DISSERTATION

November 14, 2024

Evaluation of Water Distribution Networks through simulation and roughness modeling

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PPGMSB

Bahia State University

Department of Exact and Earth Sciences II

Postgraduate Program in Biosystems Modeling and Simulation

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Evaluation of Water Distribution Networks through simulation and roughness modeling

Master's Dissertation submitted to the University of the State of Bahia, in the Graduate Program in Modeling and Simulation of Biosystems, as a partial requirement for obtaining the title of Master in Modeling and Simulation of Biossistems.

Interdisciplinary Field

Major Field: Modeling Applied to Biosystems

Research Area: Biosystems Modeling and Optimization

Advisor: Dr. Alexandre do Nascimento Silva

co-advisor:

URL do documento original: www.ppgmsb.uneb.br/dissertacao/cod

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S237a Santos, Nariely de Jesus
Evaluation of water distribution networks through simulation and roughness modeling / Nariely de Jesus Santos – Alagoinhas, 2024.
81f.: il

Advisor: Teacher Dr. Alexandre do Nascimento Silva

Dissertation (Master) - University of the State of Bahia, Department of Exact and Earth Sciences DCET II. Postgraduate Program in Modeling and Simulation of Biosystems. Master's degree in Modeling and Simulation of Biosystems – Alagoinhas, 2024.

1. Water - supply system 2. Modeling 3. Distribution I. Silva, Alexandre do Nascimento. II. University of the State of Bahia - Department of Exact and Earth Sciences – Campus II. III. TITLE

CDD – 628.1

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Acknowledgements

First of all, I thank God, the builder of my history.

To my parents who supported me at all times in my life.

The family, boyfriend and friends for the affection, understanding and support given in this journey.

To my advisor, Dr. Alexandre do Nascimento Silva, for all help and collaboration.

To the entire team of teachers and other collaborators of PPGMSB, for their commitment and effort.

CAPES, Coordination for the Improvement of Higher Education Personnel, for the financial support granted.

To all who contributed directly or indirectly to the achievement of this victory, especially Nálisson and Carmen for their support and encouragement, for not letting me give up.

Dedication

I dedicate this work to my parents, as a testimony of their belief in me and the countless sacrifices they have made for me to get here.

Resumo

O consumo de água reflete diretamente sobre aspectos sociais, econômicos e sanitários quando ofertada em qualidade e quantidade adequadas. Tornou-se extremamente importante projetar Redes de Distribuição de água Redes de Distribuição de Água (RDA) que atendam às necessidades das populações na mesma proporção em que mantêm a estrutura com bom funcionamento hidráulico por meio do atendimento de tópicos como disponibilidade de vazão e qualidade da água. Para tanto, têm-se utilizado modelagem hidráulica para conciliar expansão populacional e manutenção dos parâmetros hidráulicos. O objetivo deste trabalho é propor um modelo para avaliar os parâmetro hidráulicos pressão e perda de carga em uma RDA ao longo de 20 anos de por meio de modelagem e simulação. Inicialmente utilizou-se o software EPANET 2.0 para simulação de uma RDA empírica e em seguida realizou-se uma interação entre os softwares EPANET 2.0 e R para avaliar a RDA em seus 20 anos posteriores de funcionamento. Os resultados demonstraram que a perda de carga foi levemente afetada, enquanto as pressões foram elevadas no decorrer dos anos e por isso as tubulações devem ser alteradas para diâmetros comerciais ligeiramente superiores para os anos de 2034 e 2044.

Palavras-chave: Sistema de Abastecimento de Água, simulação, modelagem, Redes de Distribuição de Água, rugosidade.

ABSTRACT

Water consumption directly reflects on social, economic and sanitary aspects when offered in adequate quality and quantity. It has become extremely important to design water distribution networks (WDN) that meet the needs of populations in the same proportion as they maintain the structure with good hydraulic functioning through the attendance of topics such as flow availability and water quality. For this, hydraulic modeling has been used to reconcile population expansion and maintenance of the hydraulic parameters. The objective of this work is to propose a model to evaluate the hydraulic parameters pressure and load loss in an RDA over 20 years of through modeling and simulation. Initially, the EPANET 2.0 software was used to simulate an empirical WDN and then an interaction between the EPANET 2.0 and R software was performed to evaluate WDN in its 20 years of operation. The results suffered that the pressure loss was slightly affected, while the pressures were elevated over the years and therefore the pipes must be changed to superior commercial ceramics for the years 2034 and 2044.

Keywords: Water Supply System, simulation, modeling, Water Distribution Networks, roughness.

List of Symbols

π The ratio between the circumference of a circle and its diameter

mwa meters of water column

mm millimeters

m/km meter per kilometer

mg/L milligram per liter

m/s meters per second

L/hab.dia litres per inhabitant per day

h_f head loss

l/s liters per second

List of Abbreviations

CRAN Comprehensive R Archive Network

WDN Water Distribution Networks

ETA Estações de Tratamento de Água

WTP Water Treatment Plants

LEHNS Laboratório de Eficiência Energética e Hidráulica

WHO World Health Organization

OMS Organização Mundial da Saúde

PPGMSB Programa de Pós-Graduação em Modelagem e Simulação de Biossistemas

PVC Polyvinyl chloride

QGIS Quantum Geographic Information System

RDA Redes de Distribuição de Água

RNF Reservatório de Nível Fixo

FRL Fixed Level Reservoir

RNV Reservatório de Nível Variado

VLR Varied Level Reservoir

WSS Water Supply System

SAA Sistema de Abastecimento de Água

SNIS	Sistema Nacional de Informações sobre Saneamento
UFPB	Universidade Federal da Paraíba
VRP	Válvula Redutora de Pressão
PRV	Pressure Reducing Valve

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CHAPTER 1

Introduction

Water makes up 70% or more of the mass of most organisms. Its consumption reflects directly on social, economic and sanitary aspects, because when offered in adequate quality and quantity reduces levels of infectious diseases such as giardiasis, amebiasis and diarrhea when offered in adequate quality and quantity as required cessary(Heller & de Pádua, 2010). Its uses include food preparation, personal hygiene, hydration and cleaning (Tsutiya, 2006).

Given its importance, the supply of drinking water is a priority among the sanitation services to be provided to the population. The collective supply of water to the population is carried out through structures known as Water Distribution Networks WDN (Brasil, 2020). In Water Supply System (WSS), as WDN are the last to be built, demand the largest portion of the investment and are also the closest to customers. Due to the high investment associated with its implementation and maintenance over time and the high rate of losses due to leaks that occur in pipelines, WDN are a concern regarding their dimensioning and subsequent operation (Pinnto, Castro, Barbosa, & Maia, 2016).

1.1 The Problem

To provide water supply in adequate quantity and quality is not a trivial service, especially when it is intended to combine the universalization of this service with sustainable management with planned actions for conservation and rational use of water (Filho, 2016).

Question: How to evaluate the RDA according to adequate parameters of functioning?

1.2 Justification

The population growth increases water consumption and consequently, WDN have their hydraulic parameters changed. This can be observed by reducing or increasing pressure at certain points of the pipeline, increasing the loss of load in the network or even lack of water (Salomão, da Silva, da Silva, & Zadorosny, 2023). These changes can cause one of the most worrying environmental impacts generated in WDN: water losses (Ávila, Sánchez-Romero, López-Jiménez, & Pérez-Sánchez, 2021).

Losses are the deficit between the amount of water produced (water taken from the body and treated to be distributed) and the amount of water delivered to consumers (Heller & de Pádua, 2010). In 2019, Brazil had 37,8% of water distribution losses, which corresponds to approximately 8 grand Olympic pools of treated water are wasted daily (Brasil, 2023). The main type of loss that usually occurs are the actual losses caused by leaks in the pipes, whose origin is the occurrence of high pressures in the WDN (Huang et al., 2020).

As a result, there is an overload of water resources, since greater volumes of water will be required to compensate for what was lost and in fact meet the population consumption, as well as the possible occurrence of health damage due to the entry of pathogens into ruptures of pipelines and the creation of environments with stagnant water conducive to the proliferation of disease-transmitting agents (Al Qahtani, Yaakob, Yidris, Sulaiman, & Ahmad, 2020). In addition, the structures of WSS are mostly buried and in many cases in heavy traffic roads, which makes it difficult to inspect and maintain (de Araujo et al., 2020).

Therefore, the management entities have been concerned about dealing with problems such as: aging of pipes, overload of the structure, operation of WSS in addition to its useful life and neglect in maintenance (Ramos et al., 2023).It has become extremely important to design WDN that meets the consumption needs of populations over time in the same proportion in which it maintains water quality and a good hydraulic functioning of structures(Ajaz & Ahmad, 2023).

For this, technology concepts have been used together with the already conceptualized theories of hydraulics (Ociepa, Mrowiec, & Deska, 2019). Analytical models applied to the hydraulic area in the design of WDN have been used for modeling and simulation of parameters. Thus it is possible to observe variations in the behavior of WDN before changes, such as population increase (M. Marques, da Silva Junior, Marisa, Corrêa, & Zanette, 2020).Through the use of software and models for modeling it is possible to identify problems and reduce the time for project preparation (Muller, Gericke, & Pietersen, 2020).

1.3 Motivation

The motivation that led to the development of this work is in the search for greater sustainability and conciseness in the management of WDN. The expected results have characteristics that contribute positively to social, economic and environmental issues, namely: optimization and expansion WDN and maintenance of water resources.

1.4 Objectives

General

The objective of this work is to propose a model to evaluate the hydraulic parameters pressure and load loss in a WDN over 20 years of through modeling and simulation.

Specific

- Analyze the hydraulic parameters of an empirical WDN;
- Perform a simulation in R with change in the population and roughness of the adopted pipe, for 10 and 20 years later;
- Present alternatives to solve values outside the limits established in legislation;

1.5 Hypothesis

Based on the model, the following questions can be raised:

- How can modeling and simulation work as tools for maintaining proper working parameters in WDN?
- A model created to evaluate WDN over time, through the change of roughness of pipes and increase in consumption, can contribute to efficiency in the management of WDN?

From these questions arise the following hypotheses:

- Optimizing a WDN through a model promotes benefits such as: agility, observation of varied scenarios and adequacy of hydraulic parameters.
- Through a model it is possible to obtain greater sustainability in the management of WDN, since it will allow to maintain the hydraulic parameters in adequate operation to reduce real losses and thus contribute to the conservation of water resources.

1.6 Limits and limitations

The limit of this research is in composing results for hydraulic parameters without connection with the economic aspect intrinsic to structures for sizing WDN by means of commonly used budget spreadsheets.

Since it is a study in a WDN, it follows that in the execution of real projects it is necessary to adopt services specific for the locality, such as topographical study and observation of water consumption variation throughout the day.

1.7 Relevance of the study

A model, as applied in this research, allows a more precise sizing of WDN, as well as the rehabilitation of those that are already implemented. Therefore, as points of relevance of this study, we have:

1. Reduction of environmental impacts, such as actual losses;
2. Contribution of advances in technology in the area of water supply;
3. Compatibility between water resources conservation and management of WDN;
4. Reduction in the time of elaboration of WDN projects;
5. Evaluate the potential of the use of R and Epanet 2.0 software for the evaluation of WDN.

1.8 Contributions

Modeling and simulation comprise the construction of real systems in the configuration of a model to enable behavioral analyses based on the variation of determined parameters. This section highlights the main contributions of the work, which not only advance technical knowledge in the area of design WDN, but also contribute to the conservation of water resources. Among the contributions of this work, we can mention:

- Expansion of work tools for design and operation of WDN, through the interaction of a hydraulic simulation software with a statistical modeling program;
- Improvement of the ability to predict the hydraulic behaviour of WDN, since it is possible to predict future scenarios and develop effective strategies for management of WDN;
- Simulation data generation and behavior analysis of WDN with the change in roughness value, natural during use of the Polyvinyl chloride (PVC) pipe;

- Optimization of environmental management strategies, by identifying sites subject to the occurrence of leaks.

These contributions represent advances in the management of WSS.

1.9 Adherence

This dissertation focuses on the evaluation of WDN through modeling and simulation. It is aligned with the research line Modeling and Optimization of Biosystems Programa de Pós-Graduação em Modelagem e Simulação de Biossistemas (PPGMSB), whose main objective is the study and development of numerical and analytical methodologies related to Computational Modeling. The study was conducted in the MAIA Research Group. In the history of PPGMSB no dissertations related to this study were identified.

1.10 Organization of the Defense document of master

This dissertation has 6 chapters organized as follows:

- **Chapter 1 - Introduction**: Presents the research proposal by contextualizing the problem, justification, objectives, hypotheses, limits, limitations and relevance of the study;
- **Chapter 2 - Theoretical Referential**: It addresses the concepts about WSS and hydraulic simulation;
- **Chapter 3 - Materials and methods**: Display of the research classification, defines the chosen hydraulic parameters, characterizes the simulation with EPANET and R software;
- **Chapter 4 - Model**: Demonstrates the construction of the hydraulic model and presents aspects of simulation;
- **Chapter 5 - Results**: Presents the results obtained by the hydraulic model in R and EPANET;
- **Chapter 6 - Conclusions**: It expresses a final argument about the work done.

CHAPTER 2

State of the art

In this chapter, based on research, through books and scientific articles will be found a bibliographic review that aims to explain the main concepts related to the subject addressed, for this will be presented concepts of hydraulics, fluid dynamics, WSS, WDN and the parameters that influence WDN, such as consumption, pressure, load loss and roughness. Understanding these concepts is essential to understand the theoretical foundations that support research.

Finally, more details about the EPANET 2.0 software and the R software environment are presented, both used for modeling and simulation of WDN. Recent articles will be presented that have researched related subjects and applied similar solutions to the proposals in this study. This analysis will allow us to understand how the research fits into the current context and how the proposed solutions dialogue with existing contributions in the literature.

2.1 Hydraulics and fluid dynamics

The application of hydraulics in engineering and construction of WSS, include the use of pipes and pipelines. It is necessary to define the difference of conceptualization between these. Tubes are individual parts, usually in cylindrical shape, with length limited by size of manufacture or transport. Can be made of cast iron, concrete, steel, PVC and polyethylene. The pipe, in turn, consists of pipes or has long continuity manufactured on site, added with accessory parts. Among its synonyms can be cited the terms: plumbing, piping, tubing or piping (de Azevedo Netto & Fernández, 2015).

Normally, pipes are cross-sectional structures through which fluid is transported. When the fluid in flow occupies the entire cross-section, the internal pressure becomes greater than the outside (atmospheric). In this case, it is classified as forced duct. In cities, water distribution pipes must always function as forced conduits, so they are made of material resistant to the resulting internal pressure (de Azevedo Netto & Fernández, 2015).

Flow can be defined as permanent when its physical characteristics such as speed, pressure, temperature and specific mass remain constant over time at any point of the pipe. This definition can also be applied to cases in which the average values of these characteristics in each section of the flow have been evaluated and no attenuated discrepancies were noted. Whether the speed along the pipe remains constant or not, the permanent flow can be classified in uniform or varied, respectively (Gomes, 2019).

Fundamental equations

The transport of water in forced pipelines is driven by two fundamental equations known as: continuity equation and Bernoulli's equation. The continuity equation assumes that for a permanent flow a given flow (Equation 2.1), remains constant along the conduit. Therefore, in two distinct sections of the pipe, one can describe the continuity equation as in the Equation 2.2 (de Azevedo Netto & Fernández, 2015).

$$Q = A.V \tag{2.1}$$

$$A_1.V_1 = A_2.V_2 \tag{2.2}$$

Em que:
Q is the water flow in the pipe;
A is the pipe cross-sectional area;
V is the average speed of water circulation.

The Bernoulli equation (2.3), in turn, also known as the energy equation, it deduces that between two sections of a conduit, the sum of the energies of pressure, potential and kinetic of the first section is equal to the sum of these same energies in the second section with the losses of load occurred between the two sections.

$$\frac{p_1}{\gamma} + z_1 + \frac{{V_1}^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{{V_2}^2}{2g} + h_f \tag{2.3}$$

where:
p_1 e p_2 are the pressures in the sections;
z are the dimensions relative to a horizontal reference plane;
V is the flow rate of water in the pipe in both sections;
γ is the specific weight of water;

g is the value of acceleration of gravity.

The energies are described in the equation above as: kinetics, represented by the component $V^2/2g$, associated with the velocity of the fluid; gravitational potential, resulting from the vertical position (altitude) where the fluid is located, represented by Z and the pressure component at the point analyzed, represented by p/γ (Gomes, 2019).

In pressurized water networks the term corresponding to kinetic energy $V^2/2g$ is negligible among the loads along the pipes, since the average velocities vary between 1 and 3 m/s, that is, they are very small when compared to the other components of the Bernoulli equation. Therefore, the ratio between loads or piezometric quotas is reduced (Gomes, 2019):

$$H_1 + z_1 = H_2 + z_2 + h_f \tag{2.4}$$

where:
H represents the pressure energy per unit of weight, expressed in terms of water column height $H = p/\gamma$;
z_1 e z_2 are the dimensions relative to a horizontal reference plane.

