50	0.01	40.37	20.56

	Length	Diameter	Roughness	Flow	Velocity
Pipe C13	100	200	0.01	65.83	2.1
Pipe p1	24.02	39.6	0.01	No flow	No flow
Pipe p2	636.2	71.9	0.01	No flow	No flow
Pipe p4	138.2	55	0.01	No flow	No flow
Pipe p5	42.46	39.6	0.01	No flow	No flow
Pipe p6	41.42	39.6	0.01	No flow	No flow
All others	…	…	…	No flow	No flow

Analyzing the results we observed that the network is not well functioning with very high velocities in some pipes, very low in other , and no flow in a large part of the network, these findings will be confirmed by the pressure distribution over the whole network. Also, we took the roughness equal to a low value, we need calibration to get the real values.

Table 4.6: Results of the simulation of the actual network (Pressure)

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n2807	920	7.696487819	7.7	0.92
Junc n2665	891	0.500610761	0.5	1.59
Junc n1944	894	4.25341144	4.25	1.65
Junc n1945	1022	4.25341144	4.25	1.83
Junc n231	919	3.109957468	3.11	2.04
Junc n144	892	5.14511906	5.15	3.59
Junc n3318	840	0.439725439	0.44	7.19
Junc n3786	934	4.520415148	4.52	7.96
Junc n2437	1028	1.896997769	1.9	7.99
Junc n2698	839	0.581050925	0.58	8.07
Junc n230	974	5.210386633	5.21	16.71

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n1255	839	0.513261651	0.51	19.25
Junc n1256	839	0.339815195	0.34	19.25
Junc n1763	839	0.024882203	0.02	19.25
Junc n2130	869	3.147253224	3.15	28.98
Junc n14	840	0.590332483	0.59	57.98
Junc n13	839	0.371558969	0.37	58.98
Junc n1091	838	9.566276639	9.57	61.62
Junc n2436	972	2.260207574	2.26	61.96
Junc n3787	864	4.096599739	4.1	65.58
Junc n1374	852	0.663779693	0.66	67.76
Junc n2561	852	0.396055499	0.4	67.76
Junc n2445	966	3.404932992	3.4	69.77
Junc n1762	849	1.550520196	1.55	70.79
Junc n1375	849	1.365143336	1.37	71.49
Junc n2506	839	1.13540148	1.14	80.68
Junc n1551	838	1.226097977	1.23	82.85
Junc n2450	1034	2.438633861	2.44	100.03
Junc n3401	1042	2.381418781	2.38	101.51
Junc n2451	1042	2.862449269	2.86	101.98
Junc n4026	869	4.433109173	4.43	118.24
Junc n2949	773	0.16999236	0.17	126.6
Junc n3871	773	0.088195987	0.09	126.6

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n852	773	0.562784481	0.56	126.63
Junc n851	773	1.536627527	1.54	126.65
Junc n3983	773	0.099511858	0.1	126.65
Junc n1639	773	0.073277684	0.07	126.66
Junc n1592	1014	6.159309333	6.16	127.22
Junc n1638	772	9.436271262	9.44	127.66
Junc n2998	772	0.745131061	0.75	127.66
Junc n3073	830	0.262426501	0.26	135.32
Junc n3074	830	0.262426501	0.26	135.32
Junc n1728	838	0.033871327	0.03	140
Junc n1729	838	0.033871327	0.03	140
Junc n2444	934	3.041723187	3.04	145.33
Junc n2677	934	0.42973611	0.43	145.33
Junc n4018	772	0.718790933	0.72	145.33
Junc n2676	933	0.005920701	0.01	146.33
Junc n1280	985	3.539706292	3.54	149.57
Junc n1947	894	0.041076189	0.04	156.33
Junc n1946	893	0.041076189	0.04	157.33
Junc n2769	1026	4.213343932	4.21	165.81
Junc n3257	1028	0.018419018	0.02	168.23
Junc n1281	965	0.931122453	0.93	169.37
Junc N4114	0	0.847630817	0.85	1079.33

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n1043	979	3.531187603	3.53	<0
Junc n1606	981	0.115125218	0.12	<0
Junc n3264	981	0.526124448	0.53	<0
Junc n3265	981	0.03030704	0.03	<0
Junc n1607	981	4.487179543	4.49	<0
Junc n2933	981	0.040148034	0.04	<0
Junc n4042	965	0.475097073	0.48	<0
Junc n510	948	3.528856618	3.53	<0
Junc n133	944	0.502144972	0.5	<0
Junc n509	944	2.966877386	2.97	<0
Junc n2187	944	0.013061991	0.01	<0
Junc n134	936	1.048307413	1.05	<0
Junc n4084	931	0.341425693	0.34	<0
Junc n269	930	1.083102658	1.08	<0
Junc n3807	920	0.520445322	0.52	<0
Junc n270	916	0.699125898	0.7	<0
Junc n3043	869	0.193598879	0.19	<0
Junc n3897	870	0.794230076	0.79	<0
Junc n2479	861	2.305555823	2.31	<0
Junc n3022	847	0.074210078	0.07	<0
Junc n147	847	1.076321612	1.08	<0
Junc n148	846	0.204321408	0.2	<0

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n70	845	1.359472686	1.36	<0
Junc n2288	836	0.478487596	0.48	<0
Junc n1774	855	0.545874246	0.55	<0
Junc n2480	855	1.579263357	1.58	<0
Junc n433	850	0.522564399	0.52	<0
Junc n1773	849	1.01598725	1.02	<0
Junc n432	849	0.772420535	0.77	<0
Junc n1977	832	0.705652655	0.71	<0
Junc n3270	843	0.871826439	0.87	<0
Junc n3974	836	0.256874519	0.26	<0
Junc n69	844	0.73790077	0.74	<0
Junc n2664	835	0.594316347	0.59	<0
Junc n1934	831	0.583593818	0.58	<0
Junc n3994	839	0.303536596	0.3	<0
Junc n3354	839	0.683699017	0.68	<0
Junc n1933	831	1.068777697	1.07	<0
Junc n3202	825	0.302943254	0.3	<0
Junc n3543	887	1.004018703	1	<0
Junc n3285	870	2.557725991	2.56	<0
Junc n2772	865	2.223971356	2.22	<0
Junc n3212	884	0.520869137	0.52	<0
Junc n3216	858	1.100843571	1.1	<0

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n4017	857	0.018842833	0.02	<0
Junc n3418	873	0.217798738	0.22	<0
Junc n34	873	0.257510242	0.26	<0
Junc n2038	871	0.994186185	0.99	<0
Junc n33	868	0.683487109	0.68	<0
Junc n2771	863	1.078059255	1.08	<0
Junc n718	867	1.094757582	1.09	<0
Junc n1367	863	1.069710091	1.07	<0
Junc n335	860	1.654193921	1.65	<0
Junc n719	857	0.590374864	0.59	<0
Junc n4016	855	0.589527233	0.59	<0
Junc n3557	853	0.595036834	0.6	<0
Junc n336	848	0.839154509	0.84	<0
Junc n1427	860	3.860110741	3.86	<0
Junc n1523	874	1.183843581	1.18	<0
Junc n1195	871	1.084586012	1.08	<0
Junc n1426	848	1.453686851	1.45	<0
Junc n1196	859	0.586984341	0.59	<0
Junc n3552	861	0.585289079	0.59	<0
Junc n3715	844	1.643132339	1.64	<0
Junc n1919	873	2.093393829	2.09	<0
Junc n2991	863	0.294805998	0.29	<0

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n2363	862	0.846211035	0.85	<0
Junc n974	862	1.120377223	1.12	<0
Junc n2959	860	0.073108158	0.07	<0
Junc n3865	887	0.278404342	0.28	<0
Junc n543	881	2.005070698	2.01	<0
Junc n544	880	0.785287571	0.79	<0
Junc n3000	874	0.455601564	0.46	<0
Junc n143	832	15.81679105	15.82	<0
Junc n2770	1082	4.194924914	4.19	<0
Junc n2980	873	1.028599997	1.03	<0
Junc n2446	876	1.610498553	1.61	<0
Junc n2463	869	1.523701157	1.52	<0
Junc n2462	868	1.066319568	1.07	<0
Junc n2774	866	1.186767907	1.19	<0
Junc n3540	865	1.021395135	1.02	<0
Junc n211	811	8.213630555	8.21	<0
Junc n1276	811	4.13E-05	0	<0
Junc n3544	811	0.004284774	0	<0
Junc n2129	879	2.723437815	2.72	<0
Junc n3835	888	7.039573936	7.04	<0
Junc n633	884	1.720605796	1.72	<0
Junc n2164	890	0.57677039	0.58	<0

