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INTEGRATING GIS AND HYDRAULIC MODELING FOR SUSTAINABLE DESIGN OF WATER DISTRIBUTION NETWORKS: A CASE STUDY OF THE CITY OF BUKAVU IN DR CONGO

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Integrating GIS and Hydraulic Modeling for Sustainable Design of Water Distribution Networks: A case study of the city of Bukavu in DR Congo

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FEBRUARY, 2022

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.

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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.

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DEDICATION

To my beloved Mother Mapendo Cibangala Justine who passed away prematurely in 2009, I dedicate this thesis.

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Abstract

Drinking water is one of the vital needs for human beings' survival. However, access to drinking water represents strong inequalities on a global scale. While in some countries, even rural communities have access to a reliable water source, in sub-Saharan African cities, only 56 % of the population had access to tap drinking water in 2019. These inequalities are even more alarming between the different countries of the continent. An illustrative example of such conditions is the city of Bukavu in the eastern part of the Democratic Republic of Congo where access to drinking water decreased by about 90% between 2003 and 2019. The existing water treatment supplying the city was installed in 1954 with the construction of the Murhundu treatment plant, located 28km away from the city. Originally built to produce water for 50,000 residents, the treatment plant was upgraded in 1981, doubling its initial production capacity. However, the city of Bukavu currently has 1,133,000 million inhabitants, which is 20 times higher than the production capacity of the plant and its distribution network; as such, the existing water supply system is not able to handle this growth. Therefore, this study provides a solution to the current situation by estimating and forecasting the water demand and population for the city at horizon 2046, assessing the current water distribution network, and proposing a sustainable solution. The research used secondary and primary data comprising reports from the local municipal water supply company. GIS data sets and a database of the existing network designed into EPANET were used to assess the performances of the water supply system of Bukavu. The assessed model was thereafter, exported to Watergems for optimization of a proposed sustainable solution. The current water demand in Bukavu is 15.86 Mm^3/ year and is expected to reach 101,1 Mm^3/year in 2046. The existing water supply system is composed of one reservoir, 3 water tanks, 5 pumping stations, and a 300,049 m long piping network that shows poor hydraulic performance in most parts of the city. To overcome this problem, two alternatives were simulated in Epanet and Watergems involving the addition of a balancing tank in the system and increasing the pumping station capacity after renovating the entire piping system. However, a combination of these alternatives was found to be more sustainable, with a total investment and maintenance cost of 88 788 548 USD. Finally, these findings serve as a master plan for the city and water corporations, as well as for investors and decision-makers to guarantee sustainable drinking water accessibility for the citizens of Bukavu.

Résumé

L'eau potable est l'un des besoins vitaux pour la survie de l'être humain. Pourtant l'accès à l'eau potable représente de fortes inégalités à l'échelle mondiale. Alors que dans certains pays, même les communautés rurales ont accès à une source d'eau fiable, dans les villes d'Afrique subsaharienne, seulement 56 % de la population avait accès à l'eau potable du robinet en 2019. Ces inégalités sont encore plus alarmantes entre les différents pays du continent. Un exemple illustratif de ces conditions est la ville de Bukavu dans la partie orientale de la République démocratique du Congo où l'accès à l'eau potable a diminué d'environ 90 % entre 2003 et 2019. L'usine de traitement d'eau existant alimentant la ville a été installé en 1954 avec la construction de la station de traitement des eaux de Murhundu, située à 28 km de la ville. Construite à l'origine pour produire de l'eau pour 50 000 habitants, la station d'épuration a été modernisée en 1981, doublant sa capacité de production initiale. Or, la ville de Bukavu compte actuellement 1 133 000 millions d'habitants, soit 20 fois plus que la capacité de production de l'usine et de son réseau de distribution ; en tant que tel, le système d'approvisionnement en eau existant n'est pas en mesure de gérer cette croissance. Par conséquent, cette étude apporte une solution à la situation actuelle en estimant et en projetant la demande en eau et la population de la ville à l'horizon 2046, en évaluant le réseau de distribution d'eau actuel et en proposant une solution durable. La recherche combine des modèles SIG et hydrauliques pour utiliser des données secondaires et primaires comprenant des rapports de la société municipale locale d'approvisionnement en eau, des ensembles de données SIG et une base de données du réseau existant conçue dans le modèle EPANET pour évaluer les performances du système d'approvisionnement en eau de Bukavu et exportées dans Watergems pour l'optimisation d'une solution durable proposée. La demande actuelle en eau est 15.86 Mm^3/a et devrait atteindre 101.1 Mm^3/a en 2046, alors que le système d'approvisionnement en eau existant est composé d'une source, de 3 réservoirs d'eau, de 5 stations de pompage et d'un réseau de distribution de 300 049 mètres qui montre de mauvaises performances hydrauliques dans la majeure partie de la ville. Pour surmonter ce problème, deux alternatives ont été simulées dans Epanet et Watergems en ajoutant un autre réservoir d'équilibrage dans le système et en augmentant la capacité de la station de pompage dans un système de tuyauterie rénové. Cependant, une combinaison de ces alternatives s'est avérée plus durable, avec un coût total d'investissement et de maintenance de 88 788 548 USD. Enfin, cette solution servira de schéma directeur à la ville et aux acteurs du secteur de l'eau, ainsi qu'aux investisseurs et décideurs pour garantir un accès durable à l'eau potable aux résidents de la ville Bukavu.

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List of Acronyms and Abbreviations

AWWA: American Water Works Association

CAD: Computer Assisted Design software

DBPs: Disinfection by-products.

DEM: Digital Elevation Model

DRC: Democratic Republic of Congo

DDA: Demand-Driven Analysis

DMA: district metered area

EPS Extended Period Simulation

GA: Genetic Algorithm

GPS: Global Positioning system

GIZ: Gesellschaft für Internationale Zusammenarbeit

GIS: Geographic Information System

NDT: Network Diagnostic Tool

NRW: Non-Revenue Water

PDA: Pressure driven analysis

WDN: water distribution network

CHAPTER ONE

INTRODUCTION

1.1. Background Information

Throughout history, water points were important for the development of human civilizations, and nowadays, the resource remains one of the main factors to be considered for the creation and development of settlements, villages, and cities (Gowda, 2011). It is, therefore, of tremendous importance for a city to provide its citizens with water in enough quantity and adequate quality. However, having enough and adequate water supply facilities is a daily issue for any kind of settlement because water supply infrastructures have to be maintained and upgraded with some consideration with time, as well as the growth of the settlement. Failing to do that will see severe water-related crises appearing in the future (Lu *et* al., 2018). Moreover, according to GIZ (2019), only 56 % of urban citizens in Sub-Saharan Africa had access to piped water in 2019 which represents a decrease of 11% from 2003 statistics and demonstrates a lack of the sustainability aspect in the former urban water supply project on the continent. A typical example of this decrease is the Democratic Republic of Congo (DRC), being the biggest country in that region.

Chishug & Xu (2009), reported that the status of water supply services in urban areas is particularly worrisome in DR Congo. Despite the high urbanization growth between and 2006, the number of connections per km decreased from 36 to 18. Globally, the number of connections has decreased by 8 percent, and the volume of water sold also decreased by 10 percent as a result of limited production capacity. As of 2009, only 37% of the total urban population of the country had access to drinking water.

A perfect illustration of this astonishing change in the city of Bukavu in the eastern DRC, as in 2019 a 90 % decrease in the water supply of water has been reported in the city. This is mainly due to the limited capacity of the water treatment plants and the water distribution network which are no longer matching with the trend of the growing urbanization rates.

1.2. Statement of the Problem

The current water supply system in Bukavu was fully implemented in 1954 for a water demand corresponding to 50,000 inhabitants and was updated in 1984 to support a double demand of the initial one, that is to say, 100,000 inhabitants. According to Mekuriaw (2016), drinking water systems are generally designed for a design period of 30 years. The population of the city of Bukavu is 1,133,371, according to the World population review (2021) and the local municipality (Mairie de Bukavu, 2011); the current demand in the city is, therefore, twenty times greater than the amount of water produced by the Murhundu treatment plant. Moreover, it is important to point out that since 1983, no large-scale revision has been made on the system carried out in the city, both for the distribution network and for the treatment plant. As a result, the city is facing a drinking water supply crisis with all the ensuing consequences, including long-lasting water shortages, inadequate sanitation leading to recurrent epidemics of cholera and other diseases of 'water-borne and water-related, as well as social and economic burdens for city dwellers.

To overcome the crisis related to access to drinking water in the city of Bukavu, two long-term solutions are possible. The construction of a new water treatment plant, to extend the capacity of the reservoir to meet the current and future water demands, considering the growing population should be prioritized. Additionally, the water distribution network should be upgraded with a modernized network that considers technological advances to reduce the non-counted connections as well as the leakages (Non-Revenue Water), which will update the characteristics of the network (diameter, pipes, materials, reservoirs, etc.). According to (Ndyanabo *et al.*, 2010), the population growth in Bukavu is exponential in constant areas of around 60 km^2. This means that the current demand for water per municipality (avenue) has increased exponentially as the population continues to increase in the old avenues (more than saturation).

1.3. Objectives

1.3.1. Main Objective

The main objective of this study was to determine a sustainable water distribution network for the city of Bukavu, in D.R. Congo for the current and future water demands.

1.3.2. Specific Objectives

The specific objectives of this study were:

a) Determining the design period, water demand, and the required production capacity of the projected water distribution network for the next 25 years.
b) Evaluating the hydraulics performance and water quality of the existing distribution network.

c) Modeling a sustainable water distribution network for the city of Bukavu using hydraulic computer-based models in a GIS environment.

1.4. Research Questions

a) What are the current water production and water demands for the city? What will they be in the next 25 years?
b) How efficient and reliable is the current water distribution network in the city, in terms of water balance and water quality?
c) Does the existing water supply system meet the actual city's demand? Will it still be reliable for the next demand increase for the next 25 years? How sustainable is the proposed solution?

1.5. Justification of the Study

This study is important for many stakeholders in the Congolese water supply system. As a scientific-based solution, it serves as the foundation for upcoming related projects on the water supply system in the township because the study contains relevant background information for these types of projects.

In addition, the results will equip water utilities with computerized models of the current network and the proposed solution. Electronic design versions are important for effective and efficient management of a network, especially leakages management and network expansion. As of today, these models are inexistent for the city.

The study also contributes to the sustainable development of the township by laying the foundations of how clean water and proper sanitation can be provided to the more than a million citizens of Bukavu, which is an opening for prospective local and international investments, and the entire world through the Sustainable development goals.

1.6. Scope and Limitation of the Study

Modeling water quality profile (specifically residual chlorine profile) in a distribution network requires the collection of many water samples at key points of the network. This study was not able to collect the minimum number of samples for proper modeling of water quality profiles in the network. For this study, water quality analysis was not performed.

The advances in technology have made water supply network design an easier task than how it was in previous decades. Computer Assisted Design software (CAD) helps the designer to significantly reduce the allocated time to specific tasks and provide better accuracy to the design while giving options for different simulations and predictions scenarios. However, a clear understanding of the entry method of the model inputs is important to produce acceptable outputs or results which can be implemented as a project or used for scientific purposes.

Therefore, this study was limited by the availability of modeling tools because they are not financially accessible in most cases. Mostly, free software or models was used in this study. Moreover, the inexistence of a prior study or a computerized version of the network layout made the model validation and calibration process more complex.

CHAPTER TWO

LITTERATURE REVIEW

2.1. Water Production and Water Demand Management

Regardless of size or complexity, the basic goal of water distribution systems is to provide enough water from the treatment plant to the client. The reliability of water supply to customers is generally defined in terms of a level of customer service that is dependent on both the amount and quality of drinkable water (Goulter, 1999). Water distribution networks include pipes, nodes, pumps, valves, and storage tanks or reservoirs. The breakdown of one or more of such elements has a detrimental impact on the sustainability of the water provided to users. Municipal water distribution schemes are classified as branched and looped or a mix of the two, depending on how the pipes in the system are connected.

2.2. Forecasting the water demand

Typically, two steps are involved in water demand forecasting namely: Forecasting the population to be served and forecasting the total water use/demand per capita. Several methods and models are used for the prediction of future population and water demand. As mentioned by Gumbo (2020), population and demand forecast can be done by the Arithmetic increase method, the geometric increase method, the incremental increase method, the graphical method, the zoning method, ratio and correction method, the growth composition analysis, logistic curve method. However, the geometric increase method is the most commonly used in practice. In all the above-mentioned methods, the forecasted demand is calculated by the below formula:

$$Q_n = P_n * q_n = f(P_0, n, \ldots) * g(q_0, n, \ldots) \quad (2.1)$$

Where: Q_n = water demand in year n (in m^3/year);

P_n = Population in year n;

P_o and q_o= Population and per capita water demand in year 0.

q_n = Total per capita water demand in year n. (in m^3/pers./year).

2.3. Water Supply Systems

Water supply systems are composed of different components, including the raw water source, untreated water transport mains, water treatment facility, purified water transmission pipelines, and water distribution networks. The sources of water may include surface water (Freshwater Rivers and Lakes), groundwater sources from wells (Shallow and deep wells) as well saline water from the sea. The required water treatment processes depend on the source of the raw water and its quality. This is governed by the water quality contaminants that need to be removed from the water and the water quality standards that need to be met.

The supply can be done directly by delivering the water directly to the network from the clear water reservoir or delivered to another reservoir in the distribution area where it is delivered to the network either by pumping or by gravity. The water distribution pipes deliver the water to the distribution area by ensuring sufficient pressure and quantity of water as well as maintaining the quality of the water during distribution.

2.4. Water Demand Management

The demand for water resources is increasing as a result of many causes, including climate change, rapid urbanization, and population growth. This is especially the case in developing nations, where water resources are becoming more limited each day, as a result, there is increasing competition for water resources (Vairavamoorthy & Ali, 2000). To be able to analyze the performance and optimize or manage any WDN using hydraulic models, it is important to have an accurate estimation and prediction of the water demand (Trifunović, 2020). The amount of water consumed in a given location is determined by the rates of output, distribution, and leakage. Water production (Qwp) occurs at water treatment facilities, and it’s usually has a constant rate that is determined by the capacity of the WTP (Trifunović, 2020). Following the treatment, the water is collected in a clear water tank and fed into the WDN.

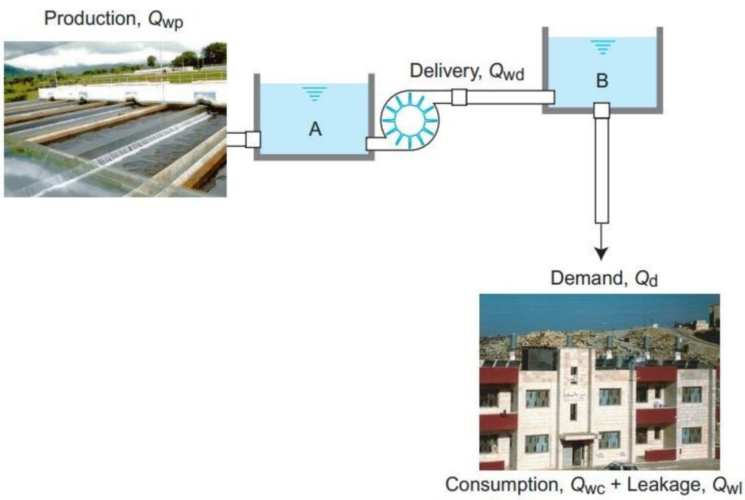


Figure 2.1:Water Production and Water Demand

2.5. Water Transportation and Distribution Networks

2.5.1. General Considerations

A water distribution system's role is to carry water from the treatment facility to the consumers. Additionally, distribution systems offer appropriate storage, flow, and pressure for the network. The distribution system infrastructure is generally the main component to assess a water utility (Luís Carvalho, 2017; Laurence Carvalho *et al.*, 2019). The American Water Works Association defines the water distribution network (WDN) as "including all water utility components for the distribution of finished or potable water by means of gravity storage feed or pumps though distribution pumping networks to customers or other users, including distribution equalizing storage'' (AWWA, 1974). Water transportation and distribution networks supply water from source and water treatment plants to consumers. Pipes, nodes, pumps, valves and storage tanks or reservoirs are components of the water distribution network. The failure of one or more of these components affects the adequacy of the water supplied to consumers negatively.

The design period of a WDN refers to the time frame in which the above-mentioned elements of the network are designed. In case the actual water demand varies from the projected one, the capacity of those components should be satisfactory during this period. The technological lifetime of a component in the WDN is the amount of time it can operate properly in a technical context, whereas the economic life is the amount of time it can fill its function until it becomes more expensive to repair. Economic lifetimes are rarely larger than technological lifetimes (Trifunović, 2020).

Depending on how the pipes are interconnected in the system, an urban WDN can be categorized as serial, branched, looped (grid) and the combination of the two, as shown in Figures 2.2 and 2.3. A branched system is good enough to supply a small community with reasonable investment costs, but it fails to guarantee the adequacy of the water supply during a pipe failure. Moreover, the fact large pipes in the system stay long without water during some irregular situations puts the water quality reliability of the system in question.

The nature of looped systems allows redundancy, which assists in ensuring that there is enough capability in the system to overcome local failure and to guarantee to supply of water to the customers (Ezio Todini, 2000). Therefore, the looped system becomes more hydraulically reliable than the branched system. In addition to hydraulic reliability, the looped system has reduced the risk of water quality problems by solving the shortcomings of the branched system (B).

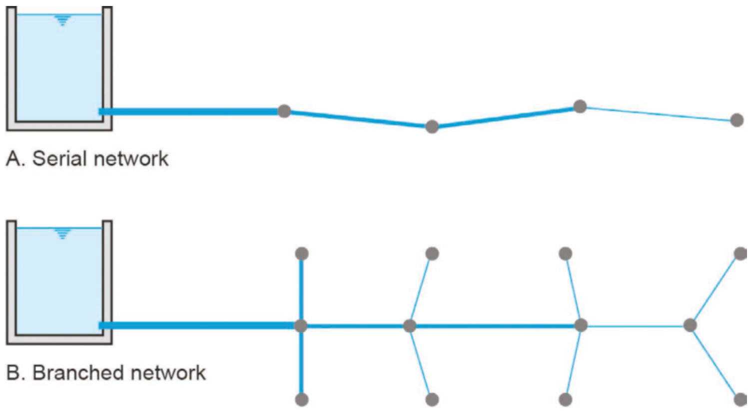


Figure 2.2: Serial (A) and branched (B) Water Distribution Network

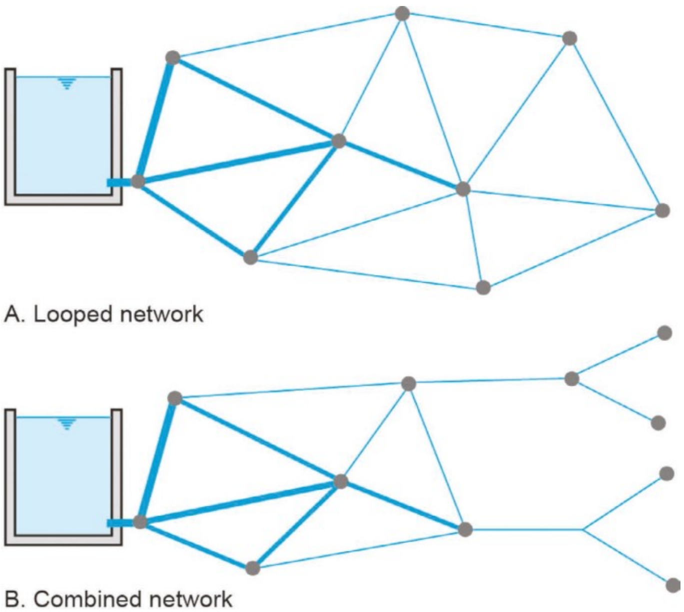


Figure 2.3: Looped (A) and combined (B) Water Distribution Network (Trifunović, 2020)

The key components of a Water Distribution System are, a link which is a section of a distribution network that carries water from one location to another (through a pipe, a supply link, or a distribution link); a node which is a place where two or more links connect, where a link originates, where a connection terminates, where a pipe diameter varies, or where a pump or a pressure reducing valve is located, and a loop which is a closed figure formed by the beginning of a node and traveling just once along its length.