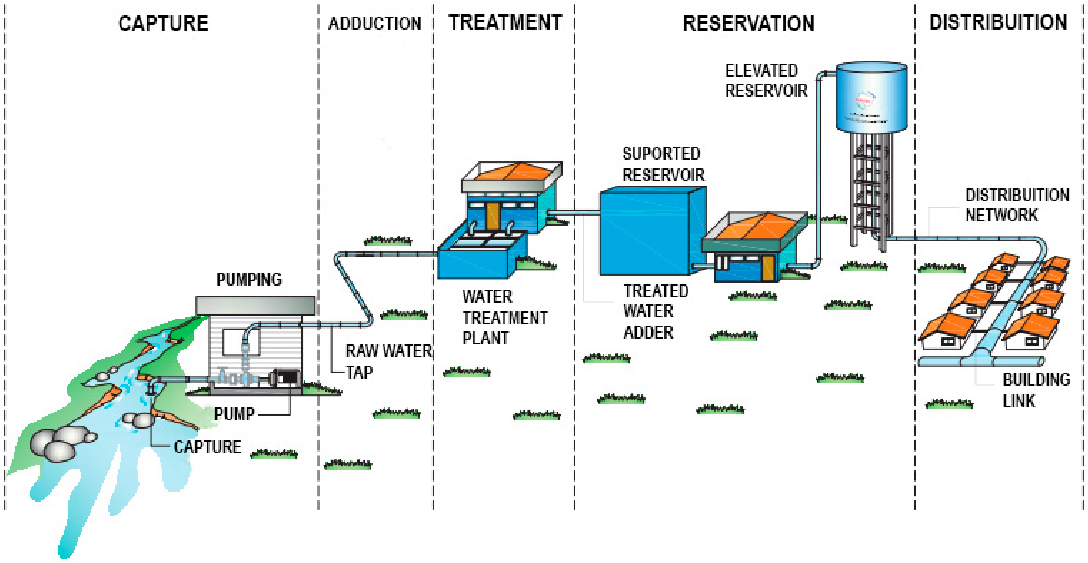
2.2 Water Supply System

The water supply is cited by Law n° 11.445/2007 as one of the topics of public service of basic sanitation that must be offered to the population (Brasil, 2007). The structure responsible for taking water from nature, adapting its quality, transporting it to human clusters and supplying it to the population in a quantity compatible with their needs is called WSS (Brasil, 2004).

The implementation of WSS results in the increase of life of the population served, reduces mortality rates, especially children and contributes to health preservation. In addition, regions with water supply coverage have greater industrial growth, because water is also a productive input of many industries (Brasil, 2004).

In general, the WSS are composed by the following structures: water source or watercourse, catchment, adduct, pumping stations, treatment, reservoirs and distribution network (Gomes, 2019). The figure 2.1 approaches these structures schematically.

Figure 2.1: General structure of a Water Supply System.



Source: ANUAL (2004)[p. 65]

Source

The spring is the source from which water will be taken for supply. Can be superficial or underground, as long as it meets the criteria of quantity, quality, operation costs and treatment (Gomes, 2019). Surface water sources consist of tributaries, such as rivers, lakes and dams, which are on the surface. In this case, a more robust treatment process is required. The underground springs, due to the confinement in which they are lozalized, need the motor-pump assembly to be extracted and are generally of good quality, therefore their treatment is done in many cases with a simple disinfection (Tsutiya, 2006).

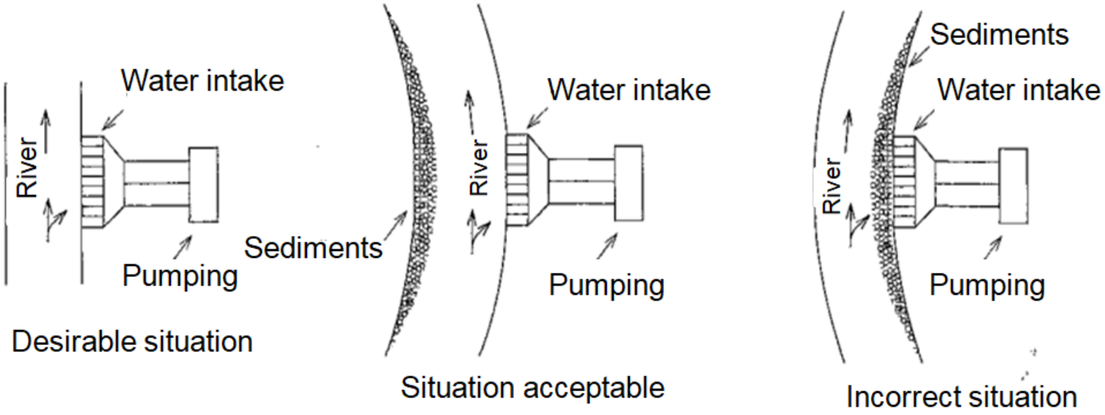
Capture

The capture makes it possible to extract water from the spring. For this purpose, a structure known as water intake is installed, composed of channels or pipes with different architectures to meet each need (Gomes, 2019). In cases of shallow catchment, it is recommended that special care be taken with the physical characteristics, the margins of the watercourse, and seasonal variations in flow due to the occurrence of bad weather (Heller & de Pádua, 2010). The choice must be well articulated so that at no time of year there is a supply interruption and maintenance can be done with easy access (Tsutiya, 2006).

In the case of groundwater, drilling is done in artesian wells. In localities similar to the concavity of a parable, turned upwards, that when perforated present water that gushes, occurs the so-called natural artesianism. In situations where the region is flat and the water does not present a gushing aspect, on the contrary, it is necessary a motor-pump assembly to carry out the extraction, there is a case of common artesianism (Brasil, 2006).

For surface captures, it is recommended that the capture be installed in rectilinear sections. When this was not possible, the location chosen should be in the concave part of the watercourse to avoid erosion of the banks caused by high water flow rate. In addition, in lakes and dams it is necessary to consider a stretch with some depth of the water level in order to prevent algae and decaying organic matter from being dragged into the WSS. In cases where the source is at a lower quota than the region to be supplied, a pumping station is built (Brasil, 2006). The representation of the water outlet positioning can be seen in figure 2.2.

Figure 2.2: Positioning of the water catchments in surface water courses.



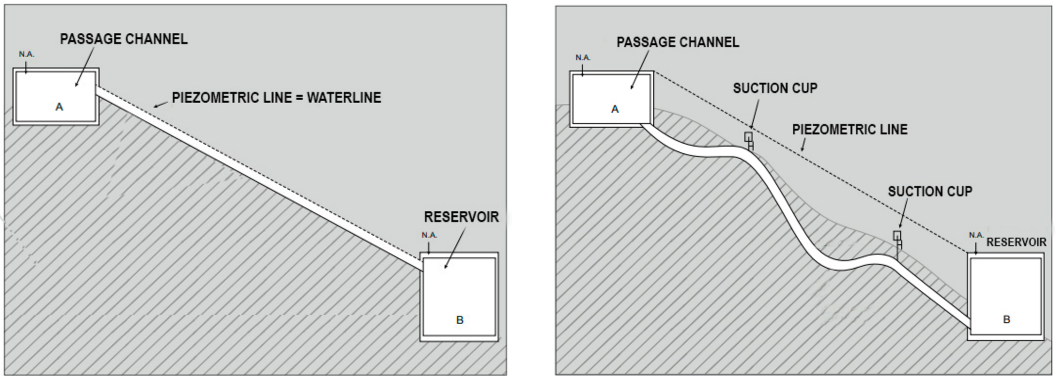
Source: Tsutiya (2006)

Adduction

The adduction is carried out by means of pipes called lines, responsible for conducting raw water or treated water. Its function is to interconnect the units of collection, treatment, pumping stations, reservation and distribution network (Heller & de Pádua, 2010).

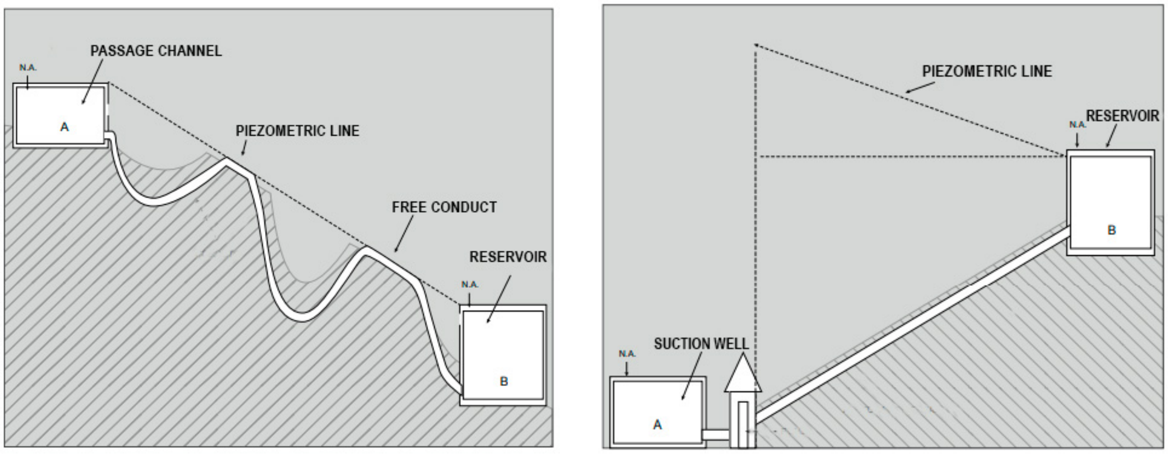
According to their hydraulic characteristics, the adductors can be classified as free, forced or mixed. The free ducts are under the effect of atmospheric pressure and may or may not have water contact with the outside. In closed ducts, water occupies the entire section of the pipe, therefore, the internal pressure is higher than atmospheric pressure. The mixed ducts merge ceilings with the two types described above (Heller & de Pádua, 2010), as demonstrated in the figure 2.3 and 2.4.

Figure 2.3: Gravity adductors in free and forced duct.



Source: Tsutiya (2006).

Figure 2.4: Mixed and by-fill adductors.



Source: Tsutiya (2006).

Pumping stations

It will not always be possible to install a WSS in topographic profile without variations. To allow raw or treated water to reach higher levels, pumping stations are used, also known as recalque or pumping. There may be WSS without any, or even with dozens of them (Gomes, 2019; Heller & de Pádua, 2010). The elevations of WSS when installed between reservoirs or in stretches of the distribution network are called booster (Heller & de Pádua, 2010).

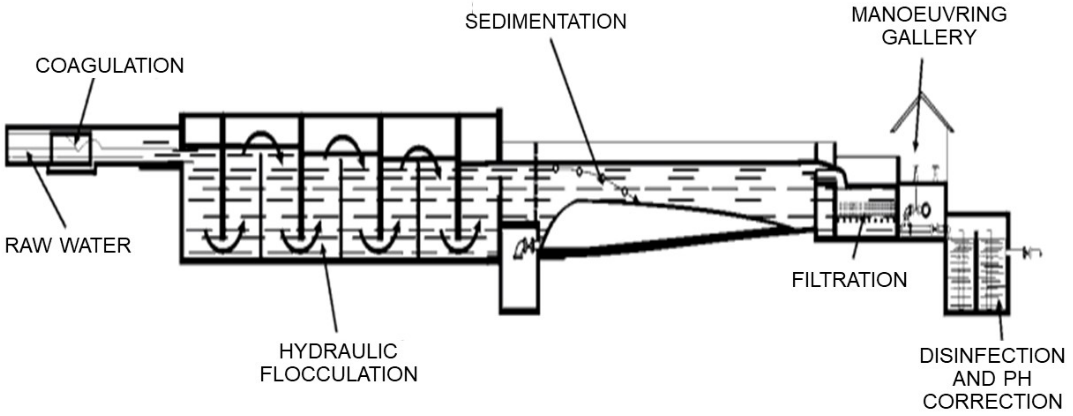
Treatment

After removing water from nature, it is necessary to make its quality compatible for human consumption as provided in Law no. 888/2021. For this purpose, the Water Treatment Plants

(WTP) (Heller & de Pádua, 2010). The complexity and how costly this procedure will be depends solely on the quality level of the raw water to be captured. When leaving the WTP, the water will be free of or with reduced percentage of pathogenic bacteria, turbidity, color, odor, taste, hardness, corrosiveness, iron, manganese and mineral salts (Gomes, 2019).

Water treatment begins with the retention of fine solids in suspension by means of sieves. Since dissolved metals such as iron and manganese can be found in water, the next step is to add chlorine for oxidation of these metals. The treatment is continued with the removal of impurities in the stage known as coagulation, in which the mixture of aluminum sulfate to water occurs so that the impurities are united and form gelatinous flakes. In another stage known as flocculation, with similar purpose to the previous one is carried out, but in this, the impurities are joined into even larger and heavier flakes by mechanical stirring. After stirring, the water remains at rest in the step called decantation, so that the flakes formed settle to the bottom of the tank and are finally separated from the water. These impurities are then removed by filtration, in which layers of activated carbon remove the odor and taste of the chemicals. The last two steps to be performed are disinfection and fluoridation which consist of: destroy microorganisms and prevent caries (Heller & de Pádua, 2010). The steps can be seen in figure 2.5.

Figure 2.5: Water treatment phases.



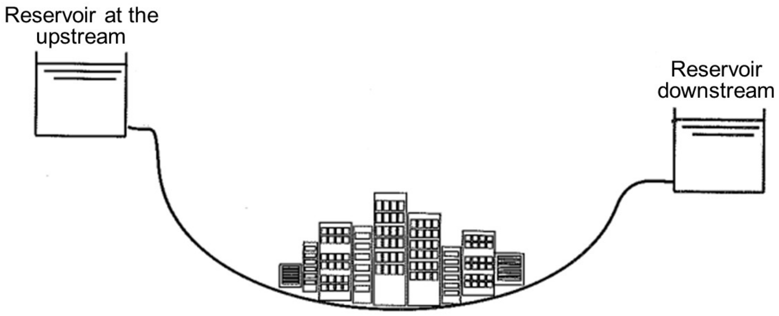
Source: Sperling et al. (1995)

Reservoirs

Becomes necessary in us WSS the implementation of structures that balance the flows of production and consumption, since the flow of production, coming from the stages of capture, adduction and treatment is little variable, while the flow of consumption, required by the population, is variable throughout the hours of the day and days of the year. The reservoirs then take on this function (Heller & de Pádua, 2010). In addition to also serve as: emergency reserve in the event of the need to break supply, water storage to fight fires and condition the available pressures in the distribution network (Gomes, 2019).

According to their location, they can be classified into upstream or downstream reservoirs. The upstream reservoirs are located before the distribution network to receive water and pass on the population. Downstream reservoirs are installed after the distribution network and their function is to accumulate water to supply consumers in times of high demand (Heller & de Pádua, 2010). Both types of reservoir can be seen in figure 2.6.

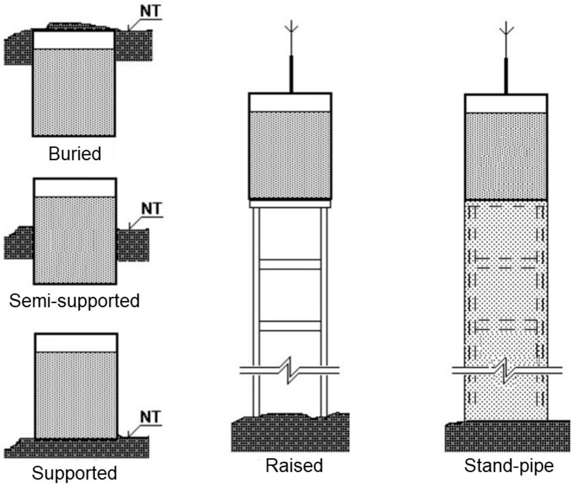
Figure 2.6: Upstream and downstream reservoirs.



Source: Tsutiya (2006)

As their position on the ground can be classified into: supported (base fully supported on the surface above the ground), raised (structures are used to raise the reservoir), semi-supported (part below and part above the ground), buried (completely under the ground) and *standpipe* (reservoir with built-in lifting structure to keep the perimeter of the building cross section continuous) (Guimarães, Carvalho, & Silva, 2007). The figure 2.7 demonstrates these types of reservoirs.

Figure 2.7: Types of water reservoirs.



Source: Tsutiya (2006)

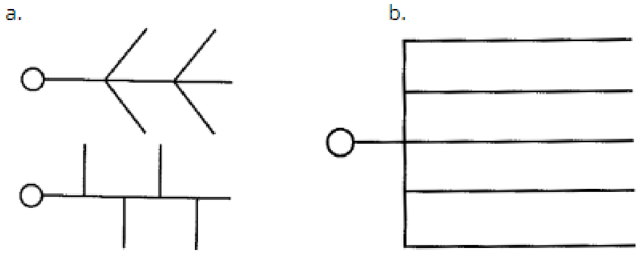
2.3 Water Distribution Network

The WDN is the ultimate goal of organizing all the parts described above. Nothing more than a set of pipes, connections and special parts, distributed in public places to lead water to homes, businesses, industries and public places. The complexity of its structure varies depending on the size of the population to be supplied, population density and topography of the supply area (Heller & de Pádua, 2010).