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n2165	889	1.24572063	1.25	<0
Junc n632	875	1.037923936	1.04	<0
Junc n3774	922	1.355361677	1.36	<0
Junc n2195	836	4.569026775	4.57	<0
Junc n3824	838	0.182537296	0.18	<0
Junc n3834	838	7.463389345	7.46	<0
Junc n1	848	0.517775285	0.52	--No flow
Junc n2	849	0.101800461	0.1	--No flow
Junc n3	791	2.83935133	2.84	--No flow
Junc n4	804	4.590217545	4.59	--No flow
Junc n7	806	0.619512173	0.62	--No flow
Junc n8	803	0.585712895	0.59	--No flow
Junc n9	800	0.691285313	0.69	--No flow
Junc n10	801	0.787660937	0.79	--No flow
Junc n11	823	1.061733885	1.06	--No flow
Junc n12	823	1.035211517	1.04	--No flow
Junc n15	856	0.872932597	0.87	--No flow
Junc n16	859	1.607828515	1.61	--No flow
Junc n17	774	0.600970249	0.6	--No flow
Junc n18	774	0.764774905	0.76	--No flow
Junc n19	811	1.238939584	1.24	--No flow
Junc n20	812	1.103445798	1.1	--No flow
Junc n21	814	0.948244595	0.95	--No flow
Junc n22	813	1.013596931	1.01	--No flow
Junc n23	811	0.982827932	0.98	--No flow

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n24	811	0.170967136	0.17	--No flow
Junc n25	797	3.054013834	3.05	--No flow
Junc n26	793	2.506868142	2.51	--No flow
Junc n27	769	0.127615058	0.13	--No flow
Junc n28	769	1.608387952	1.61	--No flow
Junc n29	764	1.115821208	1.12	--No flow
Junc n30	765	0.677384167	0.68	--No flow
Junc n31	808	0.322392143	0.32	--No flow
Junc n32	808	1.105687781	1.11	--No flow
Junc n35	812	1.593545936	1.59	--No flow
Junc n36	811	1.082466935	1.08	--No flow
Junc n37	804	1.090943243	1.09	--No flow
Junc n38	807	0.629365882	0.63	--No flow
Junc n39	826	1.644827601	1.64	--No flow
Junc n40	822	2.59841227	2.6	--No flow
Junc n41	796	1.189946523	1.19	--No flow
Junc n42	795	1.02843047	1.03	--No flow
Junc n45	931	3.190397633	3.19	--No flow
Junc n46	928	0.514511906	0.51	--No flow
Junc n49	779	0.302731346	0.3	--No flow
Junc n50	782	0.6612368	0.66	--No flow
Junc n51	782	2.538230482	2.54	--No flow

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n52	781	0.730657764	0.73	--No flow
Junc n55	765	2.286484129	2.29	--No flow
Junc n56	765	1.838529043	1.84	--No flow
Junc n57	790	3.135386392	3.14	--No flow
Junc n58	791	1.779177085	1.78	--No flow
Junc n59	794	0.716671856	0.72	--No flow
Junc n60	801	1.421222591	1.42	--No flow
Junc n61	809	0.044325455	0.04	--No flow
Junc n62	809	0.197031783	0.2	--No flow
Junc n65	780	1.057419444	1.06	--No flow
Junc n66	780	0.499678367	0.5	--No flow
Junc n67	802	0.653099545	0.65	--No flow
Junc n68	803	1.052248896	1.05	--No flow
Junc n73	805	0.827766589	0.83	--No flow
Junc n74	808	1.751120505	1.75	--No flow
Junc n75	830	2.037534958	2.04	--No flow
Junc n76	830	0.500780287	0.5	--No flow
Junc n77	899	2.140479721	2.14	--No flow
Junc n78	898	0.693362008	0.69	--No flow
Junc n79	772	0.842121217	0.84	--No flow
Junc n80	773	1.070727248	1.07	--No flow
Junc n81	798	1.176808245	1.18	--No flow

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n82	797	0.516207168	0.52	--No flow
Junc n85	769	0.416585118	0.42	--No flow
Junc n86	769	0.443734733	0.44	--No flow
Junc n87	803	2.895083056	2.9	--No flow
Junc n88	805	3.928345022	3.93	--No flow
Junc n89	801	1.85164952	1.85	--No flow
Junc n90	802	1.20389005	1.2	--No flow
Junc n91	820	2.838715606	2.84	--No flow
Junc n92	814	0.795925337	0.8	--No flow
Junc n97	777	1.171001974	1.17	--No flow
Junc n98	776	0.84771558	0.85	--No flow
Junc n99	802	2.151414158	2.15	--No flow
Junc n100	803	1.099334788	1.1	--No flow
Junc n101	785	0.499169788	0.5	--No flow
Junc n102	784	0.864837723	0.86	--No flow
Junc n103	830	2.249340947	2.25	--No flow
Junc n104	830	1.770429535	1.77	--No flow
Junc n105	797	1.51251243	1.51	--No flow
Junc n106	788	2.568321376	2.57	--No flow
Junc n107	817	3.660917499	3.66	--No flow
Junc n108	821	4.278840365	4.28	--No flow
Junc n109	787	1.342350544	1.34	--No flow

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n110	788	1.368499954	1.37	--No flow
Junc n111	825	3.749918735	3.75	--No flow
Junc n112	826	3.892702146	3.89	--No flow
Junc n113	790	0.680393257	0.68	--No flow
Junc n114	790	3.122417641	3.12	--No flow
Junc n117	773	1.357014557	1.36	--No flow
Junc n118	773	0.745915119	0.75	--No flow
Junc n119	795	0.812326994	0.81	--No flow
Junc n120	796	0.191479802	0.19	--No flow
Junc n121	818	1.799096409	1.8	--No flow
Junc n122	817	3.045537526	3.05	--No flow
Junc n123	796	1.592359253	1.59	--No flow
Junc n124	796	1.482167247	1.48	--No flow
Junc n125	921	1.579178594	1.58	--No flow
Junc n126	922	0.936038711	0.94	--No flow
Junc n127	807	1.453051128	1.45	--No flow
Junc n128	807	0.902379292	0.9	--No flow
Junc n129	847	2.521913589	2.52	--No flow
Junc n130	837	2.043214085	2.04	--No flow
Junc n131	772	1.40315534	1.4	--No flow
Junc n132	772	0.442899816	0.44	--No flow
Junc n135	816	0.540364646	0.54	--No flow

Node ID	Elevation (m)	Base Demand (LPS)	Demand (LPS)	Pressure(m)
Junc n136	817	0.426358301	0.43	--No flow
Junc n137	811	0.7696064	0.77	--No flow
Junc n138	809	0.38012004	0.38	--No flow

According to the simulation results, certain pipes nodes have negative pressures, no pressure, or insufficient velocities, and less than 5% of the pipes and nodes show some results concerning pressure and velocity. Considering the fact that this percentage sounds small, it is a serious issue that might compromise the network's reliability, efficiency, and capacity to satisfy demand. For a water delivery system to be stable and sustainable, these hydraulic deficiencies must be fixed. For this issue, the water company of water supply, to be able to supply water to the consumers, will need to deliver it sector by sector, which is so difficult and so complicated to do, many sectors have no water during days sometimes during weeks, and those supplied, are supplied just few hours. There is also a great need for the network to be redesigned and resized.

4.2. Rehabilitation of the network

4.2.1. Hydraulic calculation of the distribution network:

The distribution network will be calculated for the following the peak flow.

4.2.1.1. Determination of peak flow (design flow):

Peak flow refers to the maximum flow rate expected in a water distribution or drainage system during a specific period of time.