2.5.2. Hydraulic Aspects of Water Distribution Networks

According to Trifunović (2020), the design of a WDN consists of two parts: the hydraulic part and the engineering part. The system will operate satisfactorily during the design duration if both the hydraulic and engineering design requirements are followed. A well-designed network should not only have sufficient pressures, flows, and velocities but should also fulfill the following additional requirements:

- Reduced operational costs in regular supply requirements,
- Reasonable supply in irregular situations (power/pump failure, pipe burst, fire events, system maintenance, rehabilitation or reconstruction) and,
- Flexibility for future extensions,
- Selection of durable pipe materials, joints, fittings, and other appurtenances,
- Quick isolation of valves and easy access to the vital parts of the system, etc.

The behavior of water distribution systems is governed by physical laws that describe flow relationships in pipes and hydraulic control elements, customers demand, and system layout (Ezio Todini, 2000). The distribution of flows through the network under a certain loading pattern must satisfy two fundamental laws:

- The law of conservation of mass states, assuming that water is incompressible, the net flow at each of the junctions in a network should be zero, i.e.,

$$\sum Q_{in} - \sum Q_{out} = \sum Q_{ext} \qquad (2.2)$$

Where:

Q_{in} and Q_{out} = pipes that flow into and away from the node, respectively, and

Q_{ext} is the external demand or supply at the node.

The law of conservation of energy states that the total head loss across a closed loop in the network should be zero, i.e.,

$$\sum h_L - \sum H_{pump} = 0 \qquad (2.3)$$

Where:

h_L = the head loss in a pipe and,

H_{pump} = the head added by a pump contained in the loop.

The conservation of energy can also be applied between two sections of any pipe of the system. Applying Bernoulli's Equation, the energy balance between any two cross-sections of a pipe can be expressed as,

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} \pm h_L \quad (2.4)$$

Where:

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

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

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

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

Commonly used equations for the calculation of pipe friction losses are the Darcy-Weisbach, the Hazen-Williams and the Manning equations. The friction losses are a function of the diameter of the pipe (D in mm), length of the pipe (L in m), flow rate (Q in m^3/s), and experimentally determined friction factors (C, λ and N). Mathematically, this is shown in Equations (2.4), (2.5) and (2.6).

$$h_f = \frac{\lambda L}{12.1\, D^2} Q \quad \text{(Darcy-Weisbach)} \quad (2.5)$$

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

$$h_f = \frac{10.29\, N^2 L}{D^{16/3}} Q^2 \quad \text{(Manning)} \quad (2.7)$$

2.5.3. Hydraulic Analysis of Water Distribution Systems

According to (Trifunović, 2020), the analysis of WDN is divided into two types, one is Demand-Driven Analysis (DDA) which is used for steady-state conditions for which nodal demands are known and are constant inputs, and Pressure Driven Analysis (PDA) which applies to an abnormal condition. DDA presupposes that nodal flows are always met at all demand nodes, no matter the existing pressures. PDA, on the other hand, considers the pressure at nodal demand.

a) Demand-Driven Analysis

To calculate pressures and flows in the water distribution network, modeling tools such as EPANET, Watergems and EPASWMM employ a demand-driven technique. The demand-driven approach (DDA) implies that no matter what the present pressure is, the needed demand is always totally supplied.

b) Pressure Driven Analysis (PDA)

DDA software are excellent modeling to is an excellent tool for analyzing water distribution systems. However, they are unsuitable for simulating pressure-deficient circumstances or pipe leaks. In these instances, demand cannot be regarded as a constant specific value, but must rather be seen as pressure-related. Commonly, it is recommended to consider a pressure-demand connection and utilize it in the (iterative) simulation process to perform a pressure-dependent demand simulation (Seyoum *et al.*, 2011).

In pressure-deficient scenarios, DDA analyses are inaccurate, and a pressure-driven method (PDA) is required. PDA is usually performed by employing equations that estimate available demand/leakage as a function of current pressure(Seyoum *et al.*, 2011).

c) Water Quality Analysis in WDN

One of the most pressing issues in the drinking water sector today is the preservation of water quality in water distribution networks. Water quality deteriorates as a result of complicated chemical and microbiological processes occurring in the distribution network. One of the health risks linked with water quality issues is the creation of possibly carcinogenic disinfection by-products (DBPs) as a result of disinfectant interaction with inorganic and organic chemicals in the water (Seyoum *et al.*, 2011).

Water quality modeling has become critical for utility companies to anticipate and regulate water quality. To simulate various water quality characteristics, water distribution hydraulic models have been combined with water quality models. Nonetheless, hydraulic models must be extremely precise before they can be utilized in combination with water quality models.

2.6. Applications of GIS in water Transportation and Distribution

GIS offers a wide range of applications for water distribution system research. The use of GIS to represent and analyze water-related processes assists in their management. A water utility can create a thorough capital improvement plan and operations and maintenance strategies utilizing geographic information from modeling, mapping, facilities, and workers management.

2.6.1. GIS for modeling of water distribution networks

GIS can be used to evaluate process changes for a water company or to verify the effectiveness of some established treatments including corrosion control or chlorination. GIS might also be used to examine the occurrence of controlled pollutants for calculating compliance costs or assessing impacts on human health, and GIS can assist in the design and management of wellhead protection plans. Shamsi (2002) defined the interchange method, interface method, and integration method as the three methods to model a WDN based on GIS.

To exchange information between a GIS tool and a hydraulic model, the interchange technique applies a batch process. In this approach, the GIS and hydraulic model are not linked directly by any kind of relationship. The GIS and the model are run separately, without any link. The GIS database is mined for model input data, which are then manually transferred into a hydraulic model input file. Likewise, the hydraulic model output data are manually transferred into the GIS environment to establish a new layer for mapping and presentation of the results (A thematic map of pressures and water demands in DMA's for instance). The interchange approach includes estimating nodal demands from land-use layers and obtaining node altitudes using digital elevation models (DEM).

The interface method establishes a direct connection for data transmission between a hydraulic model and a GIS environment. This method consists of two components at least, including a pre-processing tool that imports the hydraulic model's output and then displays it in a GIS environment as a layer; and a pre-processing tool that analyses GIS information and exports it in a hydraulic modeling tool as input data. Essentially, the interface approach automates the data transfer process by adding model-specific menus and/or buttons to the GIS program. Options for data modification and running the model from inside the GIS environment are not accessible with this procedure(Shamsi, 2002).

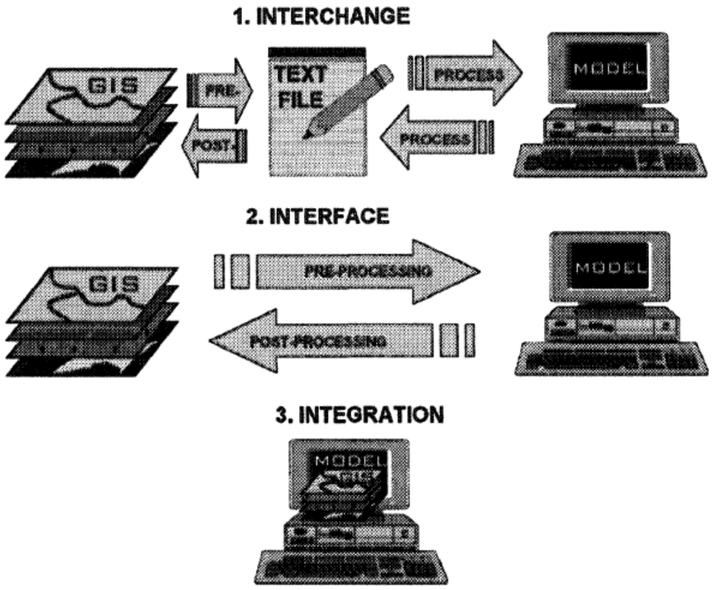


Figure 2.4: Methods used for application of GIS in hydraulic modeling

GIS integration, on the other hand, is the merging of a model with a GIS so that the merged application provides both GIS and modeling capabilities. This strategy offers the most direct link between a GIS tool and a hydraulic modeling tool. Watergems is a perfect example of such a system.

2.6.2. GIS for WDN Skeletonization

Water distribution systems' GIS and CAD layers frequently have a degree of information that is unimportant for the study of the hydraulics of a network. Fire hydrants, household connections, valves and fittings, and corner nodes are all examples of this. Even though producing models that are precise representations of the real system is today possible because of incredibly powerful computing systems, the price of obtaining, building, and running such complex models can be extremely costly. Trying to integrate all network parts might be a massive task with little influence on model findings (Trifunović, 2020). As a result, design engineers adhere to a network simplification procedure known as "skeletonization."

Automatic GIS-based skeletonization eliminates the complication of the data while preserving the integrity of the system and its hydraulic equivalence. In general, it is feasible to reduce the size of a network by 10-50 percent. The skeletonizer module of H_2OMap water system modeling software and the skelebrator module and WaterCAD (WaterGEMS) respectively, are two programs that perform the skeletonization of GIS and CAD layers.

2.6.3. GIS for Nodal Water Demand Estimation

A hydraulic model's nodal water demand is an essential input data that represents the rate of water consumption in units of volume per time (L/d for example). Consumer type (for instance, residential, industrial, or institutional) or quantity (For example average daily, peak monthly, or demand for fire) are used to categorize the water demand. Estimating nodal water demand manually based on the client's billing information is a time-consuming task. As a result, modelers have historically relied on estimative approaches such as the uniform distribution of household water consumption over all the nodes, followed by the addition of nearby business and industrial usage at multiple nodes.

GIS enables the use of more precise demand estimation methodologies. One such technique makes use of GIS to geolocate all existing water consumers (specified by the location where water meters are) and attribute the measured water usage rates for each meter position to the closest node in the hydraulic model. The geocoding method associates a street location with a geographic location and determines the position information of a point location using its address. This approach presumes that a computer file (which may be an excel spreadsheet or a text file) that contains meter addresses and measured water consumption for specific periods may be generated from the utility's billing database.

2.7. Optimization of Water Distribution Networks

Solving real-life problems in water engineering often requires finding optimal solutions because water distribution networks are costly to install and maintain. With the rising water demand, the need for WDN dependability grows day by day, necessitating optimizing their design and management (Abunada et al., 2014, Sarbu, 2010, Savi, and Mala-Jetmarova, 2018).

The goal of optimum WDN design is to ensure optimal system performance over a period of time at the lowest possible cost. Conventional design methods (trial and error) are time-consuming and might not provide ideal solutions for WDN challenges owing to the complicated interaction of network elements(Vairavamoorthy & Ali, 2000). However, according to Vairavamoorthy and Ali (2000) the optimization tool is simply used to make the engineer's job easier, not to avoid the engineer's requirement for solid technical judgment.

According to Wang et al. (2015), optimization is described as "finding an alternative with the most cost-effective or best attainable efficiency under the given restrictions, by maximizing desirable factors and reducing unwanted ones." The technique of optimization is hampered by a lack of complete information as well as a lack of time to assess what data is available." Mala-Jetmarova *et al.* (2018) used WDN optimization for their operation, designing, rehabilitating, and calibration.

Historically, the basic goal of every optimization process has been the least cost function, that is, to decrease the WDN's cost. However, there is growing recognition that there is a need to move to a multi-objective optimization problem or multi-objective functions of cost minimization as well as additional objective functions linked to system dependability (Mala-Jetmarova *et al.*, 2018). The WDN's performance is influenced by several variables. This necessitates an assessment of the effects of these elements as optimization process targets.

Several optimization methods have been developed in research. Non-linear programming, enumeration techniques, linear programming gradients, dynamic programming, stochastic search methods/metaheuristic algorithms, and genetic algorithm are among these methods. Evolutionary Algorithms or Genetic algorithms (GA) is the most successful search approach in WDN(Vairavamoorthy & Ali, 2000).

2.7.1. Genetic Algorithms

Created by John Holland GA in 1960, GA is a stochastic optimization method, based on the natural evolutionary theory developed by Darwin. GA has been widely used to solve or optimize WDS problems such as design, structural, and operating conditions optimization.GA can develop a solution based on evolutionary theory by using the concepts of the genetics of survival and adaptability of species through reproduction (natural selection), cross-over, and mutation. This approach depends on the fitness of each member of a large population at the beginning.

2.7.2. GA optimization procedure

- Randomly generate an initial population of possible solutions based on pre-specified coding scheme 2)
- Compute the fitness of each solution in the population 3)
- Generate a new population of solutions using evolution-based operators: selection, reproduction (crossover), and mutation

- Repeat steps (2) to (4) to produce successive generations of solutions until some termination criterion is met.

A solution's fitness is assessed against a set of constraints in GA, and this is either accepted or rejected. If it is chosen, it gets crossed across and modified to improve it. The probabilities of a solution surviving in a large starting population are determined by its fitness. If the solution is improved than the previously found, it is chosen to be part of the next generation of solutions, which will go through the same iterative process including, cross-over, and mutation to produce the next generation of more fitted solutions.

The main problem with GA is its inability to handle constraints when used to a WDS with multiple restrictions (for instance, pumps status, minimum pressure levels in the system, and level of tanks). To manage and meet the restrictions, an external hydraulic solver is necessary (Vairavamoorthy & Ali, 2000). According to Simpson Angus *et al.* (1994), "with GA, there is no assurance that the global minimum solution is achieved, but near-optimal solutions are reached after multiple evolutions."

2.8. Calibration of Water Distribution Networks

Model Calibration is very useful to the creation of an accurate water distribution model that can successfully serve to both realistically reflect the behavior of the actual network being modeled and to help predict future changes in network conditions. Calibration is very important in water distribution modeling, and no model should be used un-calibrated (Walski,1983; Ormsbee, 1989). Shamir et al. (1968): Calibration of a model consists of determining the physical and operational characteristics of an existing system. This is achieved by determining various parameters that, when input into a hydraulic simulation model, will yield a reasonable match between measured and predicted pressures and flows in the network.

For the WDN hydraulic model, calibration parameters include pipe roughness, pipe diameters, nodal demands, wave celerity. These parameters are calibrated by measuring pressures, flow rates, or tank water levels in the real network. The water quality model can also be calibrated using reaction rate constants. Water quality calibration involves measuring chlorine concentrations or using data from tracer tests. Other measurement data sources include regular fields tests and the emerging SCADA system.

2.9. Post-Calibration Analysis

The objective of the post-calibration is to evaluate the quality of the parameters obtained in the calibration procedure. The modern post-calibration process involves:

- Assessing model fit more thoroughly by calculating various statistics and plotting different graphs;
- Estimate parameter and model prediction uncertainties by performing the uncertainty analysis;
- Validate the calibrated simulation model on 'unseen' data. All statistics shown here can be applied to both calibration and validation data sets.

2.10. Hydraulic Analysis and Modelling Tools

WDN design and operation have shifted from conventional and manual techniques to computational technologies that make the analysis of WDN less challenging, more consistent, and faster, utilizing computer-based tools and software. In this context, research has concentrated on the development of software utilized in the modeling of WDN for both commercial and public uses (Sonaje & Joshi, 2015).

In recent decades, the use of computational modeling has become important since WDN has gotten increasingly complicated and would require a longer time to analyze manually. WaterCad, waterGEMS, EPANET, Aquis, and SWMM are some of the modeling tools assessed by Sonaje and Joshi (2015). Aquis gives the advantage to analyzing and monitors the present situation in real-time, allowing operators to make better and wiser decisions, while SWMM gives the possibility to analyze drainage systems and open channels as well (Wateronline, 2022).

These programs are either free software or commercially available. In addition, the program has a variety of skills such as water quality assessment, cost, and energy calculation, leakage and pressure modeling, network calibration, and operation optimization, among many other features that are always being enhanced through research.

a) WaterGEMS

Developed by Bentley, WaterGEMS is the most popular commercially available hydraulic modeling software for water distribution systems. The software has advanced connectivity and modeling capabilities such as Water Hammer and Darwin Designer tools. Compared to other commercial and free modeling tools, WaterGEMS may be used to assist the design of new distribution systems, estimate fire flow capacity, establish network cleansing plans, detect water losses, monitor and reduce energy consumption, and optimize pipe renewal, among other functions. According to Bentley (2021),Watergems is the perfect modeling tool for:

- **Intelligent planning of WDN reliability**: When system expansion is expected, the water network's ability to effectively service its customers must be examined. Identify future issue locations, accommodate service area development, and plan capital upgrades using OpenFlows WaterGEMS.
- **Optimized processes for WDN efficiency**: It can be challenging to realistically simulate the functioning of complicated water systems. Model pumps precisely, optimize pumping approaches, and schedule shutdowns and normal operations to minimize disturbance using OpenFlows WaterGEMS.
- **Asset renewal decision support that is dependable for system sustainability**: When it comes to renewing or replacing an existing water infrastructure, the quantity of asset-related information to evaluate might be confusing. Pipe Renewal Planner, an OpenFlows WaterGEMS capability, makes the process considerably easier by evaluating and comparing a broad variety of criteria to prioritize renewal options(Bentley, 2021).

b) Epanet

The most frequently utilized public domain is EPANET 2 (Rossman, 2000). It was created by the US Environmental Protection Agency (USEPA). In the Water distribution network, EPANET 2 can do extended period simulations (EPS), and the code is freely accessible. The solver in EPANET 2 employs the global gradient algorithm created by E. Todini and Pilati (1988), that resolves the mass conservation and energy equation, as well as the relationships between the head and flow at a given point, to provide the flows in the link and pressure at the nodes(Kabaasha, 2012). This is performed in a series of iterations till convergence is attained, at which point the resolution of the nonlinear hydraulic equations is obtained (Rossman, 2000). EPANET 2 also contains a public domain programmers' tool set that has been utilized by numerous scientists to investigate elements of water distribution, especially optimization studies. The EPANET 2 programmer's tool kit includes capabilities that allow users to customize the hydraulic functions of EPANET to meet their specific needs. EPANET 2 was designed to do demand-driven analysis; nevertheless, Pathirana (2011) and others have created editions of EPANET that can perform pressure-driven analysis (EPANET-EMITTER).

EPANET is not only capable of simulating the hydraulics and water quality in the distribution networks, but the software can also be adapted for user particular objectives. Seyoum *et al.* (2011) created a program that can forecast chlorine disinfection Byproducts (DBPs) in distribution networks with the USEPA DBPs model. The network diagnostic tool (NDT) created by Trifunović (2020) and later improved by Abunada (2012) is useful for hydraulically analyzing distribution network reliability. Both of these tools were created by combining the toolkit available in EPANET and C++ programming.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Study area

Geographically located at 2.5123° S, 28.8480° E, Bukavu is a city in the east of the Democratic Republic of the Congo (DRC), located near the extreme south-western border of Lake Kivu, west of Cyangugu in Rwanda, and separated from it by Ruzizi River. The city of Bukavu is the capital of the South Kivu province. Bukavu is limited to the west and south by the territory of KABARE. To the north by the Kivu Lake and the east by the Ruzizi valley, a tributary allowing Lake Kivu to flow into the Tanganyika Lake and which forms the natural border with Rwanda and Burundi, as shown in Figure 3.1.