The WDN have the purpose of meeting, with appropriate hydraulic parameters, each of the considered consumption points. The geometric design of the water distribution network has variances according to the size of the city to be supplied and its topography. In general, the pipe is classified into: trunk or main and secondary. The main pipe has a diameter superior to the others and its function is to lead water to the secondary pipes, and these in turn, lead water directly to the points of consumption (Porto, 2006). The water supply for the pipes can be done by means of reservoirs (elevated, supported or semi-buried) or pumping stations (Tsutiya, 2006).

From the arrangement of main and secondary pipes and fluid flow, water distribution networks can be classified as branched or matted. In the branched networks, as observed in figure 2.8, The supply is carried out from a trunk pipe fed by an upstream reservoir or otherwise under pressure of a pumping, and the distribution of water is made directly to the secondary pipelines. Therefore, in this case, the direction of water flow is perfectly defined. It is possible to deduce that the interruption in the water flow in some WDN for some reason, for example, for maintenance, will paralyze the water distribution in all subsequent stretches (Porto, 2006).

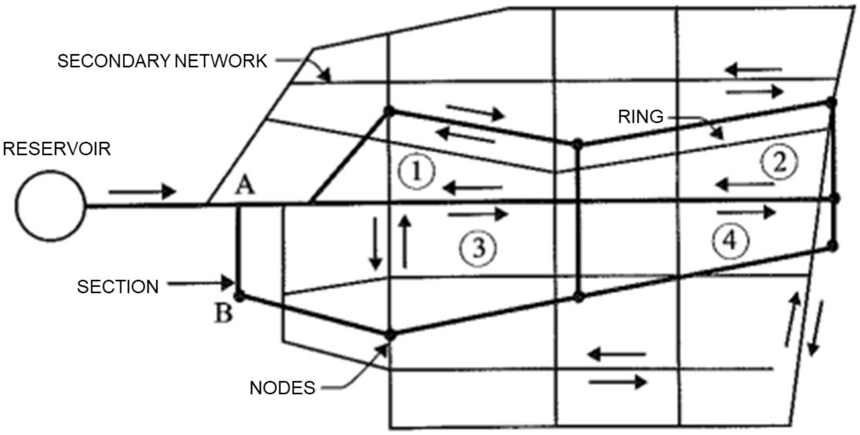
Figure 2.8: Branched net in herringbone (a) and grill (b).



Source: adapted from Porto (2006).

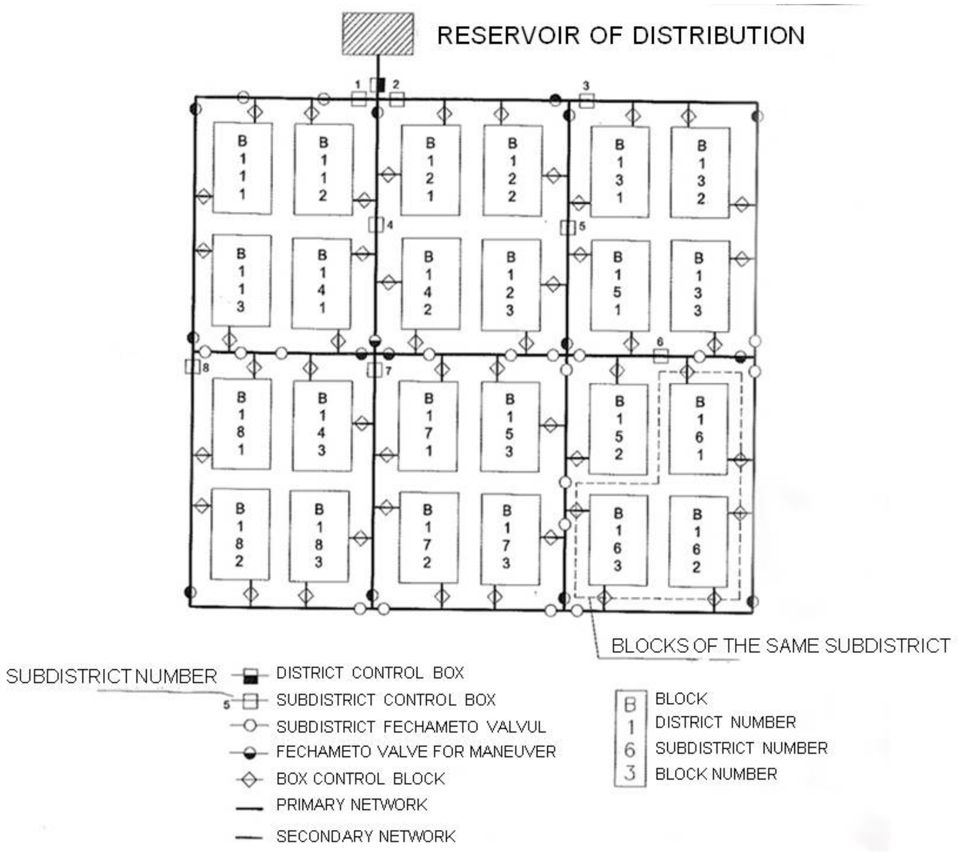
In the mesh network it is possible that the supply is made by different ways, in this way, in cases of problems in a certain stretch, the supply is not interrupted or is minimized. It can be classified into two types, mesh in rings and blocks (Tsutiya, 2006). In the network in rings the pipes are connected to each other and in the network in blocks, the networks inside the blocks have only two feeding points, as illustrated in figures 2.9 and 2.10.

Figure 2.9: Net studded in rings.



Source: Tsutiya (2006).

Figure 2.10: Mesh in blocks.



Source: Tsutiya (2006).

The calculation method for the dimensioning of branched networks follows the steps below:

1. Pre-processing step, in which the downstream stretches are numbered to upstream so that the most distant of the reservoir receives the number 1 and the extensions of the stretches and topographic dimensions are obtained.
2. Determine the total extent of WDN.
3. Calculation of the distribution flow (Equation 2.5).

$$Q_d = \frac{P.q_m.K_1.K_2}{3.600h} \tag{2.5}$$

where:
Q_d is the distribution flow;
$P$is the population to be supplied;
q_m is consumption per inhabitant;
K_1 is the coefficient of the day of greatest consumption;
K_2 éthe coefficient of the highest consumption hour;

h is the number of hours of system operation.

4. Calculation of the total running flow rate of WDN (Equation 2.6).

$$Q_m = \frac{Q_d}{E_{total}} \tag{2.6}$$

where:
Q_d is the distribution flow;
E_{total} is the total extent.

5. Calculation of the flow rate in operation for each section (Equation 2.7).

$$Q_m = Q_{m_1}.E_{trecho} \tag{2.7}$$

where:
Q_{m_1} is the distribution flow in each stretch;
E_{total} is the total extent.

6. Determine the dry tip stretches to determine the downstream flow (Qj). On the dry ends, Qj is equal to 0. In the other passages, Qj is equal to the sum of the upstream flows.
7. Calculate the flow of amount (Equation 2.8).

$$Q_{mont} = Q_{m_1} + Q_j \tag{2.8}$$

where:
Q_{mont} is the flow of each stretch;
Q_m is the distribution flow in each stretch;
Q_j is the flow of each stretch.

8. Calculate the fictitious flow (Q_f) according to the definition of dry tip stretches. The formulas of fictitious flow for dry tip stretches and stretches with subsequent supply are found in Equations 2.9 and 2.10 respectively.

$$Q_f = \frac{Q_{mont}}{1,732} \tag{2.9}$$

$$Q_f = \frac{Q_{mont} + Qj}{2} \tag{2.10}$$

9. Calculate the loss of load, by means of the formulas of Hazen-Williams (Equation 2.18) ou Darcy Weisbach (Equation 2.13).
10. Calculation of downstream piezometric quotas.
11. Calculation of piezometric dimensions.

For the design of WDN in software we seek to obtain the total population as Equation 2.11 e base consumption of each stretch to be inserted in accordance with the number of houses to be supplied, as shown in Equation 2.12.

$$Pop = n \times T_x \tag{2.11}$$

where:
Pop is the current project population;
n is the total of residences;
T_x is the occupancy rate in residences.

$$Q_b = \frac{Q_d}{n} \tag{2.12}$$

where:
Q_b is the base consumption;
Q_d is the distribution flow;
n is the number of residences in the stretch;

Some factors can affect the hydraulic performance of WDN over time, such as: consumption, pressure, loss of load and roughness.

Water consumption in households

The water supply in Brazil, in 2022, reached a total population of 171 million (SNIS, 2023). Usually, the consumption per individual is measured, representing the average daily water volume in liters per inhabitant per day L/hab.dia that a person uses for his survival, in uses such as: cooking food, baths, sanitary uses, washing clothes, watering gardens, drinking, among others (Gomes, 2019).

In urban WSS, consumption can be classified as per household inhabitant and average effective inhabitant. The first one is related to domestic water uses, therefore it is measured by means of hydrometers installed in homes. The calculation for this consumption is done by dividing the consumption, obtained with the monthly reading of the hydrometer, by the number of inhabitants of the household (Gomes, 2019). The consumption per average effective individual is defined by the sum of the consumption: household, commercial and industrial, including water losses that occur throughout WSS (Gomes, 2019).

In general, a population with higher income standards will consequently consume more water due to the practice of activities that provide more comfort and leisure such as: use of washing machines and dishes, swimming pools, showers, gardens and vehicle washes. Similarly, water consumption is directly proportional to the temperature increase, so hot and dry regions will have a higher water consumption than temperate and cold regions. The degree of development of cities, reflected in industrialized zones also influences consumption (Heller & de Pádua, 2010).

Average water consumption in Brazil in 2022 was 148.2 L/hab.dia. In figure 2.11 it is possible to note the consumption per inhabitant in Brazilian regions in 2022.

Figure 2.11: Average consumption per inhabitant in the geographic regions of Brazil.

Source: SNIS (2022)

In the technical literature, different estimated values are presented for a specific population number, as shown by the 2.1.

Table 2.1: Average consumption per inhabitant household.

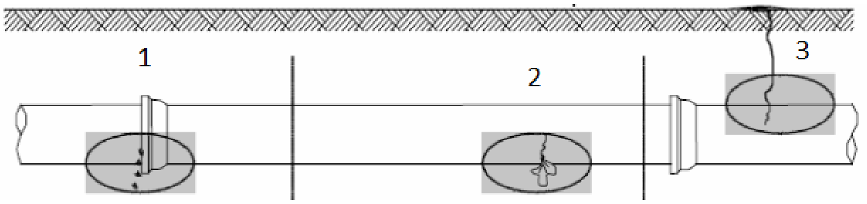
Author	Population	Consumption per inhabitant L/hab.dia
(Heller & de Pádua, 2010)	< 5.000	90 a 140
	5.000 a 10.000	100 a 160
	10.000 a 50.000	110 a 180
	50.000 a 250.000	120 a 220
	> 250.000	150 a 300
Brasil (2004)	6.000	100 a 150
	6.000 a 30.000	150 a 200
	30.000 a 100.000	200 a 250
	> 100.000	250 a 300

In what regards the WDN, the population increase over time consequently leads to an increase in water consumption. In turn, the increase in water consumption will be reflected in changes in hydraulic parameters pressure and load loss. As consumption increases, pressures are reduced and load losses increased (Salomão et al., 2023).

Pressure

Control the pressure in WDN is a key topic to reduce the number of leaks and the flow of water that escapes (Fritz, de Carvalho Gimenes, & de Pina Filho, 2020). The figure 2.12 demonstrates the types of leaks that can occur in WDN.

Figure 2.12: Types of leakage



Source: Fritz et al. (2020), pg 504.

Type 1 shown refers to inherent leaks that are not visible and not detectable by means of acoustic instruments. Similarly, type 2 is not visible either, but can be detected acoustically. Type 3 is visible on the surface, this is even the cause of complaints by the population (Tsutiya, 2006).

One of the best-known and most used techniques in pressure management in WDN to deal with the occurrence of high pressures is sectorization. As the name suggests, it means to divide the WDN in individually controlled sectors. This way it is expected to quickly identify leaks, locate better places for installation of Pressure Reducing Valve (PRV) and protect the rest of the network from accidental or malicious contamination events (Khoa Bui, S. Marlim, & Kang, 2020).

The NBR 12.218/2017 establishes specific pressure values for static and dynamic pressure. The maximum static pressure is set at zero consumption and with the reservoir at maximum level. Not exceeding your limit means protecting the integrity of pipes, fittings and valves, as well as reducing water losses (Heller & de Pádua, 2010). The maximum static pressure values in the distribution pipes should be 40 mwa. In case of regions with rugged topography, the maximum static pressure value can reach 50 mwa (“NBR12218”, 2017).

The minimum dynamic pressure is understood as the pressure referred to at the level of the axis of the public road, at a certain point in the network, on the day and time of highest consumption, and with the minimum water level in the reservoir. Its function is to overcome the topographical differences and the losses of load in the buildings branches and in the pipes of the buildings to be supplied so that the water reaches the building reservoirs, from which it will be distributed (de Azevedo Netto & Fernández, 2015). In the case of minimum dynamic pressure, this shall be at least 10 mwa (“NBR12218”, 2017). It is worth mentioning that values higher or lower than those recommended in the standard, both for static and dynamic pressure, will be accepted, provided that they are technically and/or economically justified.

Gomes (2019) reasons for setting limits on maximum network pressures:

- Higher pressures increase the energy cost of pumping, so that the manometric and impulse height is reached;
- The pipes will be more expensive, since the material needs to withstand the pressure values;
- Increased chances of ruptures in pipelines;
- Increase in real water losses, because with higher pressures, the cracks that occur in pipes and joints will have a greater flow.

Head loss

As defined by Gomes (2019)[p. 60]:

> "Part of the energy that the liquids have in dynamic regime is dissipated due to the effect of its viscosity or internal friction, coupled with the effect of turbulence or shocks between the particles of the fluid. This part of the dissipated energy, which is trans-

> formed into heat, is called friction load loss, friction energy loss or continuous load loss along the conduit".

The friction that occurs between particles of a liquid can be internal or external. Internal friction can also be called viscosity and is defined as the resistance of a given liquid to movement. The higher the viscosity, the thicker the liquid and the slower the flow. External friction is corresponding to a thin layer formed on the solid surfaces through which the liquid flows, such as the walls of a conduit (White, 2018).

In general terms, when it comes to uniform and permanent flow in pipelines, the loss of load (h_f), between two sections is proportional to the distance between them. The physical characteristics of the fluid, such as viscosity and specific mass, and the geometric characteristics of the conduit, namely: internal diameter and absolute roughness of the inner walls of the tube, determine the friction load loss (de Azevedo Netto & Fernández, 2015).

The NBR 12.218/2017 establishes that the maximum allowable value for loss of load is 10 m/km. Empirically, through different experimental conditions were elaborated formulas to determine the friction load loss in uniform and permanent flow. Among the formulas used, the equations of Darcy Weisbach and Hazen-Williams can be cited (de Azevedo Netto & Fernández, 2015).

The equation of Darcy Weisbach created in 1845 is defined as follows (Equation 2.13):

$$h_f = f\frac{LV^2}{D.2g} \tag{2.13}$$

where:
$h_f$is the loss of load along the conduit, in mca (meters of water column);
f is the friction factor of Darcy Weisbach (dimensionless);
L is the length of the pipe, in meters;
V is the flow rate of liquid in the pipe (m/s);
D is the diameter of the pipe, in meters;
g is the value of acceleration of gravity $m^2/2g$

The necessary variables are found as follows: length and diameter are observed according to design need, speed (V) is found by means of the Continuity Equation, as demonstrated by Equation 2.14.

$$V = \frac{Q}{A} \tag{2.14}$$

where:
V is the flow rate of liquid in the pipe (m/s);
$Q$is the flow rate (m^3/s);
A is the area of the flow section (m^2)

The A is the area of the flow section is calculated by Equation 2.15:

$$A = \frac{\pi D^2}{4} \tag{2.15}$$

where:
D is the diameter of the pipe (in meters).

The friction factor is obtained by means of the equation Colebrook & White (Equation 2.16):

$$\frac{1}{\sqrt{f}} = -2.log\left(\frac{\epsilon}{3,7D} + \frac{2,51}{Re\sqrt{f}}\right) \tag{2.16}$$

The roughness factor of the pipe (ϵ) is measured by specific equipment of rugosimeter name. Its value is predetermined by manufacturers and increases over the years, as can be observed in Table 2.2.

Table 2.2: Roughness of the pipes.