The flow in network is determined as follows:

- ✓ The length of each section of the network is determined.
- ✓ The in pipes flow rate during the peak hour is calculated;
- ✓ The specific flows are determined by considering the in-pipe flows;

The maximum probable daily flow:

$$\boldsymbol{Q\,max\_h = feff * Pfd * \frac{Q_{av-d}}{24}\,(m^3/d)} \qquad 4.3$$

$$\boldsymbol{Q\,max\_h = 317553,8147\ (m^3/d)}\ \textit{\textbf{for 2055}} \qquad 4.4$$

$$Q\,max\_h = 129792\ (m^3/d)\ \textit{for 2025} \qquad 4.5$$

Maximum hourly flow of the different horizons according to the diurnal diagram used by REGIDESO:

Table 4.7 : Diurnal consumption variation (REGIDESO)

Consumption	P (%)	Qh (%)
00-01	3.35	10638.059
01-02	3.25	10320.505
02-03	3.3	10479.282
03-04	3.2	10161.728
04-05	3.25	10320.505
05-06	3.4	10796.836
06-07	3.85	12225.829
07-08	4.45	14131.153
08-09	5.2	16512.808
09-10	5.05	16036.477
10-11	4.85	15401.369
11-12	4.6	14607.484
12-13	4.6	14607.484
13-14	4.55	14448.707
14-15	4.75	15083.815
15-16	4.7	14925.038
16-17	4.65	14766.261
17-18	4.35	13813.599
18-19	4.4	13972.376
19-20	4.3	13654.822
20-21	4.3	13654.822
21-22	4.2	13337.268
22-23	3.75	11908.275
23-24	3.7	11749.498
24 hours	100	317554

To calculate the maximum hourly consumption, we have:

$$Q\,max\_h = feff * Pfd * Pfh * \frac{Q_{av-d}}{24}\ (m^3/d) \qquad 4.6$$

With:

Q_{av-d}: Average daily consumption

Pfh : Hourly peak factor

$Q\ max\ \_h$: Maximum hourly consumption

$feff$: add-on efficiency factor ($f_{eff} = \frac{1}{Efficiency}$)

Assuming the hourly peak flow and the peak daily consumption to be as follow, according to the literature review:

- P_{fh}:1.25
- P_{fd}:1.35

Table 4.8: Maximum hourly flow, length and specific flow of the different horizons:

	year 2025	year 2055
Q max h (m3/h)	6760	16512.808
Q max h (l/s)	1877.77778	4594.239217
Length	562351.742	76772.09765
qsp (l/s/ml)	0.00333915	0.059842565

For our case the efficiency is estimated to be ranged between 34-48% (Regideso, 2024). The percentage used was 34%, which means that the network is 66% efficient.

4.2.1.2.Storage

Over the study area we have many tanks as mentioned in table 4.1:

Table 4.9: Storage capacity

Storage	2025	2055
Volume Storage m3	8371.584	20482.221
Total Volume Storage m3	8491.584	20602.221

We can note that the existing tanks are sufficient as storage capacity since the total storage volume required for the horizon is less than 33000 of the total volume of the existing tanks, we need to rehabilitate the actual existing tanks.

4.2.2. Choice of Materials

When selecting the most suitable pipe material for a water distribution system, several factors beyond conveying capacity must be considered. The maximum and minimum depth of pipe cover influence the material choice, as deeper installations require stronger pipes like ductile iron or concrete, while less deep ones may benefit from flexible options like HDPE or PVC (Tsakiris & Tsakiris, 2012).Water supply pipes are composed of a variety of materials and can be divided into three major groups based on how well they withstand shock and backfill loads:

– rigid materials include cast iron (CI), asbestos cement (AC), and concrete.

– semi-rigid materials include ductile iron (DI) and steel.

– flexible materials include polyvinyl chloride (PVC), polyethylene (PE), and glass reinforced plastic (GRP).

In our case, the suggested material to be used will be PEHD due to its flexibility and good characteristics.

4.2.3. Design of the new main Network

In any complex water Distribution Network, it is recommended to study well the structure and efficiency of the main network, in that way it will be easy to know how the behavior of the secondary and tertiary networks can be. For our case study a design for a network was established and simulated to observe its hydraulic behaviors.

For the designed network, considering the high elevation difference between the lowest point and the highest one (260 m), we subdivided our study zone into two floors, the first one from 770 m to 860 m, the second one from 860 to 1028 (according to the tanks locations). We will pump water from the actual pumping station to the reservoir R2, which will feed the reservoirs situated below, and we will pump water to the second flood (Reseroir R5), which will supply the upper zone.

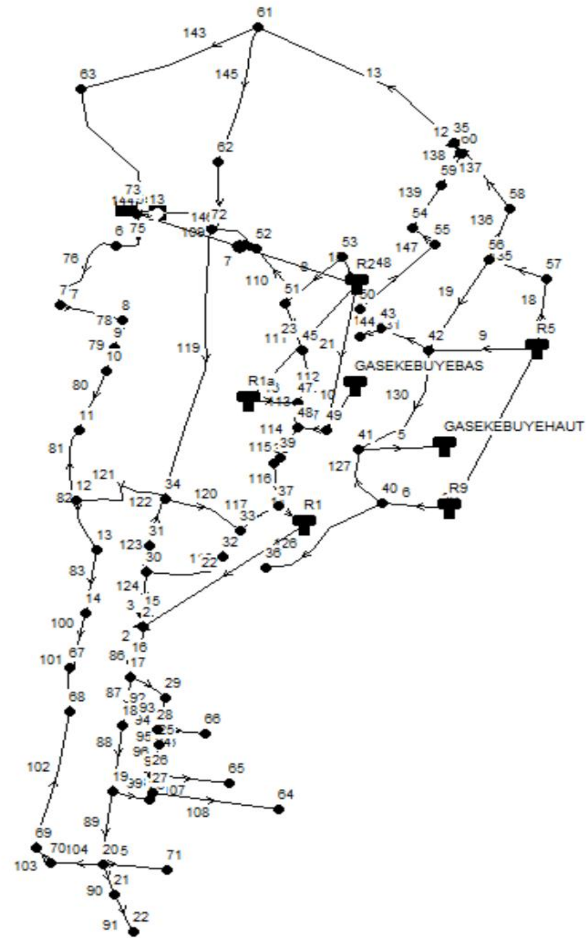


Figure 4.2 : Revised Main Network

After the network layout has been built, the next thing to do is to enter all the settings into EPANET. This includes setting up pipe properties like roughness and diameter, as well as describing node elevations and demand values.

4.2.4. Hydraulic simulation of the new network

In the simulation of a new water network, we analyze key hydraulic parameters such as pressure, flow rate, velocity, and head loss to ensure the system functions efficiently. The simulation improves pipe sizes, selects suitable pump stations, and ensures adequate water supply for all consumers. Here are the results from simulation made on our projected network:

Table 4.10: Simulation results on pressure

Node ID	Elevation (m)	Demand (LPS)	Pressure (wcm)
Junc 5	766	28.11	57.24
Junc 6	793	59.44	30.07
Junc 7	762	62.58	58.99
Junc 8	767	23.5	53.33
Junc 9	767	32.18	53.1
Junc 10	766	63.48	53.97
Junc 11	764	84.19	52.43
Junc 12	765	88.94	62.51
Junc 13	765	75.58	61.46
Junc 14	774	72.43	51.95
Junc 15	797	39.48	51.06
Junc 16	799	42.07	35.11
Junc 17	798	76.02	35.96
Junc 18	796	76.02	37.73
Junc 19	797	44.13	36.48
Junc 20	799	55.32	34.17
Junc 21	790	48.01	42.71
Junc 22	782	17.32	49.91
Junc 23	802	16.91	31.04
Junc 24	802	13.28	31.11
Junc 25	803	11.46	30.22
Junc 26	803	43.73	29.98
Junc 27	803	57.54	29.96
Junc 28	804	13.66	29.37
Junc 29	808	29.07	25.82
Junc 30	791	59.95	57.1
Junc 31	793	31.7	54.78
Junc 32	814	60.85	34.74
Junc 33	819	61.56	26.38
Junc 34	790	20.43	57.42
Junc 36	845	106.02	63.31
Junc 37	820	60.29	32.02
Junc 38	825	20.49	27.75
Junc 39	828	24.91	26.13
Junc 40	943	107.55	44.78
Junc 41	921	109.04	65.61
Junc 42	1004	52.77	20.47
Junc 43	888	42.67	69.39
Junc 44	866	38.51	53.26
Junc 45	834	24.91	27.44
Junc 47	844	65.98	16.91
Junc 48	844	11.15	16.33

Node ID	Elevation (m)	Demand (LPS)	Pressure (wcm)
Junc 49	850	54.88	14.05
Junc 50	856	51.84	72.09
Junc 51	819	76.09	43.63
Junc 52	802	27.27	60.41
Junc 53	836	55.27	37.81
Junc 54	871	37.01	51.58
Junc 55	870	48.41	52.93
Junc 56	999	51.59	28.14
Junc 57	980	32.23	48.15
Junc 58	981	29.47	44.64
Junc 59	884	14.37	37.97
Junc 60	800	135.1	105.77
Junc 61	785	219.07	67.37
Junc 62	789	88.54	60.89
Junc 63	786	65.04	34.77
Junc 64	800	128.86	27.42
Junc 65	822	27.88	10.87
Junc 66	821	13.66	11.84
Junc 67	765	27.88	59.84
Junc 68	769	76.71	55.83
Junc 69	770	66.76	62.19
Junc 70	783	27.17	49.66
Junc 71	810	27.17	22.83

We observed that the pressure distribution is acceptable, except three points where the pressure is higher than 7 bars. As a solution for those kinds of areas, we can use pressure regulating valves.