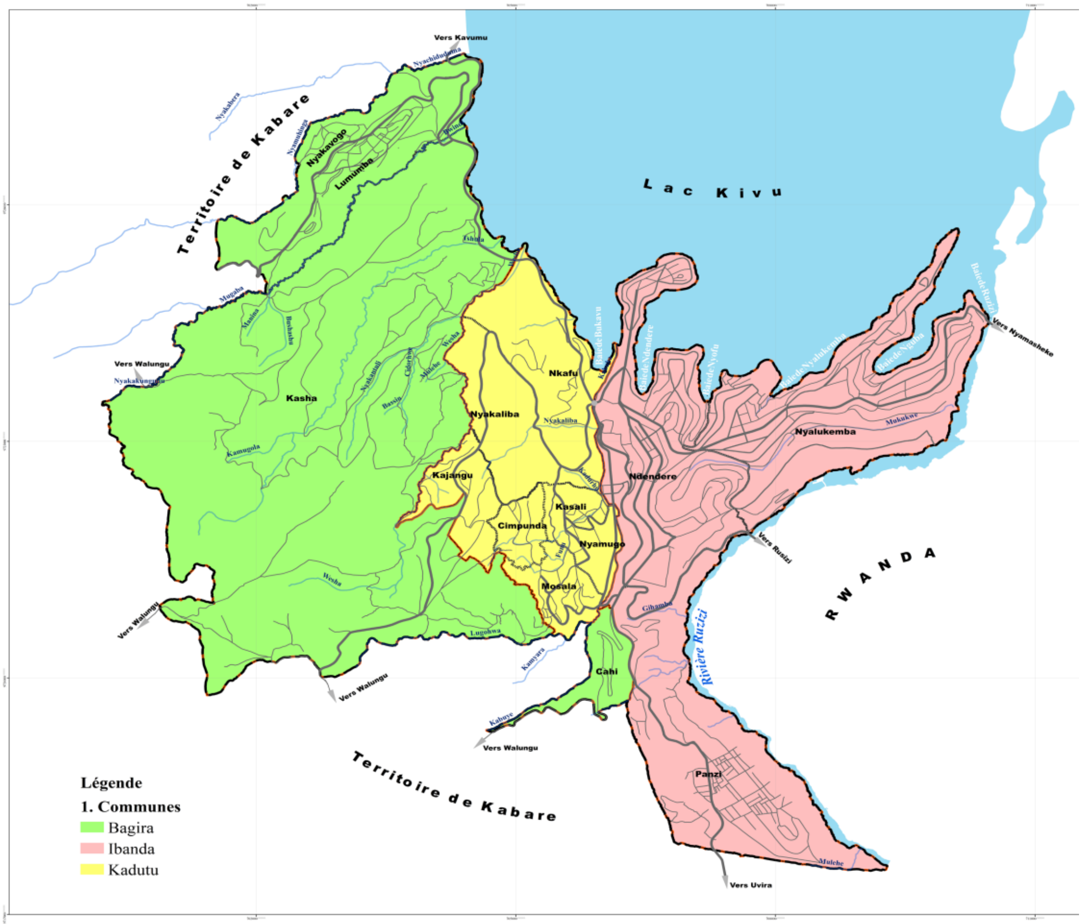


Figure 3.1: Administrative subdivision of the City of Bukavu

Only the plane allows a connection with Kinshasa (1600 km) the capital of the country, Lubumbashi (100 km) the large mining center of Katanga, and Kisangani (500 km) the large river port. Because of this isolation, the city plays an important strategic role in the political, administrative, economic and intellectual domains. As shown in Figure 3.1, the city is divided into 3 municipalities: Bagira, Ibanda and Kadutu.

3.1.1. Climate and Hydrography

Bukavu has a tropical low-altitude subequatorial or humid tropical climate at an altitude varying between 1500 m (at the site of the Société Nationale des Chemins de Fer Congolais, SNCC, where the Kawa river meets Lake Kivu) and 2,194m (on Mount Mbogwe in the Kasha district in the commune of Bagira), which moderates the temperatures a lot as it rarely exceeds 25 ° C on average in the rainy season while in the dry season it oscillates between 9.9 and 23 ° C. The hottest and the strong drops in temperature are recorded in June and July. The rainy season lasts more or less 8 months from September to mid-May (CAID, 2016).

The coastline of Lake Kivu (extended over a distance of ± 10km) is one of the important aspects of tourism in the City of Bukavu. The Kawa, Wesha, Chula, Mugaba, and Nyaciduduma rivers are the most important in the city and constitute the tributaries of Lake Kivu while the Ruzizi river, the border of the DRC with Rwanda and Burundi, discharges the waters of Lake Kivu into the Tanganyika in the far south of the city (CAID, 2016).

With an altitude of between 1,500 m (at the site of the Société Nationale des Chemins de Fer Congolais, SNCC, where the Kawa River meets Lake Kivu) and 2,194 m (on Mount Mbogwe in the Kasha district in the commune of Bagira), the City of Bukavu has a climate approaching that of subequatorial or humid tropical (of short duration) with the influence of the altitude climate of 1,500 to 2,000 m.

The climate and the relief of the city gave it forest vegetation during the 80s. Bukavu was once called ‘’the green’’ thanks to the predominance of reserved green spaces. Currently, this vegetation is disappearing as a consequence of the destructive management of the environment: irrational deforestation, anarchic granting of plots, wandering animals, etc.

3.1.2. Administrative subdivision

With an area of 44.9 km², the city of Bukavu is subdivided into three municipalities namely: Bagira (with 23.30 km²), Ibanda (with 11.57 km²), and Kadutu (with 10 km²).

As presented in Figure 3.1, the city is limited by:

- the Kivu Lake in the North,

- To the South through the territory of Kabare along a conventional line that starts from the east of Panzi and extends west to the Nyamuhinga river in the commune of Bagira. This river discharges its waters into the Nyaciduduma before flowing into Lake Kivu in the North.
- the Nyamuhinga and Nyaciduduma rivers in the West, constituting the western limit of the City of Bukavu with the territory of Kabare.
- The Ruzizi River to the East, which receives the waters of Lake Kivu and carries them to Lake Tanganyika, initially constituting the limit to the City of Bukavu but also, by its extension, the limit between the DRC and the republics from Rwanda and Burundi. Bukavu is divided into 3 municipalities, namely Bagira, Ibanda, and Kadutu, and each of these municipalities is divided into districts. Table 3.1 presents the city's municipalities and their districts.

Table 3.1: Municipalities, Districts and Streets in Bukavu (CAID, 2016)

Municipality	District	Street
BAGIRA	Lumumba, Kasha, Nyakavogo	Fariala, Bwindi, Chikera, Kasheke,Chai,Bobozo, Mulwa,Bulezi, Chiriri,Igobe,Mulambula, Potopoto, Chimamuzige,
IBANDA	Ndendere, Nyalukemba, Panzi	Nyhamona,Maniema, Fizi, Major-Vangu, Route D'uvira, Bizimana, Muhungu,Nguba, Mulengeza
KADUTU	Mosala, Nyamugo,Kasali,Chipunda, Kajangu, Nkafu,Nyakaliba	Karhunva, Buholo, Funu,Lomami,Rukumbuka, Camp Tv, Kawa, Burhalaga, Byasi, Ulindi, Nyamulagira, Nkafu, Sake, Busoke, Karhale, Elila

3.2. Methodology

3.2.1. Population Forecast, Water Demand, Required Water Supply and Water Production

The population was forecasted for the next 25 years as the design period (2021-2046) of the projected water distribution network. From a total population of 1,133,371 in 2021 (World population review, 2021), the future population was estimated with an average population growth of 5.14 %, which has been found from the World population review (2021). This value has been validated by comparing the calculated population (by the geometric increase method) with population data from different organizations such as the World Bank and the World population review. The current water coverage of about 50 % only was estimated to remain constant for the next five years (2021-2026) and then increase by 5 % each five years to reach a 70 % water coverage in the city at the end of the design period (2046). Equation 3.1. were used to calculate the forecasted population.

$P_n = P_o(1-r)^n$, (3.1)

with:

Pn: The population after n years;

Po: The population at present;

r: the population growth rate;

n: the number of years.

The water demand was divided into three categories: domestic consumption, industrial and others use as main water consumers in the city.

a) Population calculation and forecast per municipality

The population was also calculated and forecasted for each of the three municipalities (Bagira, Ibanda, Kadutu) and then for every district in each municipality since the water demand is directly linked to the population in the district. For municipalities, the population was calculated using population census data in each of them from a census carried out by the local government in 2011.

For the three municipalities, the population was later forecasted to find the present population (2021) in each municipality and also at the end of the design period (2046). The sum of the population in the municipalities in 2021 was compared to the city's global forecasted population. The difference between the two values was used to correct the population growth rate from 5.14 % to 5.13 %. However, this difference was very small (< 1%).

b) Population Forecast Per District in Municipalities

The population was also calculated for each district in municipalities since the water consumption and water demand in a district are directly linked to the size of the population. However, there was no data available about the population in districts in Bukavu. A GIS dataset from which the number of houses could be estimated in each district was used to calculate the density for every district. The density was later used to calculate the population in each district.

c) Maximum daily peak factor

d) Nodal demand allocation

The procedure used for nodal water allocation was based on the population density per district as shown in Figure 3.2, as well as the water demand in each district. This procedure is similar to the Thiessen polygonal interpolation procedure used for DEM generation and is the method is specifically recommended for nodal water distribution in residential areas(Goulter, 1999). This involved a two-step procedure as follow:

- The area of a district (in percent of the total area of the city) is divided evenly between the nodes located inside the district. That means, in areas with more than one nodal demand in its boundaries, the corresponding area was distributed equally for each node;
- The area corresponding to each node is multiplied by the density of the corresponding district (in inhab/m^2) and the water per capita demand (in m3/inhab/day), thus giving the nodal water demand in m^3/d;
- The nodal water demand is multiplied by a demand multiplier in Epanet to simulate the demand increase in the future scenario. The water demand multiplier is obtained by dividing the future water demand by the current one.

Figure 3.2: Population density per municipality in the city of Bukavu

The overall methodology for population forecasts and water demand distribution is presented in Figure 3.3.

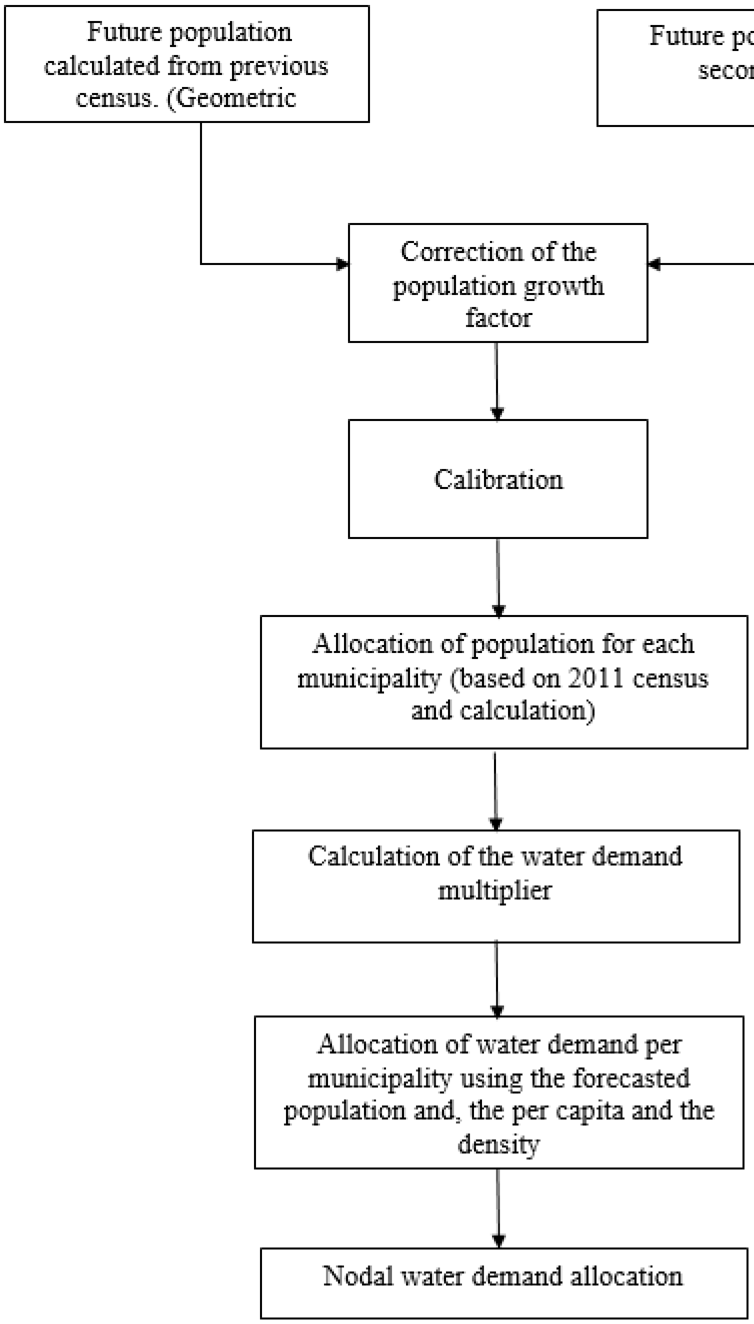


Figure 3.3: Population forecast and water demand allocation per municipality

3.2.2. Modeling and Analysis of the Water Distribution Network in Epanet

a) Generating the Digital Elevation Model (DEM) of the City

The data of the current network were collected manuscripts at REGIDESO, the local water supply company. A skeleton of the network was then modeled in Epanet, coupling with a DEM of the city, created with google earth pro and ArcGIS. The city's elevation data were exported from google earth to ArcGIS where the DEM was generated. On the city's map in Google earth pro, polygons were created to select the area of interest. These polygons are normally points with elevation information. As illustrated in figure 3.4., an image of the city was overplayed on the map to limit the zone of interest.

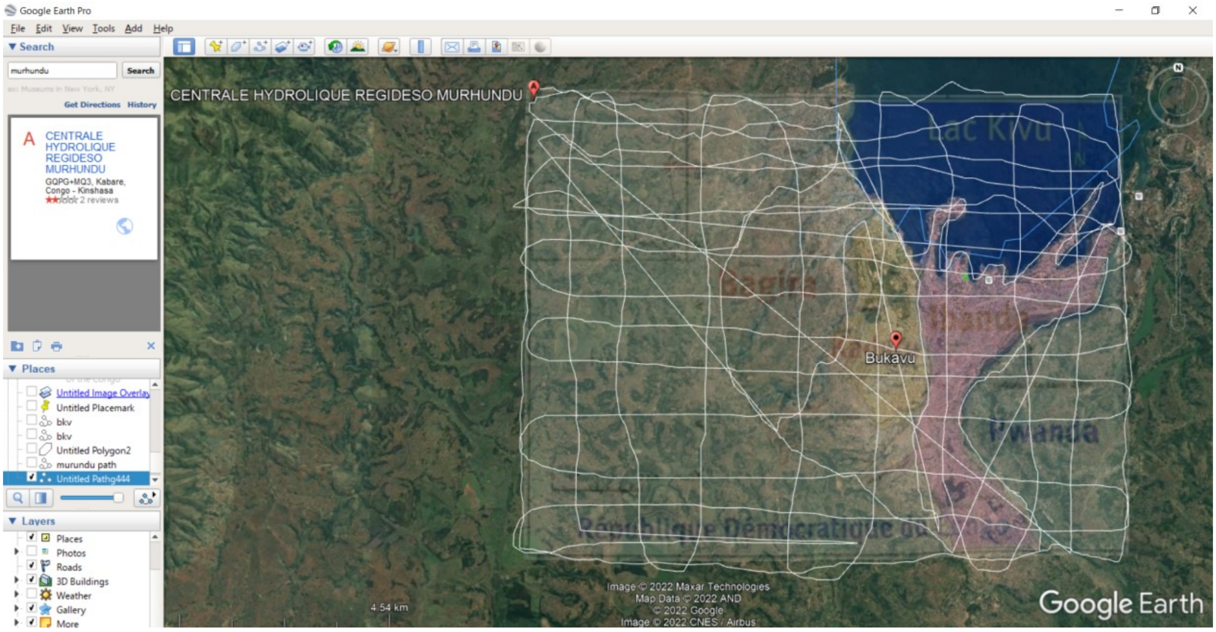


Figure 3.4. polygons with elevation information for Bukavu's DEM generation in Arcgis

The obtained file was then saved as a .kml (Keyhole Markup Language), which is a file format used to display geographic data in an Earth browser. With the GPS visualizer tool, the .kml file was converted to a .gpx file, which is readable by ArcGIS. GPX files are used to share GPS position data with others, such as maps, routes, and geocache information. As shown in figure 3.5, in ArcGIS, the ''gpx to features conversion tool'' was then used to convert the .gpx file into a shapefile with the elevation information. With the kriging interpolation method, the shapefile was then used to generate the contour lines and the DEM of the city.

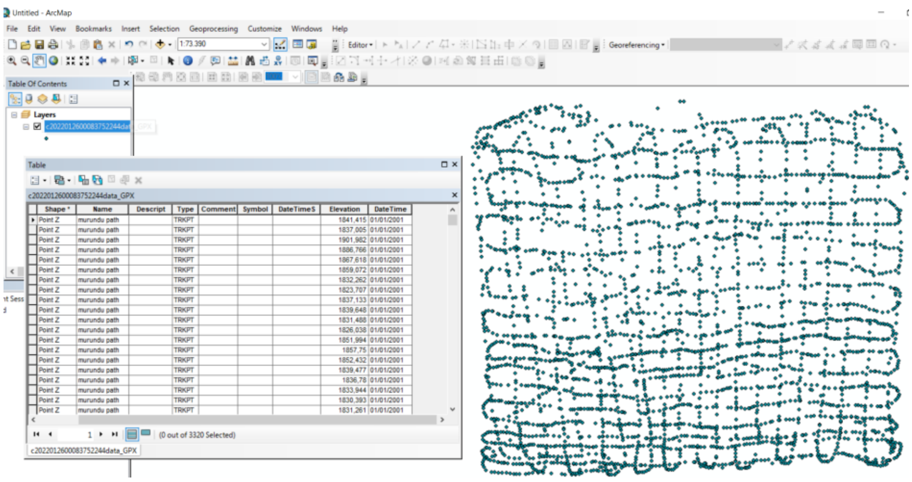


Figure 3.5. Conversion of the city's .gpx file into a shape file with elevation information in Arcgis

This data was used to calibrate the nodal elevations provided by the data from REGIDESO. Through field visits, the current network installations were inspected to highlight their major weaknesses. A demand-driven analysis (DDA) was run in Epanet to assess the current network for the current and future water demands. Later the model was overlapped with GIS layers and imported for further pressure-driven analysis in WATERGEMS to optimize the obtained results. Different scenarios were simulated in watergems to determine the optimum design in terms of hydraulic and economic performances.

For the calibration check of the developed model, a few elevation data were collected with a GPS. This data was then digitized in the model and compared to the GIS data and the data provided by REGIDESO.

b) Design and analysis of the existing network in Epanet

The data from the preceding phases were imported into the EPANET Software to generate a new model, which was then used to simulate different scenarios. The elevation of the land area was determined by overlaying the WDN model with the DEM of the city in Arcgis. A node crossing a given contour line was assigned its corresponding elevation value. This elevation was calibrated by comparing the assigned value with the nodal elevations provided with the data from the municipal water supply company, REGIDESO.

The Darcy-Weisbach formula was used to compute the head losses, and the metric system (liter per second) was employed for data entry and presentation of the results. DUPONT (1974) recommends a roughness of 0.004 for this application (1974).

The friction factors in EPANET were calculated using three approaches (Rossman, 2000):

When the Reynolds number was Re < 2000, the program employed the Hagen-Poiseuille estimation, as given by equation 3.2:

$$f = 64/Re \quad (3.2).$$

When Re > 4000, Equation 3.3 was used as follows:

$$f = \frac{0.25}{\left[\ln\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \quad (3.3)$$

With:

f = frictional factor (dimensionless);

ε= Pipe roughness factor;

d = Pipe diameter.

And the program employed a cubic interpolation from the Moody diagram for the transitional flow at 2000 < Re < 4000. The model was run for 24 hours to analyze the velocity, pressures, and system flows.

c) Optimized alternative solution analysis with watergems

After analysis in Epanet (24 hours demand-driven analysis), the network was exported to watergems to simulate new alternative solutions, with the Darwin designer. The Darwin Designer is an efficient tool for designing new pipe layouts and pipe rehabilitation projects considering some key aspects such as hydraulic constraints and cost-efficiency. This is a genetic-algorithm based technique to determine the most sustainable hydraulic design (economically and technically) while minimizing manual errors as allows the user to design pipes for an existing model in an automated way (Bentley, 2021).

Table 3.2 gives the Cost properties for pipes rehabilitation with the Darwin Designer in Bentley. As a rule of thumb, a pipe of 200 mm diameter in DI costs 200 euros (Trifunović, 2020). This analogy applies to other piping diameters as well. However, the prices were converted to US dollars with the current local conversion rate multiplier (1.15).

Table 3.2: Cost of pipes for the WDN renovation in Bukavu

Pipe Material	Diameter (mm)	Darcy-Weisbach e (mm)	Unit Cost (€/m)
DI	200	0.25	230
DI	300	0.25	345
DI	400	0,25	460
DI	600	0,25	690

With the Darwin designer, different potential solutions can be analyzed and the user can export some of them into a new scenario for the analyzed network. For this research, the pressure was considered as the constraint, to simulate pressure-driven modeling. As recommended by Trifunović (2020), the minimum and maximum pressures were set to 20 mwc and 70 mwc, respectively. A layout of the WDN in Bentley Watergems is shown in figure 3.6.