Material	New pipes (m)	Old pipes (m)
Galvanized steel	0,00015	0,0046
Riveted steel	0,0010	0,0060
Coated steel	0,0004	0,0012
Welded steel	0,00004	0,0024
Lead	smooth	smooth
Asbestos-cement	0,000025	not determined
Copper	smooth	smooth
Wrought iron	0,0004	0,0024
Cast iron	0,00025	0,0050
Ceramic shackles	0,0006	0,0030
Plastic	smooth	smooth
Glass	smooth	smooth

Source: de Azevedo Netto and Fernández (2015)

In 1883, Osborne Reynolds observed the behavior of liquids in flow with different diameters and temperatures. Through theoretical and experimental investigations, his research has agreed the type of movement of a pipe by means of the so-called, Reynolds number, a dimensionless quantity, cited in Equation 2.17.

$$R_e = \frac{VD}{\upsilon_{cn}} \tag{2.17}$$

where:
$V$is the velocity of the fluid, em m/s;
$D$is the diameter of the pipe, in meters;
υ_{cn} is the kinematic viscosity, in $\frac{m^2}{s}$.

The Reynolds number makes it possible to classify pipe flow as laminar, transition or turbulent. If the Reynolds number is less than or equal to 2000, there is a laminar flow whose characteristics are: well-defined fluid particle trajectory, without crossing, thus occurs the formation of a blade that preserves the characteristics of the medium. This type of flow is common in fluids with high viscosity and low flow rate (de Azevedo Netto & Fernández, 2015).

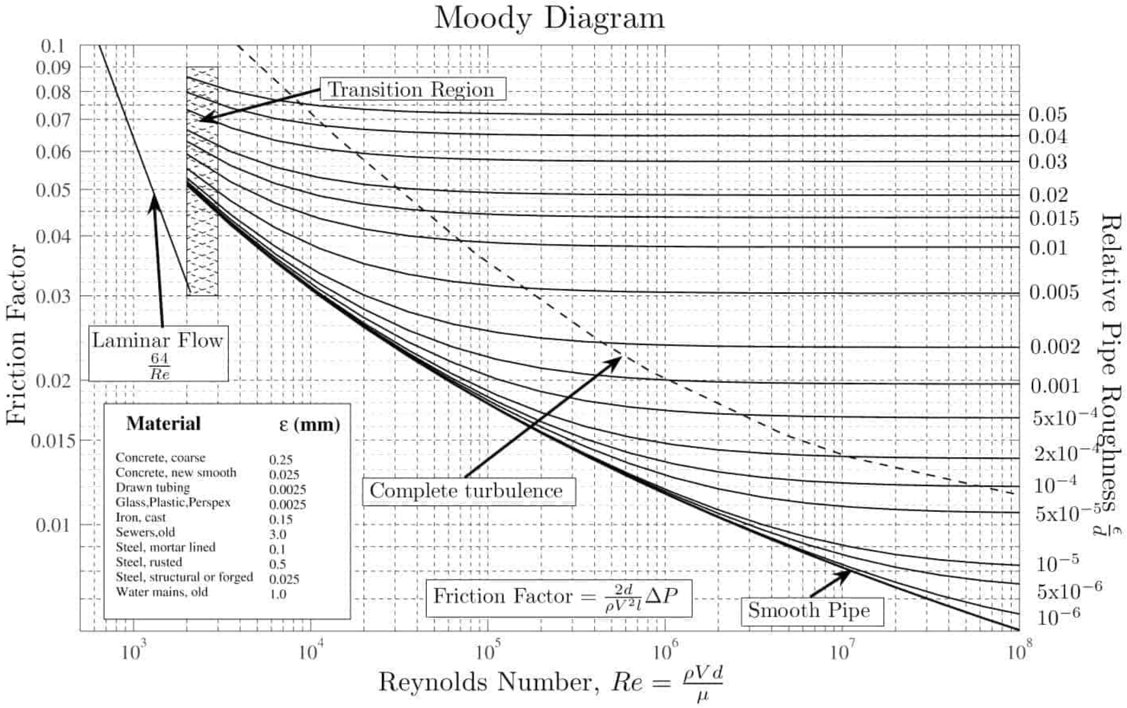
From the Reynolds number, in pipes, the flow is classified as follows:

- Laminar flow: R_e < 2000.
- Flow in transition: 2000 $\leq R_e \leq$ 4000.
- Turbulent flow: R_e > 4000.

In turbulent flow, undefined trajectories and turbulence occur. The roughness of the pipe is a factor of influence so that the higher the roughness, the greater the turbulence and consequently the greater the loss of load. This is the type of flow common in low viscosity fluids such as water. We WSS, therefore, the water flow regime is always turbulent (de Azevedo Netto & Fernández, 2015).

Since the formula of Colebrook-White did not have easy resolution in 1944, Moody created a diagram to obtain the friction factor (f) as a function of the Reynolds number and the relative roughness of a pipe (figure 2.13).

Figure 2.13: Diagram of Moody.



Moody Diagram

Material	**ε (mm)**
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass,Plastic,Perspex	0.0025
Iron, cast	0.15
Sewers,old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Source: de Azevedo Netto and Fernández (2015)

In 1903, Allen Hazen & Gardner Williams developed another loss of charge formula known as Hazen-Williams formula (Equation 2.18).

$$h_f = 10,667\frac{L}{D^{4,87}}(\frac{Q}{C})^{1,852} \tag{2.18}$$

where:

h_f is the loss of load along the pipeline, in mwa;

L is the length of the pipe, in meters;

D é o diâmetro da tubulação,em metrosis the diameter of the pipe, in meters;;

C is the roughness coefficient.

The values of the roughness coefficient (C) can be found in specific literature on hydraulics. For the formula of Hazen Williams, the authors de Azevedo Netto and Fernández (2015), suggested the following values for each type of material, as presented in the Table 2.3.

Table 2.3: Values of roughness coefficient for formula of Hazen-Williams.

Pipes	New	Used $\pm$ 10 years	Used $\pm$ 20 years
Corrugated steel (corrugated sheet)	60	–	–
Galvanized steel threaded	125	100	–
Steel riveted	110	90	80
Common welded steel (bituminous coating)	125	110	90
Welded steel with epoxy coating	140	130	115
Lead	130	120	120
Cement - asbestos	140	130	120
Copper	140	135	130
Concrete (good finish)	130	–	–
Concrete (common finish)	130	120	110
Cast iron (epoxy coating)	140	130	120
Cast iron (mortar coating)	130	120	105
Ceramic stoneware, glazed (shackles)	110	110	110
hline Brass	130	130	130
Bricks (well-executed ducts)	100	95	90
Plastic PVC	140	135	130

Source: de Azevedo Netto and Fernández (2015)

In addition to the loss of load along the conduit, there are also losses in connections and accessory parts such as curves, elbows, registers, valves and others, individually calculated as Equation 2.19.Usually in these places there are distortions in the flow that cause loss of load.

$$\Delta h_f = K\frac{V^2}{2g} \tag{2.19}$$

where:

K is the coefficient of singular loss of load (determined experimentally, as demonstrated ina Table 3.1);

V is the flow speed of water in the pipe in both sections;

g is the value of acceleration of gravity (m_2/2g).

Table 2.4: Values of the coefficient K for localized loss.

Parts	K	Parts	K
Gradual expansion	0,30*	Junction	0,40
Nozzles	2,75	Venturi meter	2,50
Open door	1,00	Gradual reduction	0,15*
Flow controller	2,50	Angle record, open	5,00
90° short radius elbow	0,90	Drawer register, open	0,20
90° long radius elbow	0,60	Globe record, open	10,00
45° elbow	0,40	Outlet of plumbing	1,00
Sieve	0,75	Have, direct passage	0,60
90° Curve, r/D = 1	0,40	Have, side exit	1,30
Curve of 45°	0,20	Have, bilateral exit	1,80
Return curve, a = 180°	2,20	Float valve	6,00
Normal entry	0,50	Foot valve	1,75
Input of edge	1,00	Check valve	2,75

Source: Gomes (2019).

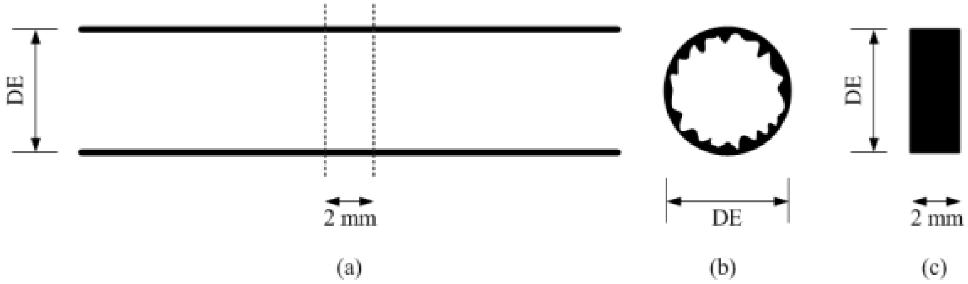
The values of loss of pressure will determine the available pressure load in each topographic quota of WDN, inversely proportional: the lower the pressure loss, the higher the pressure (Porto, 2006).

Rugosidade

The perception of roughness as an influencing parameter in WDN was identified by Darcy (1855) in the 19th century (Taylor, Carrano, & Kandlikar, 2006). Roughness is defined as the height of surface imperfections that occur on the inner side of pipes caused by use or manufacture, as shown in figure 2.14 (Bidmus, 2019). The hydraulic performance of WDN, therefore has a connection with roughness.

Roughness is a manufacturing property of the material that makes up the pipe. There are tubes with perfectly smooth inner wall, physically all have rough surfaces that can accumulate materials. The inner surface of the tubes is represented in figure 2.14. If the imperfections generate uneven surface, the surface is classified as rough, and if the inequalities are smaller, it is classified as smooth (da Costa Rocha, 2018) (Brkić, 2011; MacDonald, Chan, Chung, Hutchins, & Ooi, 2016).

Figure 2.14: Roughness of the pipes.



Source: adapted from Porto (2006).

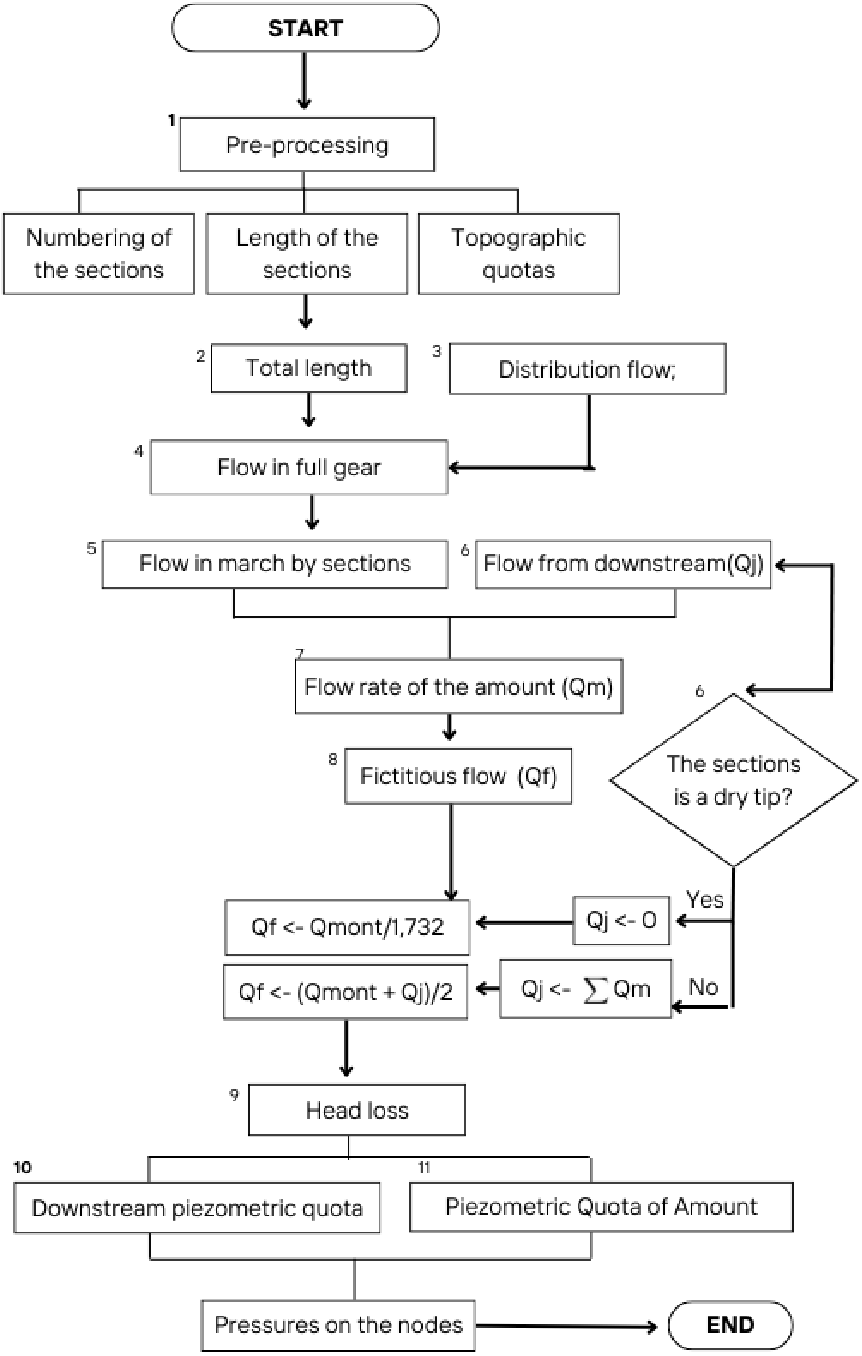
In WSS commonly used pipes are PVC to transport already treated water and therefore there is no sediment entry constantly. In the case of this type of pipe usually occurs a polishing process, in which a very thin layer is formed on the inner surface of the tube and make it smoother, over time, the roughness is reduced. This layer is known as biofilm, because micrororganisms colonies remain there and damage the quality of water to be distributed. Even the very pressure of water flowing through the pipe causes a kind of internal erosion and also makes the surface become smooth (Erdei-Tombor, Kiskó, & Taczman-Brückner, 2024; Hemdan, El-Taweel, Goswami, Pant, & Sevda, 2021). It is common that managers of WDN use disinfectant substances such as chlorine and discharge techniques to minimize biofilm formation (Douterelo, 2013).

In classical literature, authors (de Azevedo Netto & Fernández, 2015) report an increase in the loss of load as roughness is reduced. The deterioration of the roughness coefficient is therefore an indication of a decrease in hydraulic performance, since it will cause an increase in energy consumption, as well as compromising the quality of water intended for human consumption (Santos, 2020).

2.4 Modeling and simulation

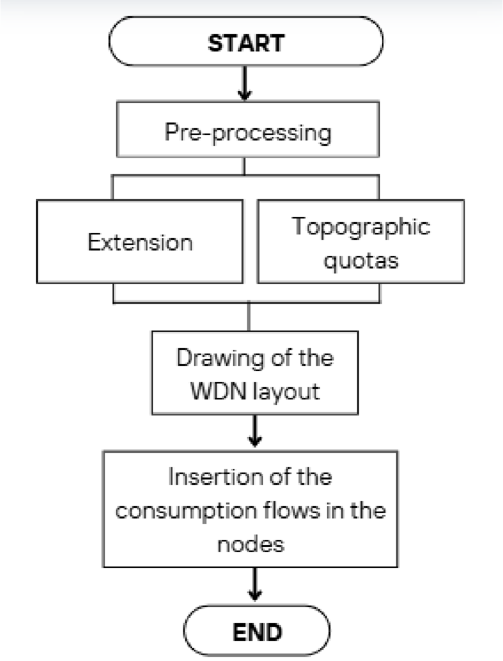
The modeling consists in using the concepts of physics, mathematics and hydraulics to reproduce the flow of water inside the pipes and fittings of the WDN. This new methodology for analysis and design of WDN has stood out, replacing the old techniques that performed the calculations mentioned in Topic 2.3 in calculators or spreadsheets of Microsoft Excel (Porto, 2006). It is possible to follow the simplification of this process through in figures 2.15 and 2.16.

Figure 2.15: Design methodology and analysis of WDN by means of calculations.



Source: adapted from Porto (2006).

Figure 2.16: Design methodology and analysis of WDN through simulation and modeling.



Source: own elaboration, 2024.

Studies in this area have been intensified due to the deepening of mathematical models and a greater development of supervision and control technologies. In this way, it is possible to build intelligent systems that bring the possibility of analyzing the behavior of WDN in different scenarios and conditions, as well as producing faster and more efficient responses to the identified problems (Salvino, Carvalho, & Gomes, 2015).