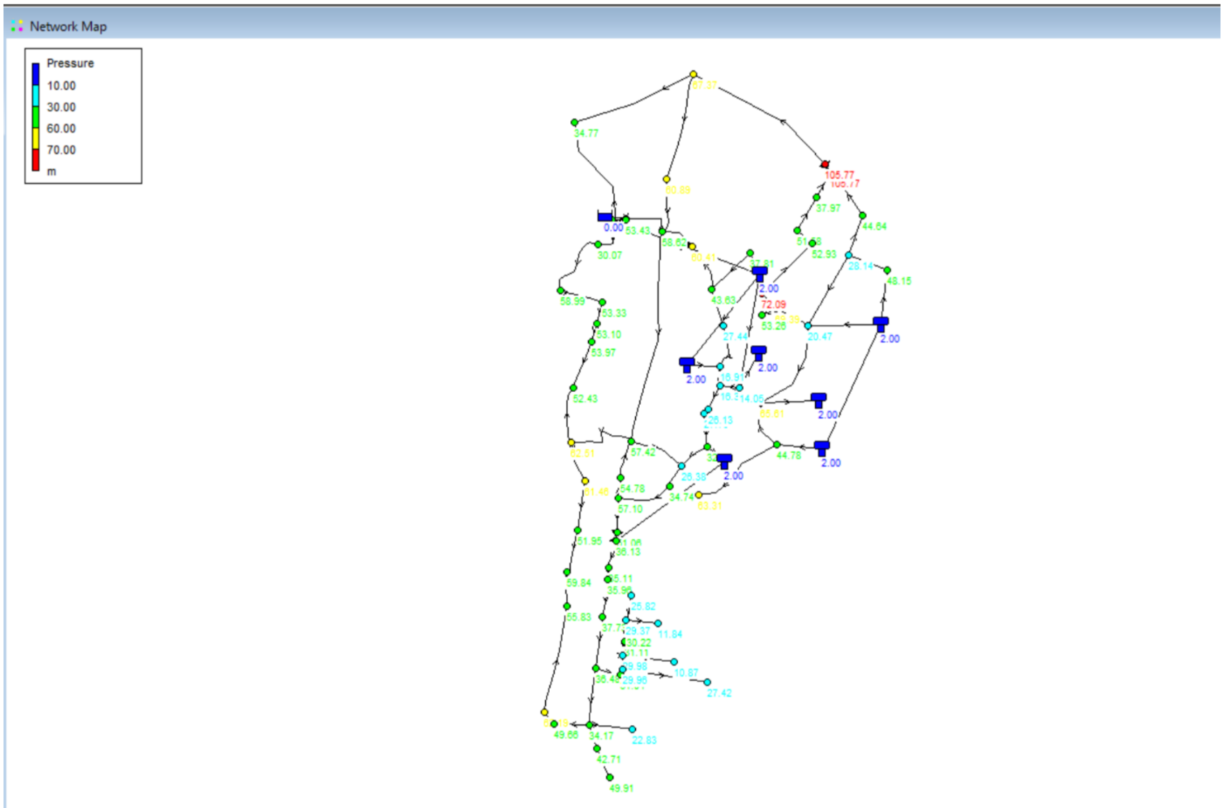


Figure 4.3: Pressure Simulation Display

After analysis of the pressure, here are the results for the velocity display:

Table 4.11: Simulation results on Velocity

Link ID	Length(m)	Diameter(mm)	Velocity (m/s)
Pipe 1	373.64	500	3.45
Pipe 10	1000	500	1.25
Pipe 100	821.279802	315	0.71
Pipe 101	611.560604	500	0.11
Pipe 102	1952.08941	250	1.11
Pipe 103	278.967267	400	0.96
Pipe 104	629.188076	500	0.76
Pipe 105	773.108646	315	0.38
Pipe 106	579.251375	200	0.43
Pipe 107	931.870633	400	0.22
Pipe 108	1545.70427	350	1.34
Pipe 109	1510.47	500	2.27
Pipe 11	416.35	710	0.21
Pipe 110	911.289409	1000	0.6
Pipe 111	679.687053	315	0.82

Link ID	Length(m)	Diameter(mm)	Velocity (m/s)
Pipe 112	832.364397	315	0.47
Pipe 113	372.761582	630	1.2
Pipe 114	467.988603	500	3.39
Pipe 115	104.147952	500	3.39
Pipe 116	580.524514	800	1.28
Pipe 117	1015.05539	630	1.79
Pipe 118	1018.76155	800	0.88
Pipe 119	3838.2338	800	0.61
Pipe 120	1042.4017	315	0.87
Pipe 121	1334.56049	500	1.73
Pipe 122	682.89826	500	0.6
Pipe 123	376.583058	500	0.76
Pipe 124	608.374006	1000	0.3
Pipe 126	1714.00483	250	2.16
Pipe 127	880.290811	800	1.33
Pipe 13	2891.85	630	1.91
Pipe 130	1763.78372	1000	2.43
Pipe 131	682.185667	500	3.86
Pipe 132	287.158351	150	2.18
Pipe 135	724.062199	500	1.01
Pipe 136	753.734947	110	0.42
Pipe 137	984.97	63	1.06
Pipe 138	514.46	630	1.91
Pipe 139	681.540767	800	1.07
Pipe 14	14.33	630	1.07
Pipe 143	2314.8818	125	1.38
Pipe 144	2173.73	315	0.7
Pipe 145	1956.3717	630	1.08
Pipe 146	1002.74779	630	1.08
Pipe 147	341.949693	800	1.15
Pipe 148	1275.98157	800	1.24
Pipe 15	421.35	1000	0.84
Pipe 16	601.82	1000	0.47
Pipe 17	1000	500	1.72
Pipe 18	1000	500	1.18
Pipe 19	1000	500	0.73
Pipe 2	520.49	800	1.77
Pipe 20	1000	500	2.77
Pipe 21	2000	630	2.25
Pipe 22	1000	630	2.46
Pipe 23	1000	500	3.36
Pipe 4	246.27	1000	0.38
Pipe 5	1000	800	4.9
Pipe 6	1900	800	1.75

Link ID	Length(m)	Diameter(mm)	Velocity (m/s)
Pipe 75	680.698414	800	0.54
Pipe 76	1305.94063	500	1.08
Pipe 77	785.44701	500	0.76
Pipe 78	387.070909	500	0.65
Pipe 79	344.172657	500	0.48
Pipe 8	1000	500	3.1
Pipe 80	888.69924	200	0.99
Pipe 81	1032.00025	200	1.69
Pipe 82	749.62936	500	1.01
Pipe 83	888.238257	500	0.62
Pipe 86	219.879378	1000	1.08
Pipe 87	671.11867	1000	0.74
Pipe 88	934.815673	1000	0.64
Pipe 89	1020.49739	800	0.59
Pipe 9	1000	1000	3.28
Pipe 90	446.681213	350	0.68
Pipe 91	578.965031	200	0.55
Pipe 92	515.064184	710	0.51
Pipe 93	456.638511	500	0.84
Pipe 94	202.545119	500	0.7
Pipe 95	180.612937	500	0.64
Pipe 96	263.123563	500	0.58
Pipe 97	266.441571	500	0.21
Pipe 98	110.898204	500	0.74
Pipe 99	454.354867	500	0.82