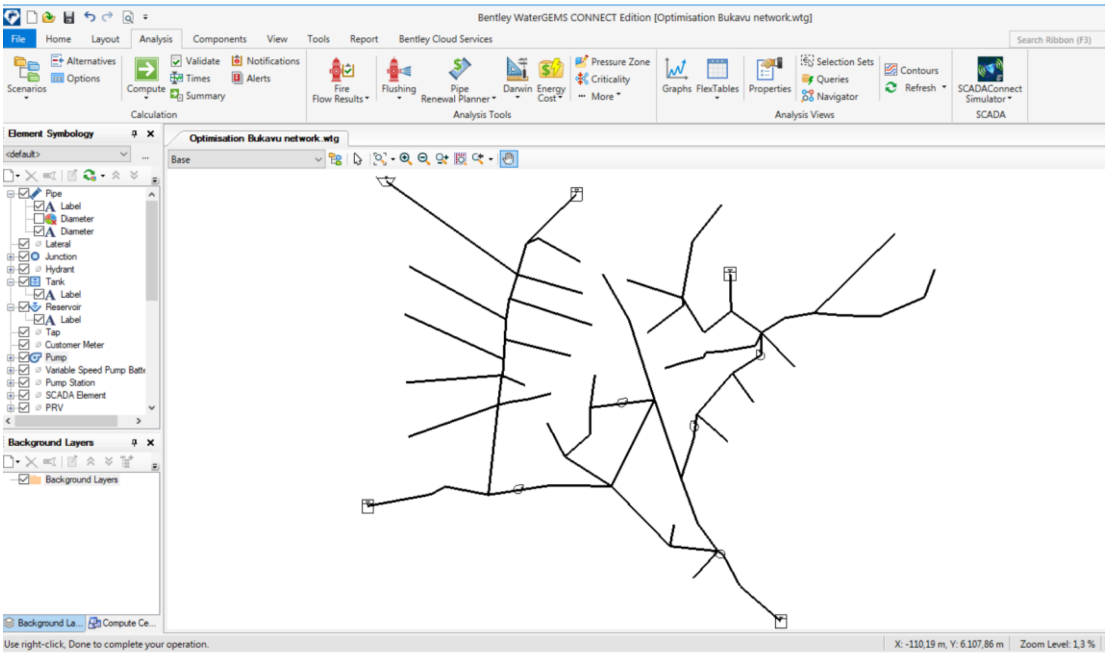


Figure 3.6: Bukavu's water distribution network in Bentley Watergems environment

The overall research methodology is presented in Figure 3.7.

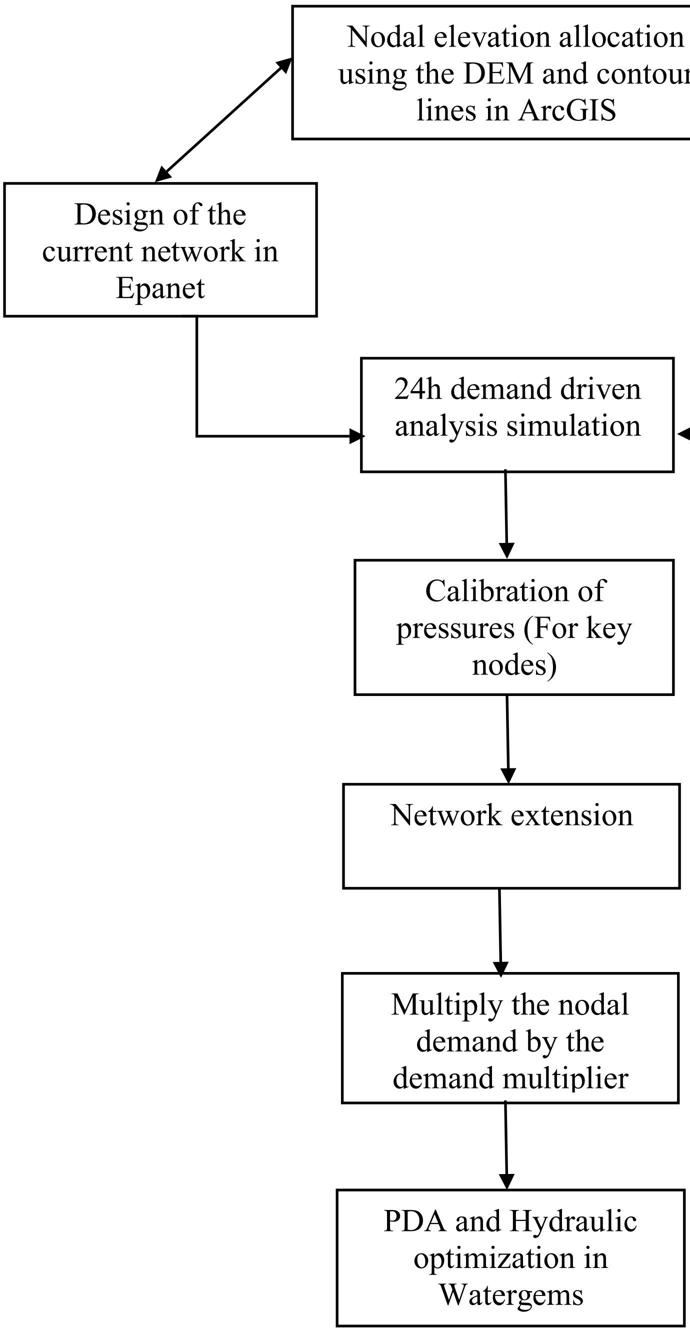


Figure 3. 7: Modeling process in Epanet and optimization of alternative solution in Watergems

3.2.3. WDN Network criticality analysis

Isolation (segmentation) valves were used to isolate certain areas of the network to simulate scheduled maintenance or emergency repairs (e.g., pipe breakage or leaking). Segments are parts of a network that contain pipes, sections of pipes, junctions (nodes), valves, pumping stations, reservoirs, and other network elements that may be closed (isolated) using isolation valves (Bentley, 2021).

The network's criticality was assessed by system demand shortfall in these segments. This means that if a given section of the network is not operational, a certain number of junctions and customers will not have enough pressure to supply the specified flow and meet the needs. The greater the system demand shortfall (percentage), the greater the network's criticality.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. General Overview

With a population of 1,133,000 inhabitants in 2021, the city of Bukavu is located in the Eastern province of Sud Kivu in DR Congo, as shown in Figure 4.1. Bukavu is well known for being surrounded by the Kivu Lake; however, the city uses River Murhundu in Kabare territory as the main source for drinking water supply. The current water supply system in the city is composed of one (1) reservoir (Murhundu), three (3) balancing tanks (Bagira, panzi, and Igoki), and five (5) pumping stations. These facilities are connected by a 300,049 meters long water distribution network, to meet the growing water demand in the city's municipalities of Bagira, Ibanda and Kadutu.

Figure 4.1. The city of Bukavu on the map of the DR Congo

As presented in Table 4.1, the population is not evenly distributed in the three (3) municipalities of the city. The most populated municipality is Kadutu, where 39.2 % of the total population are residents, while 35.75 % and 24.9 % of the city's population live in the municipalities of Ibanda and Bagira, respectively.

Table 4.1: Municipal population in Bukavu in 2021

Municipality	population in inhab. (2021)
Bagira	283,163
Ibanda	405,080
Kadutu	444,754
Total	1,132,997

As shown in Figure 4.2, at present, only 46 % (521,180 inhabitants) of people in the city have access to the produced drinking water, as reported by the local water company Regideso. However, this number is expected to increase up to 70 % at the end of the design period in 2046. As reported by Docile (2020), for the nearby city of Goma where the water supply coverage is 57.6 %; in many cities in the DRC the water supply system has never been upgraded, while the city is growing continuously due to urbanization and rural exodus. This applies also to the city of Bukavu, as its WDN has never been expended since 1984.

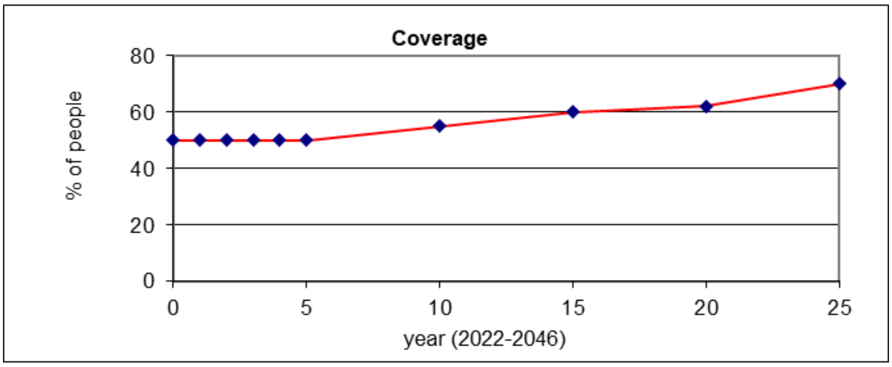


Figure 4.2: Water coverage in the city of Bukavu (REGIDESO,2020)

The city of Bukavu records an average temperature of 20°C throughout the coast and is temperate due to the presence of Lake Kivu. The Muhungu meteorological observation station in the Ndendere District (at 1,670 m altitude) reports that rainfall ranges between 1,000 mm and 2,500 mm with an annual average of 1,320 mm. The month of June records 17 mm and that of March is distinguished by a high rainfall of 165.5 mm. Rainfall at 168 mm in November, a small season, and in January. The real rainy season normally responds around the fortnight of January, the city's climate has two seasons (wet and dry). The soil is drying out. The average monthly temperature and precipitation in Bukavu are presented in Figure 4.3.

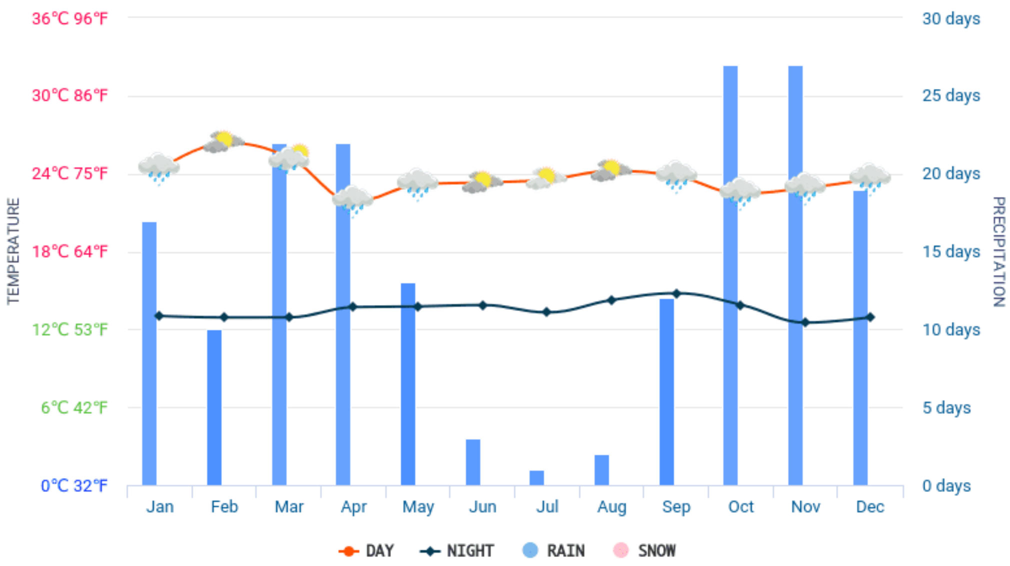


Figure 4.3: Average monthly temperature and precipitation in Bukavu (CAID, 2016)

To calculate the design demand for the water distribution network, data from REGIDESO, the local municipality report ‘’reseau de distribution de la Ville de Bukavu’’ was used. This report includes daily water demand in the city for each month in 2009, and dividing by the average daily demand for the twelve months, the daily peak factor was calculated. Since the design of the network needs to handle the maximum daily demand, the maximum peak factor of 1,16 which occurred on the 11th of June, was used for water demand calculation. The WDN should be designed for the maximum daily water demand is because it represents the worst-case scenario for its performance. Figure 4.4, represents the daily peak factors in Bukavu in 2019.

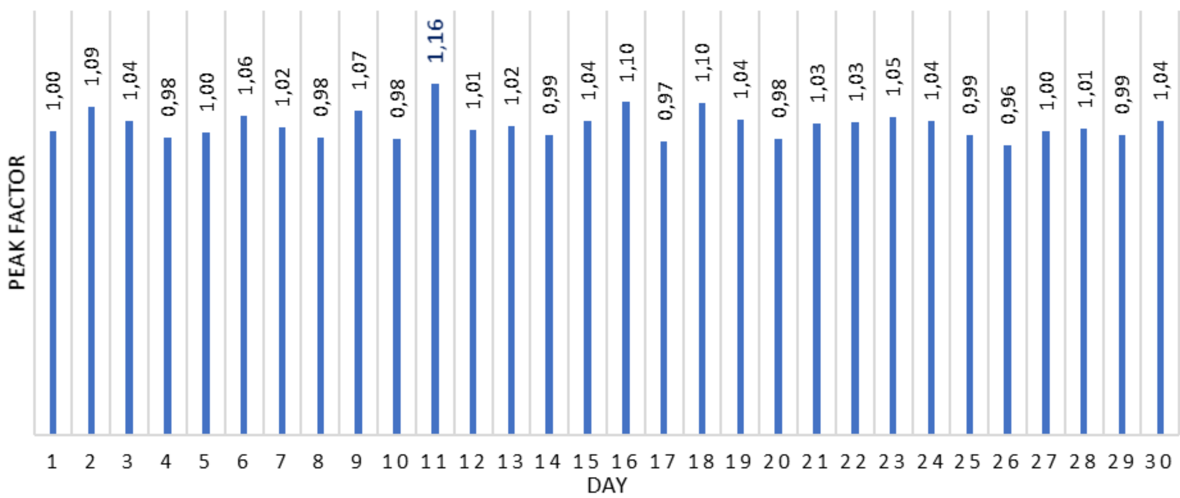


Figure 4.4: Peak Factors for Daily Water Demand in June 2019, in Bukavu Forecasted Water Demand

4.2 Water Demand, and Production Capacity of the Projected Water Distribution Network

4.2.1 Overall Population in the City of Bukavu

The population of the city was forecasted from the 2011 population records from a national population as s shown in Table 4.2. In 2011, the population of the city of Bukavu was estimated at 677,673 with Kadutu being the most populated municipality (39 %), followed by Ibanda (36 %) and Bagira (25 %).

Table 4.2 : Municipal Population in Bukavu(Mairie de Bukavu, 2011)

Municipality	Population in inhab. (2011)
Bagira	169,368
Ibanda	242,288
Kadutu	266,017
Total	677,673

As shown in Table 4.3, using Equation 3.1, the city's population in 2021 was estimated at 1,133,000 inhabitants and is expected to reach 3,625,600 in 2046 (69 % increase).

Table 4.3: Population Forecast for the City of Bukavu

		2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2031**	**2036**	**2041**	**2046**
Growth rate	%	5.1	5.1	5.1	5.1	5.1	5.1	5.14	5.14	5.14	5.14
Population	x 1000	1133	1191	1252	1315,8	1382,9	1453	1825	2295	2884,3	3625,6
Coverage	%	46	46	46	46	46	46	50	60	65	70
People served	x 1000	521,4	547,9	575,9	605,25	636,12	668,6	912,7	1377	1874,8	2537,9

This estimation is similar to the 1,333,371 inhabitants, estimated by the world population review (World population review, 2021), clearly showing the need to upgrade the existing water supply infrastructure. However, for water demand calculation, only the served (people connected to the water distribution network) population shown in Table 4.3 will be used instead of the total population.

The sum of the population in the municipalities in 2021 in Table 4.1, was compared to the city's global forecasted population shown in Table 4.3, and the difference between the two values was used to correct the population growth rate provided by the World population review (2021) report, from 5.14 % to 5.13 %. However, this difference was very small (< 1%) and negligible.

4.2.2 Population Forecast per District in Municipalities

The population per district is shown in Table 4.4, with calculation details presented in Appendix 1. The most populated district is Panzi (182,287 inhabitants in 2021 and 583,128 inhabitants in 2046), while Nyakaliba is the least populated district (35,580 inhabitants at present and 113,820 inhabitants in 2046) and this is explained by the fact that the district is newly populated with people coming from rural areas to seek a better life in the city (CAID, 2016).

Table 4.4: Population Distribution in Districts in the city of Bukavu

Municipality	District	Population (in inhab.)									
		2021	2022	2023	2024	2025	2026	2031	2036	2041	2046
Ibanda	Ndendere	81000	85131	89473	94036	98832	103872	130463	163992	206138	259116
	Nyalukemb	141778	149009	156609	164596	172990	181813	228357	287044	360815	453544
	Panzi	182287	191583	201354	211623	222416	233759	293601	369057	463904	583128
Bagira	Lumumba	73623	77378	81324	85472	89831	94412	118582	149057	187365	235518
	Kasha	152910	160708	168904	177518	186572	196087	246285	309581	389143	489153
	Nyakavogo	56633	59522	62557	65748	69101	72625	91217	114660	144127	181168
Kadutu	Mosala	66713	70115	73691	77450	81400	85551	107452	135067	169779	213413
	Nyamugo	80056	84139	88430	92940	97679	102661	128942	162080	203735	256095
	Kasali	57818	60767	63866	67123	70546	74144	93125	117058	147142	184958
	Chimpunda	88951	93487	98255	103266	108533	114068	143269	180089	226372	284550
	Kajangu	71161	74790	78604	82613	86826	91254	114615	144072	181098	227640
	Nkafu	44475	46744	49128	51633	54266	57034	71635	90045	113186	142275
	Nyakaliba	35580	37395	39302	41306	43413	45627	57308	72036	90549	113820
Total		1132985	1190767	1251497	1315323	1382404	1452907	1824851	2293838	2883354	3624376

4.1.2 Overall water demand forecast in the city of Bukavu

Figure 4.5 summarizes the detail of water demand estimation for the city of Bukavu until the end of the design period in 2046. According to the results, the daily water demands of the city in 2022 are estimated to be 16,670,000 m^3/year or 45,671 m^3/d (domestic and non-domestic demand); calculated with a per capita water demand of 65 l/person/day (Regideso, 2022). This is more than 3 times the current production capacity of the city, estimated at 15,120 m^3/d. At the end of the design period in 2046, the water demand will increase to 101,100,000 m^3/year or 276,986 $m^{3/}$d. This implies that the current water distribution network should be upgraded to meet the current and future water demands of the city, considering that the suppling source (River Murhundu) is not limited in terms of water quantity. Calculation details showing the demand categories are presented in Appendix 2.