Thus, in the management units, its applicability allows (de Jesus Gomes, 2011):

- Analyze problems related to high/low pressures
- Develop emergency operational procedures, due to fire situation or water supply interruption (failures of pump, tank breakage and maintenance and control valves);
- Develop short, medium and long-term investment plans;
- Establish priorities in terms of investment and intervention in the systems;
- Evaluate the hydraulic behavior of the system for a predictable variation of consumption;
- Compare different alternatives for water supply, transport, storage and distribution;
- Evaluate the operational costs and benefits when systems are to be granted;
- Assess the impact caused by the need to expand water supply, storage and distribution infrastructures;

- Operational control of the system in real time;
- Train operators, with regard to sensitivity to hydraulic system behavior.

To obtain such results have been developed models of: dynamic programming (Lansey & Awumah, 1994), genetic algorithms (Carrijo, 2004), linear programming (Vicente, 2005) and non-linear programming (de Lucena, 2012). Dynamic programming is a mathematical technique that breaks down a problem into several stages as a sequence to be solved in order to arrive at the final solution (Rao, 2019). The generic algorithms seek to solve problems by logically reproducing the natural evolution mechanism of species developed by Charles Darwin (Salvino et al., 2015).

Linear programming is a quantitative analysis technique to decide about a desired goal. In it, an objective function is created that has the following form: $a_o + a_1x_1 + a_2x_2 + a_3x_3 + . . . + a_nx_n = 0$ (in this function all variables have degree one). Thus a mathematical value is calculated that is considered optimal for the problem being solved. Decisions are made by maximizing or minimizing this function (Dantzig & Thapa, 1997; Kunwar & Sapkota, 2022; Stanimirović, 2022). Non-linear programming is an objective function that can be controlled by linear and/or non-linear constraint equations (Nash & Sofer, 1996).

In the field of hydraulics, the WDN have been analyzed through modeling and simulation by commercial software such as EPANET 2.0 e WaterCAD (Sonaje & Joshi, 2015), besides creating interactions between software and programming languages(Arandia & Eck, 2018a; Bizarro et al., 2020).

EPANET 2.0

Among the software that has been used for this purpose is EPANET 2.0 from 2000. This is a public domain and open source software, in Windows environment, whose version in Portuguese was translated by the Laboratory of Energy Efficiency and Hydraulics (LEHNS) in Sanitation of the Federal University of Paraíba, to simulate the hydraulic behavior of pressurized water systems over time (Gomes, 2019).

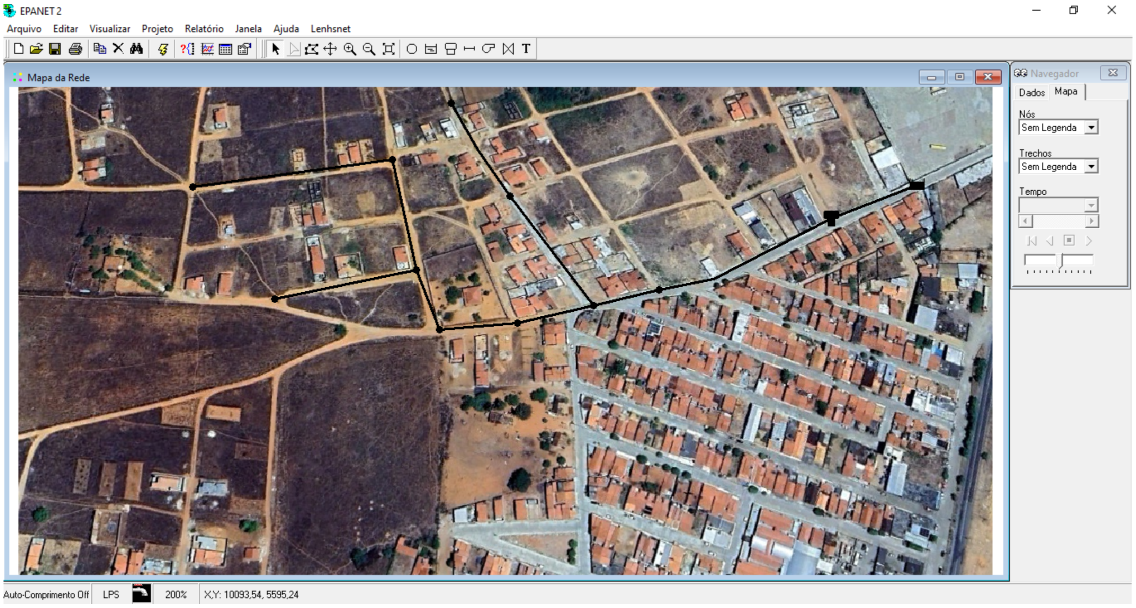
Models can be presented in a dynamic or static way. In dynamic models, hydraulic quantities such as flow rate in the sections, pressure in the nodes, water levels in the reservoirs and energy required for pumping follow the change caused by the varied consumption of water over time. In static form, values are determined for a specific operating condition without changing over time (Gomes, 2019).

The use of EPANET 2.0 for hydraulic simulation and modeling stands out for allowing: unlimited dimensioning of the number of components of the network analyzed, the calculation of the loss of load can be done with several formulas of loss of load cited in literature, as the designer's choice, among them: Hazen-Williams and DarcyWeisbach. It also takes into account the equivalent load losses, the modeling of constant or variable speed pumps, the calculation of pumping energy and its cost and the modeling of the main types of valves and reservoirs of variable level (Rossman, 2009).

In the sizing of WDN, the bypass points of flow and change in diameter are called nodes and the pipes connecting the nodes, are called stretches. The direction of water flow occurs from the main pipe to the secondary pipes and so on until it ends at the ends known as dry tips, which limit the supply to a certain point (Porto, 2006). The following is an example of a distribution network inserted in EPANET 2.0 for knowledge of the software interface in figure 2.17.

The network is composed of an unlimited reservoir or Fixed Level Reservoir (FRL) , which represents the water withdrawals with constant level and known quality, such as WTP.The water is then pumped to a distribution system. The distribution network is connected to a Varied Level Reservoir (VLR). Nodes are used to enter the quota and base consumption information and are interconnected by lines called snippets. The lengths, the material that makes up the pipe and the roughness coefficient are inserted in the sections.

Figure 2.17: EPANET Interface 2.0.



Nós: Sem Legenda
Trechos: Sem Legenda

Source: own elaboration, 2024.

EPANET 2.0 has been used in the scientific literature for case studies of WDN in different locations around the world. One of the analyses that has been done using EPANET 2.0 is water quality by measuring their age. Water age is the term used to indicate the time it takes for water to travel from a water source to consumers, governed by the design and components of the water distribution system. When walking through a WDN,drinking water undergoes aesthetic, physical and chemical transformations (Monteiro, Algarvio, & Covas, 2021). If the water remains in the WDN before being delivered to consumers, the concentration of disinfectants such as chlorine may have reduced action for control of microorganisms that affect human health (García-Ávila et al., 2020).

In the work of the authors Mabrok, Saad, Ahmed, and Alsayab (2022), The methodology of this work was based on the establishment of simulation scenarios in EPANET 2.0, in which the Kuwaiti (Middle East) was WDN would be with 20%, 50% and 100% of the territorial area occupied. The results showed that with 20% of occupancy, some nodes exceeded acceptable limits for the age of water for the disinfectant action of chlorine. The 50% increase in occupancy reduced water age at different locations throughout the network. And finally, with 100% of the area occupied, the water age in the network pipes was obtained. It can be concluded that the water quality in the system is significantly affected by occupation, so that the higher the occupation, the lower the age of the water.

Despite being important to neutralize microorganisms, the use of chlorine for disinfection in contact with organic or inorganic precursors present in water produces by-products such as trihalometanes, at their highest concentrations (Rahman, Whalen, & Gagnon, 2013; Villanueva et al., 2017). These compounds have attracted attention due to their carcinogenicity, genotoxicity and mutagenicity (An et al., 2022).

Based on this, the authors Zuthi et al. (2023), conducted a study in the city of Chittagong (Bangladesh), to identify risk areas with concentrations of trihalomethanes present. For this, a hydraulic model was developed in the EPANET 2.0 software and water samples were collected in the WDN for laboratory evaluation of quality parameters. The observed value of free chlorine in the study area ranged from 0.02 to 0.17 mg/L, below the limit set byWorld Health Organization (WHO) for free residual chlorine in 0,2 mg/L in order to keep the water protected from any microbial contamination within the WDN. Thus, the modeling of chlorine in this WDN demonstrated that an initial chlorine dose of 3 mg/L is suitable to sustain a residual content close to 0.2 mg/Lthroughout the network. On the other hand, a dose of primary chlorine of 4mg/L makes the high level of free chlorine for all nodes stay above 0.2 mg/L.

EPANET 2.0 is also used for studies on the analysis of hydraulic behavior ofWDN.In Indonesia, the city of Jember, the authors Widiarti et al. (2020) observed that the WDN did not serve the population in an adequate way. The study conducted by these authors aimed to diagnose the WDN Done through EPANET 2.0 and calibration with field data collection, for comparison and adjustment in modeling and simulation. The values of pressure and speed obtained were outside the acceptable limits in the country. It is concluded that it is necessary to correct your estrutura para abastecer a adequadamento à população.

Still aiming to use simulation and modeling for diagnosis of WDN, in the city of Guelma, Algeria, was also used EPANET 2.0 software for this purpose. The parameters established to evaluate the WDN were: pressure in the nodes, water flow rate in the stretches and chlorine decay along the WDN. Observed if in general, during the day pressures were acceptable, but at night the pressures on the WDN were larger and therefore some we reached more than 70 mwa and therefore required the insertion of PRV. Also noted aspects of oversizing the WDN, since sections with low flow velocity had high diameters, from this it was recommended to reduce the diameters in these sections (Mazouz & Abdelraouf, 2021).

In addition to these benefits, EPANET 2.0 also has as among its potentialities an interface of association with other software of Geographic Information System, such as the Quantum Geographic Information System (QGIS), for georeferencing the WDN and subsequent optimization. The interaction with QGIS allows to know the characteristics of elevation of the terrain and thus obtain the precise length of pipes and topographic quotas to be inserted in nodes, to then evaluate the behavior of the WDN (Deb, Das, Gupta, & Mukherjee, 2023). To avoid length errors in the pipes, it is also possible to export WDN in technical design of programs such as AutoCAD for EPANET 2.0 (Jawale, Kamire, & Iyer, 2022).

In the work of the authors Freitas, Silva, Silva, and Barbedo (2022), a scenario was built, called the base scenario, which reflected the same physical characteristics of WDN in analysis. The base-scenario revealed the absence of stretches in the range below 10 mwa emean pressure of 62.3 mwa, this last result outside the limit established by NBR 12.218/2017. The simulation of EPANET 2.0 was then exported to the software QGIS for analysis of the terrain level curves. Then, other scenarios were made with changes in the structure to evaluate the pressure reduction. By installing one more PRV and two pumps, the authors obtained a mean pressure reduction of 62.3 mwa for 41,0 mwa. Thus, it was possible to conclude the potential use of EPANET 2.0 and a georeferencing software.

At the end of the simulations and work performed it is possible to extract from EPANET 2.0 files with the following data and formats: Input data (*.inp*); hydraulic calculation (*.hyd*); calculation of quality (*.out*) and reporting (*.rpt*) (Rossman, 2009). It is still possible to perform simulations and create models through the interaction between EPANET 2.0, programming languages and computing environments such as Python, R, C/C++, C#, MATLAB and Visual Basic (Sela & Housh, 2019).

EPANET 2.0 and o R

The analysis of water networks is done in R by the packages *epanet2toolkit* and *epanetReader*. By definition, R is a multiplatform open source software environment with its own programming language that has resources for performing statistical and graphical analysis of the data. Has versions for use on MacOS, Windows and Linux (Ihaka & Gentleman, 1996). The R language, in this case, is used to better explain the spatial-temporal data processing and analyze the performance of water supply networks (Celar & Cisty, 2016; Rossman, 2009).

A graphical interface was developed to improve the usability of R, called RStudio. In RStudio R features like data import, command visualization, functions, results, graphics document management, become more user-friendly and functional (Henning, 2016; Racine, 2012). In addition, in R can be augmented software to perform the most varied tasks, which allows users to solve problems from various areas of knowledge (de Souza, Rodrigues, de Lima, & Chagas, 2020; Konrath et al., 2018). These are known as packages and are found in the repository named Comprehensive R Archive Network (CRAN) (Plakidas, Schall, & Zdun, 2017).

As a package used for hydraulic simulation and modeling of a RDA obtained from EPANET 2.0 is the *epanet2toolkit*. Complementary to the *epanet2toolkit* is use the *epanetReader* for analysis of EPANET 2.0 data files. Through this package it is possible to read data, generate graphs. Below are described functions for the R environment provided by *epanet2toolkit* (Eck, 2016). The functions used in the R environment provided by *epanet2toolkit.* can be found at Table 2.5

Table 2.5: Functions for the R environment provided by *epanet2toolkit.*

Name	Description
ENepanet()	Runs a complete simulation
ENopen()	Opens the EPANET 2.0 engine
ENclosed ()	Close the EPANET 2.0 engine
ENsolverH()	Solves the hydraulic network
ENsolverQ(	Resolves the water quality of the network
ENopenH()	Opens the hydraulic analysis system
ENinitH()	Initializes the network before simulation
ENrunH()	Performs a single-period hydraulic analysis
PTpróximoH()	Time period until the next hydraulic event
ENclosedH()	Closes the hydraulic analysis system
ENopenQ()	Settings for water quality analysis
ENinitQ()	Initializes water quality analysis
ENrunQ()	Calculates the results of water quality at the current time
PTpróximoQ()	Advances in water quality for the beginning of the next time period
ENstepQ()	Water quality advances for a specific time interval
ENcloseQ()	Closes the water quality analysis
ENsaveH()	Saves hydraulic results in binary file
ENsaveinpfile()	Saves the current data in the text file *INP*
ENreporting()	Records simulation report file

Source: Arandia and Eck (2018b).

Since R has high performance for statistical analysis, the authors Lourenço et al. (2024), proposed a simulation methodology in R with a WDN theoretical created in EPANET 2.0 to evaluate the results of daily consumption demand. In this proposal, the water levels in reservoirs that supply the WDN were varied according to the population's demand throughout the day. The packages used were: *epanetReader, epanet2toolkit, tidyverse, ggplot2, dplyr*. The results showed that as consumption increases, the water level in the reservoir decreases, and pressure values are reduced. It was also possible to observe that the pressure values varied throughout the day in limits outside of the normal. The authors conclude their work with the assertion that an integrated model between EPANET 2.0 and R can help to evaluate the performance of WDN and identify opportunities for optimization, loss reduction and increased energy efficiency.

Based on this proposal, the authors S. M. Marques et al. (2023), analyzed a theoretical water distribution network in order to obtain the best scenario for roughness and diameters to generate pressure values in a WDN with 48.4% losses. In the EPANET 2.0 simulation, it was possible to verify unfavorable pressure values. In some points low pressures, less than 10 mwa and in other high pressures, more than 80 mwa, which justified the high percentage of losses due to the occurrence of ruptures in WDN. In R, the minimum value of 10 mwa and the maximum value of mwa for pressure was established, as determined by NBR 12.218/2017. Then, a scenario was generated with random values for reservoir levels, roughness and diameters in order to obtain the ideal pressure values. The results obtained were pressures between 20 and 40 mwa. The node with the lowest value had an increase of 56.19% in pressure and the node with the highest value, had a 46.70% reduction in its pressure.

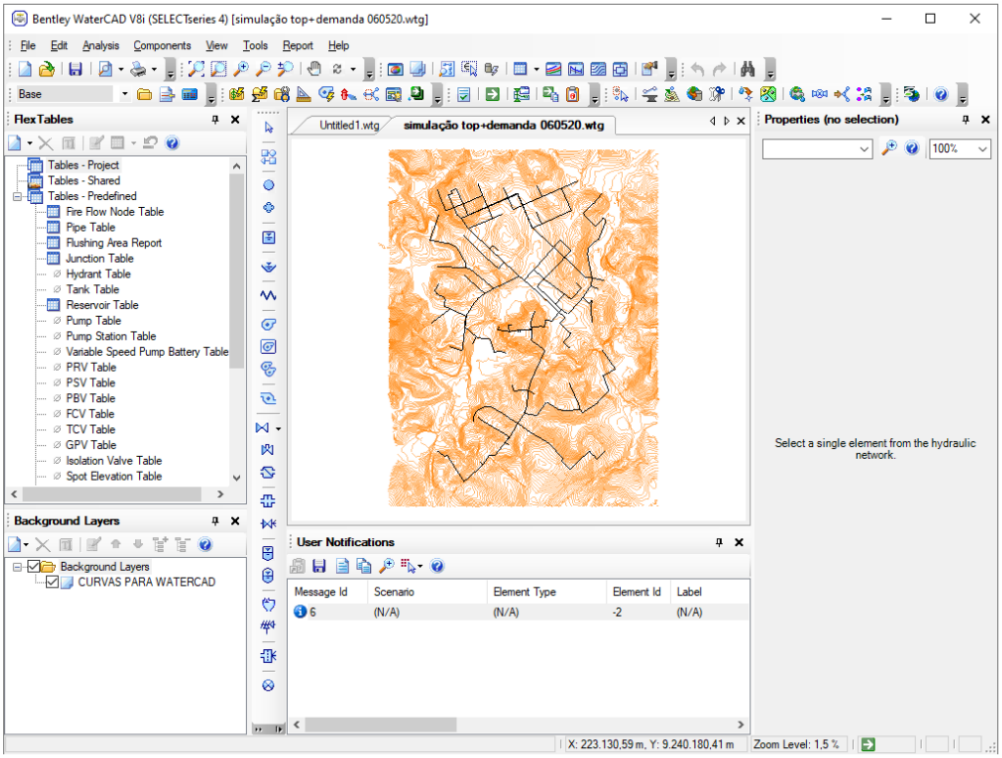
WaterCAD

WaterCAD software, as well as EPANET 2.0, is also used for simulation and modeling of WDN and water quality. Manufactured by supplier *Bentley Systems*, has as a major highlight the possibility of direct interaction with other software by assimilating AutoCAD files (*.dwg*), of QGIS (*.shp*) and even spreadsheets. The RDA designed can be exported to AutoCAD and EPANET 2.0 (Diuana & Ogawa, 2015). The figure 2.18 demonstrates the WaterCAD graphical interface in which RDA is displayed with emphasis on terrain contour lines.