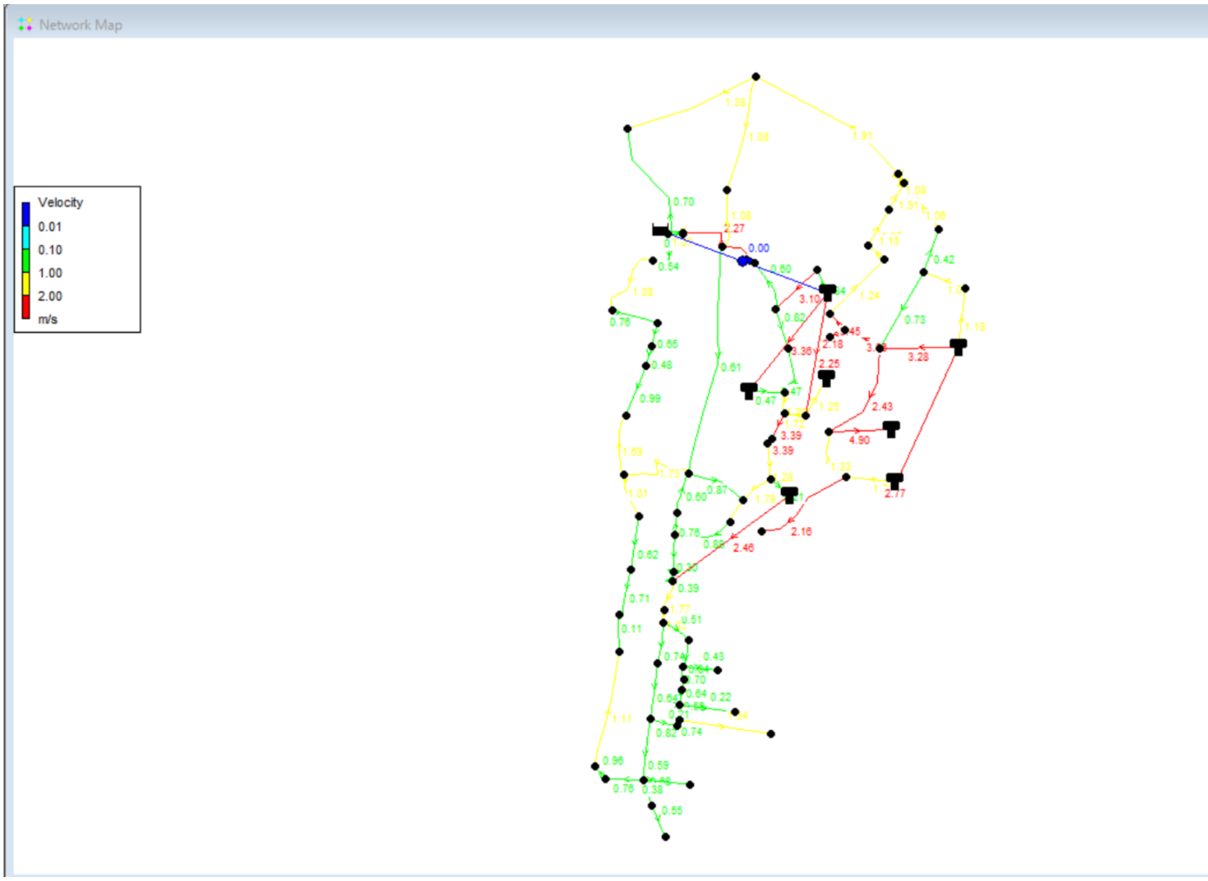


Figure 4.4 : Velocity Simulation Display

Based on the results of our projected network, the hydraulic parameters obtained from our model simulations indicate that the system can effectively supply water to all areas within the study region. That means that upgrading aging infrastructure, carrying out regular water quality monitoring, and expanding supply coverage constitute important measures to ensure reliability and safety of a Water Distribution Network.

4.2.5. Design of water transport system

The pumping system encompasses two pumping lines: the first one from the pumping station to the tank R2 and the second one from the tank R2 to R5. The pumping system is functioning 24/7. so it is designed to pump the max daily discharge (3.64 m^3/s) according to the discharge corresponding to the horizon 2055 calculated above.

Figure 4.5 : Pumping System

We opted for the economic balance approach which consists of estimate the investment costs ,operating ones and the sum of two are the total costs according to a time scale of one year. We must do this for each possible diameter. The diameter chosen corresponds to minimum costs. The pipe material chosen is Ductile iron because of its availability and its convenience to importance elevation differences and high pressure (25 bars).

- **Total Manometric Head (TMH):**

It is the head developed by the pump to lift a discharge over a certain elevation through a pipe of diameter D and length L.

$$TMH = H_g + \sum \Delta H \qquad 4.7$$

Hg: geometric elevation (starting point and arriving one)

$\sum \Delta H$: sum of head losses.

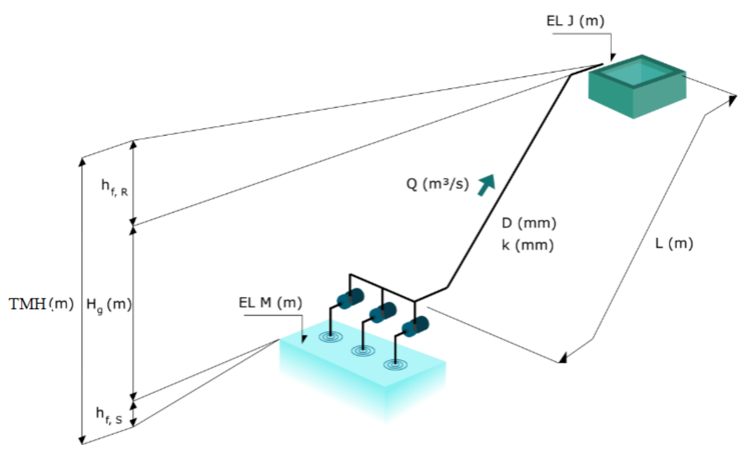


Figure 4.6: Total Manometric Head

The estimation of the head losses was done used the Hazen Williams formula:

$$\Delta H_{lin} = H_g + \left(\frac{3.592 * Q}{C_{HW}}\right)^{1.852} * \frac{L}{D^{4.87}} \qquad 4.8$$

❖ Line Pumping Station-R2

Table 4.12: TMH of the line: pumping station- R2

D (mm)	**L (m)**	**Q (m3/s)**	**Velocity (m/s)**	**CHW**	**ΔH$_{lin}$ (wcm)**	**ΔH$_T$ (wcm**	**Hg (m)**	**TMH (wcm)**
600	7429	1.834	6.49	140	311.17	342.29	102	444.29
700	7429	1.834	4.77	140	146.88	161.57	102	263.57
800	7429	1.834	3.65	140	76.66	84.32	102	186.32
900	7429	1.834	2.88	140	43.20	47.52	102	149.52
1000	7429	1.834	2.34	140	25.86	28.44	102	130.44
1100	7429	1.834	1.93	140	16.26	17.88	102	119.88
1200	7429	1.834	1.62	140	10.64	11.71	102	113.71
1500	7429	1.834	1.04	140	3.59	3.95	102	105.95
1800	7429	1.834	0.72	140	1.46	1.60	102	103.6

❖ For the line R2-R5

Table 4.13: TMH of the line :R2-R5

D (mm)	**L(m)**	**Q (m3/s)**	**Velocity (m/s)**	**CHW**	**ΔHlin (wcm)**	**ΔHT (wcm)**	**Hg (m)**	**TMH (wcm)**
600	4989	1.834	6.49	140	208.97	229.87	156	385.87
700	4989	1.834	4.77	140	98.64	108.50	156	264.50
800	4989	1.834	3.65	140	51.48	56.63	156	212.63
900	4989	1.834	2.88	140	29.01	31.91	156	187.91
1000	4989	1.834	2.34	140	17.37	19.10	156	175.10
1100	4989	1.834	1.93	140	10.92	12.01	156	168.01
1200	4989	1.834	1.62	140	7.15	7.86	156	163.86
1500	4989	1.834	1.04	140	2.41	2.65	156	158.65
1800	4989	1.834	0.72	140	0.98	1.08	156	157.08

➢ **Operation costs:**

The total costs of a pumping system are subdivided into operation costs (energy costs) and investment costs. For the first part. the costs are calculated based on the electrical energy consumed annually.

Electrical and hydraulic power:

$$\boldsymbol{Efficiency} = \frac{\boldsymbol{Power_{hydraulic}}}{\boldsymbol{Power_{electric}}} \qquad \textit{4.9}$$

The efficiency is assumed 75% in our case.

Electrical power : is the power absorbed by the pump

Hydraulic power : Power delivered by the pump

$$\boldsymbol{P_{hydraulic} = \rho * g * Q * TMH} \qquad \textit{4.10}$$

Operating costs in (USD for example) are defined by the following formula:

$$\boldsymbol{Cop = E \times e} \qquad \textit{4.11}$$

E: Energy consumed by the pump in (KWh).

e: Unit price of one KWh. 0.08USD in our case.