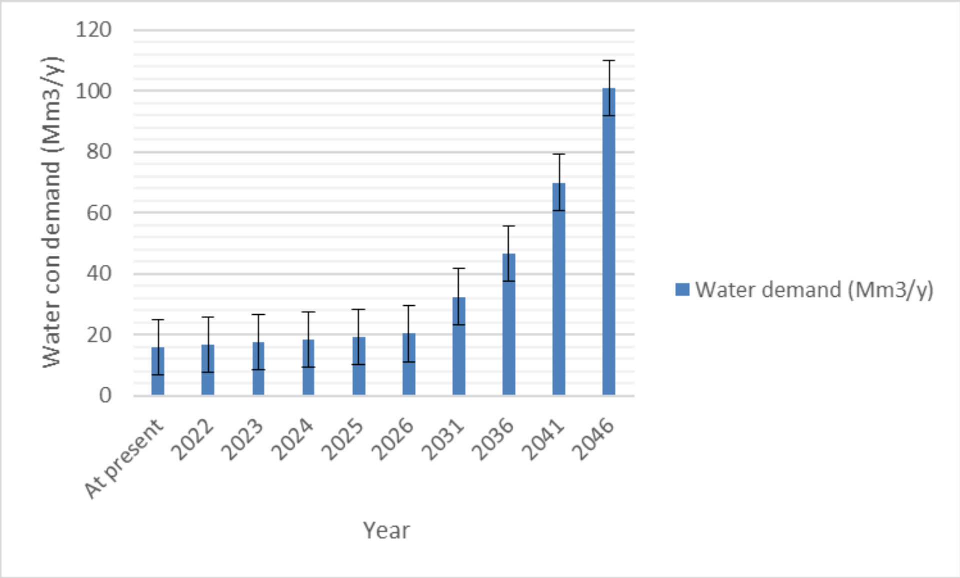


Figure 4.5. Current and future water demand in the city of Bukavu

4.1.3. Current and Future Water Demand Per District

The result comparing the water demand in different quarters in the city of Bukavu is presented in Figure 4.6, with calculation details shown in Appendix 1. The results show that the highest water demand is at the eastern part of the city, which is also the most developed part of the city and where the highest water consumption habits are observed (Regideso, 2022). This water demand is found in the district of Panzi with an estimated current water demand of 6988,8 m^3/d and forecasted water demand of 44,551 m^3/d. On the other hand, the central part of the city presents the lowest water demand, particularly, Nyakaliba (estimated: 1634.15 m^3/d in the year 2022 and projected as 8,695.85 m^3/day in the year 2046) in the municipality of Kadutu. The district of Nyakaliba presents the lowest water demand among all the quarters in the township. As shown on the city's DEM (Figure 4.5), Kadutu is the most elevated part of the city with 2100 m, while the elevation in Ibanda is only 1450 m. This requires higher pumping energy to meet the water demand in that part of the city. This low water demand could also be attributed to the type of water service available in that area since most people use yard connections and stand posts and are therefore expected to consume less amount of water as compared to those with house connections. Kadutu is also the poorest municipality in Bukavu(CAID, 2016).

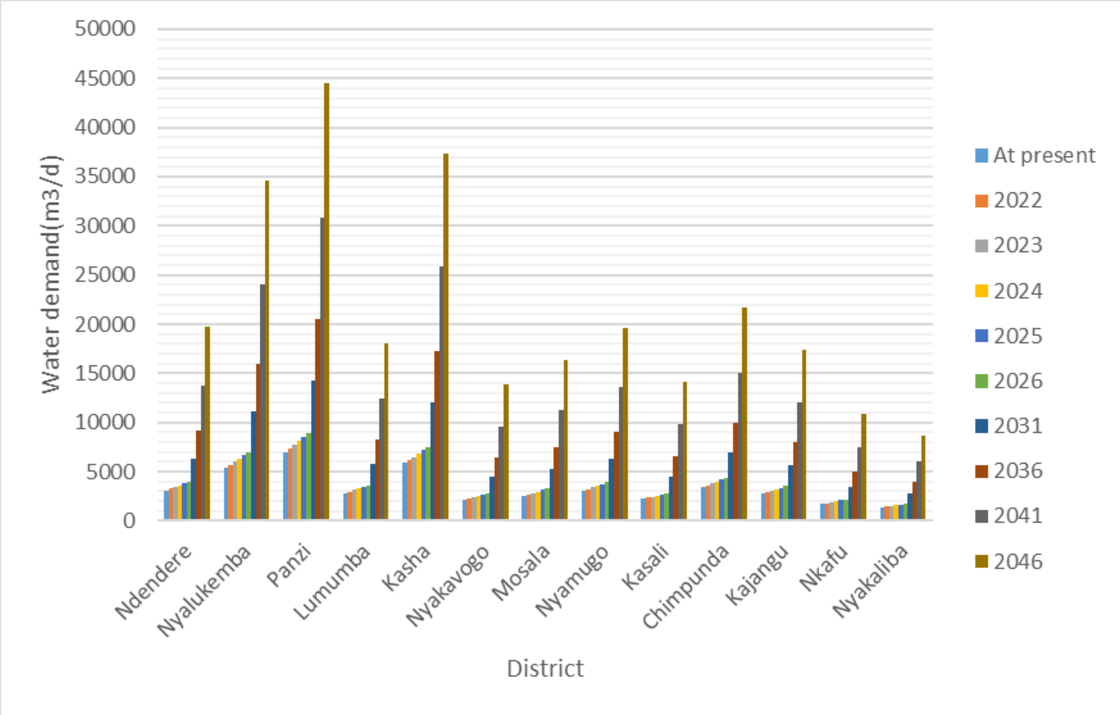


Figure 4.6: Water Demand Distribution in the City of Bukavu

The water demand estimated highlights the necessity to expand the capacity of the city's water supply system to satisfy the increasing demand. The findings of this study agree with those of earlier studies on the difficulty of satisfying water demand in most Sub-Saharan African Urban areas (Docile, 2020). Water demand in Bukavu has exceeded the plant production capacity, as is the case in other regions. This is also explained by the high level of leakage reported by Regideso (2022) (more than 40 %) in the water distribution network since there is no plan to detect, control, and repair leakages in the aging piping system. The predicted water demand for the year 2046 (276,902 m^3/d) is more than 6 times the city's current supply (45,671 m^3/d), reinforcing the suggestion to upgrade the existing facilities.

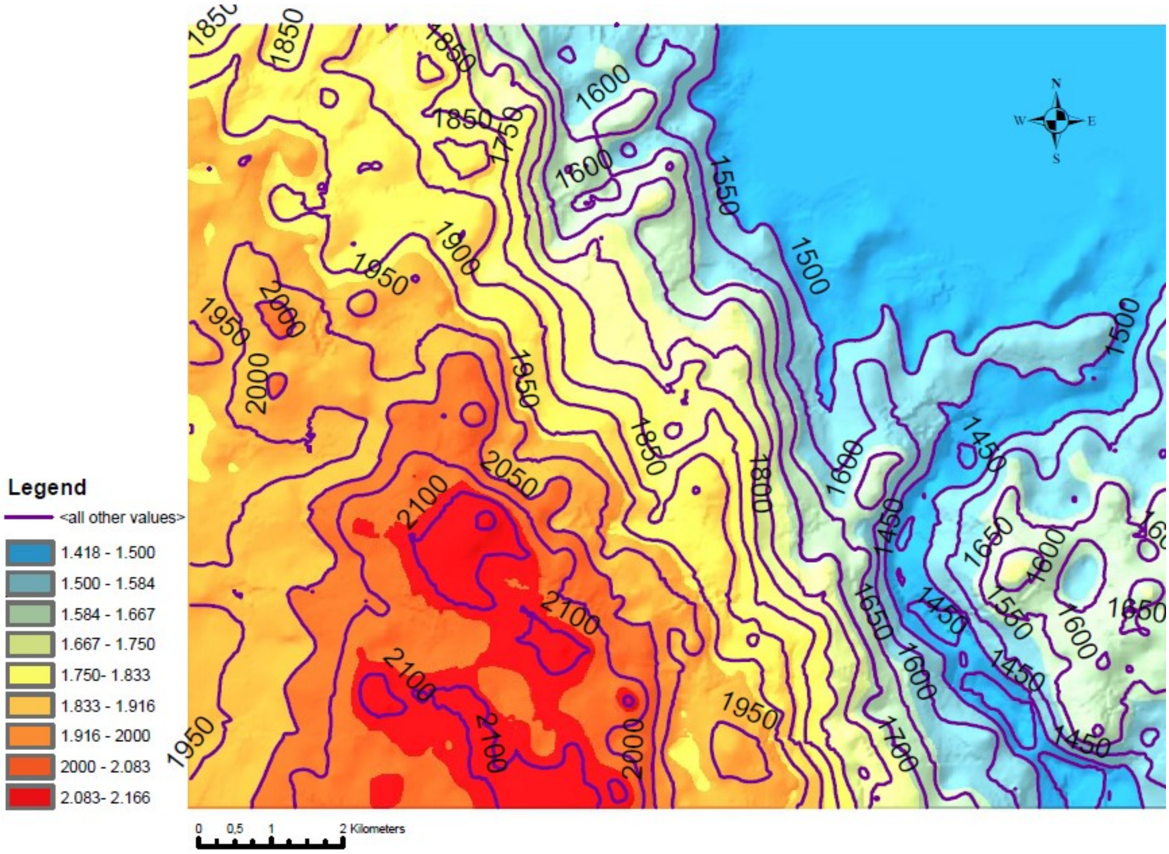


Figure 4.7: Digital Elevation Model of the City of Bukavu and the Surrounding

4.2. Hydraulics Performance in the Distribution Network

4.2.1. Description of the current Bukavu's WDN

As shown in Figure 4.8, the water supply system of Bukavu comprises one (1) water treatment Plant (Murhundu WTP) and three (3) tanks (Bagira, panzi, and Igoki) to balance the supplied flow in the system. These facilities are interconnected by a branched piping system that almost follows the road network of the city. The network is equipped with both flow and pressure control valves and some metering equipment in several locations. These include: float meters for measurement of the water depth in the reservoirs, pressure gauges which are attached to the batteries of water meters used to bill the consumption of individual house connections, flow meters, and pressure gauges are also installed on the suction and pressure pipes inside the pumping booster stations.

Figure 4.8: Bukavu's Water Distribution Network Validated with Google Earth

As reported in the data given by Regideso the municipal water supply company, the main piping system is made of ductile iron and the secondary piping system is made of PVC and GI, and their diameters vary between 25 and 600 mm. The system is composed of 5 pumping stations. In each of these stations, 2 pumps are installed in parallel with an additional standby pump at only 3 of the 5 stations, mainly PS2, PS4, and PS5 (Regideso, 2022). This implies that the supply should be interrupted in case the pumping station in PS1 and PS3 have to be maintained or are damaged, with an overall negative impact on the entire network in terms of flow and pressures. The pumps characteristics as in the current model, are shown in Table 4.5.

Table 4.5: Pumping stations in Bukavu's WDN (Regideso, 2022)

Pumping station	Duty flow (l/s)	Duty head (m)
PS1	400	85
PS2	655	125
PS3	1400	178
PS4	950	80
PS5	1200	140

In addition, the network operates on a balancing tank principal, in an intermittent supply because negative pressures are observed in some of the nodes, mostly at 6 am. The 24 hours EPS simulation in EPANET demonstrated that the pumping stations are in operation for only 18 hours a day, while for the remaining time, the tanks are supplying the required flow to the city by gravity. As a result, electrical energy is critical for the network's operation because it is required for 18 hours every day. The volume of water held in the 3 tanks is utilized to provide water to the customers for the remaining 6 hours, utilizing the gravity-fed mode. The Epanet model of the city's network is shown in Figure 4.9.

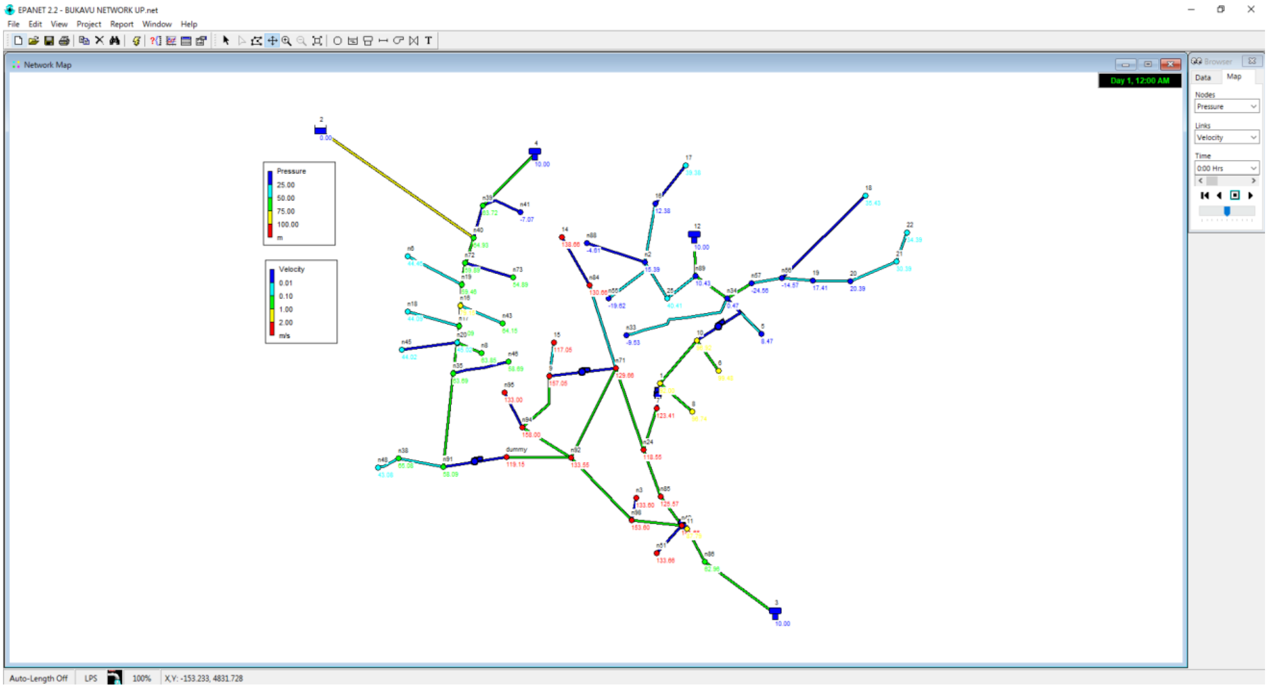


Figure 4.9. Epanet Model of the Existing Water Distribution Network in Bukavu

4.2.2. Piping system

The existing water distribution system is 300,049 meters long; with 52 % made in ductile iron (DI) which is a suitable material for the volcanic soils in the Kivu region as reported by Docile (2020). The secondary pipes are made of steel (31,3%), especially in the municipality of Kadutu. However most of these pipes have never been renovated since 1974 and this harms the hydraulic performance of the network in terms of pressures, water flow rates and water quality. As suggested by Docile (2020), for such conditions, a leakage detection and repairment campaign should be put in place, because the sustainability of steel pipes has to be assessed on a regular basis to ensure their capabilities (roughness) are not harmed by corrosion. Other piping materials are PVC, Galvanised steel, or unknown; while some asbestos cement pipes (with unknown total length) were also observed in the quarter of Ibanda. This piping material is dangerous to health since asbestos cement is cancerogenic and forbidden in many European countries (Slokar, 2021).

4.2.3. Hydraulic Performances

a) Water Demand variation in Bukavu

As shown in Figure 4.10, the flow in the network is not balanced. The water production line (red line) is below the water consumption line (green line) for most of the time in a day.

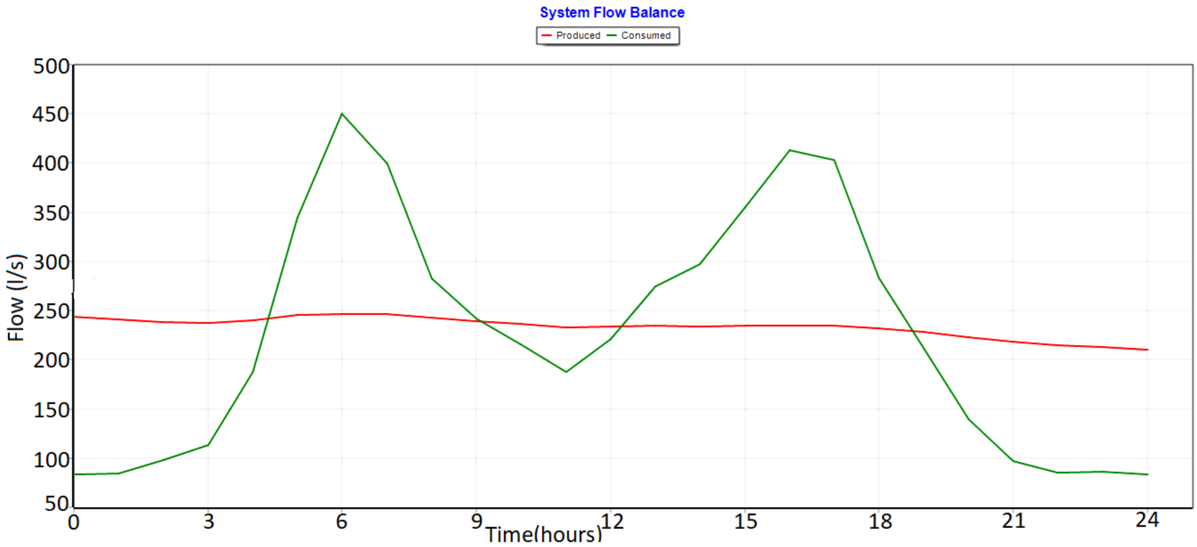


Figure 4.10: 24-hour Diagram of Demand Variation in Bukavu on the Maximum Consumption Day

The water production varies between 240 l/s at 00 hours, and 220 l/s at 24 hours (following day). The maximum consumption occurs at 6 am, while the minimum happens at midnight. This result makes sense, considering that people consume more water in the morning when they wake up, whereas they consume less water in the middle of the night while they are resting. However, this result is far from the reality since Cikuru (2018) reported that the flow in most of the city of Bukavu does not exceed 80 l/s. The explanation for this could be the high level of leakage in the network due to a lack of maintenance and upgrade of the piping materials.

Overall, the water demand increase in the future will have a negative impact on the water consumption in the city and this impact is likely to increase further in the future as the population grows. This emphasizes the need to renovate the distribution network.

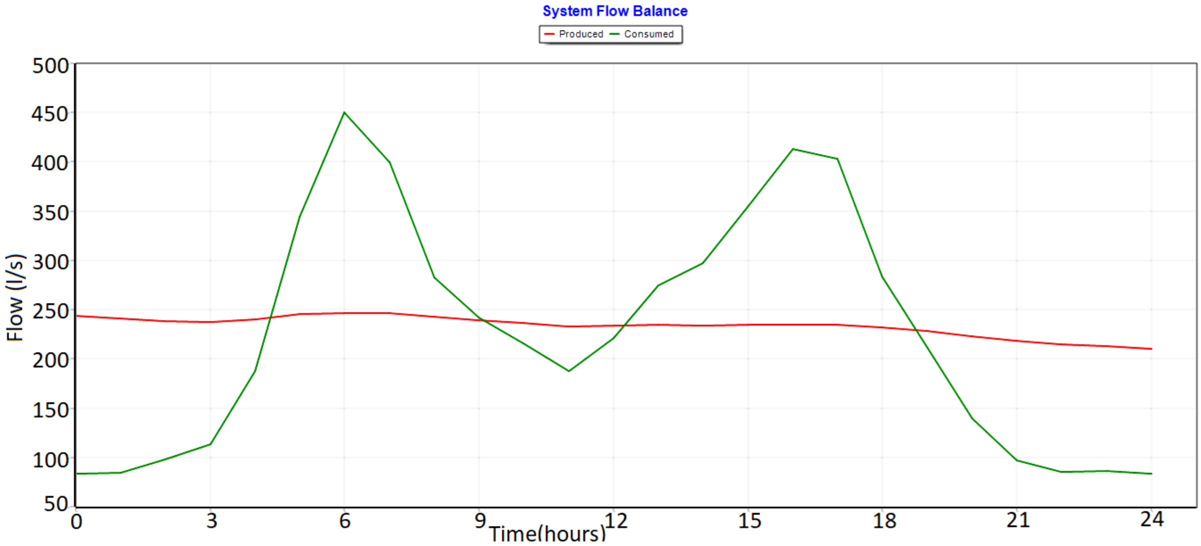


Figure 4.11: 24-hour diagram of demand variation in Bukavu on the maximum consumption day

b) Distribution of Pressures in the network

According to Trifunović (2020), the pressure in a water distribution network should preferably vary between 80 mwc and 20 mwc. However, as shown in the contour map in Figure 4.12 and detailed in Appendix 3, during the maximum consumption hour (6 am), only 1 node satisfies the pressure criterium and 21 nodes (38 %) have pressures below 20 mwc. Additionally, 18 nodes (35.1 %) have unit head losses above the threshold value of 10 m/Km (Trifunović, 2020).