With simple and easy-to-use mechanism, it can be a resource-saving and reliable water infrastructure decision support tool. WaterCAD's functions allow: to analyze fire flows, to dimensioning pumps, to evaluate energy costs, to analyze the water quality (Sarker, 2021), calibrate and detect leaks and model the insertion of (Diuana & Ogawa, 2015). WaterCAD has hydraulic operation developed through generic algorithms. Thus, it is possible that the designer gets good results by means of calibration (reproduce in software some result measured in field) of the WDN (Sutharsan, 2023).

Your use is released upon payment of a license. From 200 dolares, you can get a license for the sizing of networks with up to 10 lengths, access technical support and receive the manual. In addition to payment, some requirements are required for use of the software: processor superior to a Pentium IV, RAM memory of 256 MB and operating system Microsoft® Windows 2000 or newer (Diuana & Ogawa, 2015).

Figure 2.18: WaterCAD Interface.



Select a single element from the hydraulic network.

Message Id	Scenario	Element Type	Element Id	Label
6	(N/A)	(N/A)	-2	(N/A)

X: 223.130,59 m, Y: 9.240.180,41 m

Zoom Level: 1,5 %

Source: da Silva (2020).

The authors Sutharsan (2023) used WaterCAD to assist water service managers in optimizing investment cost and operational efficiency. The results showed a variation in consumption throughout the day, usually the highest demand arises in the early morning and late evening, when people consume more water to bathe, wash and cook. Pressure monitoring indicated adequate values for the performance RDA, above 10 mwa. The justification given for this was the small difference in elevation at the ground level of the study area. The water flow rate in some stretches was below the recommended value of 0.6 m/s. In these cases, it is advised to reduce the pipe diameter to increase the speed and thus reduce the likelihood of sludge deposition in the pipe. However, in this work, since most of the sections had adequate speed, it was chosen not to increase the diameter of the pipes, with a view to reducing budgetary expenses. To solve this problem it was established that greater quantities of cleaning operations would be performed in WDN by means of discharges.

In Umbulan, Indonesia, a WSS aimed to distribute water to four cities. In this case, WDN began to show low performance in meeting the water demand and increased operating costs of electricity. The simulation of this WDN in WaterCAD demonstrated low pressures at 08 am, seen as peak hours. One of the parts of WDN defined as zone 1 presented the lowest pressure values, according to the analysis of WDN and topographic quotas, it was concluded that this is the region with naior elevation. As intervention measures was defined the insertion of gate valves with the aim of directing the supply in a single direction to zone 1 and PRV in the so-called zone 3 to reduce pressures (Kurniawan, Santosa, & Nasihien, 2021).

WaterCAD is also used for chlorine decay analysis in WDN. In one study, the simulation performed was very close to reality. Three nodes in the simulation presented error less than 5% when compared to the values of the chlorine collection in the field. The simulation showed that chlorine values in the network were within the permitted values in more than 95% of the pipes in the network and decrease at peak times and high pressure values. The available data indicate a decrease in the percentage of free residual chlorine at some points. It was concluded with the caveat that it is necessary to inject chlorine in some points of the network at certain times was important (Alsaeed, Alaji, & Khouri, 2024).

Since one of the WaterCAD's potential includes interaction with georeferencing software, the authors Ibrahim et al. (2023) explored the use of this software in conjunction with QGIS. The problem involved lack of supply in a National Institute of Water Resources, in Kaduna, city of Nigeria. WaterCAD was used in the assessment of WDN, while QGIS was used to develop the topographic map of the institute in order to obtain the topographical information needed for analysis. The results showed that pressure, flow and speed were adequate enough to supply water. The reasons for the inefficiency in water supply were the inability of pumps to fill the main air tank, inadequate connections, broken pipes and power outages.

CHAPTER 3

Materials and methods

This chapter presents the detailed methodological framework used in this research, outlines the strategies adopted to analyze the behavior of a hydraulic network before changes in consumption and roughness parameters over three different scenarios. It also serves as a guide to understand the context and structure of the experiments conducted, with transparency and replicability of the process of evaluating the different scenarios. The methodological approach outlined here is also the basis for the analysis and interpretation of the results presented in the chapter in order to provide the necessary conditions for understanding the contributions of this study to the field of hydraulic networks analysis.

The following sections will discuss the description of simulated scenarios, which involve different populations and levels of roughness of pipelines; data and tools used; the configuration and experimental procedure that contains the steps of parameterization of the data and the development of the simulations for each scenario; the evaluation metrics selected to quantify the impact of changes in the network parameters; the statistical analysis and finally; the type of this research.

3.1 Scenarios evaluated

For the simulations and analyses, the following tools were used:

- EPANET: A widely used software for modeling water distribution systems, employed here to simulate the behavior of the hydraulic network in the different scenarios proposed. EPANET allowed the construction of WDN in the first scenario and detailed analysis of pressure and load losses along the network.
- R: Um ambiente e linguagem de programação para computação estatística e gráfica, utilizado nesta pesquisa para abordar a RDA gerada no primeiro cenário do EPANET 2.0.

> O R foi empregado na construção dos próximos cenários com redução da rugosidade e aumento do consumo de água devido ao crescimento populacional, criação de gráficos, execução de análises estatísticas e interpretação dos dados gerados pelo EPANET.

The first base scenario was created in EPANET 2.0 with empirical data for 2024. The input data of the simulation were: the network layout, the position of the nodes, the base consumption, the topographic dimensions of the terrain (obtained from Google Earth) and the reservoir, the diameter and length of the pipes. Thus, the empirical WDN proposal has the following characteristics:

- Population in 2014: 200 inhabitants.
- Population in 2024: 500 inhabitants.
- Per capita consumption (q_m): 100 L/hab.dia.
- Occupancy rate per residence (T_x): 4 inhabitants.
- Type of WDN: branched.
- Material of pipes: PVC.
- Formula for loss of charge: Hazen-Williams. (Equation 2.18)
- K_1: 1,2.
- K_2: 1,5.

Table 3.1: Information about us and excerpts from the empirical WDN.

Identifier of the node	Topographical quota	Identification of the segment	Length of the segment
1	183	1	295
2	183	2	166
3	187	3	216
5	189	4	526
6	189	5	85
7	175	6	311
8	176	7	344
9	177	8	295
10	176	9	190
11	175	10	453
12	188	11	260
13	188	12	185
14	184	13	106
15	188	14	604
16	180	15	155
17	180	16	391
18	175	17	415
19	193	18	204
20	190	19	394
21	189	20	349
22	198	21	247
23	195	22	309
24	174	23	117
25	186	24	321
26	178	25	176
27	189	26	63
28	194	27	774
29	188	–	–

Source: own elaboration, 2024.

The second and third scenarios were created in R from the base scenario developed in EPANET 2.0. The second scenario represented the hydraulic behavior of WDN 10 years ahead (2034), in which the roughness coefficient of the pipe PVC is reduced to the value of 135. The third and last scenario reflected the behavior of WDN with a population growth for 20 years ahead (2044) and reduction of roughness coefficient of the pipe PVC to 130.

The arithmetic projection formula (Equation 3.1) was used to calculate the population variation in the years 2034 and 2044 (Heller & de Pádua, 2010; Rezagama, Handayani, Zaman, & Putra, 2020).

$$P_t = P_0 + K_a.(t - t_0) \tag{3.1}$$

em que:
P_t is the project population;
P_0 is the empirical initial population;
K_a is the arithmetic growth rate;
t is the year of project end;
t_0 is the initial project year.

$$K_a = \frac{P_2 - P_0}{t_2 - t_0} \tag{3.2}$$

where:
K_a is the arithmetic growth rate;
P_2 is the final empirical population;
t_2 is the final project year;
t_0 is the initial year.

The hydraulic simulations in the three evaluated scenarios have the following data:

- Roughness of pipes in scenario 1: 140.
- Roughness of pipes in scenario 2: 135.
- Roughness of pipes in scenario 3: 130.
- Formula for loss of charge: Hazen-Williams.

These tools were essential for the development of the study because they allowed a robust and detailed analysis of the different hydraulic network scenarios evaluated.

3.2 Simulation in R software

In the R software environment a model was built to simulate hydraulic composting of WDN based on the reduction of roughness of the pipe PVC for 10 and 20 years later (de Azevedo Netto & Fernández, 2015) and the increase in population reported these years. At the end, it was observed the behavior of hydraulic parameters: pressure and loss of load in these new scenarios. The model used for this test is described in Chapter 7 - Proposed model.

For model construction, initially the libraries were installed: *epanet2toolkit*, *magrittr*, *epanetReader* and *ggplot2*. Its functions are: to carry out the interaction between Epanet 2.0 with the programming language, read and analyze data from WDN sized, improve the readability of the code and lead to a better visualization of complex results in simple and intuitive graphs.

We then inserted WDN to read and execute the other commands in R. The files *.inp* and *.rpt* obtained in EPANET 2.0, by exporting the data from WDN, so that WDN is known in terms of data and operation report respectively. These files were stored in the same folder and then, in R, the directory was set to be found and read. The execution of the hydraulic analysis was requested with the command *ENepanet*.

It is possible to consult the summary of data and make the graphical visualization of WDN, by means of the commands *summary* and *plot*. Then the commands *ENopen, ENopenH and ENinitH(0)* open the hydraulic network, start the analysis and establish the initial conditions. To configure the algorithm for counting nodes and segments necessary for R modeling, *EN _NODECOUNT and EN_LINKCOUNT* commands were used.

Then the *ENgetnodevalue and ENgetlinkvalue* functions create vectors to store pressure and load losses on all nodes and pipelines. Roughness values also need to be stored. In this case, at first, a matrix was created to contain the roughness values for the different scenarios, namely: 140, 135 and 130. Each line of this matrix represents a different scenario.

The pressure and load loss results in each scenario were also stored in matrices. In a second moment of the modeling, the scenarios were changed as population increase to increase consumption demand to WDN. For each roughness reduction scenario, the consumption elevation values were also adjusted. The *ENsolveH* command was responsible for solving the hydraulic system.

The penultimate step before obtaining the data consisted in calculating the absolute error between the pressure losses and the pressures in each scenario. The scenario with the lowest error is considered the ideal scenario for the requested analysis. These results are then stored in *files. csv* to open in spreadsheets. The *EncloseH and Enclose* commands close the hydraulic simulation.

3.3 Evaluation parameters

There are hydraulic parameters to be followed with respect to pressures, diameters, and pressure losses. In Brazil, the “NBR12218” (2017) establishes procedures for the preparation of water distribution network projects for public supply, among which we highlight:

- The minimum diameter of the secondary ducts shall be 50 mm.

- Pressure on nodes is a crucial metric to ensure adequate water supply to end consumers. During the simulations, pressures at different nodes of the network were monitored to verify that they were within the recommended limits for an efficient distribution system. The objective was to ensure that the network maintains adequate pressure at all points, to avoid both excessive pressures, which can damage infrastructure, and insufficient pressures, which can compromise water supply. In Brazil, the "NBR12218" (2017) establishes procedures for the preparation of water distribution network projects for public supply, among which it is noteworthy that the maximum static pressure in distribution pipes must be 50 mwa, and the minimum dynamic pressure of 10 mwa;
- The pressure drop along the pipes is another fundamental metric for the evaluation of the hydraulic network performance. It indicates the reduction of pressure caused by internal friction in pipes, and is directly influenced by roughness and water flow. In the simulations, the load loss was calculated using the Hazen-Williams formula, which is widely used in water distribution systems. The analysis of the losses of load allowed to evaluate the efficiency of the network and identify potential points of improvement, especially in relation to the variations in the roughness of the pipes in the different simulated scenarios. As for pressures, the "NBR12218" (2017) establishes that the loss of pressure must be less than or equal to 10 m/km calculated by means of the universal formula;

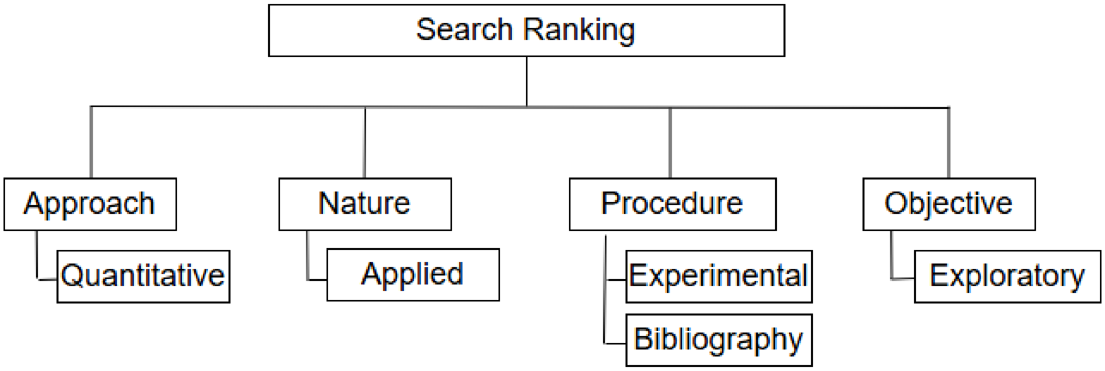
Although the loss of load is less than or equal to 10 m/km, this work sought to reduce it as much as possible to provide pressure increase in the posterior nodes.

3.4 Type of research

This research was developed with the operation of simulation and statistical software to evaluate the hydraulic parameters pressure and loss of load, in a quantifiable way. It is understood therefore its approach as quantitative. Its nature is applied, since it is directed to the solution of a specific problem (Gil, 2008).

As types of procedures, it was initially used the procedure of bibliographic analysis of areas related to the theme such as: hydraulics and modeling WDN in books and scientific articles. The study developed here was concentrated in a distribution network elaborated with its own characteristics. This was simulated in EPANET 2.0 and then a model to analyze WDN was created, based on the reduction of pipe roughness over time. It is understood that besides the bibliographic procedure, the experimental and documentary procedures are also present in this research. Finally, the objective of this research can be classified as exploratory (Gil, 2008). The classification of this research was represented schematically in figure 3.1.

Figure 3.1: Search ranking.



Source: adapted from Gil (2008).