The annual energy used by the pumping station is given by the following formula:

$$\boldsymbol{E = P \times T \times 365} \; \boldsymbol{[KWh]} \qquad \textit{4.12}$$

E: Total energy consumed by the pump during one year (kWh).

P: Absorbed power (elctricty) (KW).

T: Pumping time (hours). in our case 24h.

❖ For the line from the pumping station -R2

Table 4.14 : Operation costs Pumping station-R2

D (mm)	**TMH (wcm)**	**P_{abs} (KW)**	**E (KWh)**	**Price KWh (USD)**	**C_{op} (USD)**
600	444.291	10657.978	93363886.720	0.080	7469110.938
700	263.572	6322.744	55387239.706	0.080	4430979.176
800	186.323	4469.641	39154057.946	0.080	3132324.636
900	149.515	3586.675	31419273.581	0.080	2513541.887
1000	130.444	3129.187	27411680.318	0.080	2192934.425
1100	119.882	2875.810	25192092.983	0.080	2015367.439
1200	113.705	2727.643	23894150.565	0.080	1911532.045
1500	105.948	2541.568	22264135.526	0.080	1781130.842
1800	106.948	2565.557	22474276.713	0.080	1797942.137

❖ For the line R2-R5

Table 4.15 : Operation costs Pumping station-R2

D (mm)	**TMH (wcm)**	**P_{abs} (KW)**	**E (KWh)**	**Price KWh (USD)**	**C_{op} (USD)**
600	385.87	9256.48	81086804.28	0.08	6486944.34
700	264.50	6345.13	55583305.57	0.08	4446664.45
800	212.63	5100.66	44681792.07	0.08	3574543.37
900	187.91	4507.70	39487440.31	0.08	3158995.22
1000	175.10	4200.47	36796111.36	0.08	2943688.91
1100	168.01	4030.31	35305531.04	0.08	2824442.48
1200	163.86	3930.81	34433888.19	0.08	2754711.05
1500	158.65	3805.85	33339239.51	0.08	2667139.16
1800	159.65	3829.84	33549380.70	0.08	2683950.46

- **Investment costs:**

The amortized investment costs in (USD for example) are given by the following formula:

$$Camort = Prc \times A \qquad 4.13$$

P_{rc} : The cost of the pipe (supplying and laying).

A : Annual depreciation in (%). it is given by the following formula:

$$A = \left(\frac{i}{(i+1)^n - 1} + i\right) \times 100 \qquad 4.14$$

i : The annuity rate. (in our case we took. i = 8%).

n : Number of years of amortization (depreciation) (30 years in our case).

After that. the total balance is estimated as:

$$Ctotal = Cop + Camort \qquad 4.15$$

- For the line from the pumping station -R2

Table 4.16 : Investment costs Pumping station- R2

D (mm)	**Pipe price (USD/m)**	**L (m)**	**Pipes total costs (USD)**	**i%**	**n**	**A %**	**Amortised costs (USD)**
600	658.80	7429	4894225.20	8.00	30	8.88	434607.20
700	831.60	7429	6177956.40	8.00	30	8.88	548602.53
800	1047.60	7429	7782620.40	8.00	30	8.88	691096.69
900	1260.90	7429	9367226.10	8.00	30	8.88	831809.68
1000	1455.30	7429	10811423.70	8.00	30	8.88	960054.42
1100	1657.53	7429	12313790.37	8.00	30	8.88	1093464.58
1200	1859.76	7429	13816157.04	8.00	30	8.88	1226874.75
1500	2466.45	7429	18323257.05	8.00	30	8.88	1627105.23
1800	3073.14	7429	22830357.06	8.00	30	8.88	2027335.71

- For the line R2- R5

Table 4.17 : Investment costs Pumping R2- R5

DN (mm)	Pipe price (USD/m)	L(m)	Pipes total costs (USD)	i%	n	A %	Amortised costs (USD)
600	658.80	4989	3286753.20	8.00	30	8.88	291863.68
700	831.60	4989	4148852.40	8.00	30	8.88	368418.09
800	1047.60	4989	5226476.40	8.00	30	8.88	464111.10
900	1260.90	4989	6290630.10	8.00	30	8.88	558607.95
1000	1455.30	4989	7260491.70	8.00	30	8.88	644731.66
1100	1657.53	4989	8269417.17	8.00	30	8.88	734324.24
1200	1859.76	4989	9278342.64	8.00	30	8.88	823916.83
1500	2466.45	4989	12305119.05	8.00	30	8.88	1092694.57
1800	3073.14	4989	15331895.46	8.00	30	8.88	1361472.32

- **Total costs :**

The total costs are the sum of the fore mentioned ones:

- For the pumping Station-R2 :

Table 4.18: Total costs. Pumping station-R2

DN	Cop	Amortised costs	Total costs (USD)	Total costs (Million USD)
600	7469110.938	434607.198	7903718.135	7.904
700	4430979.176	548602.528	4979581.705	4.980
800	3132324.636	691096.692	3823421.327	3.823
900	2513541.887	831809.678	3345351.564	3.345
1000	2192934.425	960054.425	3152988.850	3.153
1100	2015367.439	1093464.585	3108832.023	3.109
1200	1911532.045	1226874.745	3138406.790	3.138
1500	1781130.842	1627105.226	3408236.068	3.408
1800	1797942.137	2027335.707	3825277.844	3.825

❖ For the line R2-R5 :

Table 4.19: Total costs. R2-R5

DN	Cop	Amortised costs	Total costs (USD)	Total costs (Million USD)
600	6486944,34	291863,68	6778808,03	6,78
700	4446664,45	368418,09	4815082,54	4,82
800	3574543,37	464111,10	4038654,47	4,04
900	3158995,22	558607,95	3717603,18	3,72
1000	2943688,91	644731,66	3588420,57	3,59
1100	2824442,48	734324,24	3558766,73	3,56
1200	2754711,05	823916,83	3578627,88	3,58
1500	2667139,16	1092694,57	3759833,73	3,76
1800	2683950,46	1361472,32	4045422,77	4,05

The annual cost variation function of the diameter is drawn below :

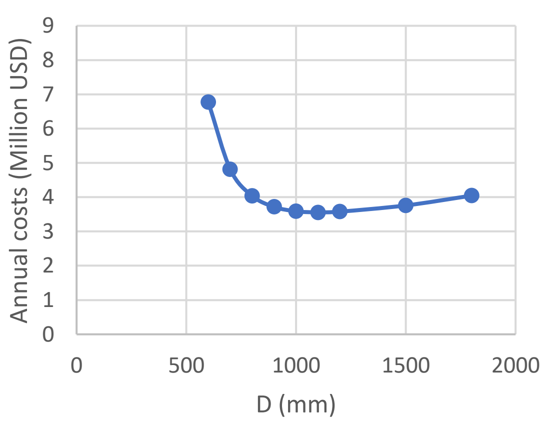


Figure 4.8: Total costs, Pumping station-R2

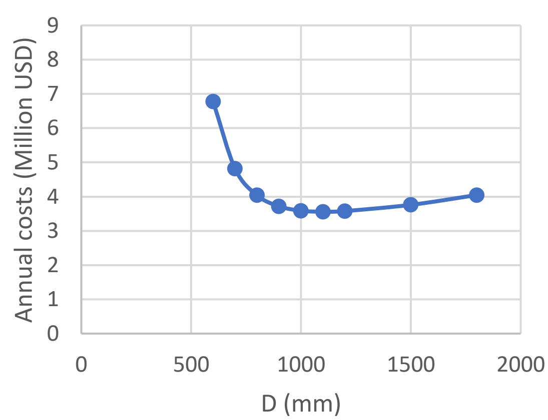


Figure 4.7: Total costs, R2-R5

We can observe that the economical diameter for both pipelines is 1100 mm.

CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

Hydraulic modeling serves as an important tool for the analysis and optimization of water supply networks. This functionality enables engineers to calculate flow rates, pressures, and water quality at any designated point within the system. The accuracy of these estimations is based on appropriate calibration, necessitating a well-structured monitoring network. In the absence of reliable field data, models tend to provide inaccurate results, which can adversely impact decision-making processes and overall system performance.