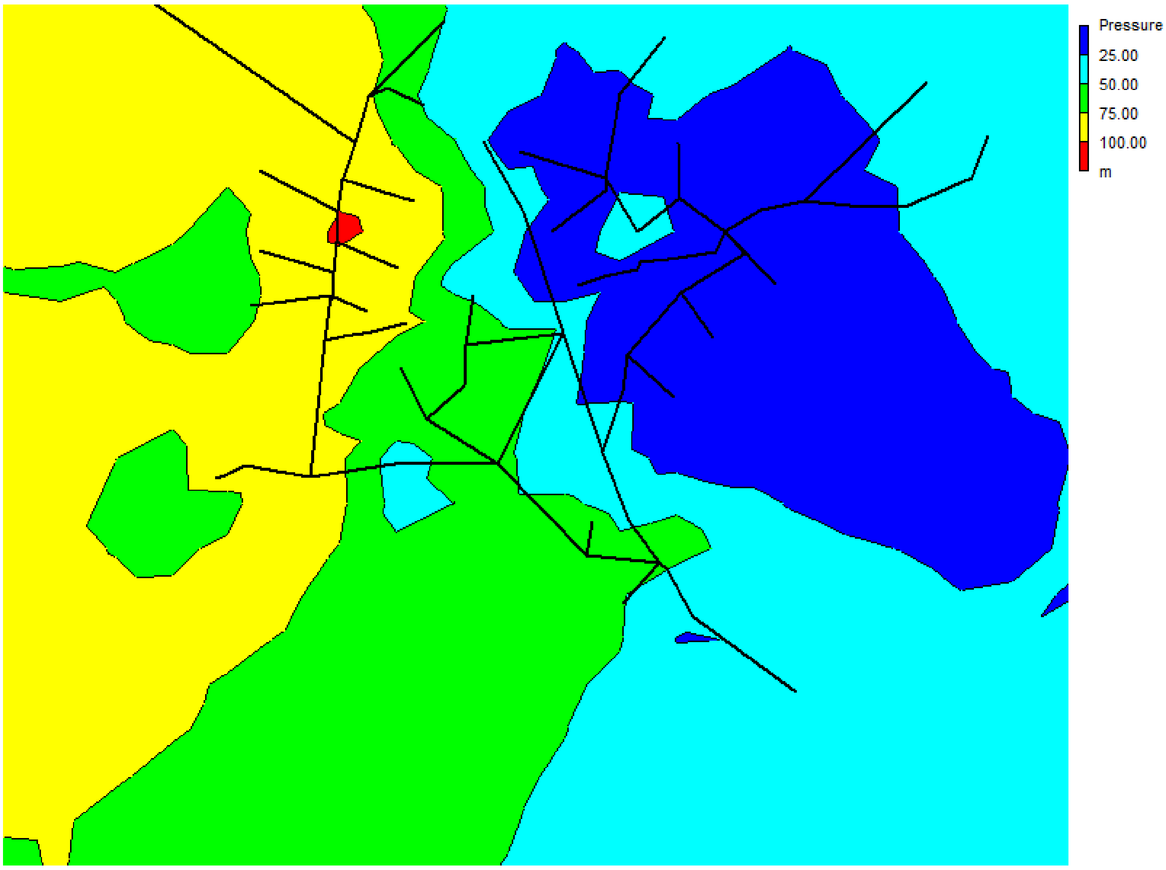


Figure 4.12: Contour Plot of Pressures Distribution in the Network at 6.00 a.m

The most affected district in Bukavu is the Ibanda district (the area in blue on the contour map), where 61.2 % of nodes have negative pressures values and none of all the nodes meet the minimum pressure requirement at 6 am. The degree of interruption is such as water will never reach those people at 6 am.

The critical node is found in the same district with a pressure of -29 mwc, while the critical pipe is found in the district of Bagira (pipe p35) with a unit headloss of 13.75 m/km.

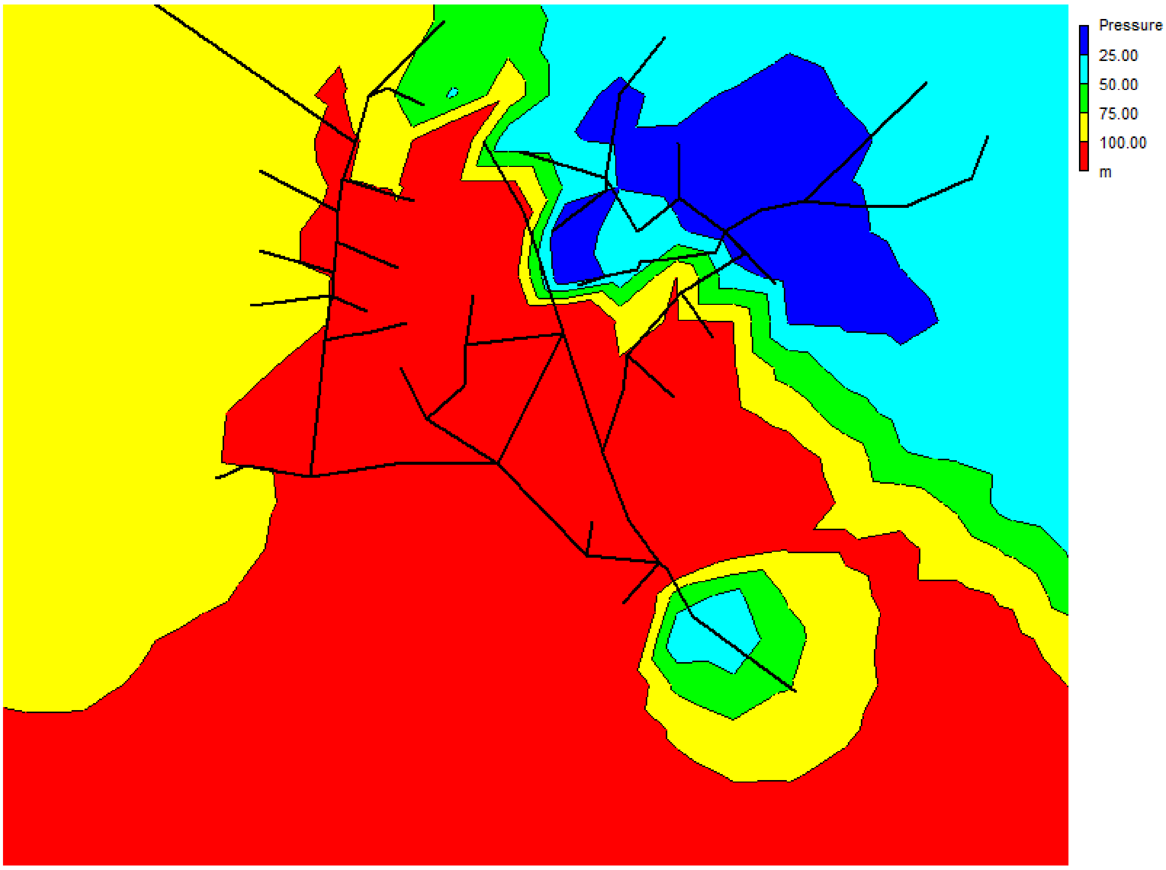


Figure 4.13: Contour Plot of Pressures Distribution in Bukavu's WDN at Midnight

As shown in Figure 4.13, At 24 hours (mid-night) high pressures occur in the network because only 32,2 % of the node have pressure below 80 m, and pressure of up to190 m occur in the network, especially in the industrial municipality of Ibanda. This explains the high level of leakage reported by Regideso (2022) the local municipal company, and emphasis the need to implement a leakage detection campaign as suggested by Utashi (2020) for the nearby city of Goma. In addition, pressure-reducing valves (PRVs) should be installed at some locations in the municipality of Ibanda to control the high pressures occurring at night.

c) Distribution of Velocities in the Network

The distribution of velocities in the network is shown in Figures 4.14 and 4.15. The velocity ranges between 0 m/s and 2,4 m/s at 6 hours and between 0 m/s and 0.75 m/s at 12 pm. At 6 a.m and 12 pm, the velocity can decrease up to 0.00 m/s, which is not good from a water quality point of view as reported by Trifunović (2020) in his book. Conveying the water at an acceptable velocity (> 0.3 m/s) helps to reduce the retention time, which prevents the deterioration in water quality, which can result in low chlorine residuals, the appearance of sediments, and growth of microorganisms. In developing countries, for example, where residual chlorine is crucial for water quality; a minimum velocity must be maintained in the network (Trifunović, 2020).

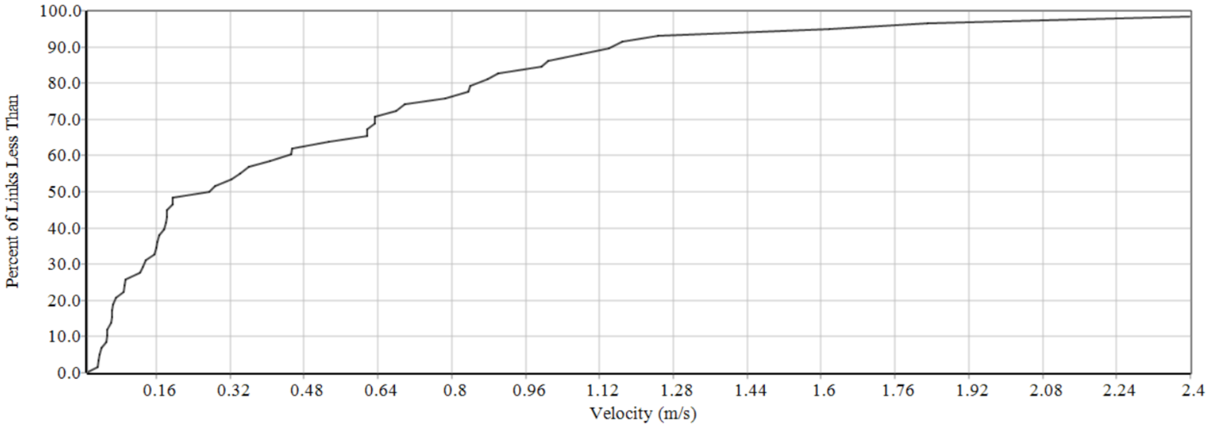


Figure 4.14: Distribution of velocities in the network at 6 a.m

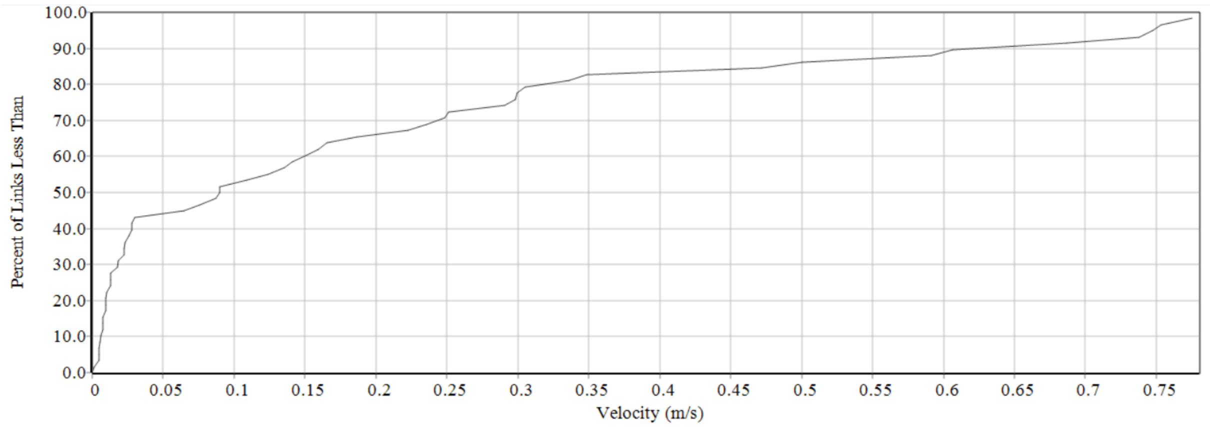


Figure 4.15: Distribution of velocities in the network at 12 p.m

The results demonstrate that the existing WDN is not sustainable for the water supply in the city of Bukavu. The findings show that the balancing tank approach has a serious drawback in terms of pressure variations within a day, resulting in a high level of leakage and an intermittent water supply with potential water quality deterioration during transportation. Finally, a network expansion is required in the newly populated western part of the city (Bagira).

4.3. Modelling of a Sustainable Water Distribution Network in Watergems

4.3.1. Choice of the solution

The sustainable solution for the water supply system in Bukavu include a renovation plan of the water distribution network piping system, as shown in Figure 4.17; an addition of a balancing tank in the system to meet the demand in the municipality of Ibanda, where the minimum pressure requirement is not met at some hours in a day and an extension of the network in the municipality of Bagira where most of the residents are still not connected to the system. The balancing tank's position is shown in Figure 4.16. The tank is placed on the most elevated part of the city (2100 m) in the municipality of Kadutu to benefit from the gravity.

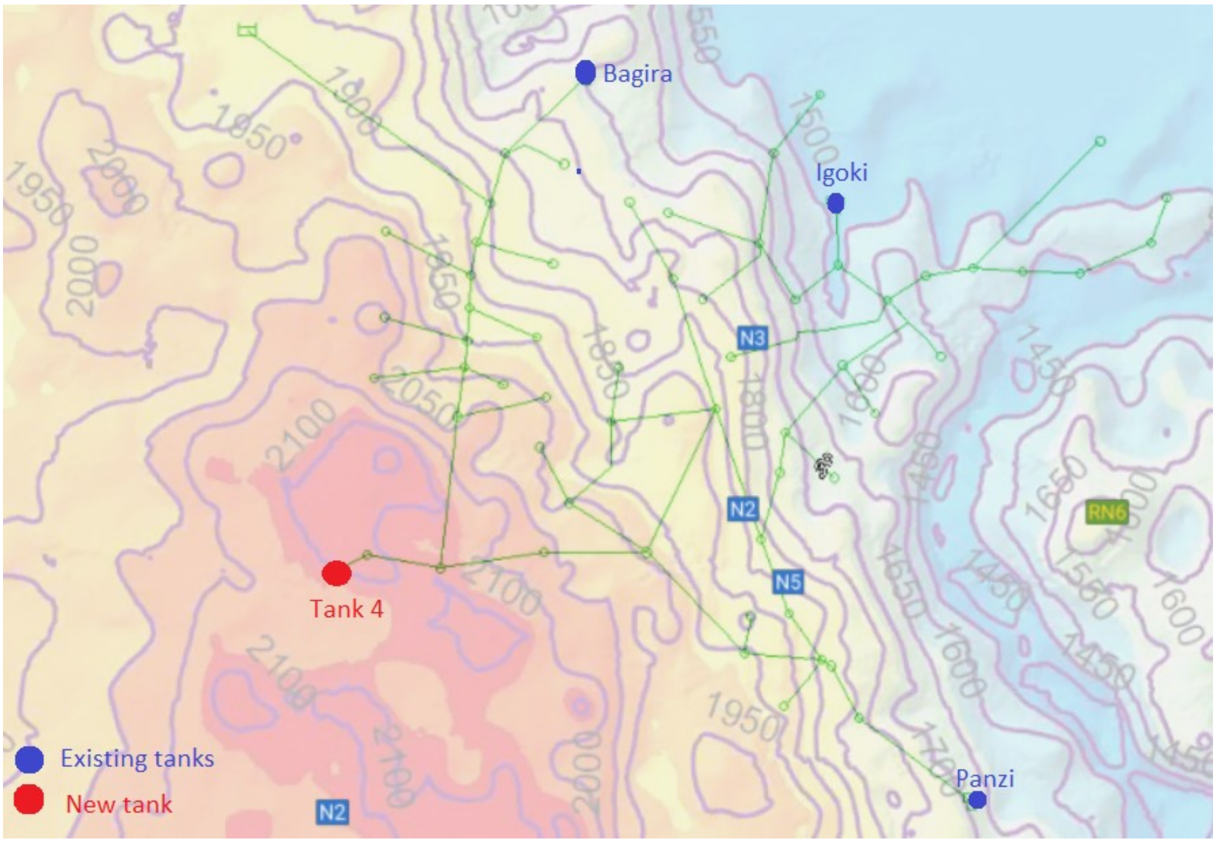


Figure 4.16: Position of the New Water Balancing Tank in Bukavu

4.3.2. Water Distribution Network Renovation Plan

The piping system is shown in Figure 4.14 as a result of the network optimization in Watergems. The main pipelines (in green and blue) should be priorities as they carry much of the flow and their performance impact the entire network. The required diameters are presented in Table 4.4. The entire piping material, length, and diameters will be presented in the next section about cost calculation. The pumping systems will also be replaced as their capacity should be increased to meet the increasing pressure.

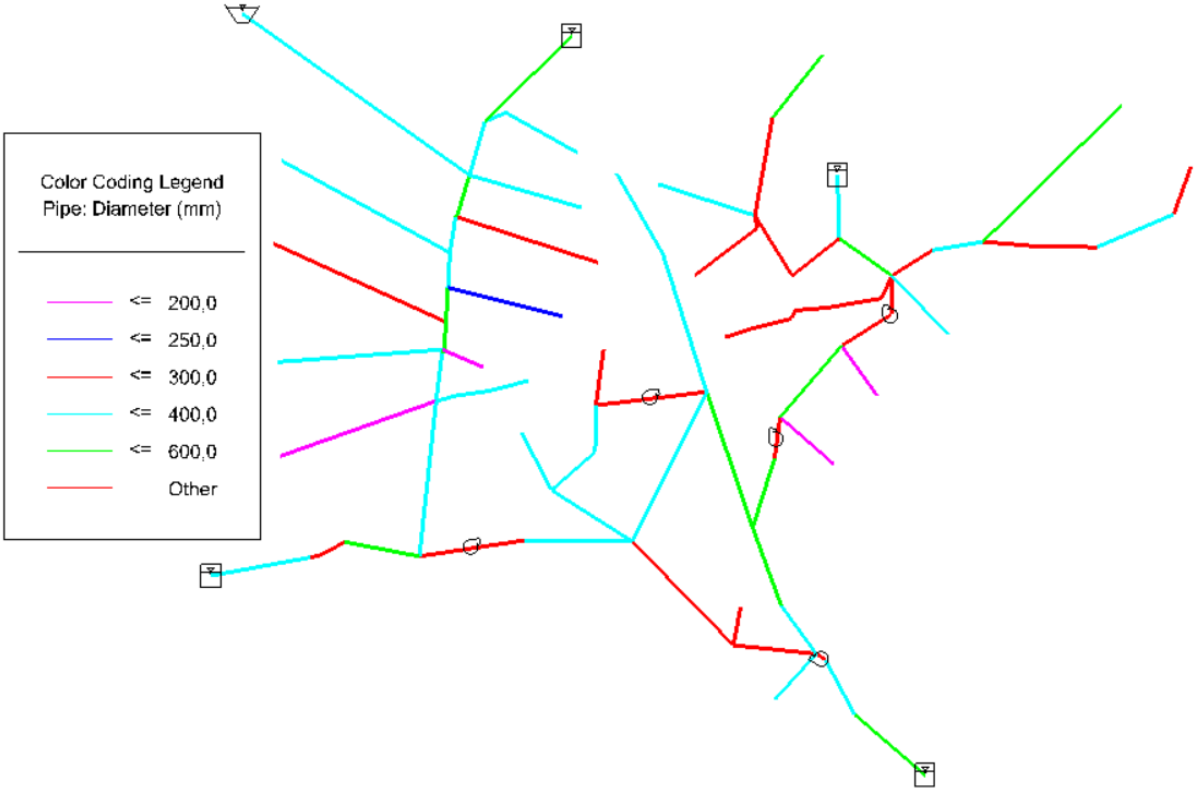


Figure 4.17: Piping System Renovation Plan for the City of Bukavu

After rehabilitation and pipes replacement, the flow in the system is balanced as shown in Figure 4.18. The maximum consumption occurs at 06: 00 hours with a demand of 130 l/s, whereas the minimum consumption happens at 24:00 hours with a demand of 28 l/s. It's important to mention that in Figure 4.15, the production line (in green) and consumption line (in red) are overlapped over each other's as all the produced flow is consumed.