CHAPTER 4

Proposed model

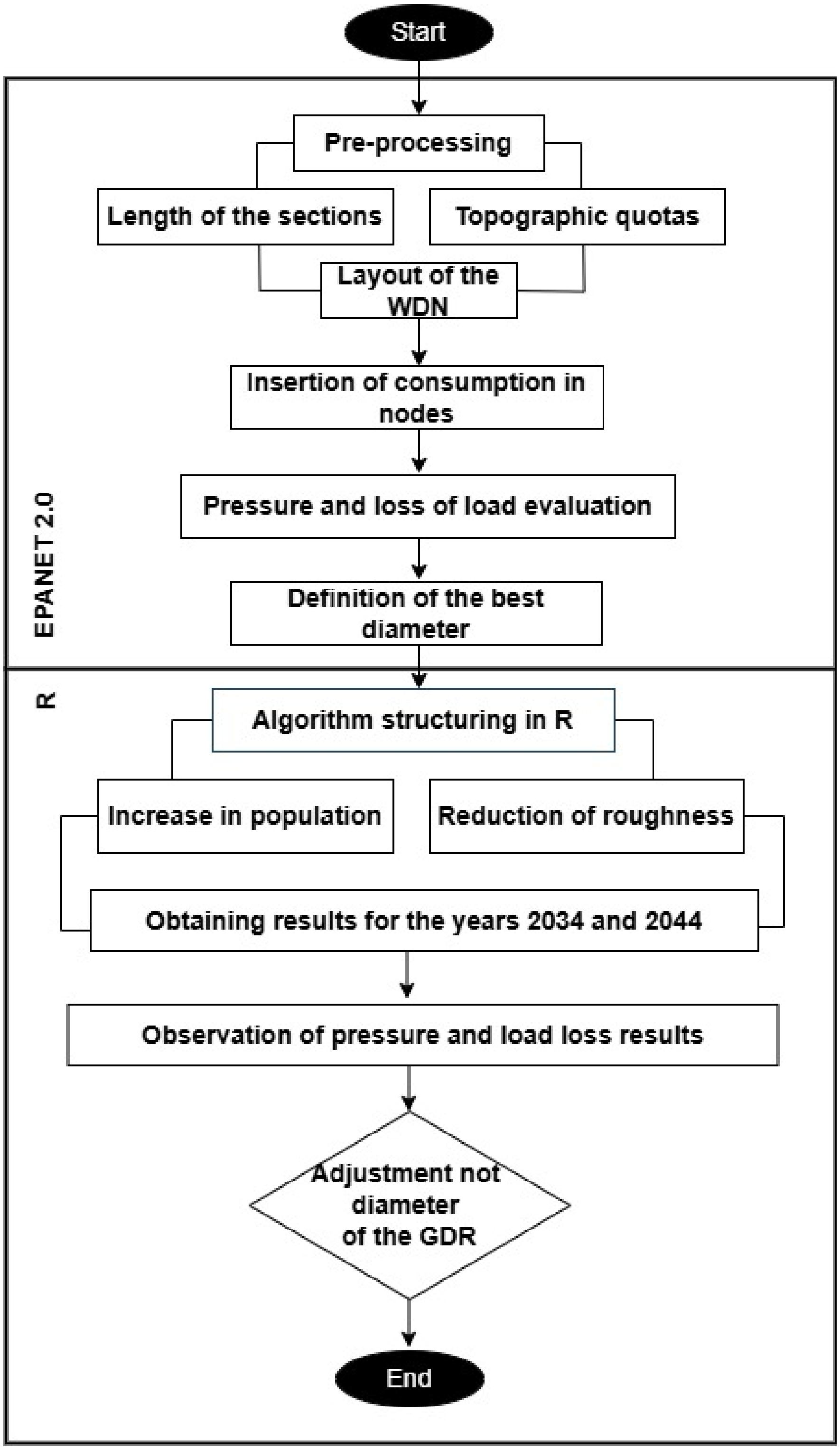
The proposed model begins with the pre-processing of the data necessary to perform the simulation in EPANET 2.0. In this step data are inserted about the extent of the stretches and the topographic quotas. Then the layout (drawing) of the WDN is built according to the flow of water from the reservoir towards the stretches.

On each node created during the layout definition of the WDN was inserted the consumption value, according to the total flow rate and nodal (Equations 2.11 and 2.12), respectivamente). After insertion of this information the simulation was performed and pressure values and load loss were observed. Pressure values should be between 10 and 50mwa, while the values of loss of load must be equal or less than 10 m/km.Before adjusting these values were defined the diameters of the pipes.

Then that WDN the R console was exported in formats *.inp*, that loads the information from the data entered and *.rpt* that brings a report on the operation of RDA. Then the algorithm was structured 1 with the necessary functions to change two variables: increase in consumption and reduction of roughness, in WDN inserted. The consumption was increased according to population estimates for 2034 and 2044. And the roughness values for the tube PVC were reduced to 135 (10 years ahead, in 2034) and 130 (20 years ahead, in 2044), as the author (de Azevedo Netto & Fernández, 2015).

The modeling with algorithm in R console generates files at the end *.csv* for analysis of the results and generation of graphs. In this way, it is possible to follow the pressure variations and pressure loss and then decide for the increase in the diameter of the pipes or not.

Figure 4.1: Flow chart of the model for pressure and load loss evaluation in a WDN over the course of time.



Fonte: own elaboration, 2024.

CHAPTER 5

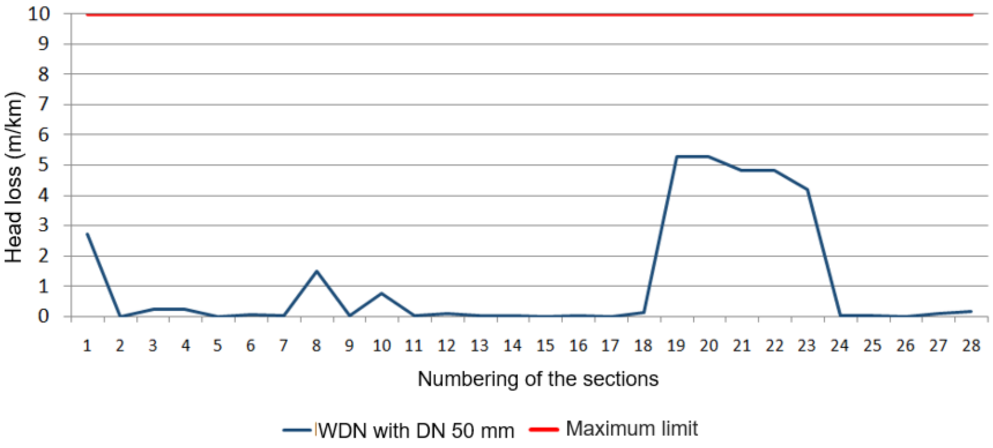
Results

5.1 Scenario 1: simulation of the RDA and correction of hydraulic parameters pressure and load loss.

The values obtained for population and project flow were respectively: 500 inhabitants and 1.04 l/s. The construction of the network layout according to typographical characteristics required 29 nodes and 28 section.

The initial simulation, in which the outlet section of the reservoir had 100 mm diameter and the remaining sections had 50 mm diameter showed negative results for the operation of WDN. For the loss of load parameter, values of loss of load are observed within the permitted in legislation, but still, in stretches 19 to 23, actions should be taken to reduce the loss of load and increase the pressures on posterior nodes in figure 5.1 shows the graph with the values of the load loss.

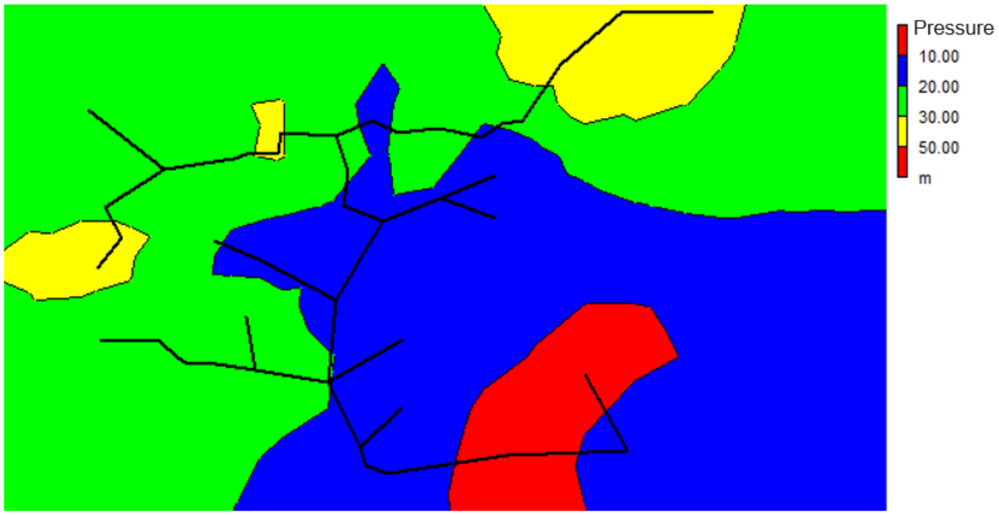
Figure 5.1: Graph of the loss values in each section with Dn 50 mm.



Source: Own elaboration, 2024.

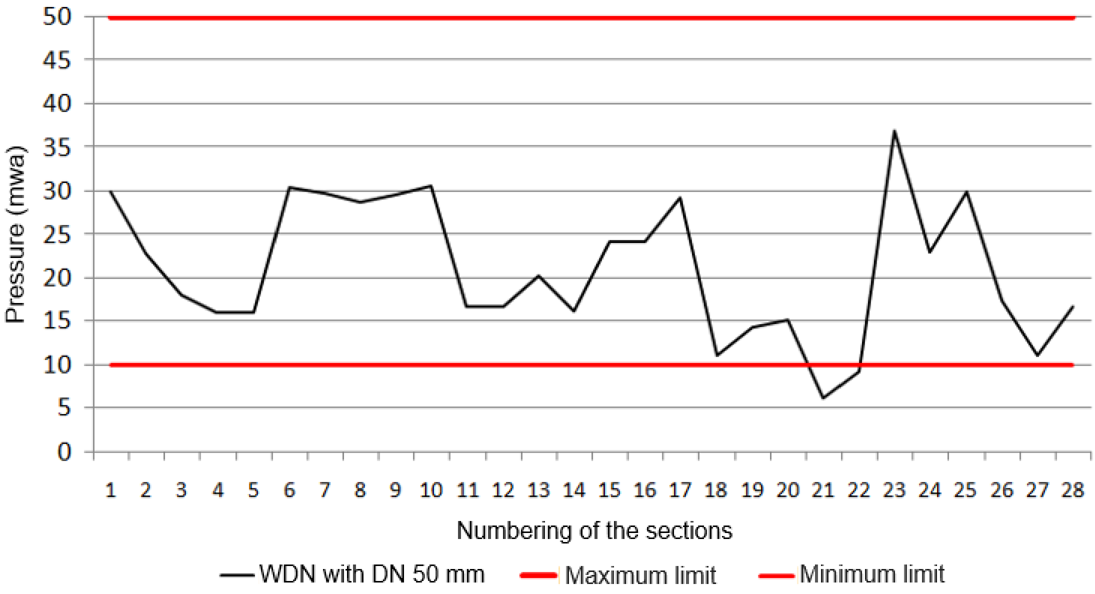
It was noted that the pressures were mostly adequate. Positively, no pressures above 50 mwa occurred. In nodes 21 and 22, the pressures were low, below 10 mwa, which shows that there was supply in this area, but insufficient. The pressure results are shown by means of the isoline graph (in figure 5.2) and by means of a graph with the pressure values at each node (in figure 5.3).

Figure 5.2: Pressure graph in isolines.



Source: Own elaboration, 2024.

Figure 5.3: Graph of the pressure values at each node.



Source: Own elaboration, 2024.

In other works such as this, the authors used as a solution for pressures below 10 mwa, increasing the pipe diameter in sections of the WDN with the aim of reducing the loss of load and raising the pressure at the desired nodes (Lourenço et al., 2024; Pratama & Soedjono, 2023).

Thus, the diameter of the outlet pipe of the reservoir was kept at 100 mm and the diameter of the entire main pipe was replaced from 50 to 75, as can be seen in the figure 5.4. The result achieved the desired goal.

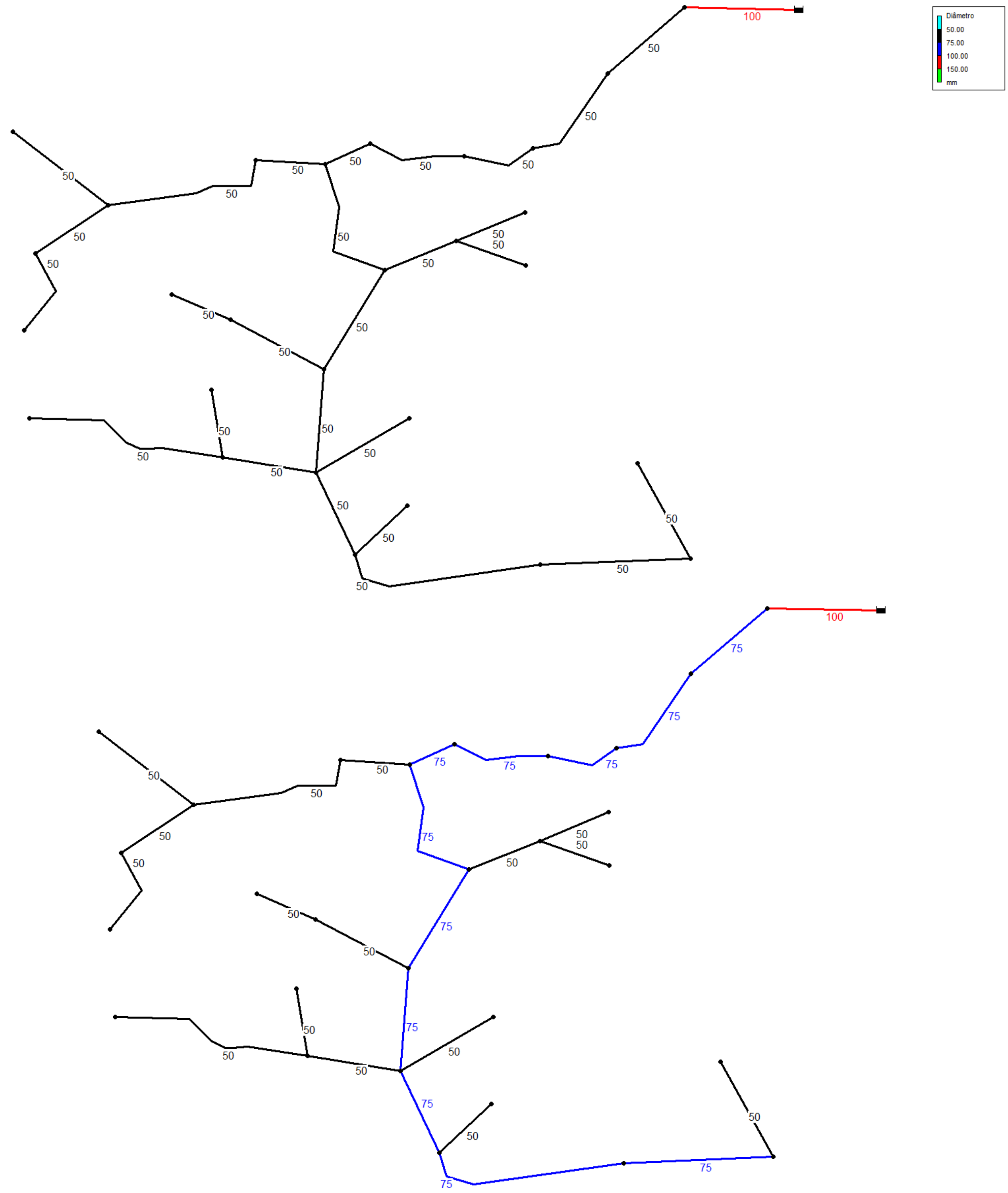
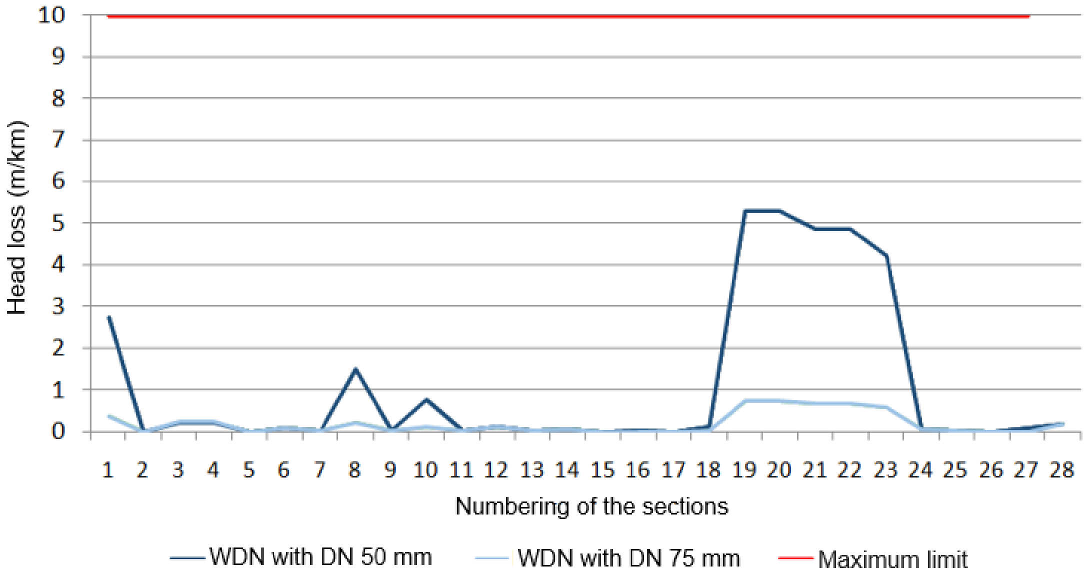


Figure 5.4: Change of diameter of main pipe.

Source: Own elaboration, 2024.

The loss of load was reduced satisfactorily in the sections 19 to 23, as can be seen in figure 5.5.