The hydraulic simulation of the existing network showed a very bad hydraulic characteristics, with a large zones without water, negative pressures, which indicate that the network cannot function in a good conditions, adding the probable high level of leakage, the problem will be worst. To resolve these technical problems, we opted for a new network, because the old one is too old and cannot supply the city at the present, nor in the future with a high increasing demand rate. The simulation of the new network gave better results, but the problem of the position of the pumping system compared to the existing reservoirs still complicating the homogenization of the pressure distribution over the whole city, we used pressure reduction valve to reduce high pressures. The choice to maintain the actual water pumping system and reservoirs positions in requested by REGIDESO to reduce the total cost of the project.

A complete monitoring network must incorporate flow meters, pressure sensors, and water quality monitoring devices, which should be strategically positioned throughout the system. Supervisory Control and Data Acquisition (SCADA) systems enhance this process by delivering real-time data for model validation. Through the comparison of simulated results with measured values, it is possible to identify gaps that need adjustments to model parameters, including pipe roughness coefficients, nodal demands, and settings for pumps or valves. An iterative calibration process is frequently necessary to adjust these parameters and obtain a correct representation of the real-world system.

It is important for water supply companies to integrate these technologies to further develop their understanding and improve the accuracy of performance analysis in the distribution network. This methodology helps to get quality service, ensures a reliable and efficient water supply, and allows early identification of problems or disruptions. This proactive strategy may lead to customer satisfaction and facilitate the early detection and resolution of potential issues, thereby contributing to a more sustainable and effectively managed water distribution system.

5.2. RECOMMENDATIONS

A detailed analysis reveals that Bujumbura's water distribution network is outdated, with most pipes and infrastructure having been in service for over 50 years. Due to aging materials and increased risks of leaks, contamination, and inefficiencies, a complete rehabilitation of the network is essential to ensure reliable water supply and improve overall performance. To enhance distribution, it is recommended that the water supply be managed sector by sector. By dividing the city into well-defined distribution zones, the water utility can regulate supply more effectively, optimize resource allocation, and respond more efficiently to operational challenges. This approach will also help contain potential contamination incidents, ensuring that issues in one sector do not compromise the entire system.

The water supply system of the study area is very complicated, we recommend to install a monitoring system to be able to manage correctly the network and to calibrate the hydraulic model using the records of pressure and discharges.

Furthermore, integrating modern water management technologies, such as real-time monitoring and advanced leak detection systems, will improve operational efficiency and enhance service delivery. These upgrades will contribute to a more sustainable, resilient, and safe water supply system for the residents of Bujumbura.

REFERENCES

Abdelbaki, C., & Touaibia, B. (2014). Contribution of geographic information systems and hydraulic modeling to the management of drinking water supply networks. The case of Tlemcen Urban Grouping, Algeria. *Techniques - Sciences - Methodes*, *5*, 52–60. https://doi.org/10.1051/tsm/201405052

Ahmadullah, R., & Dongshik, K. (2016). Designing of Hydraulically Balanced Water Distribution Network Based on GIS and EPANET. *International Journal of Advanced Computer Science and Applications*, *7*(2), 118–125. https://doi.org/10.14569/ijacsa.2016.070216

Anisha, G. (G), Kumar, A. (A), Kumar, J. A. (J), & Raju, P. S. (P). (2016). Analysis and Design of Water Distribution Network Using EPANET for Chirala Municipality in Prakasam District of Andhra Pradesh. *International Journal of Engineering and Applied Sciences*, *3*(4), 257682. https://www.neliti.com/publications/257682/

Arampatzis, G., Perdikeas, N., Kampragou, E., Scaloubakas, P., & Assimacopoulos, D. (2014). A water demand forecasting methodology for supporting day-to-day management of water distribution systems. *12th International Conference "Protection & Restoration of the Environment*, 1–8.

Awad, H., Yassin, A., & Ayad, A. (2012). Geographic Information Systems in Water Distribution Networks. *Conference Paper*, *June*, 14.

BIZIMANA, A. (2023). *La pénurie d'eau potable pousse les burundais to consommer l'eau de la rivière – Ibihe*. Ibihe.Org. https://www.ibihe.org/la-penurie-deau-potable-pousse-les-burundais-a-consommer-leau-de-la-riviere/

Coelho, B., & Andrade-Campos, A. (2014). Efficiency achievement in water supply systems - A review. *Renewable and Sustainable Energy Reviews*, *30*, 59–84. https://doi.org/10.1016/j.rser.2013.09.010

Des, S., & Ingénieur, M. D. E. L. (2019). *Mémoire scientifique par Olivier PILLER En vue d ' obtenir*. *June*. https://doi.org/10.13140/RG.2.2.23972.53122

Dongare, P., Sharma, K. V., Kumar, V., & Mathew, A. (2024). Water distribution system modelling of GIS-remote sensing and EPANET for the integrated efficient design. *Journal of Hydroinformatics*, *26*(3), 567–588. https://doi.org/10.2166/hydro.2023.281

Edwards, J., Koval, E., Lendt, B., Ginther, P., Black, A., Larsen, L. C., & Hauffen, P. (2012).

Benefits of integrating GIS and hydraulic modeling. *Hydraulic Modeling and GIS*, 3–23.

Gesellschaft, D., & Zusammenarbeit, I. (2021). *Deutsche Gesellschaft für Internationale Plan de Gestion de la Sécurité Sanitaire de l ' Eau (PGSSE) Pilote to Bujumbura , Burundi Présenté par Hydroconseil*.

Gupta, G., El-Zahab, S., Zayed, T., Rojek, I., Studzinski, J., Oliveira, E. M., Liu, Y., Ma, X., Li, Y., Tie, Y., Zhang, Y., Gao, J., van der Walt, J. C., Heyns, P. S., & Wilke, D. N. (2019). Pipelines 2019 95. *Sensors (Switzerland)*, *19*(23), 953–960. https://doi.org/10.1080/1573062X.2019.1597375

Ingutia, R. (2024). Who is being left behind in water security , where do they live , and why are they left behind towards the achievement of the 2030 agenda ? *Sustainable Water Resources Management*, *10*(5), 1–21. https://doi.org/10.1007/s40899-024-01140-0

Kabanyegeye, H., Sikuzani, Y. U., Sambieni, K. R., Mbarushimana, D., Masharabu, T., & Bogaert, J. (2023). Analysis of Anthropogenic Disturbances of Green Spaces along an Urban–Rural Gradient of the City of Bujumbura (Burundi). *Land*, *12*(2). https://doi.org/10.3390/land12020465

Kepa, U. (2021). Use of the hydraulic model for the operational analysis of the water supply network: A case study. *Water (Switzerland)*, *13*(3), 1–15. https://doi.org/10.3390/w13030326

Kirchner, L. (2017). Water and Sanitation Programme. *World Bank*. https://www.youtube.com/watch?v=NXnCtadvvhU

Kuma, T., & Abate, B. (2021). Evaluation of Hydraulic Performance of Water Distribution System for Sustainable Management. *Water Resources Management*, *35*(15), 5259–5273. https://doi.org/10.1007/s11269-021-03000-4

Kumar, A., & Das, K. C. (2014). Drinking Water and Sanitation Facility in India and Its Linkages with Diarrhoea among Children under Five: Evidences from Recent Data. *International Journal of Humanities and Social Science Invention*, *3*(4), 50–60.

Kumar, A., & Thakur, V. (2015). DESIGN OF WATER DISTRIBUTION SYSTEM USING EPANET Himalayan Seismology View project. *Article in International Journal of Advanced Research*, *September*. http://www.journalijar.com

Niyongabire, E., & Rhinane, H. (2019). Geospatial techniques use for assessment of vulnerability to urban flooding in Bujumbura city, Burundi. *International Archives of the*

Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, *42*(4/W12), 147–154. https://doi.org/10.5194/isprs-archives-XLII-4-W12-147-2019

Picazo, M. Á. P., & Tekinerdogan, B. (2024). Urban water distribution networks: Challenges and solution directions. In *Management and Engineering of Critical Infrastructures* (Issue September). https://doi.org/10.1016/b978-0-323-99330-2.00005-2

Preis, A., Whittle, A. J., Ostfeld, A., & Perelman, L. (2011). Efficient Hydraulic State Estimation Technique Using Reduced Models of Urban Water Networks. *Journal of Water Resources Planning and Management*, *137*(4), 343–351. https://doi.org/10.1061/(asce)wr.1943-5452.0000113

Rhugwasanye, C., Rao, C. H., Agarwal, S., & Lakhshmi, K. R. (2022). Rainfall Trend Analysis and IDF Curve Generation for Bujumbura Mairie in East Africa. *International Journal of Special Education*, *37*(3), 14636–14649.