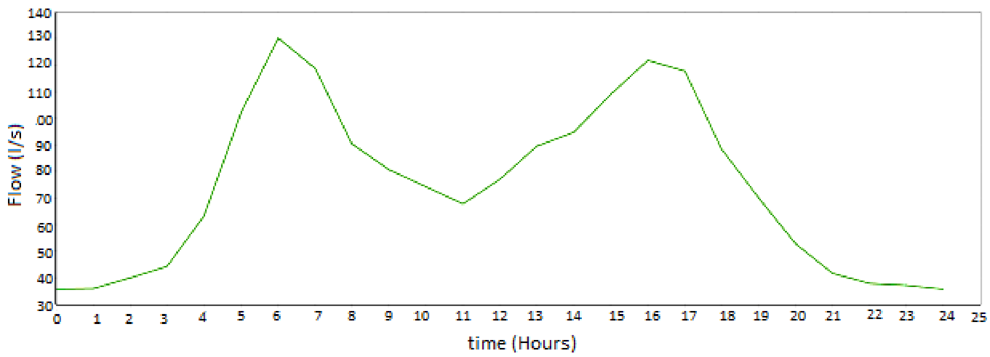


Figure 4.18: System Flow Balance in the Proposed WDN Renovation for the City of Bukavu

Table 4.4: Old and New pipe Diameters for WDN Renovation in the City of Bukavu

Pipe Epanet ID	Old diameter(mm)	New Diameter (mm)	Cost (USD)
PS1	300	300	929,6
PS2	300	300	929,6
21-A	250	600	1045,8
21-B	250	600	1045,8
20-A	250	300	987,7
20-B	300	400	1045,8
9-A	150	200	697,2
9-B	150	200	548,64
PS3	150	250	548,64
PS 4	150	300	548,64
p67	300	400	592344
p61	400	400	2102400,24
p55	300	300	353088
p44	300	600	228528,024
p42	600	600	739908
p35	400	400	267084
p32	250	400	490212
p31	250	400	396684
p27	300	400	887760
p26	400	600	244188
p25	600	600	397116,036
p22	400	600	367956
p20	150	400	276912
p19	200	600	1588680,108
p9	200	300	654588
26	300	300	648000
25	300	400	1080000
24	400	400	324000
23	250	400	826200
17	400	600	1080000
16	600	600	852120,054
12	300	400	1296000
11	300	600	1339200
10	250	600	436320,036
56	300	600	577800,054
55	200	300	707400,054
54	200	300	707400,054
51	200	300	709560
50	250	400	613440
49	400	600	1080000
48	300	300	612360
47	400	300	1328400
46	250	300	709560
45	400	400	864000
44	400	300	1080000

42	300	300	1356480
40	250	400	489240
38	250	400	648000
37	300	600	1080000
36	300	600	1080000
35	200	400	492480
22	600	600	829440,054
6	600	300	486000
43	200	400	673920,054
14	300	400	324000
32	150	200	852120,054
31	300	400	969840,108
30	400	400	432000
19	200	400	324000
18	400	300	337716
15	150	200	844560
13	200	200	703296
8	250	400	756000
7	300	300	324000
5	300	400	772200
4	300	400	540000
3	400	300	497016
2	400	300	324000
1	300	400	612360
p80	300	400	621432
p72	150	400	552420,054
Total (US Dollars)			**43390056,4**

As a result of pipes renovation, the unit headloss in the system decreased significantly as shown in Figure 4.19, the maximum unit headloss at the maximum consumption hours is only 0,1 m/km, which is acceptable, considering that a sustainable unit headloss in a distribution network should be between 0 and 10 m/km recommended by (Luís Carvalho, 2017).

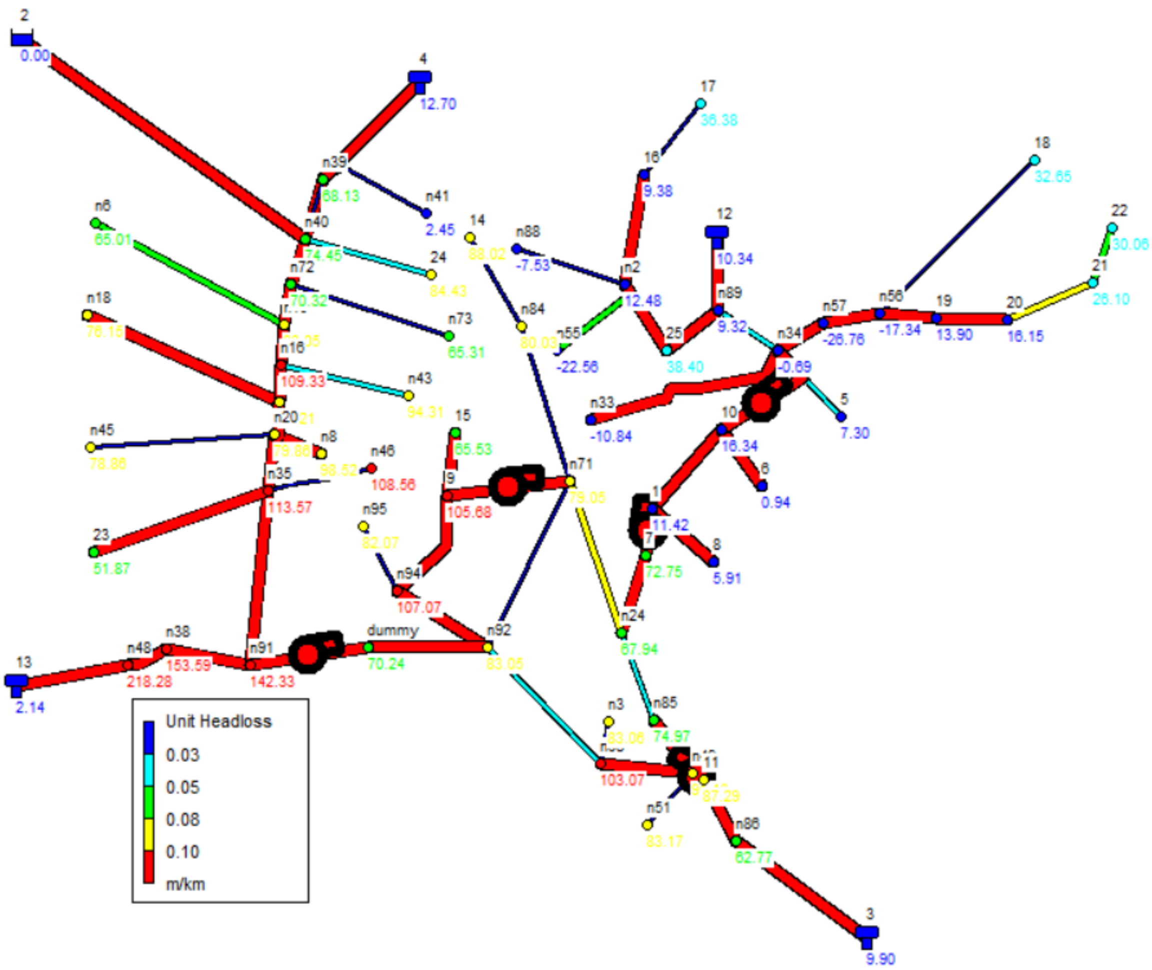


Figure 4.19: Unit Headloss in the Renovated WDN in the City of Bukavu

4.3.3. The Pumping Station and Tank Calculation

The pumping curve was created in EPANET using the KSB catalog (Aktiengesellschaft, 2005) with a pumping efficiency of 75 %.

After the renovation of the piping system, the pumping capacity increased in 3 of the 5 existing pumping stations, mainly at PS1 and PS2 in Ibanda, and PS5 in Bagira. For these stations, the characteristic curves changed from 400 l/s and 85 m to 640 l/s and 110 m, from 1200 l/s and 140 m to 1280 and 146 m, from 655 l/s and 125 m to 980 m and 170 m, respectively. The remaining pumping station kept their duty flow and duty head as currently. However, this was not expected since the demand is increasing greatly, the pumping characteristics were expected to do so. This can infer that the pumping stations are currently operating at their design characteristics as they are old enough and lack regular maintenance as claimed by Regisedo (Regideso, 2022). Furthermore, in practice, these pumping characteristics curves should take into account the net positive suction head as well as any other aspiration considerations, to preserve the pump's impeller against a potential cavitation phenomenon (Trifunović, 2020). Therefore, the real pumping head is slightly lower than the existing one.

4.3.4 The Balancing Volume of the New Tank in Bagira

The balancing volume of the new tank in Ibanda is shown in Table 4.5, the tank is almost full at midnight (97 %), which is good enough for the following day's balance. As recommended by Saripalli *et al.* (2000), the tank was calculated considering an emergency provision of three hours of average flow on the maximum consumption day.

Table 4.2: Choice of the New Tank Capacity in Bagira

Hour	Tank In	Tank Out	Peak	In-Out	Cum.	Volume
	(m3/h)	(m3/h)	Factor	(m3/h)	(m3/h)	
1	2120	1475	0,96	645,00	645,00	15
2	2120	1412	0,92	708,00	1353,00	19
3	2120	1415	0,92	705,00	2058,00	23
4	2120	1510	0,98	610,00	2668,00	28
5	2120	1532	0,99	588,00	3256,00	31
6	2120	1497	0,97	623,00	3879,00	35
7	2120	1600	1,04	520,00	4399,00	39
8	2120	1612	1,05	508,00	4907,00	42
9	2120	1625	1,05	495,00	5402,00	45
10	2120	1597	1,04	523,00	5925,00	48
11	2120	1513	0,98	607,00	6532,00	51
12	2120	1452	0,94	668,00	7200,00	55
13	2120	1600,8	1,04	519,20	7719,20	59
14	2120	1494	0,97	626,00	8345,20	62
15	2120	1489	0,97	631,00	8976,20	66
16	2120	1622	1,05	498,00	9474,20	70
17	2120	1600	1,04	520,00	9994,20	73
18	2120	1586	1,03	534,00	10528,20	76
19	2120	1490	0,97	630,00	11158,20	79
20	2120	1621	1,05	499,00	11657,20	83
21	2120	1601	1,04	519,00	12176,20	86
22	2120	1523	0,99	597,00	12773,20	90
23	2120	1536	1,00	584,00	13357,20	93
24	2120	1605,5	1,04	514,50	13871,70	97
Average		1542,013	1	577,9875		
Balancing (m3)	14516,7					
Fire storage (m3)	2120					
Total volume (m3)	16296,7					
Nominal volume (m3)	20000					
Number of tanks	2					
Height (m)	4					
Diameter (m)	45					
Choice	**2 tanks of 10000 m^3**					

4.3.5. Network Criticality Analysis

The criticality analysis results are shown in Table 4.5 and Figure 4.20. The most critical area of the network is located in Bagira, with a demand shortfall of 87 %. Several cases of water-related diseases are already regularly reported in Bagira due to regular water supply shortages (NDSCI, 2022). If this part is isolated for maintenance purposes, only 13 % of people will have access to water. The least critical area of the network is located in Ibanda with a demand shortfall of 6 percent. However, in the same area a demand shortfall of 58 % can be observed; covering the municipalities of Ibanda and Kadutu.

Table 4.3: Network Criticality Analysis

Segment	Colour code	Isolation Nodes Count	Pipes count	Demand shortfall (%)
Segment - 1	Peak	2	15	87
Segment - 2	Red	4	44	56
Segment - 3	blue	1	5	58
Segment - 4	green	1	6	6
Segment - 5	Blue light	1	6	6

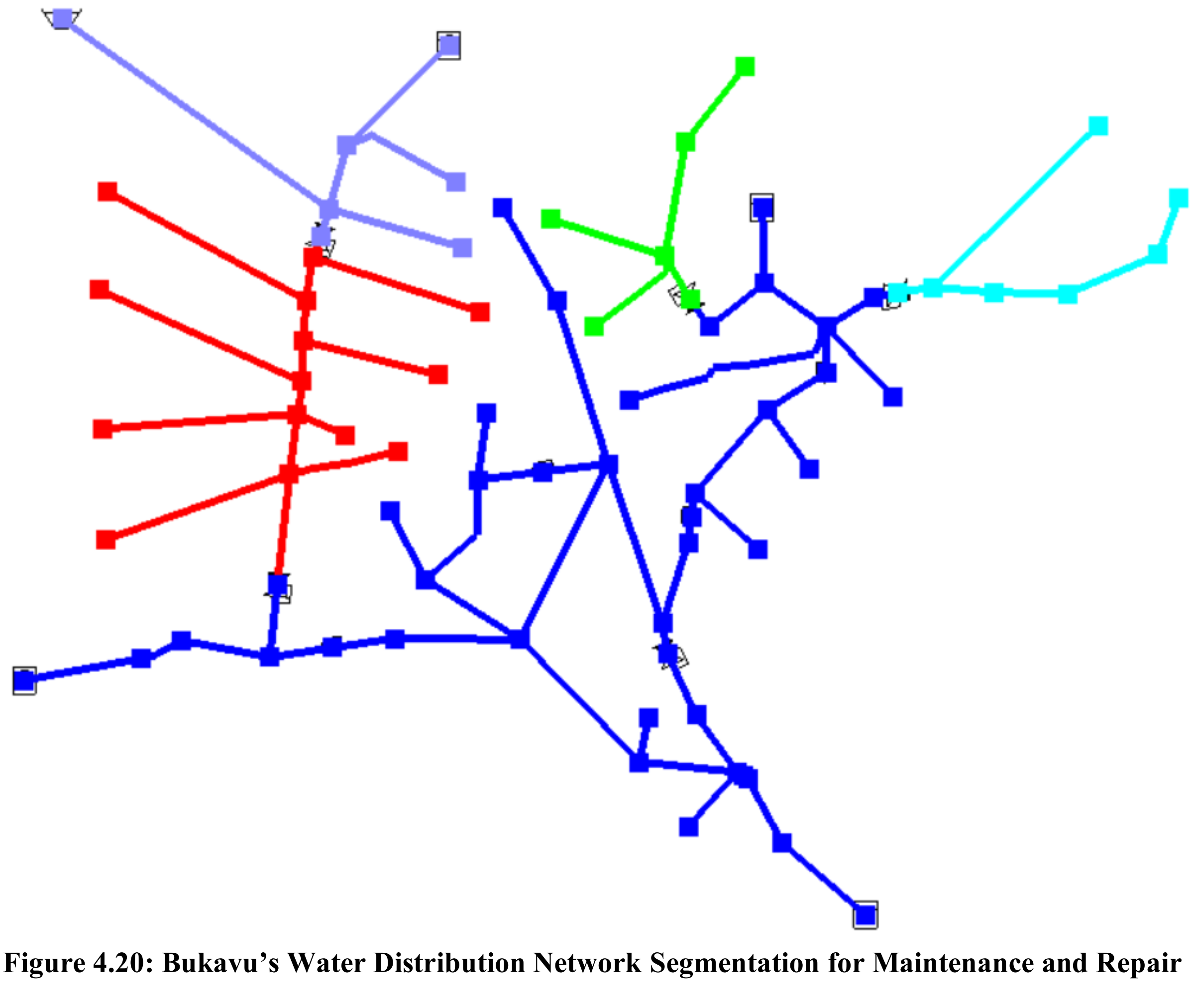


Figure 4.20: Bukavu's Water Distribution Network Segmentation for Maintenance and Repair

4.3.6. Cost estimation

Using the unit prices from Bentley, the total cost for pipe renovation was estimated to be 43,380,398 USD. The cost of the new reservoir (20000 m^3) was estimated to be 498,502 USD. The total cost for operation and maintenance was estimated to be 30 % of the total investment cost, as recommended by (Trifunović, 2020). The cost estimation is shown in Table 4.7.

Table 4.4: Investment Cost for Water Supply System Improvement in Bukavu

PARAMETER	**BEGINNING OF DESIGN PERIOD**		**AFTER 10 YEARS**	
Diameter (mm)	Total length (m)	Total price (USD)	Total length (m)	Total price (USD)
D=200	-	-	23940	5201690
D=250	-	-	5602	1248729
D=300	-	-	122835	18787530
D=400	73290	8888224,4	-	-
D=600	77727	9254225	-	-
Total pipes	151017	18142449,4	152377	25237949
Pumping additional capacity	Installed capacity (L/s)	Total price (USD)	Installed capacity (L/s)	Total price (USD)
PS1	-	-	240	1157603,2
PS2	-	-	80	385867,7
PS5	-	-	325	1567587
Total PST	-	-	-	3111057,9
Reservoirs	Total volume (m^3)	Total price (USD)	Total volume (m3)	Total price (USD)
New reservoir	20 000	498,502	-	-
Total reservoirs	-	498,502	-	-
Sub total		18142947,9		28349006,9
O&M (30%)	Diameter (mm)	Total price (EUR)	Diameter (mm)	Total price (EUR)
O&M	-	-	-	13947586,4
Total investment	-	18142947,9	-	70645600,2
Total Cost (USD)				**88788548,1**

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Following the specific objectives stated in the first chapter, the study concluded that:

(i) The water demand of the city of Bukavu is predicted to be 15.86 Mm^3/year (43 452 m^3/d) in 2046, which is almost 20 times the current water supplied to the city.

(ii) The current water distribution network is inadequate. The existing infrastructure does not cover the entire city, and most of the piping system needs renovation owing to age. Furthermore, the hydraulics characteristics in many areas of cities do not satisfy the minimum standards: very high pressures at night, high level of leakage, huge pressure falls between working phases and intermittent water supply.

(iii)The city's sustainable alternative supplying system is a hybrid system of gravity supply reinforced by an additional tank in the municipality of Bagira and a pumping system lying on increasing the existing pumping capacity. This solution includes also a renovated water distribution network.

5.2 Recommendations

The following dispositions are recommended by this study for the durability of the water supply in the city of Bukavu:

(i) An expansion of current water production capacity to minimize the rapidly expanding gap between long-term water demand and production capacity should be studied;

(ii) Adoption of modern water management technologies such as the SCADA system, which allows for simulation analysis, control, and tracking to assist operational choices while creating a trustworthy database for the water business;

(iii)As an optimized solution, this study will help policymakers to address the water supply challenge for the city in the long term. This study constitutes a framework for all stakeholders in the water supply sector in the city, including donors, NGOs, and government agencies.

Appendices

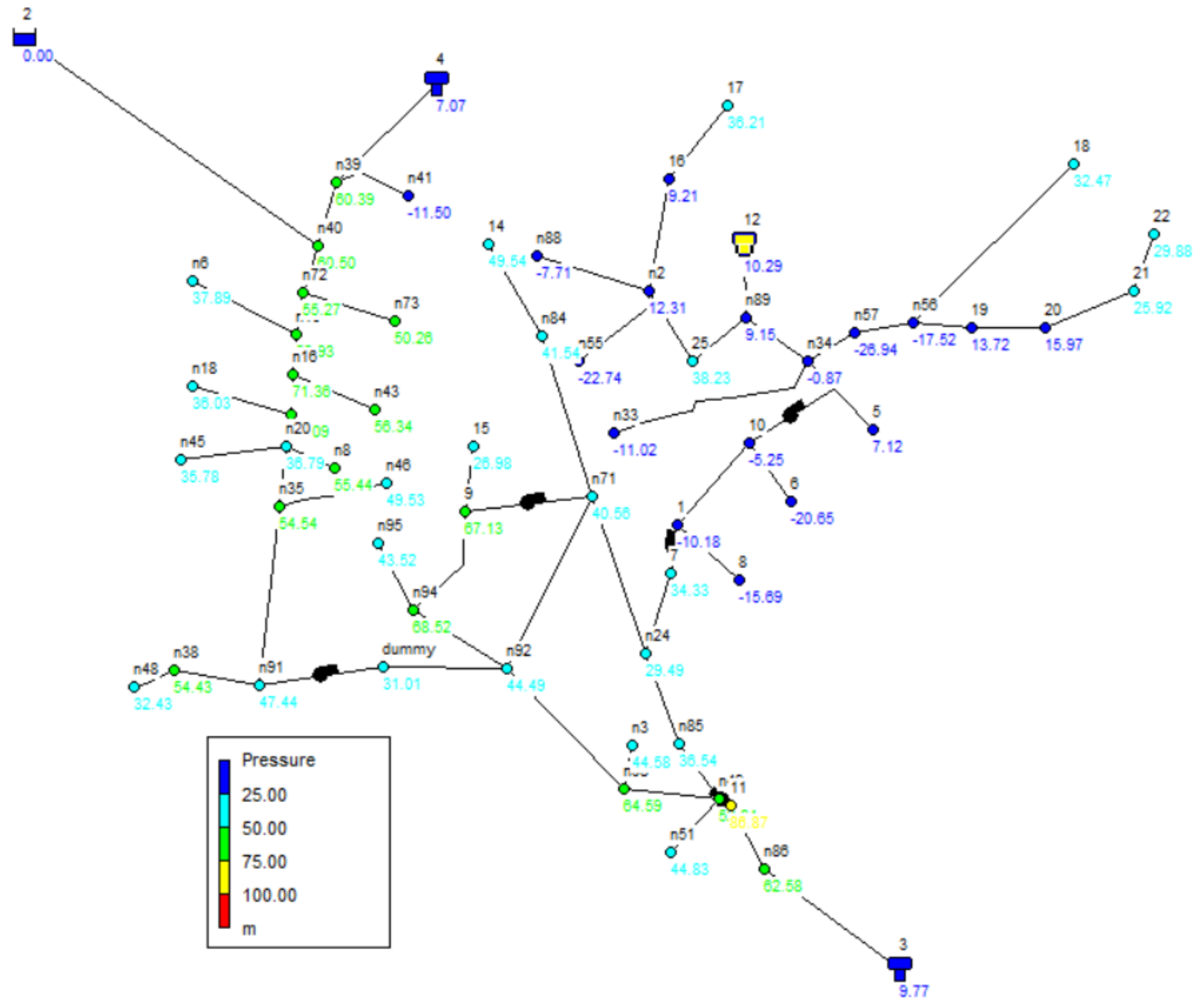
Appendix 1. Water demand distribution and population per district in the city of Bukavu.