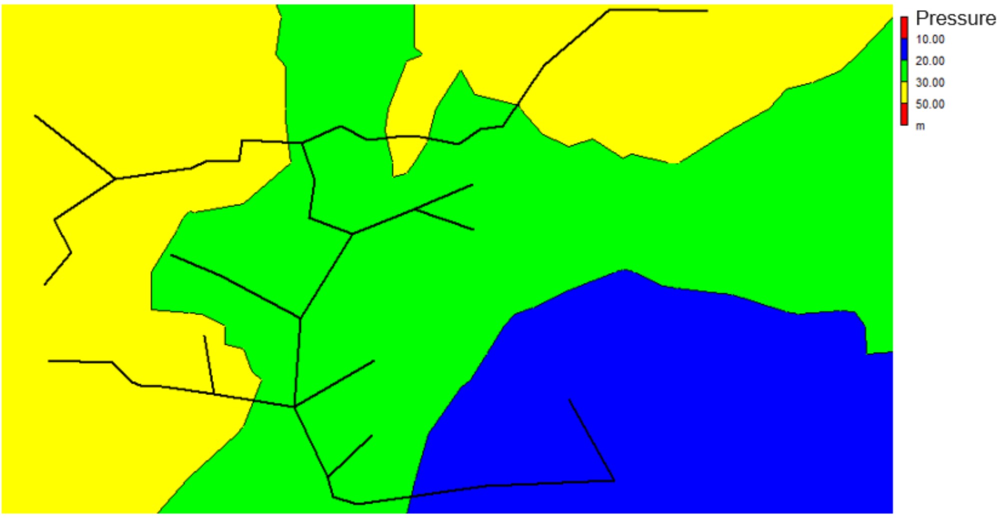
Figure 5.5: Chart of the values of losses in each section.



Source: Own elaboration, 2024.

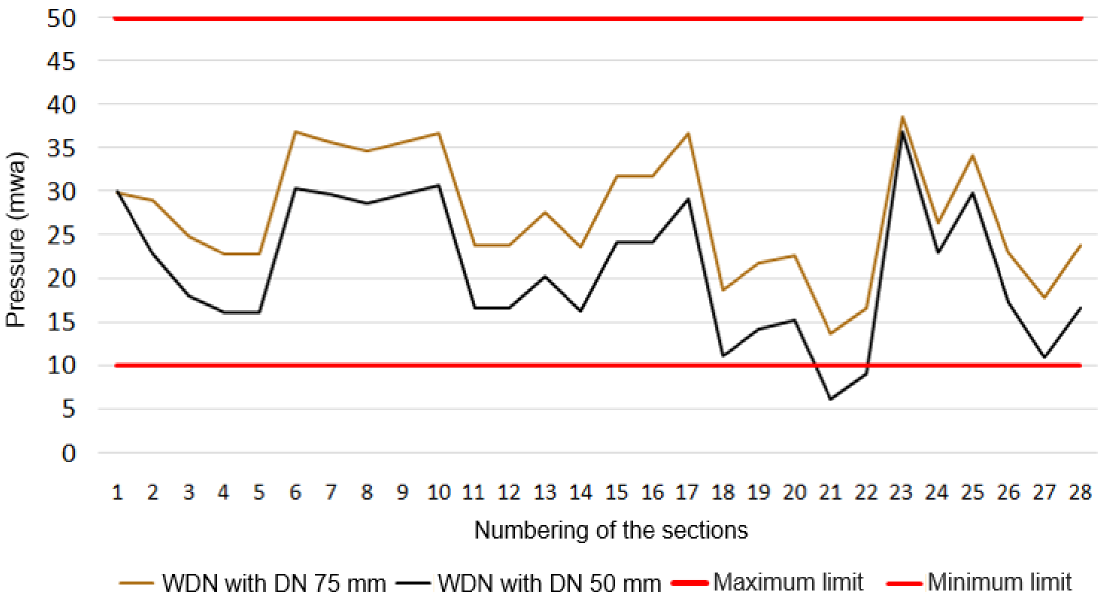
The pressure parameter was also adjusted by the change in diameter in the main pipe so that nodes 21 and 22, before with pressure less than 10 mwa, had their pressure values elevated and framed within the limit required by NBR 12.218/2017, as can be seen in the figures 5.6 and 5.7.

Figure 5.6: Graph of the pressure values at each node.



Source: Own elaboration, 2024.

Figure 5.7: Graph of the pressure values at each node.

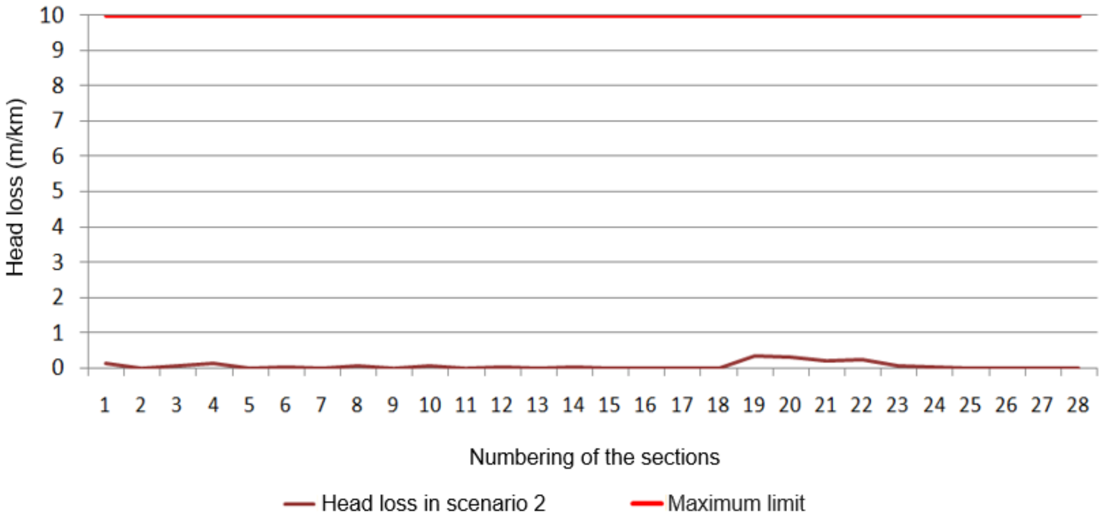


Source: Own elaboration, 2024.

5.2 Scenario 2: year 2024 and roughness of 135.

This scenario serves a population of 800 inhabitants whose total consumption flow is 1.67 l/s. The loss of load results remained below 10 m/km in all stretches, as shown in figure 5.8. It is noticed that the load loss was reduced by approximately 4% when compared to the first scenario, this can be justified by the increase in water consumption in WDN.

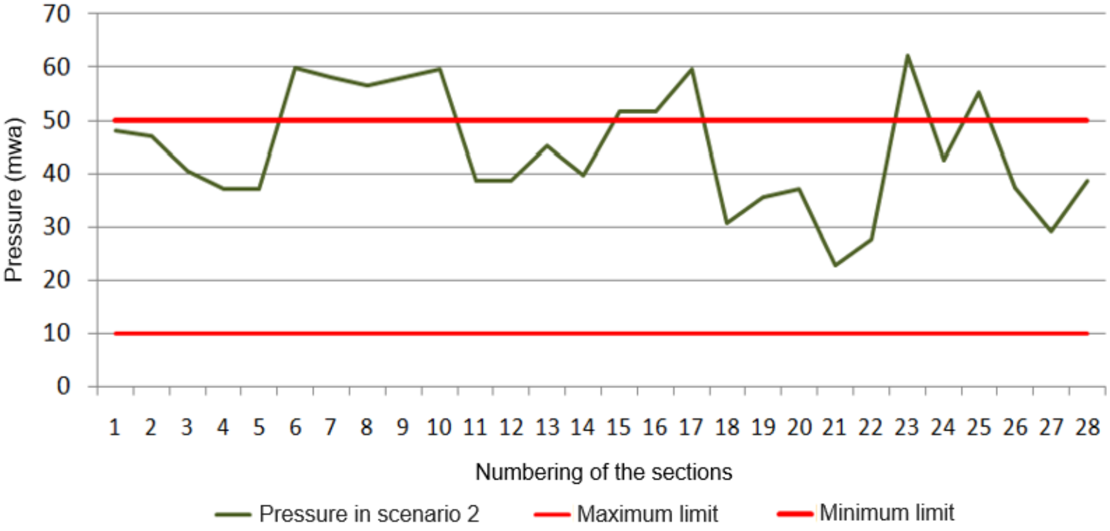
Figure 5.8: Chart of the values of loss of load in each section in scenario 2.



Source: Own elaboration, 2024.

In addition, there is an increase of the pressures in WDN caused by population increase and reduction of roughness. In this scenario, there were no pressures lower than 10 mwa. However, in some nodes the pressure was higher than 50 mwa. The pressure values for scenario 2 are represented in figure 5.9.

Figure 5.9: Graph of the pressure values at each node in scenario 2.

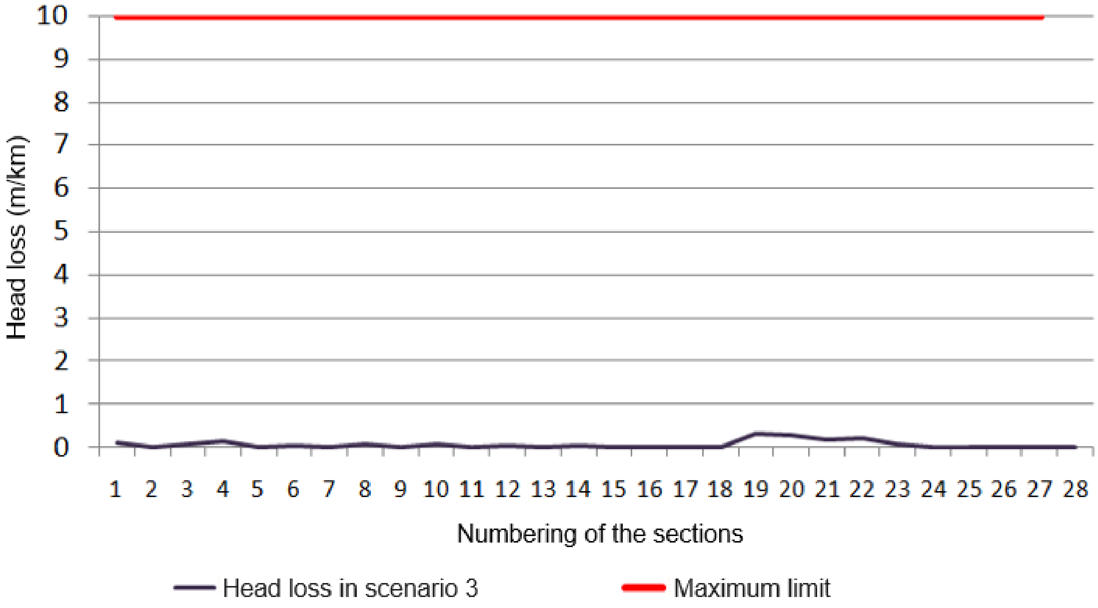


Source: Own elaboration, 2024.

5.3 Scenario 3: year 2044 and roughness of 130.

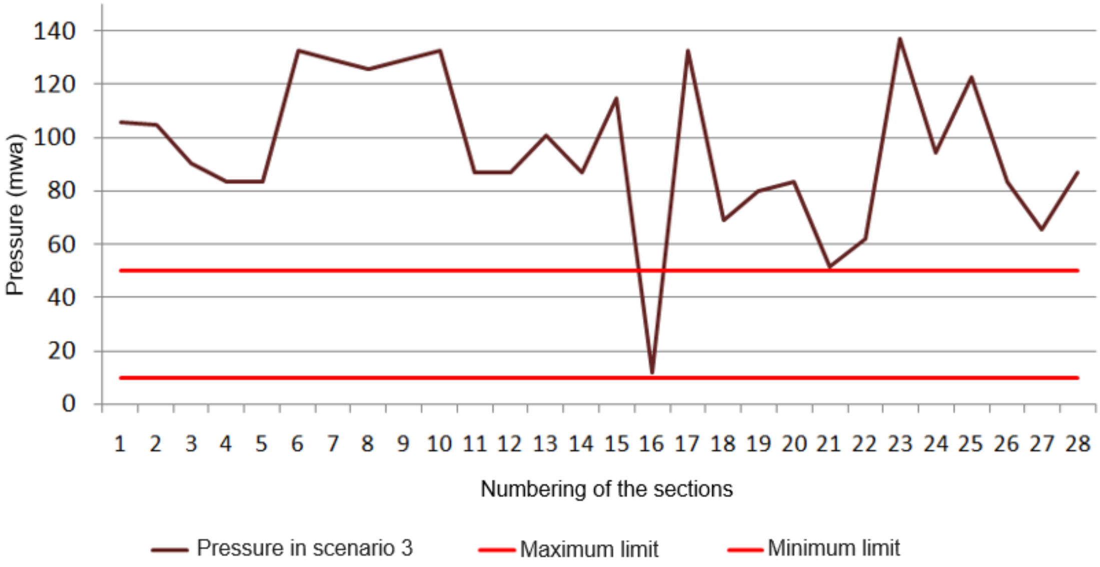
The estimated population of this scenario is 1,100 inhabitants. The flow rate required to meet this population is 2.3 l/s. In scenario 3, the pressure losses remained within the required limit, but with results 7.5% higher than in scenario 2. Already the pressure results were mostly above 50 mwa.

Figure 5.10: Chart of the values of loss of load in each section in scenario 3.



Source: Own elaboration, 2024.

Figure 5.11: Graph of the pressure values at each node in scenario 3.



Source: Own elaboration, 2024.

In this scenario it is exposed that when the roughness reaches the value of 130, an increase in load loss occurs. It is concluded that the roughness value at 130 has considerable influence on the hydraulic performance of WDN.

CHAPTER 6

Conclusion

In the study, the construction of a model to evaluate the hydraulic parameters pressure and loss of load in a WDN over 20 years, by the association of EPANET 2.0 and R tools, demonstrated good results for performance observation in WDNand identification of problems. EPANET 2.0 is versatile, dynamic and intuitive to assist in everyday situations and to represent any type of layout in the structure of WDN. R, in turn, provides a better statistical treatment of the data and allows to create varied scenarios. Therefore, they are tools with great potential for use in organizations and also for the development of studies in the academic environment, both for efficiency to generate technical information and for free, since they are free software.

In addition, it was found that the population increase and the reduction of roughness are the reasons for the rise of pressures on us of WDN. The loss of load parameter was slightly affected by the proposed modifications and only presented considerable results in the third scenario, in which the roughness had value 130. The diameters used in the base scenario did not meet the consumption required in 2034 and 2044, so they should be replaced by slightly higher commercial diameters. Thus, year 2034 the pipes with diameter of 75 mm shall be replaced by others with diameter of 100 mm e as tubulações com diâmetro de 50 mm, in turn, substutidas by pipes with diameter of 75 mm. In the year 2044, the change should be followed for larger diameters and in that year, the diameters of 100 mm will be substutided by pipes of diameter 150 mmand pipes with diameter 75 mm replaced by others with diameter 100 mm.

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CHAPTER 7

Apêndice A

Algoritmo 1 utilizado Codigo para interação entre R e EPANET

```
função simulação de rugosidade
entrada: $epanet2toolkit, epanetReader, magrittr, ggplot2$ {carrega biblioteca}
{definir semete para gerar números aleatórios}
{definir parâmetros (coeficiente de rugosidade, diâmetro, perda de carga e vazão)}
para cada $i \leftarrow 1$ até $j$ faça
    {calcula a perda de carga}
fim para
{Definir diretório de trabalho}
$ENepanet("arquivo.inp","arquivo.rpt")$
$read$ {Leitura dos arquivos .inp e .rpt}
$summary$ e $plot$ {Resumo e visualização dos dados}
$ENgetcount(“ENNODECOUNT”)$ {obter valores de pressão nos nós}
$ENgetcount(“ENLINKCOUNT”)$ {obter valores de pressão nos trechos}
{definir 1000 (mil) pontos para matriz de resultados}
$pressaoReferencia < -sapply(1 : numNo, function(node_i d), times \leftarrow ENgetnodevalue(node\_id,$EN_PRESSURE$)$
$tabCenario \leftarrow matrix(runif(numTubulacao * numTeste, min \leftarrow 100, max \leftarrow 150), nrow \leftarrow numTeste)$ {matriz de cenários}
$pressaoCenario \leftarrow matrix(0, nrow \leftarrow numTeste * numNo, ncol \leftarrow numNo)$ {matriz com resultados de pressão de cenário conforme aumento da rugosidade}
para $y \leftarrow 1$ até $\beta$ faça
    {calcula valores de rugosidade}
    $ENsetlinkvalue$ {definir valores de rugosidade}
    para $z \leftarrow 1$ até $\delta$ faça
        {matriz com reavaliação da pressão conforme as novas perdas de carga geradas pela variação da rugosidade}
    fim para
    {obter valores de erros absolutos nos nós}
    {obter valores de erros absolutos nos cenários}
    {obter valores de índice de cenário ótimo}
    {obter valores de cenários}
    $ENclose$ {execução fechamento da conexão com o EPANET}
    {grava valores de cenários}
    {grava valores das pressões do cenários}
fim função
```