Rossman, L. A. (2000). EPANET 2 Users Manual EPA/600/R-00/57. *Water Supply and Water Resources Division, U.S. Agency, Environmental Protection*, *September*.

Rukundo, Y. (2024). *Burundi / Bujumbura : L ' eau au compte-gouttes*. https://www.aa.com.tr/fr/afrique/burundi-bujumbura-l-eau-au-compte-gouttes-/2715581#!

Savić, D. A., & Walters, G. A. (1995). An evolution program for optimal pressure regulation in water distribution networks. *Engineering Optimization*, *24*(3), 197–219. https://doi.org/10.1080/03052159508941190

Scheele, U., & Malz, S. (2017). Water demand and water use in the domestic and industrial sectors – An overview. *Water Uses and Human Impacts on the Water Budget*, 95–99. http://www.klima-warnsignale.uni-hamburg.de/wp-content/uploads/2016/01/scheele_malz.pdf

Sindayigaya, I., & Toyi, O. (2023). *Water public policy in Burundi : Case of the city of Bujumbura*. *September*. https://doi.org/10.13140/RG.2.2.35148.18565

State of Queensland. (2021). *Water supply planning Guideline for water service providers*.

Tabesh, M., & Saber, H. (2012). A Prioritization Model for Rehabilitation of Water Distribution Networks Using GIS. *Water Resources Management*, *26*(1), 225–241. https://doi.org/10.1007/s11269-011-9914-y

Tsakiris, G., & Tsakiris, V. (2012). Pipe technologies for urban water conveyance distribution systems. *Water Utility Journal*, *3*, 29–36.

Tsegaye, S., Kebedew, M. G., Albrecht, K. K., Missimer, T. M., Thomas, S., & Elshall, A. S. (2024). Integrated GIS-hydrologic-hydraulic modeling to assess combined flood drivers in coastal regions: a case study of Bonita Bay, Florida. *Frontiers in Water*, *6*(October). https://doi.org/10.3389/frwa.2024.1468354

United Nations Human Settlements Programme. (2024). *Urbanization in Burundi: Building inclusive & sustainable cities*. https://unhabitat.org/burundi

Vališ, D., Hasilová, K., Forbelská, M., & Vintr, Z. (2020). Reliability modelling and analysis of water distribution network based on backpropagation recursive processes with real field data. *Measurement: Journal of the International Measurement Confederation*, *149*, 1–14. https://doi.org/10.1016/j.measurement.2019.107026

Walski, T. M. (1983). Technique for Calibrating Network Models. *Journal of Water Resources Planning and Management*, *109*(4), 360–372. https://doi.org/10.1061/(asce)0733-9496(1983)109:4(360)

World Bank. (2024). *Burundi Urban Population 1960-2024 | MacroTrends*. https://www.macrotrends.net/global-metrics/countries/BDI/burundi/urban-population

Zanfei, A., Menapace, A., Santopietro, S., & Righetti, M. (2020). Calibration procedure for water distribution systems: Comparison among hydraulic models. *Water (Switzerland)*, *12*(5), 1–18. https://doi.org/10.3390/w12051421

APPENDIX

Table 1 Calculation of the flow in each node

Node ID	Common pipes	Q en route (l/s)	Q n odale (l/s)
n61	p142	182.5355954	219.0691797
	p143	138.5284639	
	p145	117.0743001	
n63	p144	130.0813248	65.0406624
n4	p144	130.0813248	96.4170637
	p73	47.2671435	
	p74	15.4856590	
n3	p73	47.2671435	23.6335718
n5	p75	40.7347388	28.1101989
	p74	15.4856590	
n6	p75	40.7347388	59.4427876
	p76	78.1508364	
n7	p76	78.1508364	62.5769999
	p77	47.0031635	
n8	p77	47.0031635	23.5015817
	p78	23.1633159	
n9	p78	23.1633159	32.1778324
	p79	20.5961745	
n10	p79	20.5961745	63.4801290
	p80	53.1820417	
n11	p80	53.1820417	84.1874133
	p81	61.7575415	
n12	p81	61.7575415	88.9388607
	p82	44.8597434	
	p121	79.8635226	
n13	p82	44.8597434	75.5843270
	p83	53.1544553	

n14	p83	53.1544553	72.4324886
	p84	42.5630323	
	p100	49.1474896	
n15	p84	42.5630323	39.4848465
	p124	36.4066608	
	p85	39.4846740	
n16	p85	39.4846740	42.0711850
	p86	13.1581459	
	p92	30.8227617	
n17	p86	13.1581459	76.0224985
	p87	40.1614624	
n18	p87	40.1614624	76.0224985
	p88	55.9417673	
n19	p88	55.9417673	44.1294708
	p99	27.1897605	
	p89	61.0691810	
n20	p104	37.6522281	55.3237908
	p90	26.7305494	
	p105	46.2648041	
n21	p90	26.7305494	48.0120270
	p91	34.6467523	
n22	p91	34.6467523	17.3233762
n101	p67	15.48565897	15.4856590
	p68	15.48565897	
n68	p101	36.5973550	76.7076959
	p102	116.8180368	
n69	p102	116.8180368	66.7560768
	p103	16.6941167	
n70	p103	16.6941167	27.1731724
	p104	37.6522281	

n29	p92	30.8227617	29.0745907
	p93	27.3264196	
n28	p93	27.3264196	13.6632098
	p94	12.1208194	
	p106	34.6638878	
n25	p94	12.1208194	11.4645804
	p95	10.8083414	
n24	p95	10.8083414	13.2771651
	p96	15.7459888	
n26	p96	15.7459888	43.7280322
	p107	55.7655286	
	p97	15.9445469	
n27	p97	15.9445469	57.5399438
	p98	6.6364330	
	p108	92.4989076	
n23	p98	6.6364330	16.9130967
	p99	27.1897605	
n64	p108	92.4989076	128.8641328
n65	p107	55.7655286	27.8827643
n35	p125	109.4638295	54.7319147
n36	p125	109.4638295	106.0171371
	p126	102.5704447	
n40	p127	52.6788598	107.5459346
	p126	102.5704447	
	p6	59.8425646	
n30	p123	22.5356960	59.9538303
	p124	36.4066608	
	p118	60.9653038	
n31	p122	40.8663833	31.7010397
	p123	22.5356960	

n32	p118	60.9653038	60.8544108
	p117	60.7435178	
n33	p117	60.7435178	61.5617544
	p120	62.3799911	
n34	p122	40.8663833	20.4331916
	p120	62.3799911	
	p121	79.8635226	
n37	p117	60.7435178	60.2930412
	p11	59.8425646	
n38	p115	6.2324805	20.4862782
	p116	34.7400758	
n39	p115	6.2324805	31.1218785
	p114	28.0056382	
n48	p114	28.0056382	11.1535045
	p113	22.3070091	
	p129	21.1774427	
n47	p16	59.8425646	65.9801970
	p112	49.8108202	
	p113	22.3070091	
n46	p112	49.8108202	24.9054101
n49	p10	59.8425646	54.8824477
	p129	21.1774427	
	p128	28.7448880	
n41	p130	105.5493412	109.0353828
	p5	59.8425646	
	p127	52.6788598	
n42	p130	105.5493412	52.7746706
	p131	40.8237399	
	p9	59.8425646	
	p134	101.8384600	

n43	p131	40.8237399	42.6693854
	p149	27.3307388	
	p132	17.1842922	
n44	p132	17.1842922	38.5134284
	p13	59.84256465	
n45	p111	40.6742164	24.9054101
	p133	43.8373814	
	p112	49.8108202	
n50	p148	76.3580093	51.8443741
	p149	27.3307388	
n51	p110	54.5338954	76.0927324
	p111	40.6742164	
	p141	56.9773530	
	p14	59.8425646	
n52	p110	54.5338954	27.2669477
	p109	90.3906297	
n53	p141	56.9773530	55.2698387
	p140	53.5623244	
n54	p147	20.4631466	37.0127355
	p140	53.5623244	
n55	p147	20.4631466	48.4105780
	p148	76.3580093	
n56	p8	59.8425646	51.5861518
	p135	43.3297390	
n57	p135	43.3297390	72.5840995
	p134	101.8384600	
n58	p137	58.9428847	29.4714424
	p136	45.1054323	
n59	p138	28.7525975	14.3762987
	p139	40.7851474	

n60	p138	28.7525975	135.1155388
	p137	58.9428847	
	p142	182.5355954	
n62	p145	117.0743001	88.5406496
	p146	60.0069992	