Ibanda	Ndendere	Population(inh)	81000	85131	89472,7	94035,8	98831,6	103872	130463	163992	206138	259116
		Water demand (m3/d)	3105,54	3263,92	3430,38	3605,33	3789,2	3982,45	6360,08	9117,97	13708,2	19796,5
	Nyalukemba	Population(inh)	141778	149009	156609	164596	172990	181813	228357	287044	360815	453544
		Water demand (m3/d)	5435,79	5713,01	6004,37	6310,6	6632,44	6970,69	11132,4	15959,7	23994,2	34650,8
	Panzi	Population(inh)	182287	191583	201354	211623	222416	233759	293601	369057	463904	583128
		Water demand (m3/d)	6988,87	7345,3	7719,91	8113,63	8527,42	8962,32	14313,1	20519,6	30849,6	44551
Bagira	Lumumba	Population(inh)	73623,3	77378	81324,3	85471,9	89830,9	94412,3	118582	149057	187365	235518
		Water demand (m3/d)	2822,72	2966,67	3117,97	3276,99	3444,12	3619,77	5780,87	8287,59	12459,8	17993,6
	Kasha	Population(inh)	152910	160708	168904	177518	186572	196087	246285	309581	389143	489153
		Water demand (m3/d)	5862,56	6161,55	6475,79	6806,06	7153,17	7517,98	12006,4	17212,7	25878	37371,3
	Nyakavogo	Population(inh)	56633,3	59521,6	62557,2	65747,6	69100,7	72624,8	91216,8	114660	144127	181168
		Water demand (m3/d)	2171,32	2282,06	2398,44	2520,76	2649,32	2784,44	4446,82	6375,07	9584,45	13841,2
Kadutu	Mosala	Population(inh)	66713,1	70115,4	73691,3	77449,6	81399,5	85550,9	107452	135067	169779	213413
		Water demand (m3/d)	2557,78	2688,23	2825,33	2969,42	3120,86	3280,02	5238,28	7509,73	11290,3	16304,7
	Nyamugo	Population	80055,7	84138,5	88429,6	92939,5	97679,4	102661	128942	162080	203735	256095
		Water demand (m3/d)	3069,34	3225,87	3390,39	3563,3	3745,03	3936,03	6285,94	9011,67	13548,4	19565,7
	Kasali	Population	57818	60766,7	63865,8	67123	70546,2	74144,1	93125	117058	147142	184958
		Water demand (m3/d)	2216,74	2329,8	2448,62	2573,49	2704,74	2842,68	4539,84	6508,43	9784,95	14130,8
	Chimpunda	Population	88950,8	93487,3	98255,1	103266	108533	114068	143269	180089	226372	284550
		Water demand (m3/d)	3410,37	3584,3	3767,1	3959,22	4161,14	4373,36	6984,37	10013	15053,8	21739,6
	Kajangu	Population	71160,6	74789,8	78604,1	82612,9	86826,1	91254,3	114615	144072	181098	227640
		Water demand (m3/d)	2728,3	2867,44	3013,68	3167,38	3328,91	3498,69	5587,5	8010,38	12043	17391,7
	Nkafu	Population	44475,4	46743,6	49127,6	51633,1	54266,3	57033,9	71634,6	90044,7	113186	142275
		Water demand (m3/d)	1705,19	1792,15	1883,55	1979,61	2080,57	2186,68	3492,19	5006,49	7526,88	10869,8
	Nyakaliba	Population	35580,3	37394,9	39302	41306,4	43413,1	45627,1	57307,7	72035,8	90549	113820
		Water demand (m3/d)	1364,15	1433,72	1506,84	1583,69	1664,46	1749,34	2793,75	4005,19	6021,51	8695,85
Total		Population	1132985	1190767	1251497	1315323	1382404	1452907	1824851	2293838	2883354	3624376
		Water demand(m3/d)	43438,7	45654	47982,4	50429,5	53001,4	55704,5	88961,5	127537	191743	276902
		Water demand (Mm3/a	**15,86**	**16,66**	**17,51**	**18,41**	**19,35**	**20,33**	**32,47**	**46,55**	**69,99**	**101,07**

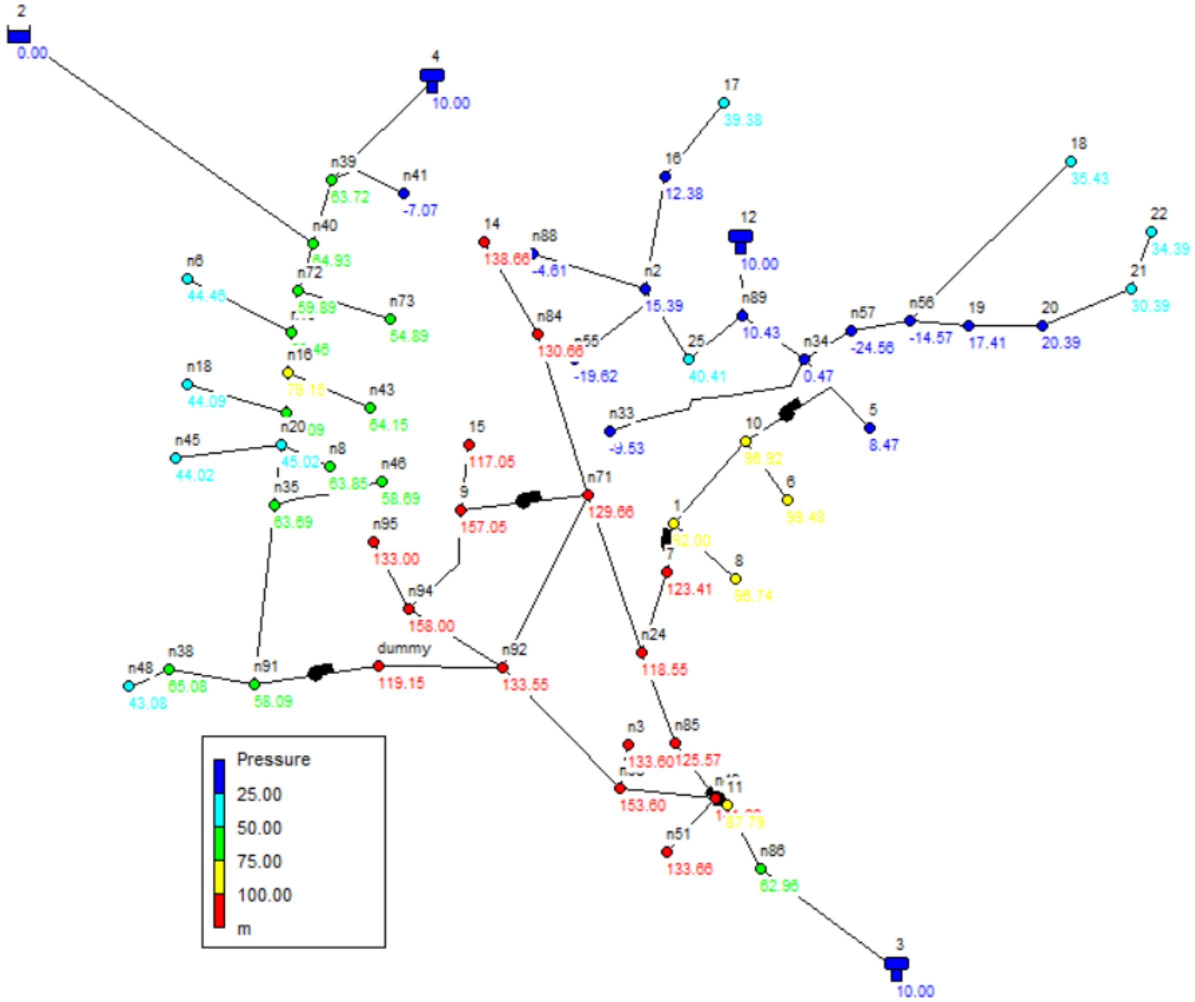
Appendix 2. Forecasted and current water demand in Bukavu

Water demand (WD)											
Water demand (WD)	Year	*At present*	*2022*	*2023*	*2024*	*2025*	*2026*	*2031*	*2036*	*2041*	*2046*
	After	*0*	*1*	*2*	*3*	*4*	*5*	*10*	*15*	*20*	*25*
a. Domestic use											
* house connections											
% population depending	%	60	60	60	60	60	60	65	70	75	80
number of inhabitants	x 1000	312,81	328,76	345,53	363,15	381,67	401,14	593,28	963,74	1406,11	2030,34
average consumption	l/c.d	35	35	35	35	35	35	50	50	60	60
total consumption	Mm3/a	4,00	4,20	4,41	4,64	4,88	5,12	10,83	17,59	30,79	44,46
* yard connections											
% population depending	%	30	30	30	30	30	30	32	38	42	45
number of inhabitants	x 1000	156,41	164,38	172,77	181,58	190,84	200,57	292,08	523,17	787,42	1142,07
average consumption	l/c.d	20	20	20	20	20	20	20	20	20	20
total consumption	Mm3/a	1,14	1,20	1,26	1,33	1,39	1,46	2,13	3,82	5,75	8,34
* stand posts											
% population depending	%	10	10	10	10	10	10	3	-8	-17	-25
number of inhabitants	x 1000	52,14	54,79	57,59	60,53	63,61	66,86	27,38	-110,14	-318,72	-634,48
average consumption	l/c.d	20	20	20	20	20	20	20	20	20	20
total consumption	Mm3/a	0,38	0,40	0,42	0,44	0,46	0,49	0,20	-0,80	-2,33	-4,63
b. Industrial use											
average consumption	l/c.d	15	15	15	15	15	15	17	18	20	25
total consumption	Mm3/a	6,21	6,52	6,85	7,20	7,57	7,96	11,33	15,08	21,06	33,08
c. Other use											
average consumption	l/c.d	10	10	10	10	10	10	12	13	14	15
total consumption	Mm3/a	4,14	4,35	4,57	4,80	5,05	5,30	8,00	10,89	14,74	19,85
Total water demand	Mm3/a	15,86	16,67	17,52	18,41	19,35	20,34	32,48	46,57	70,01	101,10

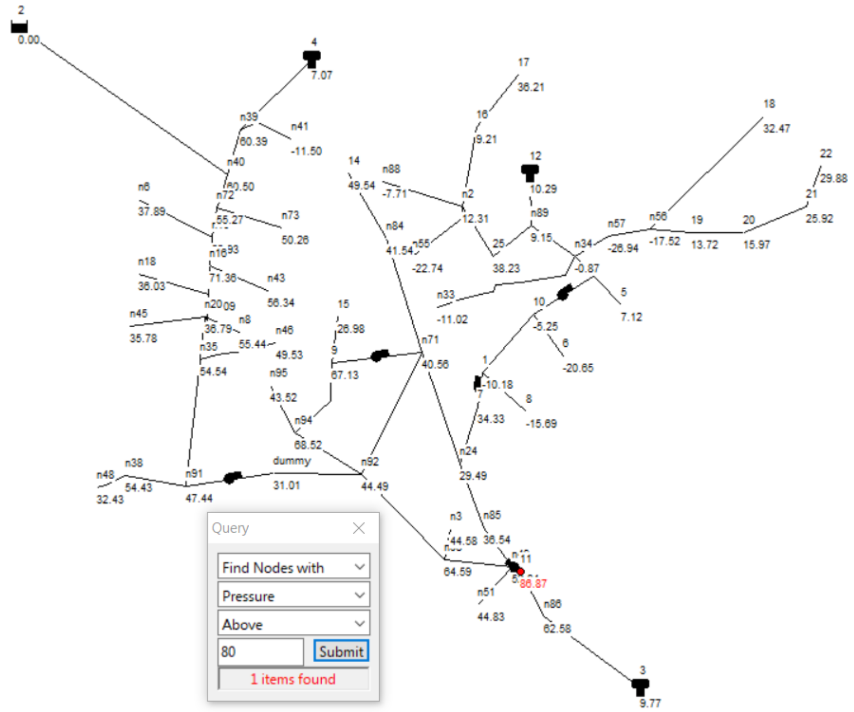
Appendix 3. Pressures in Bukavu's WDN at 6 am

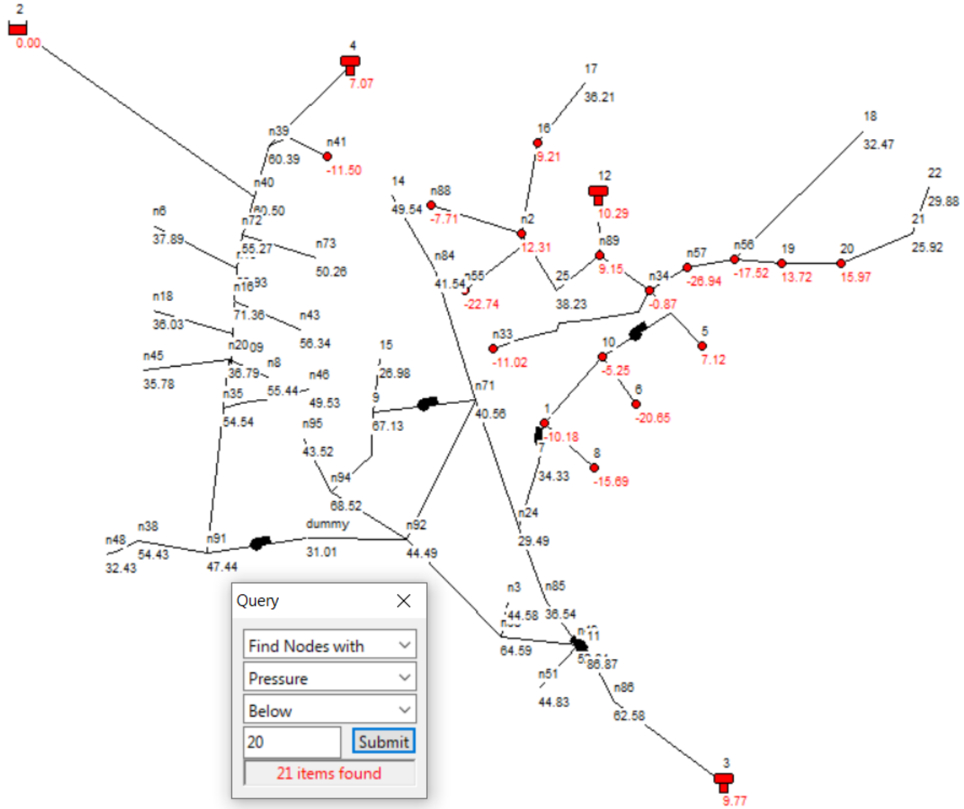


Appendix 4. Pressures in Bukavu's WDN at 12 pm (midnight)

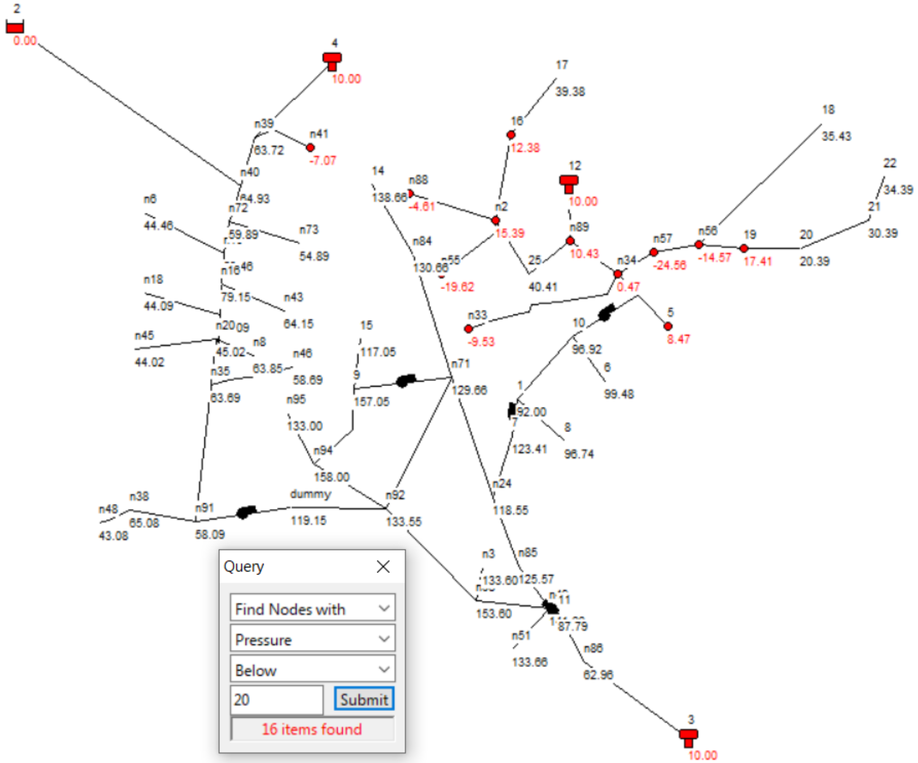


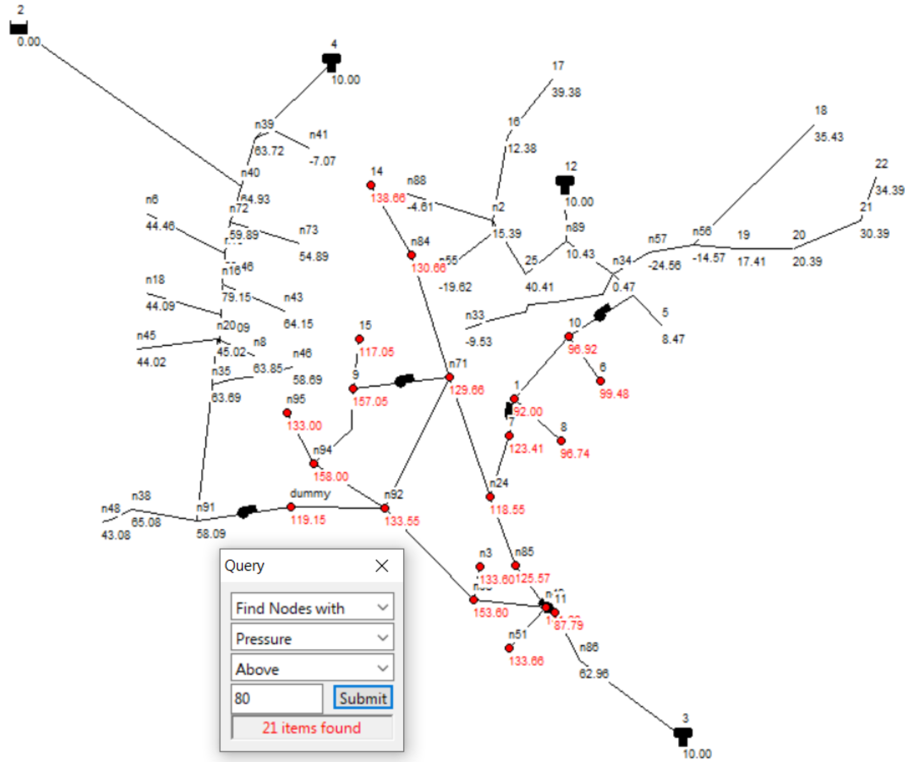
Appendix 5. Minimum and maximum pressure requirement at the maximum consumption hour





Appendix 6. Minimum and maximum pressure requirement at the minimum consumption hour.





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